Failure Atlas for Hertz Contact Machine Elements

Failure Atlas for Hertz Contact Machine Elements

Second Edition

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Preface to the First Edition

This Atlas is the product of four decades of photographic failure documentation relating to Hertz machine elements, assembled by numerous workers in the United States, Europe and Japan. The documentation was contributed to the Atlas by about thirty institutions and individuals. The exacting work of assembling the images in reproducible form and providing the data required for their use, was performed selflessly by all contributors. In addition, all contributors have reviewed the Plate material prepared from their inputs. Most of the contributions are identified in the Contributors list at the end of the book. A few institutions, for business reasons, have elected not to be explicitly acknowledged. The author's sincere gratitude is extended to them as to all others.

A full review of the draft manuscript for correctness in materials science interpretation was performed by Mr. George H. Baile, an independent consultant. Without his expert advice, errors in materials science interpretation may well have been unavoidable.

The contribution of all participants notwithstanding, responsibility for the technical content of the Atlas as a whole rests, of course, with the author.

Publication of the book is made possible by ASME Press, the book publishing arm of the American Society of Mechanical Engineers. Sincere thanks are due Ms. Caryl Dreiblatt, and the other editors of ASME press, whose flexibility, helpfulness and patience never flagged during the rather elaborate effort of publishing a volume as complex and specialized as this Atlas.

ASME and STLE, the Society of Tribologists and Lubrication Engineers, have both supported this work by their endorsement and willingness to place announcements seeking image sources in their journals.

I owe my wife more than I can say, for the many hours of meticulous labor spent in finalizing the manuscript with its image material, into a form suitable for publication.

Preface to the Second Edition

The Second Edition of this Atlas has been revised to accommodate information that became available since 1990, when the First Edition went to press. Additions were made to Chapters 6, 7, 10, 11, 13 and 18 for the purpose of including failures of vapor phase lubricated rolling bearings and Hertzian contact components made of silicon nitride ceramics. Additions were also made to Chapter 8 reflecting new information on galling and skidmarking failure, based on investigations performed on cam systems. One failure class (casting defects, FC 00.05) to which new material was added, is relocated from Chapter 5 to Chapter 6 which is now its more appropriate place. Refinements aimed at making text clearer, or reflecting developments in the understanding of failure mechanism, have been made in several other parts of the Atlas. A few new references were added. Some Failure Codes were added to cover newly illustrated failure modes. The changes and additions require the updating of all failure code lists, indexes, cross-references, and many Plate numbers, with the result that the entire Second Edition was newly typeset while reusing all existing image material from the First Edition.

Image material and text left unchanged is judged to remain valid as presented in the First Edition.

I wish to express my sincere appreciation to all contributors of new image material and related technical information, without whom the revisions would not have been possible; and to ASME Press who have found the Atlas useful enough to publish this Second Edition. My special thanks to Mr. John Corrigan and Ms. Tara Collins Smith, ASME Press editors, who have superintended the publishing of the Second Edition. The reception of the First Edition by the tribological community, which justified a Second Edition, is most gratifying. My debt of gratitude to my wife, acting as copy editor, remains the same as ever.

Part I
General Information

INTRODUCTION 1

1.1 STRUCTURE OF THE ATLAS

This Atlas is composed of two parts. Part I comprises the following chapters: Introduction, Failure Classification Codes, and Appearance Classification Tables. Part II consists of detailed image material showing failure morphologies and is arranged in a number of Plate chapters organized by failure modes.

More specifically, Part I. General Information, comprises the following:

Chapter 1. Introduction, comprises a review of background on diagnosis by failure morphology, relevant literature, general concepts of contact failure classification and distinguishing features of this Atlas.
Chapter 2. Failure Classification, describes the hierarchical classification code *(failure code, FC)* of failure modes: a decimal numbering system and text designation of each failure mode. The Atlas image material is organized around this failure classification. Numeric and alphabetic indexes of the failure codes are found in this chapter.
Chapter 3. Appearance Classification, contains several pages grouping failure modes by appearance as an aid in finding the Plate chapter appropriate to the observed failure.

Part II. Plates, is the main body of the book. It is composed of a series of chapters, each containing one or more sections consisting of image pages, called Plates, which illustrate one major failure class. Each chapter is introduced by a description of the *definition, failure process, appearance, causes* and *effect* of the failure mode(s) covered.

Indexing. As stated, the image material of the Atlas is indexed by failure code. *Cross-indexing* of failure modes is provided between Plates, as explained later in Chapter 1. *Text material*, including all of Part I and the *descriptions* introducing each chapter in Part II are indexed in the usual way by key words.

1.2 BACKGROUND

1.2.1 Definitions

1. Load-carrying moving contacts between machine elements exhibit peculiar *tribological* failure modes caused by time-variable stressing of the contact surfaces. *Concentrated* or *Hertz contacts* are characterized by their nonconforming geometry, high pressures, distinct contact materials and lubrication regimes, and exhibit a well-defined subset of these tribological failure modes.
2. A Hertz contact component is one featuring load-carrying Hertz contacts. A Hertz contact machine element is a complete subassembly of Hertz contact components and supporting (non-contact) components working together.
3. A failure mode is the physical condition of a component resulting from a specific physical failure process.
4. A (tribological) failure mode database for Hertz contact machine elements is an organized body of information on the failure modes of these elements and their engineering causes.
5. A failure *morphology atlas* is a failure mode database concentrating on topographic (visual) features of the failures, using images as a main data form, supplemented by a classification of

failures and concise descriptions of failed component, failure mode, and classes of likely engineering causes of failure. Images illustrating degrees, variants and combinations of failures are used for comparison with user-observed failures.

1.2.2 Application of Morphology Atlas for Diagnosis

Tribological engineering of Hertz contact machine elements (and of their applications) is aimed at the dual objectives of (a) achieving the function intended for the machine element; and (b) preventing, delaying or reducing any tribological failures.

Engineering for the desired *function* follows distinct principles for each of the major classes of Hertz contact machine elements such as gears, rolling bearings, traction drives, cams, etc. Engineering for *failure control* is, by contrast, based on much common ground, due to the commonality of contact failure modes, even though specific practices have evolved for each major machine element class. Owing to this commonality, it is possible to design technical aids for failure control engineering that serve most classes of Hertz contact machine elements.

Tribological failure control is highly empirical. It begins with the identification of operating conditions, such as geometry, load, speed, temperature, lubrication and environment. This is followed by the selection of a machine element design class with a history of successful service under the given operating conditions. Based on experience, a hierarchy of failure risks by failure mode is then established which leads to specific design, manufacturing and applications choices for the control of these risks according to their severity. In many cases, prevention of tribological failure throughout the desired useful life of the device cannot be assured with certainty, and choices of acceptable survival probabilities are made.

After building the device, it is tested either formally or through placement in service, and any failures are observed. They are diagnosed according to failure mode and cause, and modifications in machine element design, manufacturing process and application specifications are made until reliability and longevity objectives are met.

Tribological engineering for failure control requires precise diagnosis of failure modes and the identification of their engineering causes, as guides for corrective action in design, manufacturing and application engineering.

Data concerning tribological failures can be of many types. Examples are: statistical data on service life under spalling fatigue, wear rate data, formulas relating dimensional instability of steel to retained austenite, etc. A distinct data category is *morphological data*, defined as failure features that are visible by eye, by light microscope or by scanning electron microscope (SEM), or discernible by surface tracing or (micro)geometric measurement.

Hertz contact tribology diagnosis greatly depends on the recognition of the morphology of a failure. Such morphological diagnosis demands very specific experience, besides proper imaging and measurement facilities. An atlas of reference images with interpretation, representing, within reason, a complete catalog of failure morphologies correlated with the design, manufacturing and application parameters of the failed machine element, is a well recognized resource for training less experienced diagnosticians and in supporting the experienced diagnostician when confronted with a machine element or failure appearance outside their experience.

A morphology atlas differs from an illustrated textbook on failure diagnosis and supplements it. A *textbook* contains instructions on recovery of the component from the machine, cleaning, preservation, various examination techniques and record keeping methods. It may offer information on corrective engineering action following failure diagnosis. Illustrations in a textbook are limited to typical failures needed to support the verbal descriptions. A *morphology atlas,* on the other hand, provides a collection of failure images illustrating degrees, variants and combinations of failures in rich detail, to facilitate

matching the often untypical and complex *observed* failures. It thereby lends specificity to the diagnostic methods of the textbook. An atlas does not cover diagnostic methodology.

This Failure Atlas is, accordingly, an aid in the identification and diagnosis of failure modes and their causes. That, in turn, forms an integral part of failure control design and application engineering of Hertz contact machine elements.

1.2.3 Related Publications

Early publications describing tribological contact failure morphology were intended for service engineers and specialized in one of the two most common machine element classes (rolling bearings or gears). References [1][1] and [2] are manuals for rolling bearing diagnosis for service engineers. They are well illustrated and comprehensive, but do not interpret failure beyond the needs of service diagnosis, and do not classify failures to the depth necessary for detailed correlation with failure causes.

Similar, but proprietary, manuals have been published by many major manufacturers of Hertz contact machine elements, especially of bearings and gears.

Parallel with practical diagnostic purposes, interest in failure mode classification by morphology arose during research into machine element life prediction. As an example, classical rolling bearing life theory [3] is based on a study of spall formation from subsurface defects. Failure control research, with extensive use of morphological criteria, was later extended to the systematic classification of contact failure modes. (See, e.g., [4], [5], [6].) Even more than the previously listed manuals, these publications concentrate on the typical features of failures, and contain only enough illustrations to document the classifications made.

The *Rolling Bearing Damage Atlas* published in 1974 by Tallian et al. [7] was designed as a primary reference source of contact failure morphology for rolling bearings. It attempted to cover all tribological failure modes comprehensively in photographs, including macrographs, micrographs and SEM images. It contains a single-tier classification of failure modes but only terse descriptions of each failure and no specific cause correlations.

For gears, the American Gear Manufacturers Association publishes a failure nomenclature standard [8]. It is a narrative failure description with illustrations of typical failures, intended for primary failure identification. Some cause correlations are provided. A thorough practical textbook of failure diagnostics for gears is by Alban [9]. It contains extensive image material on failures with detailed tutorial diagnostic instructions, but no hierarchical classification.

Volume 11: "Failure Analysis and Prevention" of the *ASM Handbook* [10] contains wide ranging information on metallic material failures classified primarily by generic failure types and their causes. Separate chapters on rolling bearing failures and gear failures are also provided. These chapters contain narratives of failure description, with illustrations of typical failures.

Volume 18: "Friction, Lubrication and Wear Technology" of the *ASM Handbook* [11] contains a brief summary of rolling contact failures, with a few illustrations.

A tutorial text by Wulpi [12] covers a wide range of mechanical failures, in less detail than the *Metals Handbook*. Illustrations are of typical failures.

An atlas of metal surface damage shown in SEM images, including but not limited to Hertz contacts or to tribological failures, is Engel et al. [13]. This publication contains high-quality image material and clear scientific descriptions, but is not systematized around Hertz contacts.

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[1]Numbers in brackets cite references at the end of this book.

In chapters dealing with individual failure modes, references pertaining to the theory of these failure modes will be cited as required.

1.3 FEATURES OF THE ATLAS

1.3.1 New Features

This Atlas supplements other existing literature in several ways. First, it permits ready comparison with observed failures through copious illustration, not only of the most typical failures, but also of the commonly occurring degrees, variations and combinations of failures. It covers the major classes of Hertz contact machine elements, permitting observation of common failure characteristics. It also includes information on the failure of *supporting* (non-contact) components of the subassemblies to elucidate interactions among all failure modes.

Second, a *hierarchical* failure classification is provided for easy searching during practical diagnosis. This classification is several tiers deep. (Example: spalling in general, surface origin spalls, local surface origin spalls, defect origin spalls.) Failure classes are formalized by numeric *failure codes*, so that failure modes are unambiguously classified. Some advantages of such a system are:

- Users can trace a hierarchical search path to a specific morphological match fast and with a minimum of lost motion. (For instance, they can find an image showing a spall in a surface-distressed contact with multiple debris denting.)
- Ready access is provided to families of failure appearances classified by the specific feature under study. (For example, one can find all images containing signs of galling, whether it be the principal or an incidental failure mode.)
- Unambiguous cross-referencing of failure modes is available across several Plate chapters. Many Plates show composite failures. They are arranged in the Atlas by a *primary* failure mode, and also illustrate *secondary* failure modes via cross-reference tables in the appropriate chapters.
- Common causation chains operative over entire failure classes are documented.[2]
- Failure morphology is correlated with engineering failure causes by attaching a short list of causes to each failure illustration. The user can accumulate evidence for a given cause over several diagnostic matches. As an example: If surface distress and also overheating of contact surfaces are diagnosed, both of which correlate with inadequate lubrication, then this cause assignment gains support from both correlations.

In the Second Edition, new material has been included to illustrate the specific appearance of failures in ceramic contact materials and those characteristic of metallic materials lubricated by means other than organic fluids. Failure images and descriptions have been updated throughout the volume where new or better material became available.

1.3.2 Format of Image Pages

This section describes the machine element classification used in the Atlas and the format of the image pages. Two types of image pages are used in this Atlas: Appearance Classification pages and Plate pages classified by failure mode. (The failure classification system is described in Chapter 2.)

[2]A major strength of the numerical classification is its appropriateness for electronic search, making it well suited for a computerized diagnostic system, as well as for a book.

Machine Element Classification. This Atlas covers rolling bearings, gears and cams as the primary machine elements (subassemblies) featuring moving Hertz contacts. Traction drives are treated under bearings, drive chains and splines under gears. A group other machine elements is provided to capture machine elements not falling in these categories. Table 1.1 presents the abbreviations for machine elements and their components used in the Plate texts. (The machine element symbol always precedes the component symbol.)

Table 1.1 MACHINE ELEMENT CLASSIFICATION

Symbol	Machine Element	Symbol	Component
	Rolling Bearings		**Rolling Bearing Components**
B	Rolling bearing		Contact components:
BB	Ball bearing	IR	Innerring, shaft washer
DGBB	Deep groove ball bearing	OR	Outerring, housing washer
ACBB	Angular contact ball bearing	B	Ball
MCBB	Maximum complement ball bearing	R	Roller
SABB	Self-aligning ball bearing	G	Guiding component
ABB	Axial (thrust) ball bearing	C	Closure (seal, shield)
RB	Roller bearing	I	Integrated bearing unit
TRB	Taper roller bearing	M	Mounting part
CRB	Cylindrical roller bearing		
SRB	Spherical roller bearing		
NRB	Needle roller bearing		
TRTB	Taper roller thrust bearing		
SRTB	Spherical roller thrust bearing		
CRTB	Cylindrical roller thrust bearing		
LB	Linear bearing		
BSB	Ball screw		
RSB	Roller screw		
TDB	Traction drive		
	Gearing		**Gearing Components**
G	Gear		Contact components:
SG	Spur gear	P	Pinion
HG	Helical gear	W	Wheel (bull gear)
BG	Bevel gear	O	Worm
HYG	Hypoid gear	R	Rack
WG	Worm gear	C	Drive chain
SPG	Chain drive	S	Sprocket
RPG	Rack and pinion	M	Mounting part
SLG	Spline		
	Cam System		**Cam System Components**
C	Cam and follower		Contact components:
		CM	Cam
		CR	Cam follower roller
		CT	Tappet
	Clutch System		**Clutch System Components**
SC	Sprag clutch	SR	Sprag ring
		S	Sprag element
		M	Mounting part
O	**Other machine element**		

Appearance Classification (Chapter 3)

When diagnosticians first inspect a failed machine element, their primary guide to failure mode identification is the appearance of the failure. In tribological failures, it is not uncommon for very different failure classes to produce superficially similar failure appearances. This is one of the difficulties in tribological failure diagnosis. To facilitate the initial diagnostic orientation, the Atlas offers a chapter of images arranged by appearance class, that is, a brief collection of typical failure appearances. As far as the subject permits, appearance classes differ sharply from each other in failure appearance, whereas appearances that are apt to be confused are in one class. In this way, the user can find the right orientation page with little ambiguity, and can then use the distinctions offered by the several images on the page for differentiation between failure classes. Every effort was made to select illustrations of single failure modes (even though in diagnostic practice, multiple failure modes are common). All images in Chapter 3 are selected from Plate chapters.

Each failure class identified within an Appearance Class is referenced to a chapter of Plates, devoted to that class.

Note: Images are not provided in the appearance classification chapter for failures that are self-classifying by their nature. For example, bearing separator failures are all found in one Plate chapter, as are shaft failures. Therefore, neither is illustrated in Chapter 3. For completeness, the failure classes not illustrated in the Appearance Classification are still listed there by name.

The format for Appearance Classification used in Chapter 3 is described as follows:

Class header. An *appearance class* is printed consecutively on one or more pages. At the head of each appearance class is the *class header*, consisting of:

- *Appearance class name:* The name of the appearance class in capital letters. Example: ''PLOWING MARK.''
- *Appearance description:* A line of text giving the distinguishing features of appearance for the class. Example: ''Depressed line defect from material removal by plowing action.''

Appearance illustrations. A series of images with descriptive text, identifying the several failure modes that show an appearance falling within the appearance class. In detail:

- *Failure code and mode:* The numeric and text designation of the illustrated failure mode according to the Failure Code classification described in Chapter 2. Example: ''FC 00.02: Finishing mark (furrow, chatter, wheelhit).''
- *Appearance:* A line of text giving the distinguishing features and typical causation of the failure mode. Example: ''Scratch mark by injury during assembly or mounting.''
- *Images:* A line captioned 'Archive No' and one captioned 'Plate No' defined in the same way as for Plate pages (see Section 1.3.2.3). Examples: ''Archive No: 080-101,'' ''Plate No: 5.11.''

An image accompanies most of the Appearance Illustration entries. When there is no illustration, an explanation is provided. Example: ''Shown under 'general texture change.' ''

Plate Chapters (Part II)

In this Atlas, the failure images with descriptive text, classified by failure mode, making up Part II are designated as *Plate*s. A chapter of Plates illustrates one or more *primary* failure modes, each of which occupies a section. Secondary failure modes may also be present in the Plates, and if so, are identified in the text. Plates in a section differ in the specific principal failure mode shown (within the section class), the severity of failure within a given mode, the accompanying secondary failure

mode, the presentation (imaging) of the failure, or the appearance of failure as it may vary within a given mode. Each chapter and section is indexed by the Failure Code of the failure class described in it.

Chapters start with descriptive text, defining each of the failure classes illustrated in a section of that chapter (with differentiation criteria among subordinated failure modes). The description gives *definition, nomenclature, failure process,* likely *failure causes* and principal *effects.*

Next follows a Cross-Index of Secondary Failure Codes. It lists the Plate numbers in *any chapter* that feature secondary failure codes falling within the failure class of the chapter at hand. Such Plates can serve to augment the collection of failure illustrations in this chapter.

Finally, the body of the chapter is composed of the Plates, each of which contains a failure image, accompanied by interpretive text.

Note: A Plate chapter (or section) covers *one* failure class, but *all* machine elements in which it occurs. As an example, Chapter 00.12: Wear (of Hertz contact components) includes bearing ring wear, gear wear and cam wear, but not shaft wear, because a shaft is not a Hertz contact component. Shaft wear is found in Section 2.2 Shafts.

Plate Format Description

Each Plate consists of three main parts: Images, Data and Descriptions. The images are one or more related photographs illustrating the same failure mode. The data comprise quantitative information describing the illustrated failure and the imaging process, as well as four failure codes. Descriptions are given for the failure mode, the image appearance and suspected failure causes. One or more Plates may occupy a book page; if there is more than one, they are separated by a heavy line.

Page Header. Each Plate page carries a header with the failure code of the Plate(s) shown on that page near the binding. The chapter title in the header is near the outside page edge. The failure code(s) are copied from the *primary code* of each Plate on that page, as defined below, and serve as the principal Plate look-up coding of the Atlas. The appearance classification in Chapter 3 and the failure code in Chapter 2, both refer to this Plate coding. Each page header also carries the book page number, as referenced in the Table of Contents.

Image(s). The *image(s)* are printed near the top of each Plate. If there is more than one, the images are identified as (a), (b), etc.

Data. *Plate No.* locates the Plate in the book. A Plate number has two parts, such as 11.25. The first part is the chapter number, the second part is the serial number of the Plate within that chapter. Plate numbers are used for cross-referencing between Plates. (See Section 1.3.4 for detail.)

Archive No. is a two-part number, such as 066-001, and identifies the image(s) on the Plate in the master image archive. These numbers are used to give source credit for image material.

Image type can be:

- *View*—black/white or color view of an entire component.
- *Light macro or color macro*—a slightly magnified or demagnified image of part of a component.
- *Light microgram*—black/white image at substantial magnification.
- *Light metallogram*—microgram of a metallographic section, etched or unetched.
- *SEM*—scanning electron microgram. Secondary electron images are not identified. Backscatter images are so marked.
- *TEM*—transmission electron microgram (of thin film or replica, as indicated).

Color images are located in a separate Appendix, 'Color Images,' where they are identified by Plate number. In place of the image on the Plate, a reference appears, stating: ''See image in Appendix.'' If there is more than one image per Plate, each is identified by (a), (b), etc., and each is described.

Scalebar = . . . mm means that the length of the bar drawn on the image equals . . . mm on the original object. These lengths are given either in millimeters (mm) or micrometers (μm). If there is more than one image, a scalebar value, identified by (a), (b), etc., is given for each.

Image sources do not always indicate scales of views and macro images. Scales of micrographs are generally (but not always) available. Due to this uncertainty, scales given are *informational* only. An error range of ±20% for micros, and +100%, −50% for other images is indicated on all Plates as a precaution. These ranges are quite conservative for most Plates.

Component is the (coded) designation of the machine element and its parts shown on the image, with indication of material condition (if relevant) and whether the part was in service (run). The machine element classification code and the parts code are taken from Table 1.1.

Speed, load and lubrication are given for parts that were in service, if this information was received from the image source. This information is useful in placing the failure in perspective, but not strictly *necessary* to the diagnosis. It must be borne in mind that even where the information is available, it may represent *typical* rather than failure-specific values. The definition of these parameters is as follows:

Speed is a linear surface speed, where available. Speed-related failures generally correlate with peak speed in service, but that value is often unavailable.

- For rolling bearings, the simple measure used is *dN* [mm·r/min], i.e., the bore diameter of the inner ring in mm, multiplied by the shaft speed in revolutions per minute ($KdN = 10^3\ dN$, $MdN = 10^6\ dN$). The measure Nd_m, where the rolling element pitch circle diameter is substituted for the bore diameter, is the more modern usage, but this information is not widely enough available for the failure illustrations collected for this Atlas, to be used. Occasionally, only speed of rotation in r/min is available and is given.
- For gears and cams, *linear rolling speed* [m/sec] (at the pitchline for gears) is used.

Load for all *contact* components is the *normal contact pressure* [GPa]. No meaningful load value can be generalized for non-contact components.

Lubrication is described by two elements: the *lubricant type* and a typical *operating temperature* [C°].

- *Lubricant type* is described generically. Examples: mineral oil, synthetic polyester oil, lithium-thickened mineral oil base grease, etc. Often, however, only the major class is known, such as grease.
- *Temperature* is the typical bulk temperature (sustained maximum temperature) of the component. In failures where temperature rise is produced, the temperature given is that *before onset of failure.* Again, typical temperature is often unknown.

Failure code consists of the numerical code and text designation detailed in Chapter 2. Room is provided for four distinct failure codes to accommodate composite failures. The four codes are ordered generally by their prominence on the image shown (not the order of their importance to the serviceability of the component or their sequence of occurrence). This ordering is somewhat loose, and great weight should not be attached to it in reading the Plates. The sequence, relative importance and mutual interaction of failure events is discussed thoroughly in the Description part of the Plate text.

''*See also* PLATES'' is a cross-reference to other Plates in the Atlas, which are related to or help illuminate the contents of the present Plate.

Descriptions. The Descriptions are narrative statements explaining the failure illustrated. Uniform terminology for a given failure is attempted for bearings, gears and cams. This may make the nomenclature appear unusual to some readers. Comments regarding failure mode terminology are in the Introduction of Chapter 2, and in the Nomenclature paragraph of the General Description in each Plate chapter. There, the terminology used in the Atlas is correlated with that customary for the various machine elements.

Failure Description. This is the central statement of failure diagnosis. The failure modes are described in terms of the physical failure process. A statement is made about the serviceability of the component under further running, and its likely final failure, if expected on the basis of its observed condition.

Image Description. Diagnostic image features (those which serve to diagnose a failure) are pointed out and described. The "map convention" is adopted for *orientation* on the image. The upper edge of the image is Image North (N); compass points are used as on a map. Left or right, and up or down are avoided in designating direction on the image plane. In describing *position* on the image, fractions of image size are used. A point one quarter of the way to the right of the left-hand edge is 1/4 E of W image edge. These conventions may appear contrived, but they are unambiguous. If there is more than one image on a Plate, each is referenced by (a), (b), etc., and each is described.

Suspected Causes. This paragraph identifies engineering causes that may lead to the diagnosed failure. Examples: service speed, load, manufacturing process. As is well known, too many possible causes exist for any given failure to present an exhaustive discussion on each Plate. The *actual* failure cause is listed on the Plate, wherever the source data include it. In addition (or when actual failure causes are unknown), *most likely* causes are identified. More detailed discussion of failure causes for an entire failure class is found in the General Description in each Plate chapter. If there is more than one image on a Plate, each is identified with a lowercase letter and is described.

Sorting Order of Plates

The order of Plates within each chapter is as follows:

- The primary sorting key is Failure Code 1 (FC 1). Failure codes are sorted strictly in the order listed in the Failure Code list at the end of the Atlas.
- Plates with identical FC 1 are sorted by their FC 2, then FC 3 and then FC 4, if they exist.
- Plates for which all existing failure codes are identical (of which not many occur) are sorted in arbitrary order.
- Once established, the sorting order of the Plates is fixed by their sequential Plate No.

1.3.3 Failure Mode Grouping

The detailed classification of failures used in this Atlas is contained in the Failure Code presented in Chapter 2. The classes are broad, so as to encompass all of the machine element types covered in the Atlas. Of course, all failure classes do *not* occur on all machine element types.

An overview of the arrangement of the Atlas by failure grouping is given in the list of Plate chapter titles in Table 1.2.

1.3.4 Cross-Indexing of Failure Modes

Because each Plate carries up to four failure codes, it can serve as an illustration for more than one failure mode. Each Plate is placed in the chapter corresponding to the *first (primary)* code. It can be found through each of its secondary failure codes by referring to a cross-index located after the General Description in the Plate chapter for the failure class sought. The cross-index lists all Plates carrying a failure code within that chapter's class, giving the specific failure code on the Plate that falls into the chapter's class, and the Plate number.

Table 1.2 LIST OF PLATE CHAPTERS

Chapter No.	Chapter Code	Chapter Title (failure class)	Page No.
		Contact part failures	
4	00.01	Nicks	41
5	00.02–04	Surface defects from manufacturing	51
6	00.05–09	Material and assembly defects	71
7	00.12	Mild wear	109
8	00.13–14	Galling, skidmarking	139
9	00.15	Fretting wear	163
10	00.16	Spalling	179
11	00.17	Surface distress	233
12	00.18	Denting	255
13	00.19	Heat imbalance failure	277
14	00.20–21	Corrosion, electric erosion	293
15	00.22–23	Bulk cracking, fracture, permanent deformation	313
16	01.1–2	*Guiding component failure*	349
17	02	*Integral closure failure*	381
18	1	*Lubricant failure*	389
19	2	*Mounting part failure*	423

FAILURE CLASSIFICATION 2

This chapter presents the formal failure classification system ('failure code', abbreviated 'FC') by which the Atlas is structured.

2.1 DEFINITION OF FAILURE AND NOMENCLATURE USAGE

In this Atlas, the word 'failure' *specifically* refers to damage occurring in service. The word 'defect' is used *specifically* for an off-specification condition or damage predating service. The Atlas covers both defects and failures. Where this distinction is irrelevant, 'failure' (occasionally, the word 'damage') is used in the broad sense to cover both conditions.

The failure code (both numeric and text) describing failure classes in this Atlas is applied consistently across the several Hertz contact machine element classes. Because industry designations for failures of bearings, gears and cams often differ and nomenclature variants abound even within one industry, general descriptions to each Plate chapter list the most common nomenclature alternatives for the major failure classes. Plate descriptions, however, adhere for uniformity to the designations in the formal failure classification code. The physical process causing each major failure class (failure process) is used for the brief definitions in the tables that follow in this chapter. Additional discussion of failure mechanism as well as differentiation within classes is provided in the general description in the Plate chapters and on the Plate pages showing individual failure modes.

There are occasional differences of view among tribologists regarding the failure mechanism of individual failure classes. As an example, the failure class designated '00.17: Surface distress (surface fatigue)' is considered in this Atlas to be peculiar to rolling contacts and is identified as asperity scale plastic flow brought on by high normal stresses and followed by asperity scale fatigue cracking and microspalling. Some authors designate it 'fatigue wear'. This designation is avoided in this Atlas, because the term 'wear' is reserved for surface material removal by tractive stresses arising in sliding. Where such differences are recognized, they will be commented upon.

2.2 FAILURE CLASSIFICATION SYSTEM

The Failure code classification system of morphological defects is an adaptation of the decimal classification principle. It is hierarchical and coded by groups of one or two numerals, with groups separated by periods.

The classification is aimed at morphological failures, i.e., failures (defects) detectable by examination of surface topography (after suitable preparation). Other types of defects, such as dimensional errors, material structure deviations, chemical deviations or residual stresses, are covered only in their morphological manifestations.

The aim of this Atlas is completeness in classifying morphological failures of contact components, guiding-components, integral seals, and lubricants, but not in classifying mounting parts. Accordingly, the detail of coverage for the former group is limited by available data only, whereas detail of coverage for mounting parts has been limited to that believed necessary in elucidating fully covered failures. Of course, many, if not most, lubricant failures, especially oil failures, are not morphological, so that the Atlas failure coding does not approach completeness in classifying lubricant failures. Also notable is the regrettable scarcity of image material on integral seal failures.

Counting code groups from the left to the right, the following coding rules apply: Group 1 designates the component function in relation to the load carrying Hertz contact. Groups 2 and higher describe progressively more detailed failure classes and failure modes applicable to the component specified in Group 1.

The present chapter offers definitions of the main failure classes and lists that are useful as indexes for failure code lookup. Specifically:

1. Group 1 and (in most cases) Group 2 cover the Main Failure Classes. They are listed in numerical order and defined in Section 2.3 of this chapter. Much additional detail is found in the General Description in each Plate chapter.
2. Complete lists of the classification including all group orders are presented in Sections 2.4 through 2.6 of this chapter. Details of definition of the classification criteria for these lower-order groups can be gleaned from the failure descriptions on each Plate page, where they are readily associated with the morphology of each failure mode.

Table 2.1 enumerates the Failure Code lists and indexes contained in the Atlas.

Table 2.1 FAILURE CODE INDEXES

List Title	Content
Failure class list	Listing, with interpretation, of major (1 or 2 code group) failure classes.
Failure code list	Listing of all failure modes in numerical code order.
Failure class index	Alphabetic index of major (1 or 2 code group) failure classes.
Failure mode index	Alphabetic index of all failure modes, grouped by class.

2.3 FAILURE CLASS LIST

2.3.1 Component Function

Table 2.2 COMPONENT CLASS CODES

Group No.	Digits	Classification Basis
1	1 or 2	Component type

LISTING OF GROUPS

Failure Code	Component Function	Example
00	Hertz contact component	Bearing ring, ball, gear, cam
01	Guiding-component	Bearing retainer, guidering
02	Integral closure	Integral seal, shield
1	Lubricant	Oil, grease, other lubricant
2	Mounting part	Shaft, spacer, housing, locknut

2.3.2 Hertz Contact Component Failure

The components sustaining (rolling) Hertz contact are typically (relatively) hard, and highly and cyclically stressed. Normal surface pressures dominate, with tractive stresses dependent on degree of sliding. The surfaces are typically ground (or finely cut as in some gears) and may be superfinished by polishing or honing. These components show several unique failure modes, with major classes listed in Tables 2.3–2.8.

Table 2.3 FAILURE CODE GROUP 2: CONTACT COMPONENT MANUFACTURING DEFECT

Group No.	Digits	Classification Basis
2	1 or 2	Major failure class

LISTING OF GROUPS

Failure Code	Major Failure Class	Definition
00.0. . .	Manufacturing or assembly defect	Defects from manufacturing, assembly or mounting but *prior to service.*
0.00	Manufacturing or assembly defect, by location	Qualifier used in conjunction with other codes, to identify defect location.
00.01	Nick	Surface indentation from a sharp object pressed, impacted or moved across surface, *prior to service*
00.02	Finishing mark	Unintended surface mark caused by finish machining
00.03	Pit or unfinished area	Surface cratering *prior to service* or surface missed in a finishing operation
00.04	Forming defect	Forming (forging, pressing) defect within the material
00.05	Casting defect	Casting, molding, sintering defect within the material
00.06	Inclusion	Particle of extraneous material in the matrix.
00.07	Material structure defect pre- or in heat treatment	Deviations from specified material structure incurred prior to or during heat treatment (e.g.: heat treat errors, off-specification structure, visible retained austenite, defective ceramic binder, forging or heat treat stress origin crack).
00.08	Material structure damage, post-heat treatment	Structural change, including cracking in near-surface material due to defective hard finishing.
00.09	Geometry, assembly or mounting defect	Manufacturing error of geometry, scoring, galling, cracking in assembly.

Table 2.4 FAILURE CODE GROUP 2: CONTACT COMPONENT SERVICE FAILURE

Group No.	Digits	Classification Basis
2	1 or 2	Major failure class

LISTING OF GROUPS

Failure Code	Major Failure Class	Definition
00.1. . .–00.2. . .	Service failure, contact part	Failures arising *in service,* including machine shipment and storage.
00.12	Wear, mild	"Mild" mechanical wear. Adhesive or abrasive surface material removal through tractive forces in (sliding) contact, without macroscopic material transfer.
00.13	Galling (smearing, severe mechanical wear)	"Severe" mechanical wear. Macroscopic surface material transfer through tractive forces in (sliding) contact.
00.14	Skid marking (microscopic severe wear)	Microscopic severe wear (from high acceleration of free element).
00.15	Fretting wear	Material removal (and oxidation) through microscale vibratory motion.
00.16	Spalling (Hertzian contact fatigue)	Hertz contact fatigue failure through macroscopic surface crater formation from cracks driven by Hertz stress fields extending to macroscopic subsurface depths.
00.17	Surface distress (surface fatigue)	Fatigue failure of surface material in asperity dimensions, through microscopic surface plastic flow followed by microspall formation driven by Hertz stress fields extending to asperity dimensions.
00.18	Denting (indentation)	Local plastic depressions (points or lines) on contact surfaces *in service,* by hard edges, asperities or contaminants pressed into and/or rolled over the surface.
00.19	Heat imbalance failure	Plastic flow and/or chemical damage to component by (local) overheating.
00.20	Corrosion	Pits, stains or structural attack on surfaces by aggressive chemical environment.
00.21	Electric erosion	Macro or micro-cratering by local melting from electric current passing through Hertz contact.
00.22	Cracking or fracture, bulk	Crack formation with or without part separation, from bulk stresses other than Hertzian. Includes bulk fatigue, residual-stress cracking, thermal cracking, cracking from chemical attack in service.
00.23	Permanent deformation, bulk	Permanent bulk change from as-manufactured dimension or shape by plastic deformation or structure change.

2.3.3 Guiding-Component Failure

Table 2.5 FAILURE CODE GROUPS 1 AND 2: GUIDING-COMPONENT FAILURE

Group No.	Digits	Classification Basis
1	2	Component class
2	2	Specific component and major failure class

LISTING OF GROUPS

Atlas Code	Major Failure Class	Definition
01. . .	Guiding-part failure	Manufacturing or service failure of (bearing) guiding component.
01.1. . .	Separator failure	Separator failure from manufacture or service.
01.10	Separator manufacturing geometry defect	Separator geometry off-specification, as manufactured.
01.11	Separator bulk defect	Fracture, cracking, weld failure of metal or plastic component, melting of plastic component.
01.12	Separator plastic deformation	Permanent deformation of separator.
01.13	Separator wear	"Mild" wear of separator.
01.14	Separator galling	"Severe" wear (galling) of separator.
01.15	Separator corrosion	Chemical surface attack on separator.
01.16	Separator heat imbalance failure	Plastic flow and/or chemical change in separator from (local) overheating.
01.17	Separator contact spalling	Hertz contact fatigue failure in separator by macroscopic surface cratering.
01.2. . .	Guidering failure	Guidering material defect, fracture, wear, galling.

Note: See Sections 2.4 and 2.6 for detailed listing of failure modes of guiderings.

2.3.4 Integral Closure Failure

Table 2.6 FAILURE CODE GROUPS 1 AND 2: INTEGRAL CLOSURE FAILURE

Group No.	Digits	Classification Basis
1	2	Component class
2	2	Specific component and major failure class

LISTING OF GROUPS

Failure Code	Major Failure Class	Definition
02. . .	Seal (integral), failure	Defect of integral seals
02.1. . .	Rubbing-seal defect	Defects of contact seals as listed below.
02.10	Material or manufacturing defect in rubbing seal	Morphological defects arising prior to service.
02.11	Rubbing seal wear	Mild wear of seal in service.
02.12	Torn rubbing seal lip	Tear of elastomer seal lip.
02.13	Rubbing seal counterface wear	Wear on (metal) surface against which seal lip slides.
02.14	Rubbing seal leak	Lubricant retention or contaminant exclusion defect.
02.15	Chemical attack on rubbing seal	Chemical attack on elastomer lips or structural parts.
02.19	Geometry or assembly defect in rubbing seal	Geometry defect from manufacture or suffered in assembly.
002.2. . .	Non-rubbing closure defect	Unintended contact in closure, corrosion, leakage.

2.3.5 Lubricant Failure

Table 2.7 ATLAS CODE GROUP 1: LUBRICANT FAILURE

Group No.	Digits	Classification Basis
1	2	Lubricant type

LISTING OF GROUPS

Failure Code	Component Type	Definition
1. . .	Lubricant failure	Failure of any lubricant.
11	Oil failure	Failure of liquid organic lubricant.
12	Grease failure	Failure of semi-solid lubricant with organic base oil.
13	Solid, composite, vapor or gas lubricant failure	Failure of solid lubricant, liquid lubricant in porous or solid gel matrix, vapor phase, gas, water or cryo-fluid lubricant, etc.

Note: See Sections 2.4 and 2.6 for listing of failure modes of lubricants.

2.3.6 Mounting Part Failure

Table 2.8 FAILURE CODE GROUP 1: MOUNTING PART FAILURE

Group No.	Digits	Classification Basis
1	2	Mounting part type

LISTING OF GROUPS

Failure Code	Major Failure Class	Definition
2...	Mounting part damage	Failure of any mounting part.
21	Housing damage	Failure of housing as mounting part (e.g., for bearing).
22	Shaft damage	Failure of shaft, integral or mounted.
23	Spacer, shoulder damage	Failure of ring-shaped spacing element (*not* contact part) in housing or on shaft.
24	Mounting sleeve, nut, lockwasher damage	Failure of fastening element.
25	Seal (external), failure	Failure of seal (other than integral bearing seal).
26	Support bearing damage (of gear, cam)	Failure of support bearing in gear or cam assembly.

Note: See Sections 2.4 and 2.6 for listing of failure modes of mounting parts.

2.4 FAILURE CODE LIST

The Failure Code list at the end of this book enumerates all assigned Failure Codes and the corresponding text designations. The list is in ascending order of numeric failure code and serves to find the text designation when the numeric code is known. Owing to the hierarchical structure of the code, this list keeps failure modes in logical relational order and thus offers a perspective of the code system structure. Plates in Part II are indexed by their primary failure code (Failure Code 1).

Some failure codes are included for completeness, even though no illustration is available for the corresponding failure mode.

Although the text designation for each failure mode attempts to be self-contained, reference to the hierarchically superior failure classes is helpful in placing the failure mode in context.

2.5 FAILURE CLASS INDEX

The brief list in this Section enumerates the major failure classes in ascending alphabetic order of their text designation. It is a useful overview of existing major failure classes.

Table 2.9 FAILURE CLASS INDEX

Failure Designation	Failure Code
Contact Part Failure	**00**
Casting defect	00.05
Corrosion	00.20
Cracking or fracture, bulk	00.22
Denting (indentation)	00.18
Electric erosion	00.21
Finishing mark	00.02
Forming defect	00.04
Fretting wear	00.15
Galling (smearing, severe mechanical wear)	00.13
Geometry, assembly or mounting defect	00.09
Heat imbalance failure	00.19
Inclusion	00.06
Manufacturing or assembly defect, by location	00.00
Material structure damage, post-heat treatment	00.08
Material structure defect, pre- or in heat treatment	00.07
Nick	00.01
Permanent deformation, bulk	00.23
Pit or unfinished area	00.03
Skidmarking (microscopic severe wear)	00.14
Spalling (Hertzian contact fatigue)	00.16
Surface distress (surface fatigue)	00.17
Wear, mild	00.12
Guiding-Part Failure	**01**
Lubricant Failure	**1**
Grease failure	12
Oil failure	11
Solid, vapor or gas lubricant failure	13
Mounting Part Damage	**2**
Housing damage	21
Mounting sleeve, nut, lockwasher damage	24
Seal (external), failure	25
Shaft damage	22
Spacer, shoulder damage	23
Support bearing damage (of gear, cam)	26
Seal (Integral), Failure	**02**

2.6 FAILURE MODE INDEX

An alphabetic index of failure mode designations, with attached numeric failure codes is at the end of this book. The index is alphabetized in two tiers: (a) alphabetized headings for the major failure classes, and (b) alphabetized entries for each failure mode in that class. This is the main index of failure mode designations. It is used to look up the image material related to a failure mode of known designation. First, one finds the numeric code assigned for the failure mode in the index, and then one looks up the Plate chapter or individual Plates using the code.

A grouped list rather than a single-level alphabetic index is provided because lookup of a failure mode by its designation proceeds logically in two steps: (1) find the failure class, and (2) find the specific failure mode therein.

The alphabetized failure mode designations are identical with those in the numeric list of Failure Codes cited in Section 2.4.

APPEARANCE CLASSIFICATION 3

Arrangement

This chapter classifies failure images by *appearance*. This differs from the principal classification of the Atlas, which is by failure mode. Having located the appearance class of the observed failure on a page of this chapter, the user finds, alongside the image, the failure code(s) under which similar appearances can be found in the Plate chapters.

The principal distinguishing marks of appearance are the changes they produce in the as-manufactured surface (or the material section produced for examination).

The layout of this chapter is, briefly, as follows. (See also the detailed description of Chapter 3 page formats given in Chapter 1):

- The chapter consists of Sections, each covering a major appearance category as listed in Table 3.1.
- Within each section are class headers, naming an appearance class and describing its appearance.
- Under each class header, individual failure modes are illustrated with images and explained in text.

In this chapter, the failed part is not specifically named if it is a contact component. However, guiding components, seals, and mounting parts are specifically named.

Table 3.1 APPEARANCE CATEGORIES

Type of Change	Explanation
	Wide Area Failure
General surface removal	Surface uniformly ablated (wear or etching) or deformed (rolldown)
General surface texture change	Discoloration, film deposit, polishing, unfinished surface
Material change	Softening, decomposition, consistency change, structure defect
	Point or Line Failure
Material locally removed	Pit, crater, gouge, electric erosion, false brinnelling
Material locally deformed	Nick, dent, line
Material transferred	Galling, skidmarking, welding
Material separation	Fracture, cracking, seam, lap
Material defect	Casting defect, forming defect, finishing damage
Foreign material	Inclusion, contamination
	Geometry Failure
Dimension error	Manufacturing tolerance error, dimension instability
Distortion	Plastic deformation, residual stress, mounting error

3.1 WIDE AREA FAILURE

GENERAL SURFACE DISPLACEMENT
Original surface material displaced

FC 00.12: Wear
Finished topography removed, Metallic.
Shown under General Texture Change.

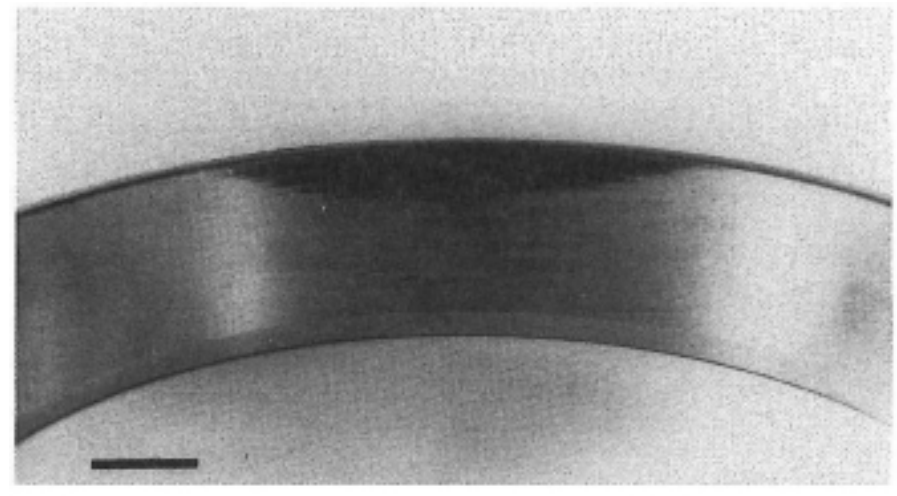
FC 00.19: Heat Imbalance Failure
Plastic flow, surface discolored.
Shown under General Texture Change.

FC 00.15: Fretting
Worn surface, with rust-colored deposit.
Shown under General Texture Change.

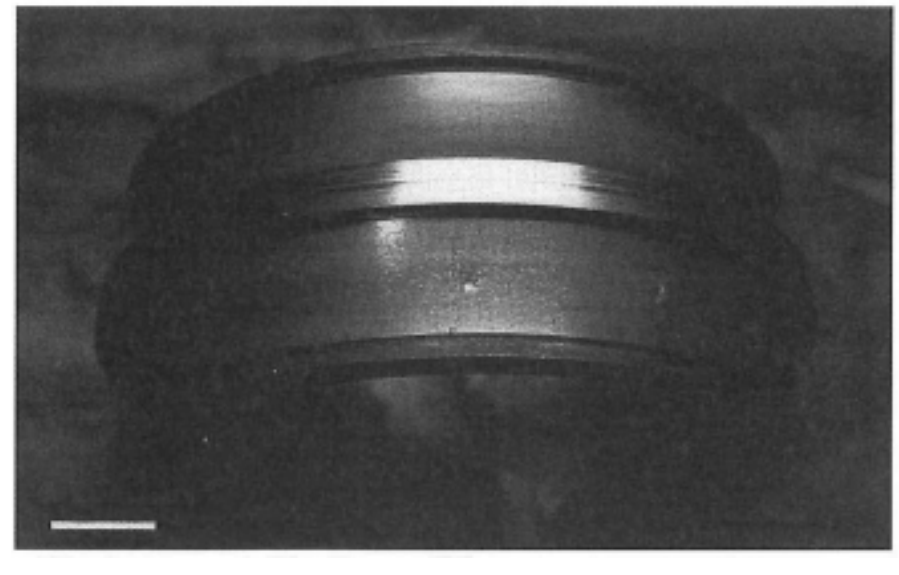
FC 00.23: Plastic Deformation
Cold plastic flow.
Not illustrated.

GENERAL TEXTURE CHANGE
Finishing marks, luster or color changed

FC 00.03: Unfinished Area
Surface carries the finishing marks of the next-to-last operation.
Archive: 093-3.1.4
Plate No: 5.16

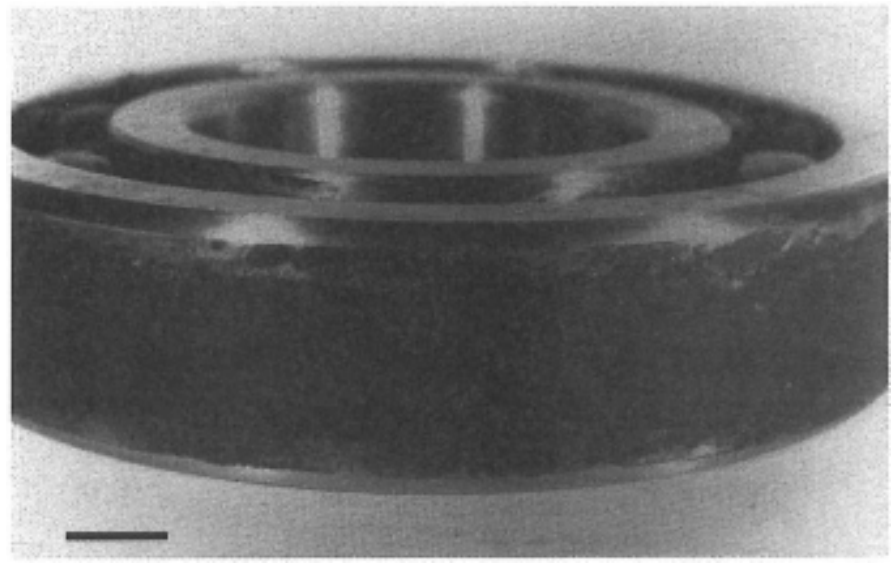


FC 00.12: Wear
Partially or totally replaces original finishing marks with wear-marked texture.
Archive: 087-036
Plate No: 7.8

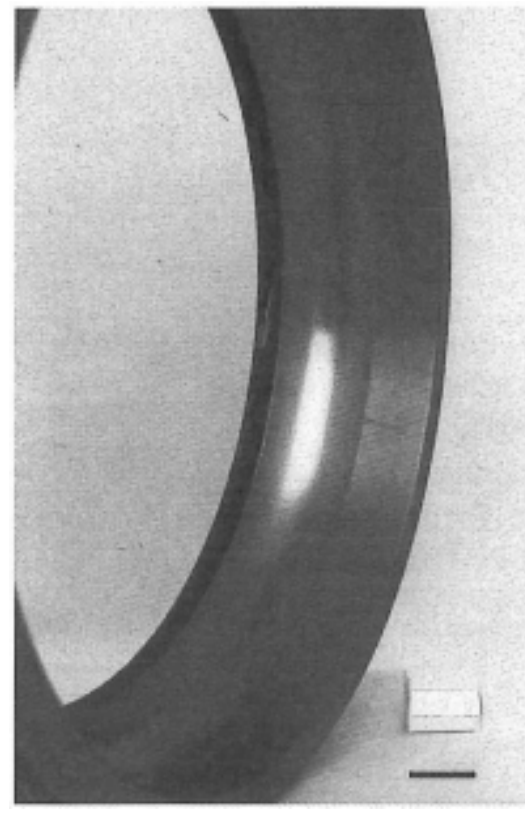


GENERAL TEXTURE CHANGE (continued)

FC 00.15: Fretting
Produces a rust-colored deposit on worn steel *contact* or *fit* surface.
Archive: 027-119
Plate No: 9.3



FC 00.17: Surface Distress (Glazing)
Burnished surface on which original finishing texture is plastically smoothed.
Archive: 027-234
Plate No: 11.3

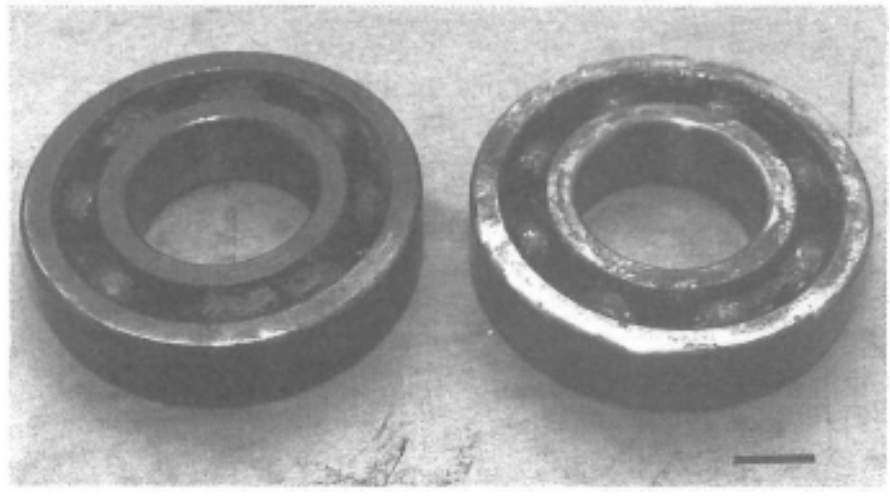


FC 00.19: Heat Imbalance Failure
Temper color, friction polymer and/or signs of plastic flow on surface.
Archive: 018-617
Plate No: 13.9(a)



GENERAL TEXTURE CHANGE (continued)

FC 00.20: Corrosion
Rust-colored stains or pits on any steel surface.
Archive: 027-211
Plate No: 14.1



MATERIAL FAILURE
Composition, physical properties, structure changed

FC 00.04: Forming Defect
Metallographic. See Plate chapter.
Not illustrated.

FC 00.07: Material Structure Defect
Metallographic. See Plate chapter.
Not illustrated.

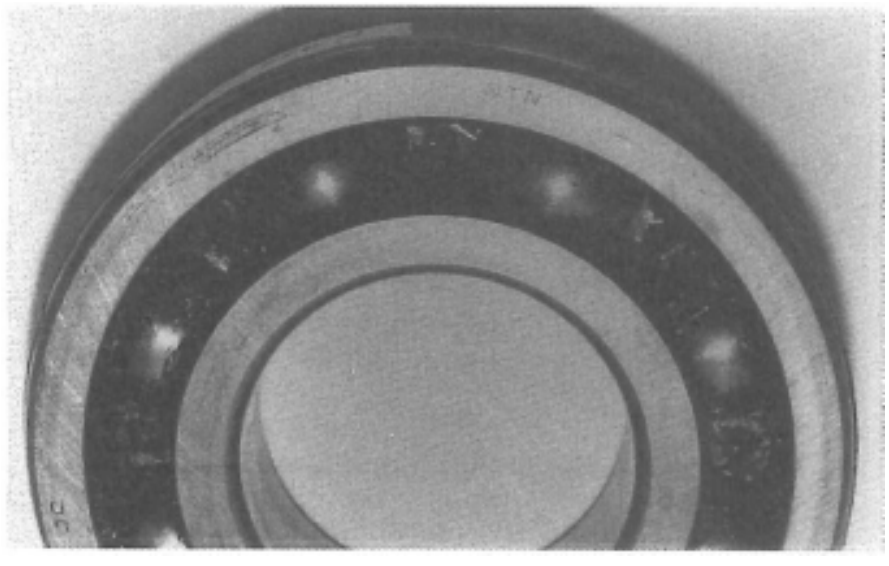
FC 00.08: Structural Damage, Post Heat Treatment
Metallographic. See Plate chapter.
Not illustrated.

FC 00.19: Heat Imbalance Failure
Metallographic. See Plate chapter.
Not illustrated.

FC 01.11: Separator Material Damage
Metallographic. See Plate chapter.
Not illustrated.

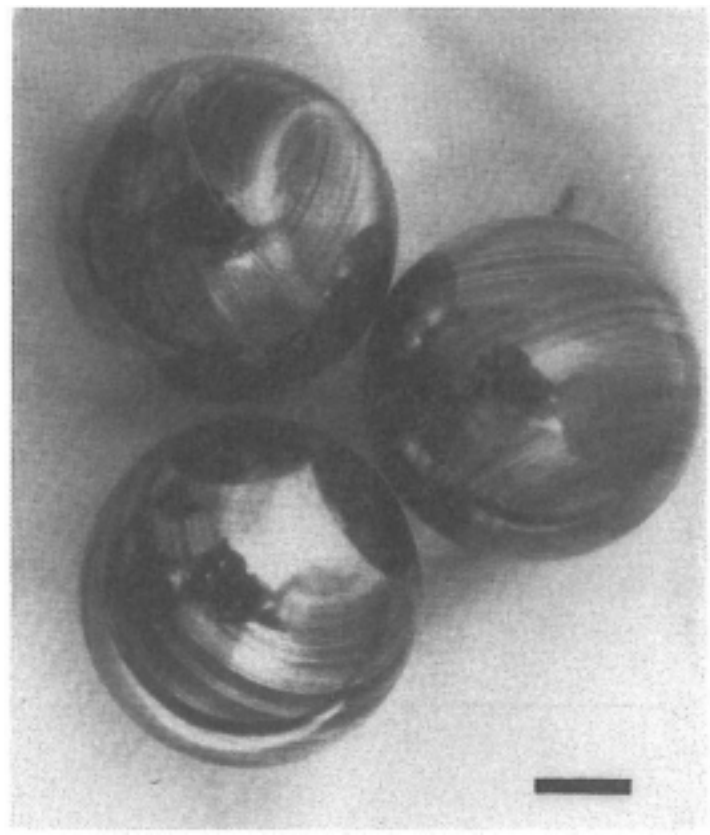
FC 11: Oil Damage
See Plate chapter.
Not illustrated.

FC 12: Grease Damage
Discoloration, consistency change, grittiness.
Archive: 027-131
Plate No: 18.15



MATERIAL FAILURE (continued)

FC 11 or 12: Friction Polymer from Lubricant
Brown deposit on contact surface.
Archive: 027-173
Plate No: 18.12(a)



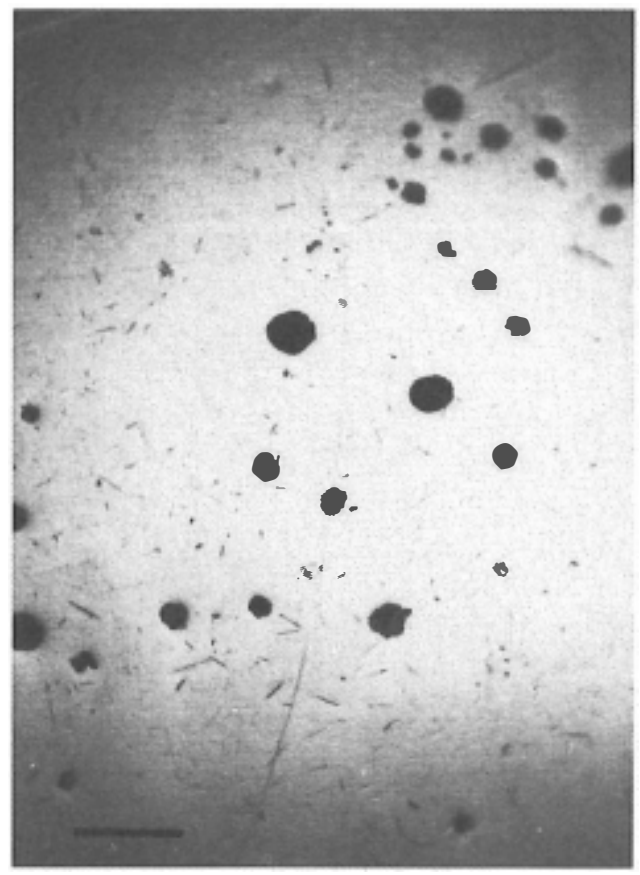
FC 22: Chemical Decomposition of Mounting Part
See Plate chapter.
Not illustrated.

3.2 POINT OR LINE FAILURE

3.2.1 Material Locally Removed

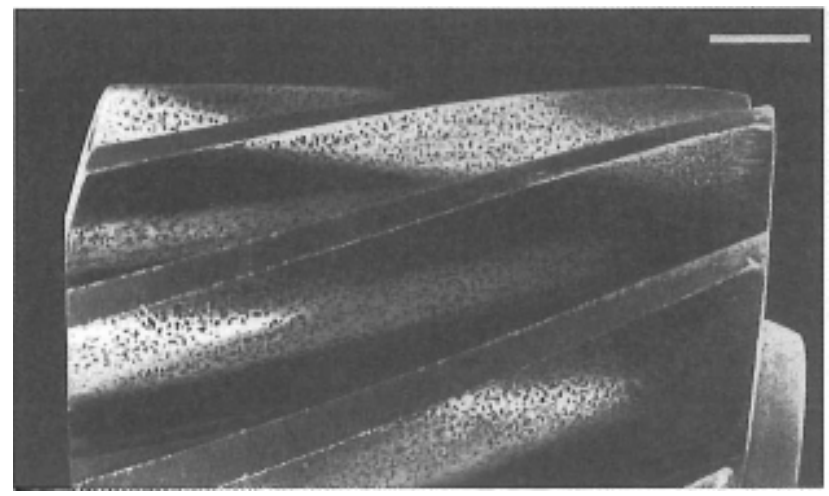
PIT
Dark-bottomed crater (not fracture surface)

FC 00.03: Surface Porosity
Crater open to surface, with metallic unmachined surface (not fracture surface).
Archive: 093-3.1.6
Plate No: 5.15



PIT (continued)

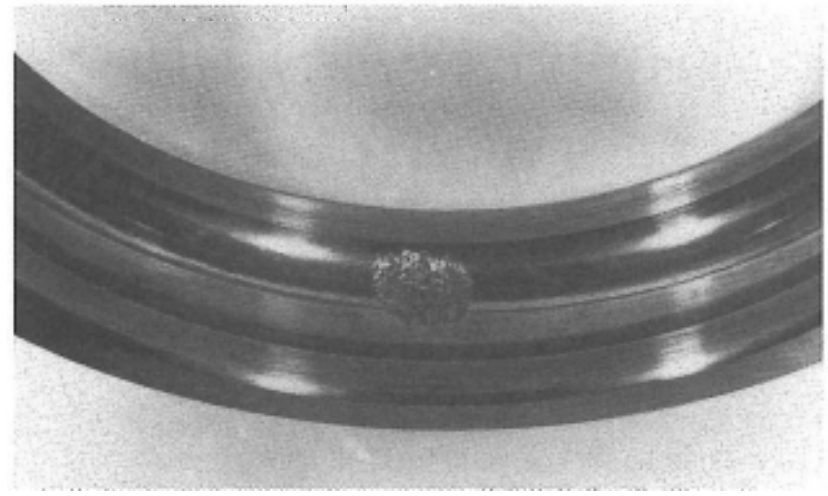
FC 00.20: Corrosion Pit
Crater open to surface, with corroded surface (not fracture surface).
Archive: 080-104
Plate No: 14.7



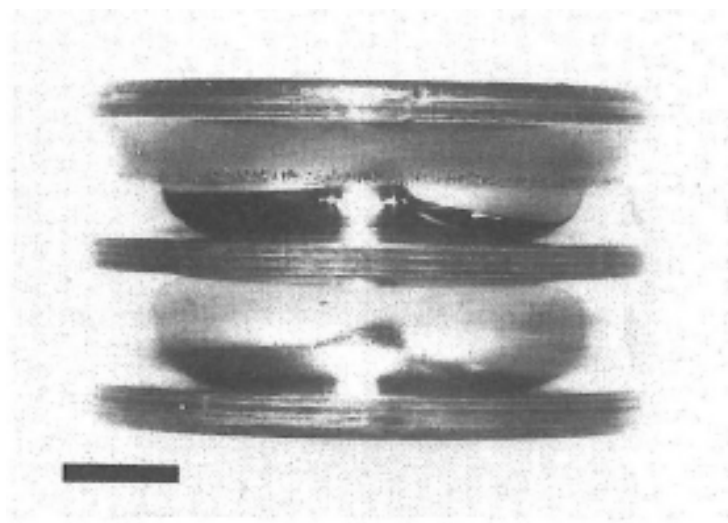
FC 01.15: Corrosion Pit (Separator)
As above.

SPALL
Fracture-bottomed crater

FC 00.16: Hertz Contact Fatigue
Crater left after surface material removal by fatigue cracking.
Macroscopic (depth 100 μm to several mm).
Archive: 027-133
Plate No: 10.3

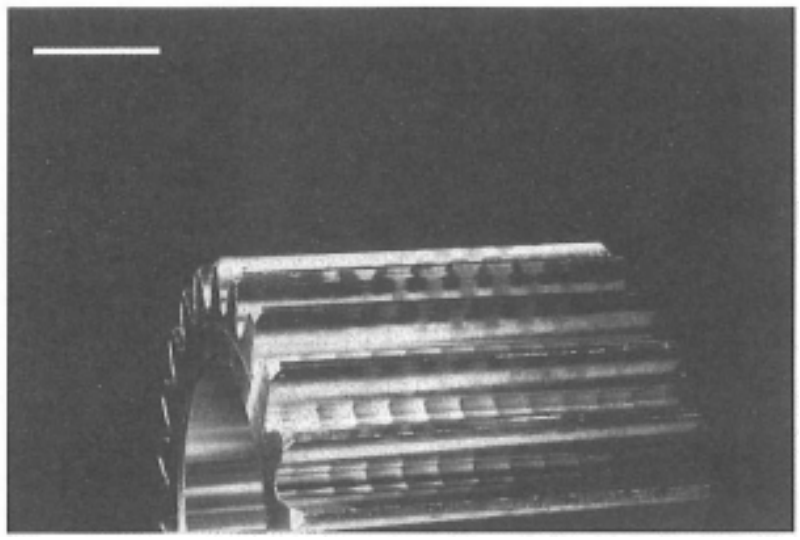


FC 00.17: Surface Distress
Black point-marks from surface material removal by fatigue cracking. Microscopic (depth < 30 μm).
See also 'Surface Distress (Glazing)' under 'Texture change'.
Archive: 074-1
Plate No: 11.13



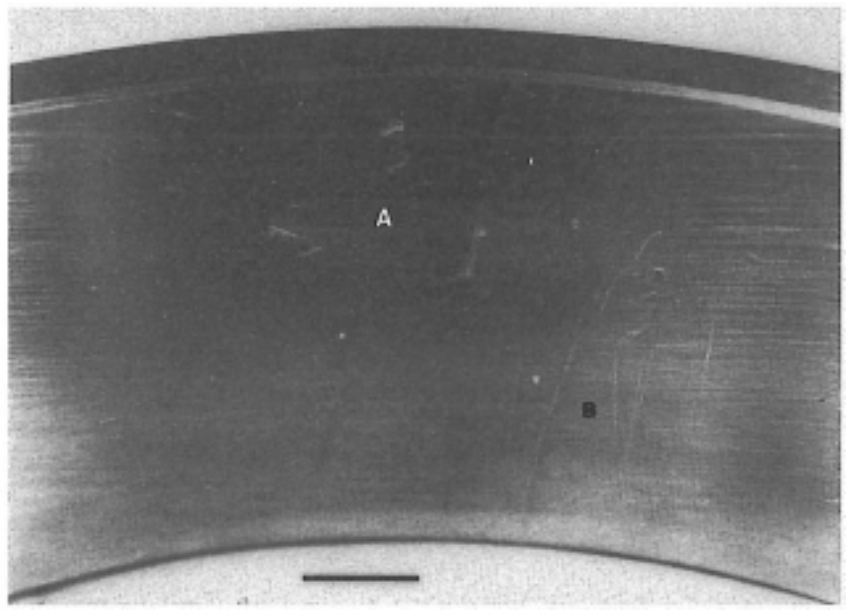
PLOWING MARK

Depressed line defect from material removal by plowing action



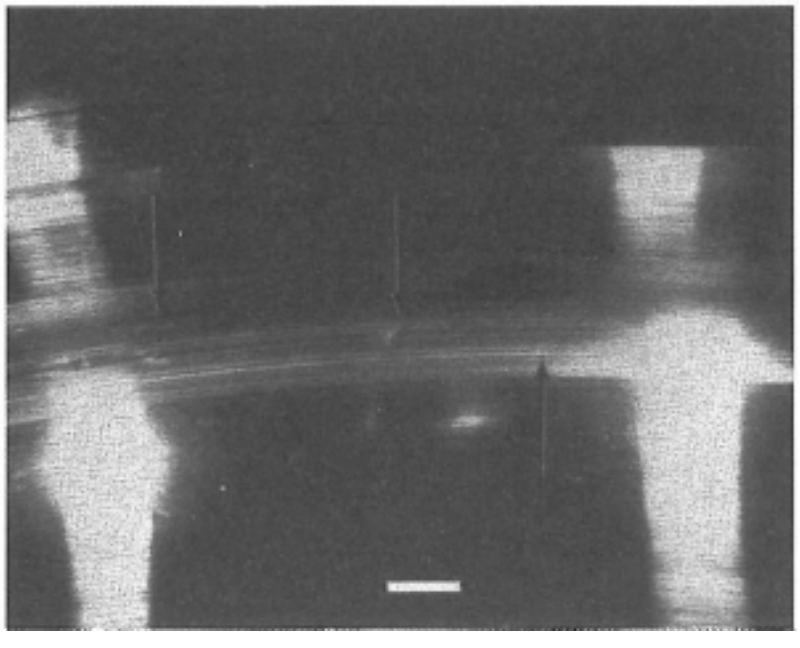
FC 00.02: Finishing Mark (Furrow, Chatter, Wheelhit)

Excessive or irregular cut-mark from chip-making finishing process.
Archive: 080-101
Plate No: 5.11



FC 00.09: Gouge (Assembly)

Scratch mark by injury during assembly or mounting.
Archive: 014-54
Plate No: 4.4



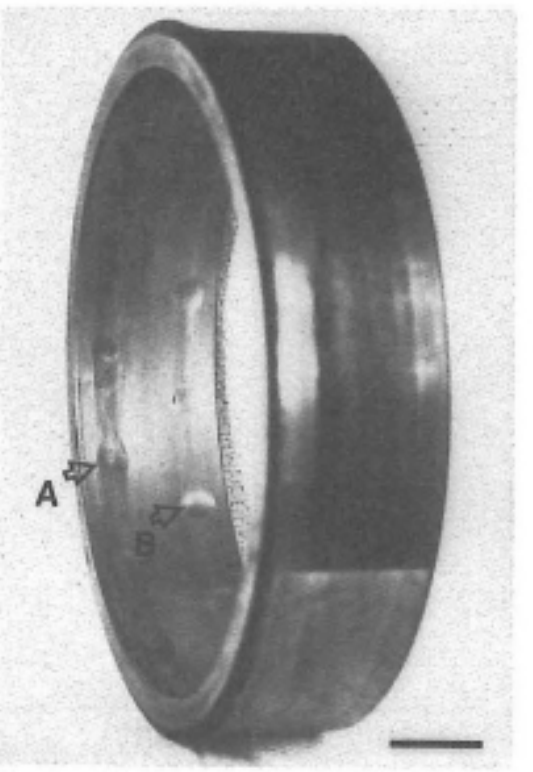
FC 00.12: Wear

Scratch mark made by sliding asperity or third body.
(see arrows on image).
Archive: 027-154
Plate No: 7.18

PLOWING MARK (continued)

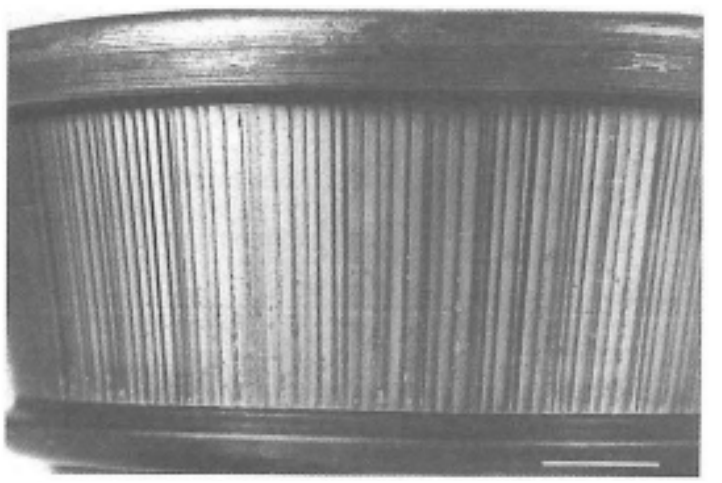
FC 00.15: False Brinnell Mark

Rounded local depression made by fretting wear in stationary Hertz contact. See Plate chapter for discrimination.
from true Brinnell mark (FC 00.18)
Archive: 093-15.2.1
Plate No: 9.15



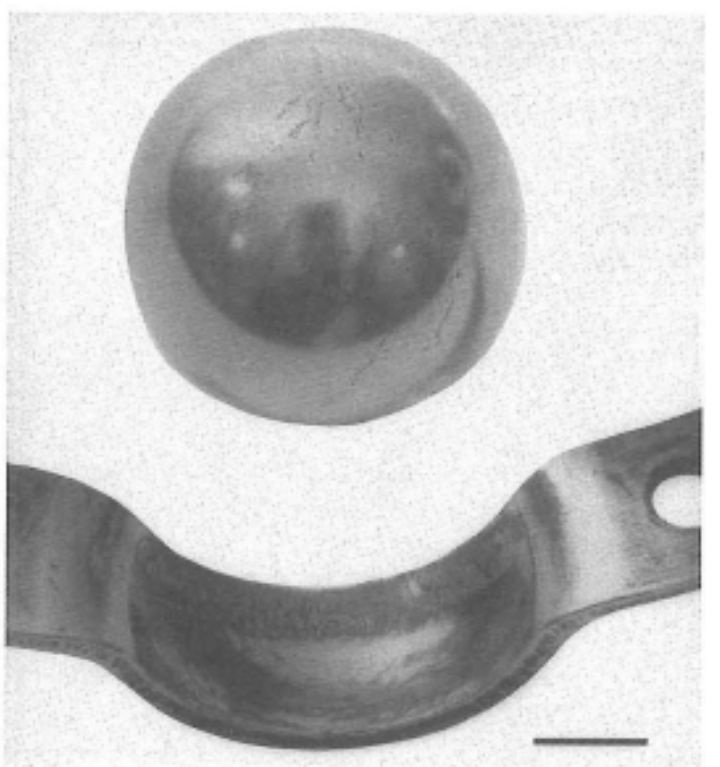
FC 00.21: Electric Current Erosion

Pit (point depression) or flute (line depression) with molten surface, made by electric current passage through Hertz contact.
Archive: 014-68
Plate No: 14.22



FC 01.13: Separator Wear

Scratch mark made on separator by sliding asperity or third body.
Archive: 087-111
Plate No: 16.21



PLOWING MARK (continued)

FC 20: Mounting Part Wear
Scratch mark made on fit surface of mounting part by sliding asperity or third body.
(See Plate chapter.)
Not illustrated.

3.2.2 Material Locally Deformed

NICK
Material locally (point, line) depressed in manufacture

FC 00.01: Nick
Nick is a point defect caused by plastically depressing the surface in manufacture. (Dents are caused in service. See Plate chapters for differentiation.) Nick bottom is the finished surface, with finishing lines usually visible.
Archive: 003-012
Plate No: 4.7(a)

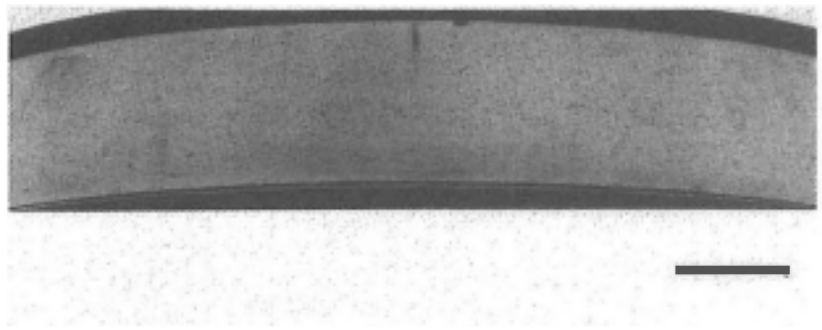
FC 00.01: Scuffmark
Line defect produced similarly to a nick. See **wear marks** and **gouges** for similar-appearing defects from plowing action.
Archive: 014-50
Plate No: 4.8

FC 01: Nick, Scuffmark (Guiding-Component)
As for contact component. (See Plate chapter.)
Not illustrated.

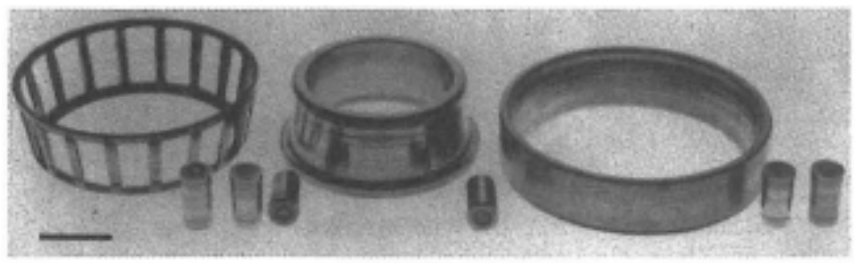
FC 22: Nick, Scuffmark (Mounting Part)
As for contact component. (See Plate chapter.)
Not illustrated.

DENT
Material locally (point, line) depressed in service

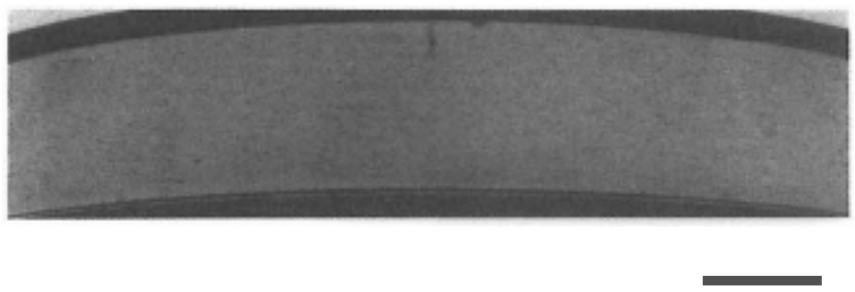
FC 00.18: Dent
Dent is a point defect caused by plastically depressing the surface *in service*. (Nicks are caused in manufacture. See Plate chapters for differentiation.) Dent bottom is the finished surface, with finishing lines usually visible. Dents may be *sharp* (from metal particle), *rounded* (from soft debris) or *multi-fragment* (from brittle debris). For distinction between dent types, see Plate chapter.
Archive: 014-8
Plate No: 12.1(b)



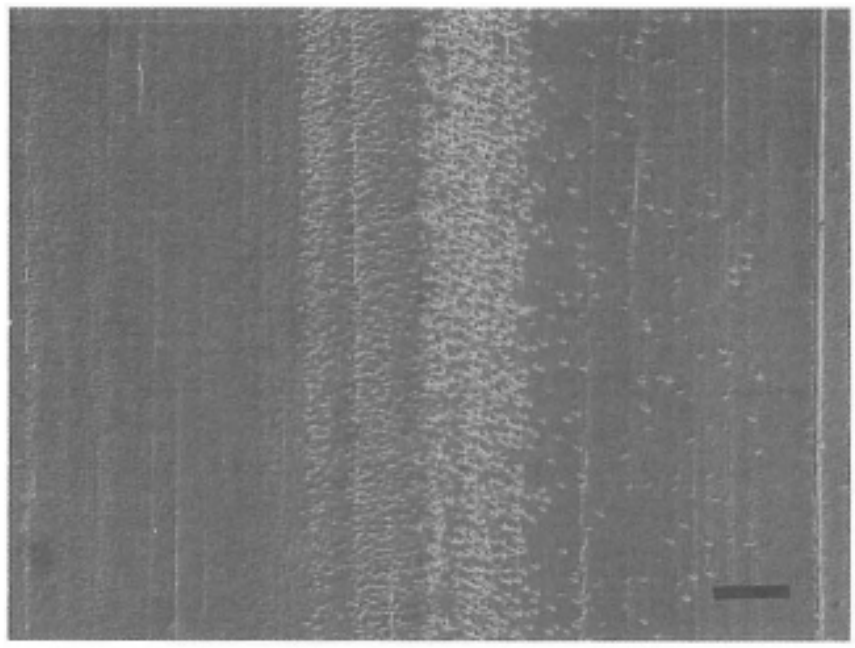
FC 00.18: Rolled-in Line
Line defect in rolling direction (on ring rolling-track in image), produced as plastic depression by a contacting edge (on rollers in image). See **wear marks** and **gouges** for similar-appearing defects from plowing action.
Archive: 014-9
Plate No: 7.14



FC 00.18: Debris Denting
Original surface covered randomly with multiple small dents from loose debris.
Archive: 014-4
Plate No: 12.1(a)

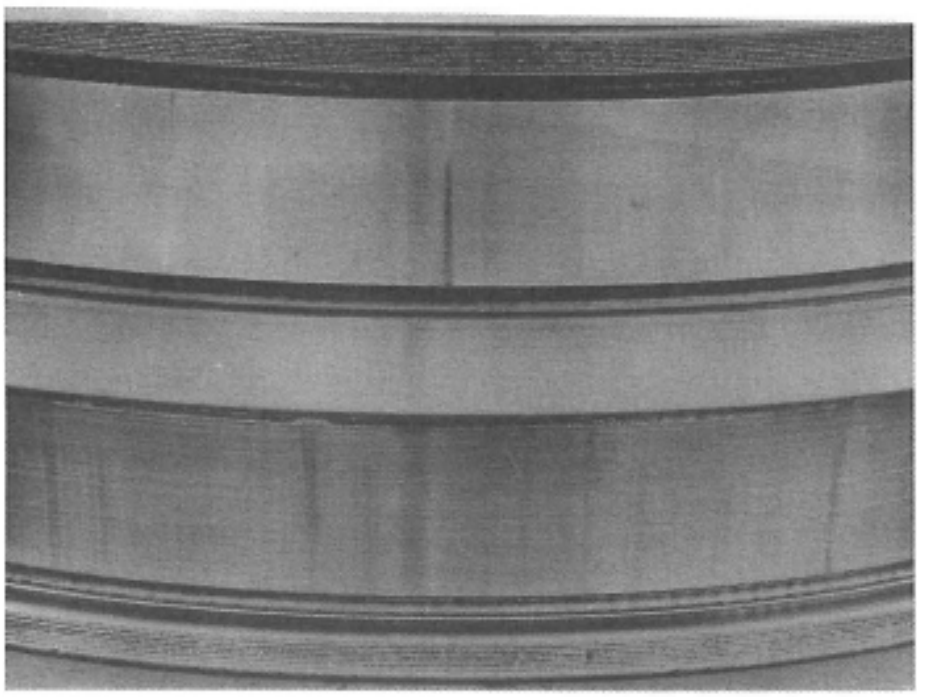


FC 00.18: Stippled Line
Line in rolling direction, consisting of many identically shaped dents from an asperity or from debris imbedded in the mating contact surface. (Image is magnified about 20×.)
Archive: 005-28
Plate No: 12.13(b)



DENT (continued)

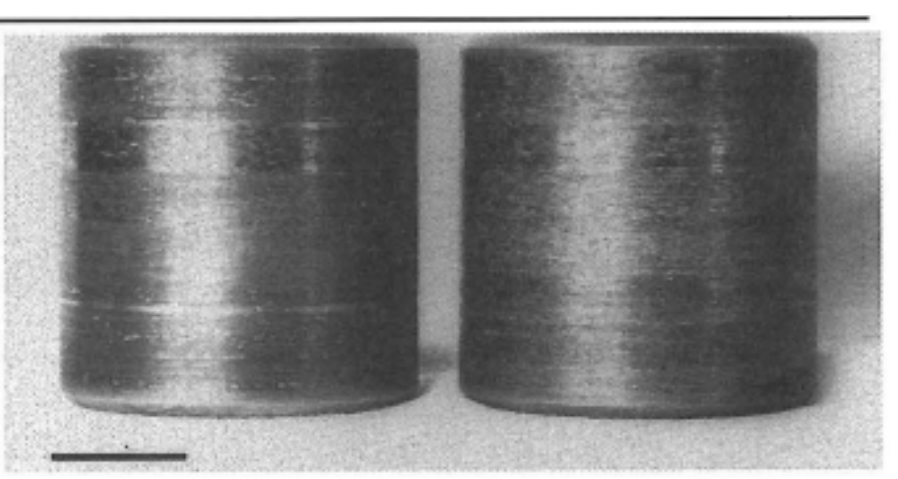
FC 00.18: Brinnell Mark
Plastic impression of one contacting body into the other. See Plate chapters for distinction between *true* (FC 00.18) and *false* (FC 00.15) brinnelling (fretting).
Archive: 018-109
Plate No: 12.16



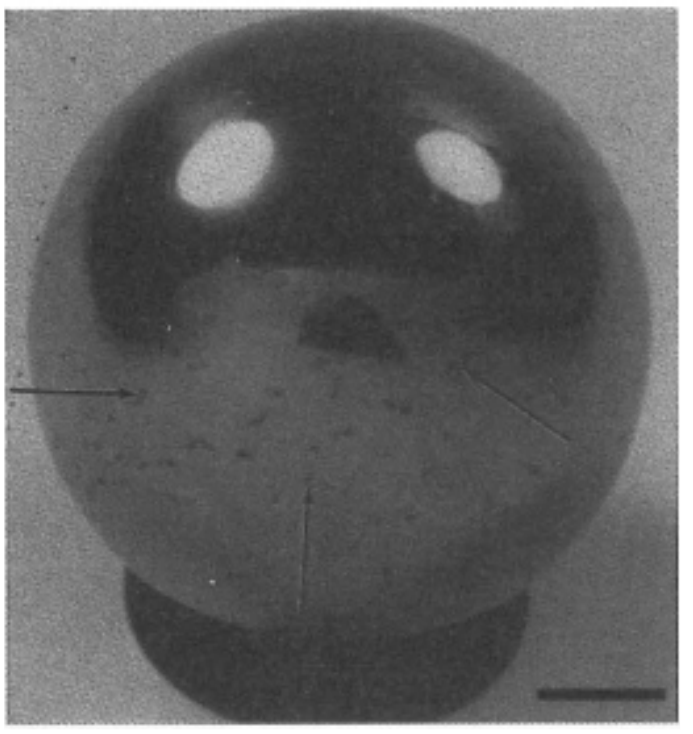
FC 01: Dent (Guiding-Component)
As for contact component. (See Plate chapter.)
Not illustrated.

3.2.3 Material Transferred

GALLING
Metal torn from surface and welded elsewhere on surface



FC 00.13: Galling
Lamina of original contact surface removed by tearing; material removed is welded onto contact surface elsewhere. Resulting surfaces are rolled over.
Archive: 093-027×
Plate No: 8.7



FC 00.14: Skidmarking
Microscopic galling from temporary sliding between high-speed contact surfaces.
Archive: 027-178
Plate No: 8.18

GALLING (continued)

FC 01.14: Galling (Guiding-Component)

As for contact component.
Archive: 093-13.1.12
Plate No: 16.30

FC 2: Galling (Mounting Part)

As for contact component. (See Plate chapter.)
Not illustrated.

WELDING

Unintended joining of surfaces

FC 00.19: Heat Imbalance with Welding

Components unintentionally joined in seized assembly (bearing, etc.)
Archive: 093-034
Plate No: 13.14

3.2.4 Material Separation

CRACK, FRACTURE
Separation of material

FC 00.04: Lap, Seam
Unintended separation interface in bulk material, usually with surface contamination, arising in a forming operation. A *lap* is material folded-over onto the surface; a *seam* is a fold normal to the surface.
Archive: 093-4.1.1
Plate No: 5.21

FC 00.07: Forging or Heat Treat Crack
See below.
Not illustrated.

FC 00.08: Grinding Crack
See below.
Not illustrated.

FC 00.09: Mounting Crack
See below.
Not illustrated.

FC 00.22: Bulk Crack or Fracture in Service
Cracks appear as dark lines on the surface or in the metallographic section. *Fractures* are part separations. For distinction among cracking causes see Plate chapters.
Archive: 018-602
Plate No: 15.1(a)

FC 01: Crack or Fracture (Guiding-Component)
See above.
Not illustrated.

FC 2: Crack or Fracture (Mounting Part)
See above.
Not illustrated.

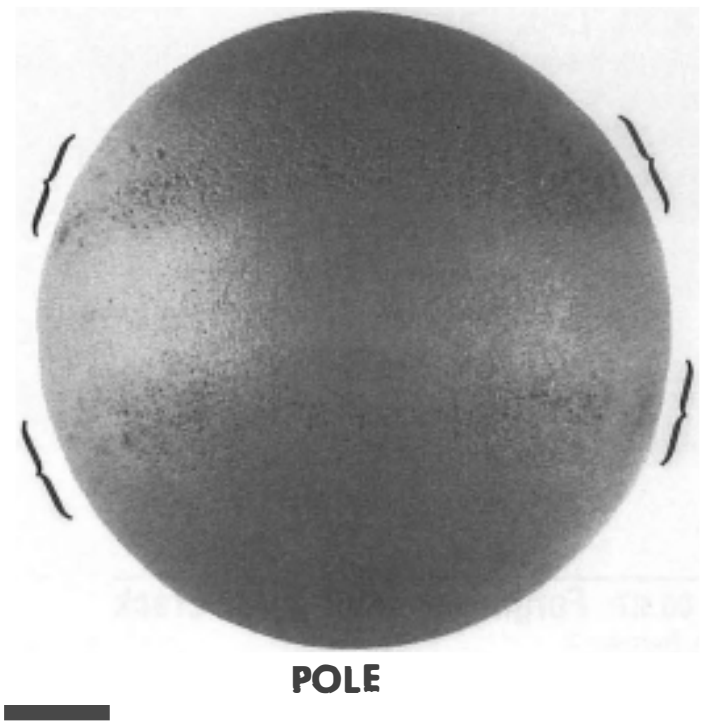
3.2.5 Material Defect

FORMING OR CASTING DEFECT (LOCAL)

Local alteration of material

FC 00.04: Forming at Incorrect Temperature

Local structural alteration due to overheating in forging. May be visible in metallographic section or on etched surface (as in image).
Archive: 002-024c
Plate No: 5.23(a)

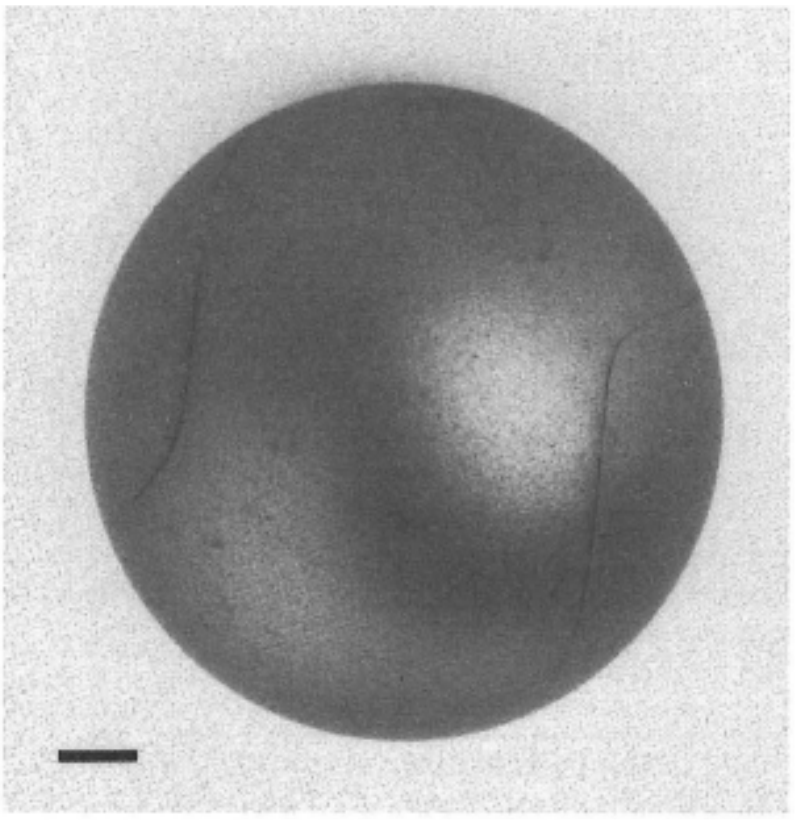


FC 00.05: Porosity, Molding Defect

Void in contact component material due to casting defect. Visible in metallographic section.
Not illustrated.

FC 00.07: Heat Treatment Crack

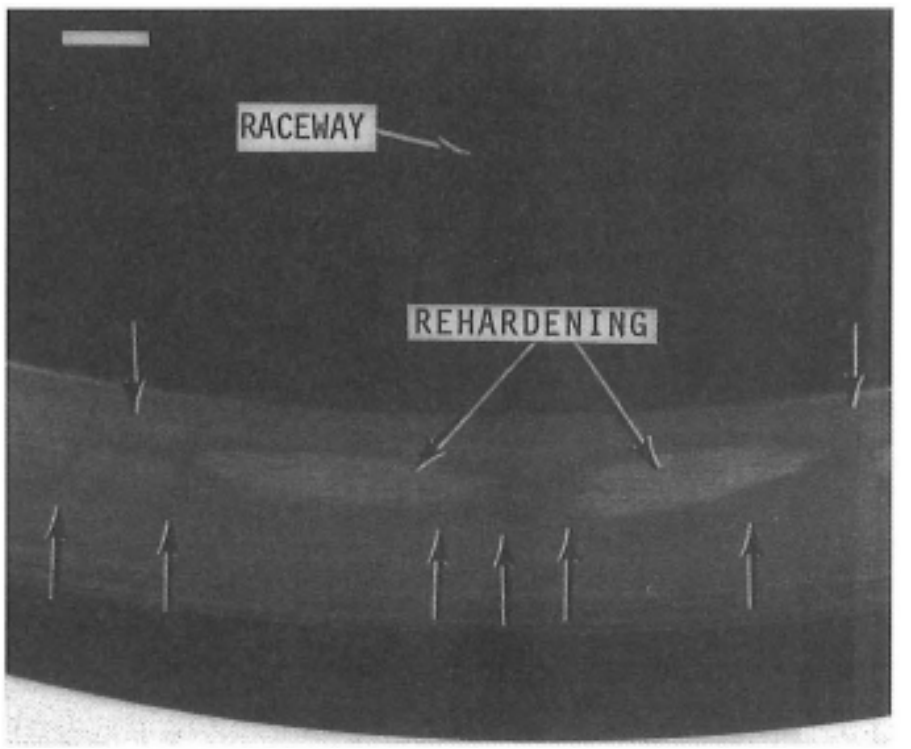
Crack formed due to excessive thermal or residual stresses from heat treatment (of steel).
Archive: 087-108
Plate No: 6.18(b)



FORMING OR CASTING DEFECT (LOCAL) (continued)

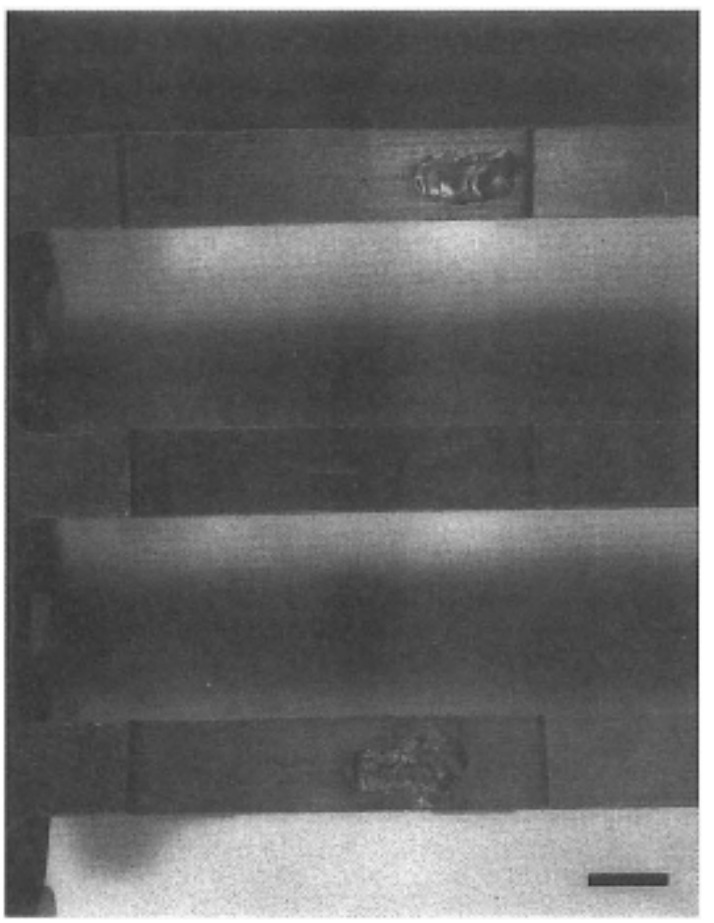
FC 00.08: Finishing Damage (Grinding Burn)

Alteration (tempering, rehardening) of near-surface structure due to abusive finishing. May be visible on surface after diagnostic etching.
Archive: 001-36
Plate No: 6.23



FC 01: Casting, Molding Porosity (Guiding-Component)

Void in guiding-component material due to casting or molding defect. (Shown in image as repaired.)
Archive: 093-201
Plate No: 16.14



FC 2: Mounting Part Casting, Forming Defect

Void in mounting part material due to casting or molding defect. (See Plate chapter.)
Not illustrated.

3.2.6 Foreign Material

INCLUSION
Foreign body in material

FC 00.06: Inclusion
Bodies of foreign material included in the matrix material. Of globular, elongated or fragmented shape. Occasionally visible at surface, otherwise in metallographic section. For differentiation among inclusion types, see Plate chapters.
Archive: 075-201
Plate No: 6.7(a)

FC 01: Inclusion (Guiding-Component)
As for contact components. (See Plate chapter.)
Not illustrated.

FC 1: Contamination
Solid particulates or water in oil or grease, or loose in the chamber. (See Plate chapter.)
Not illustrated.

3.3 GEOMETRY FAILURE

GEOMETRY, ASSEMBLY OR MOUNTING ERROR
Dimension or form out of tolerance

FC 00.09: Geometry, Assembly, Mounting Error
Deviation from design tolerance, incorrect assembly of machine element or incorrect mounting in machine.
Not illustrated.

FC 01: Geometry Error (Guiding-Component)
Deviation from design tolerance, incorrect assembly of machine element.
Not illustrated.

FC 2: Geometry Error (Mounting Part)
Deviation from design tolerance, incorrect assembly of machine element or incorrect mounting in machine.
Not illustrated.

PERMANENT BULK DEFORMATION

Shape distorted

FC 00.23: Permanent Deformation, Bulk

Distortion of shape from as-manufactured condition, occurring during service.
Not illustrated.

FC 01: Permanent Deformation (Guiding-Component)

As for contact component.
Not illustrated.

FC 2: Permanent Deformation (Mounting Part)

As for contact component.
Not illustrated.

Part II
Plates

Nicks

4

Failure Code 00.01

4.1 Definition

Nicks (in metals) are plastic depressions (short gashes; multiple, aligned or randomly oriented marks; or rounded depressions). They are caused by impressing (statically or by impact) a hard, possibly sharp object into a surface of a contact component. Nicks are produced at the time of, or subsequent to, final finishing of the surface, after the part has been brought to its final hardness.

Depressions produced prior to final finishing are *unfinished areas (FC 00.03).* Depressions suffered in service are *dents (FC 00.18).*

A defect of ceramic surfaces corresponding to a nick is a *chipped nick* in which a small volume of material is broken out of the surface. A chipped nick may occur at an edge of the component if impacted or indented by another hard, sharp-edged object. It may also occur elsewhere on the surface if impacted or indented by a sharp-edged or pointed hard object.

Nicks differ from *finishing furrows (FC 00.02),* which are ploughing marks made in grinding, honing, etc.; and from *score* or *gouge marks (FC 00.09)* made by sliding a hard edge over the surface in assembly or mounting.

4.2 Nomenclature

Indentations formed when the component is not (yet) in service are designated *nicks.* Indentations formed in service are designated as *dents.* The Atlas displays nicks (this chapter) and dents (FC 00.18) separately. As a generic name for both, it uses *indentations.* The Metals Handbook [10], in its chapter on rolling bearing failures, designates both nicks and dents (see Chapter 18) as indentations. Nicks are not mentioned in the literature as a significant failure mode in gears.

4.3 Failure Process

A nick is formed by plastic flow of the (metal) component surface material around an indenter. When it is a short gash or rounded depression, then its mode of formation resembles that caused by an indentation hardness test, i.e., the indenter penetrates the surface in an approximate normal direction, carries surface material down with it, and usually throws up significant raised edges, except for nicks created by edge-free rolling bodies such as a ball (identical with brinnell marks, FC 00.18). An elongated indentation can form by plastic flow beneath a rolling indenter (an edge on the mating rolling element), and may be difficult to distinguish from a wear mark (gouge) arising from a sliding indenter.

Chipped nicks may be formed in ceramic surfaces or at their edges from heavy impact, for example, the component is dropped onto a hard surface from great height, or as a result of indentation under heavy pressure with an object as hard or harder than the ceramic. Because of the limited ductility of ceramics, chipped nicks are predominantly fractures, although some plastic deformation may occur.

4.4 Distinctive Appearance

A nick appears as a depression. In metal surfaces, original finishing marks generally remain visible at the nick bottom. Raised edges usually exist. The mark has a shiny surface. By contrast, the surface of a score or scratch mark (ploughing mark, FC 00.02 or 00.09) is matte (but not oxidized). The surface of a gouge (FC 00.09) contains transferred metal (visible under the microscope) if formed by galling.

Chipped nicks in ceramic surfaces show fracture surfaces where the indentation has caused cracking and separation of surface material.

Differentiation between nicks (pre-service indentations) and dents (in-service indentations) is made by considering the location and direction of the indentation.

Nicks can appear on any surface and run in any direction because they are the result of random impacts. Knowledge of the manufacturing and mounting practices usually suggests the specific process that produced a nick of observed shape and location.

Dents, by contrast, are formed in operating contacts, which limits them to contact surfaces (including separator contact surfaces). Their geometry must be compatible with the kinematics of relative motion. These constraints are detailed under FC 00.18. A nick on the contact surface of a component that has already seen service can be clearly differentiated from a dent only if its direction is kinematically impermissible. In other cases such differentiation may be difficult to make. The most common of these dubious cases is an isolated nick or dent made by a hard contaminant particle indented normally to the surface. For such a nick or dent, it may be possible to determine whether substantial running time was accumulated by the surface since indentation. In a metal surface, a fresh indentation is likely to have sharp, perhaps raised edges and any finishing marks in the depression appear similar to those outside it. An indentation that accumulated much running time tends to have no raised edges, and finishing marks inside it may be sharper than those on the more worn surrounding surface. Another possible distinction is the surface distress decoration surrounding the nick or dent after substantial running (see FC 00.17: Surface Distress).

4.5 Causes

Some causes of nicks are common to all types of contact components. Others occur only on rolling bearing elements. Examples of events causing nicks follow.

4.5.1 Common Causes of Nicks

- Gash caused when component is dropped on sharp edge of a hard object (landing on an edge when discharged from a machine tool).
- Smooth depression caused when component is dropped on smooth hard surface (a ball discharged into a hard chute from a machine tool).
- Scratch or nick from poorly blended edge of a component handling device in manufacture.
- Nick from a hammer or 'drift' (a blunt tool used to transmit hammer blows) used in mounting or dismounting rings, gears, etc., onto shafts (or into housings).
- Loose bulk packaging of components with finished external surfaces. Components impact on each other when loaded into the pack or when the closed pack is dropped. Components with edges cause gashes, others cause smooth depressions. Balls impacting each other cause flat circular depressions in the sphere surface.
- Solid contaminant debris indentation during assembly, inspection, or mounting.
- Indentations from placing the finished surface of a (heavy) component on a (rough or dusty) work area.

4.5.2 Nick Causes Specific to Rolling Bearing Assemblies

- Many deep groove ball bearings are assembled by deflecting the outerring elastically to insert the last ball and snapping the ball into place. The land edge of a ring can nick the ball as it snaps across.
- Angular contact ball bearing rings may have a low shoulder ('dam') adjacent to the groove, over which the balls must pass in assembly. The edge of the dam may nick the ball.
- Some roller bearings (sphericals) and some ball bearings (double rows and maximum complement bearings) require assembly of rolling elements through a loading slot. Edges of the slot

may scratch or nick (or score, FC 00.09) the rolling elements. In roller bearings an edge on the roller may nick (or score, FC 00.09) a ring rolling surface.
- Some bearings require assembly of rolling elements into separators by a 'snap assembly', pressing them past a retaining prong. Excessive snap causes gashes (or score marks, FC 00.09).
- Contamination of bearing assembly causes indentations (or scratch marks, FC 00.09) on rolling surfaces, when the assembly is rotated for test or in the assembly process.
- Assembly or disassembly of complete rolling bearings on shafts or in housings with force transmitted through rolling elements may cause indentations (see brinnell marks, FC 00.18).
- Assembly of parts of a separable (roller) bearing, with one ring mounted on a shaft and the other in a housing, may cause impact marks (or scores, FC 00.09) between rolling elements and rings.
- Ceramic components featuring *edges* are at great risk of chipping at the edges when impacting each other, or other hard parts. Edges of ceramic components can also chip other components. This is one reason why ball bearings with ceramic balls and metal rings are used wherever possible, as balls have no edges and their surface resists chipping by metal components.

4.5.3 Nick Causes Specific to Gears

- The working surfaces of gears (the tooth surfaces) are not greatly exposed to nicking. The gear industry does not treat nicking as a common failure mode. However, given unfavorable circumstances, sharp objects can impact on tooth surfaces to cause nicks.
- Some medium-hard gears with relatively rough surfaces are more tolerant of nicking than the hard, smooth surfaces of fully hardened bearings or gears.

4.5.4 Nick Causes Specific to Cams

- Because their working surfaces are external and exposed, cams and cam followers suffer the "general" causes of nicking previously listed.

4.6 Effects of Nicks

- The plastic indentation process forming the nick in metal surfaces imposes high local stresses on the surface. These can initiate cracks.
- The nicking process in ceramics includes cracking.
- Sharp edges may form at the nick which, when rolled over, cause cyclic edge stress leading to spalling failure near the nick.
- Spalls tend to initiate downstream of a nick in the rolling direction. A narrow unspalled ridge is often left between the nick and the spall edge.
- The nick represents a *sink* for the EHD (elastohydrodynamic) film in the contact, which may locally depressurize the film, resulting in local film thinning around the nick edges. Asperity contacts may form, producing local surface distress (a shiny, 'glazed' possibly microspalled 'halo' decorating the nick). The surface distress, in turn, may initiate spalling fatigue.
- Raised edges around a nick in a contact with significant sliding may initiate *galling.*
- When over-rolled, nicks cause clicking noise, which may represent a failure of quiet running components.
- In an aggressive environment where corrosion is a risk, any disruption of the smooth surface finish, such as by a nick, may be the initiation point for corrosion pitting in metal surfaces.

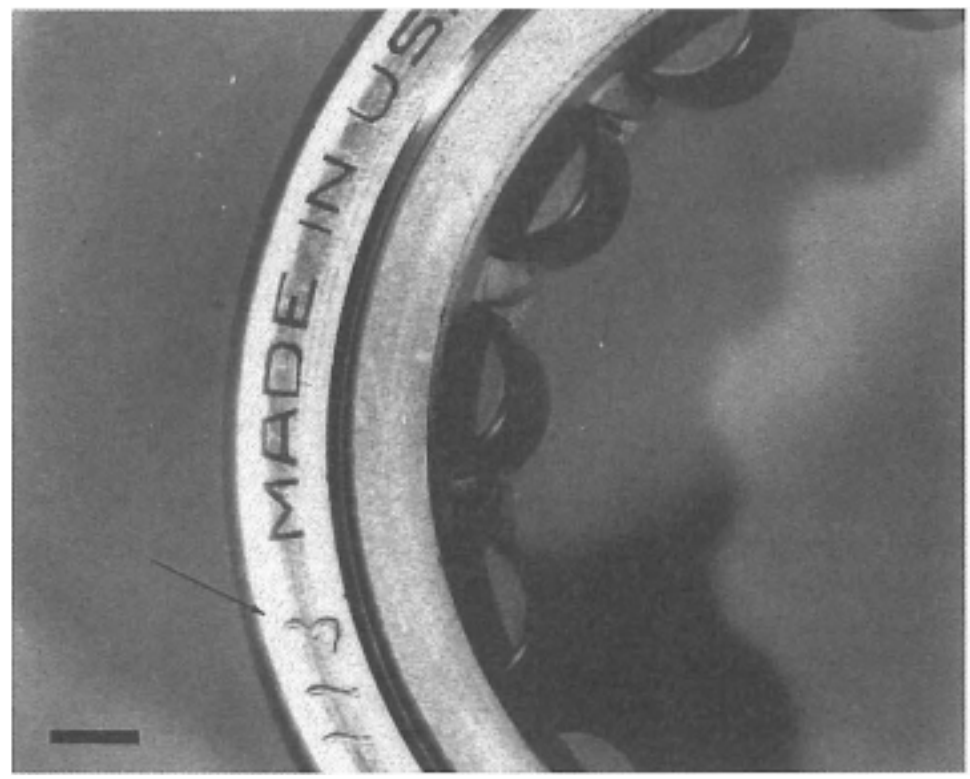
Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.00.01	4.1 4.2 4.5 6.30
00.00.02.1	4.3 4.4 4.6 4.7 4.8 4.10 5.3 5.9 5.13 5.14 5.15 5.16 5.17 6.32
00.00.03	5.10
00.01.1	10.52 10.67
00.01.1.1	4.3 13.12
00.01.2	4.4 11.6 15.6
00.01.4	10.57

PLATES

DATA

Plate No: 4.1
Archive No: 087-008
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; OR & S & R, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.01 Nick
Failure Code 2: 00.00.01 Defect by location: in fit surface
Failure Code 3: -
Failure Code 4: -

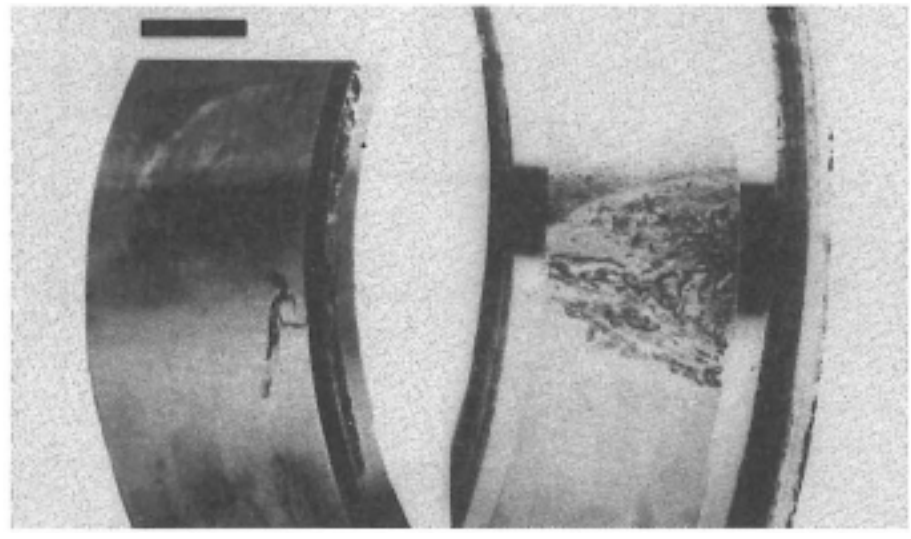


DESCRIPTIONS

Failure Description: Numerals spark-etched on sideface of CRB OR with an electric pencil form raised asperities of molten metal. In precision applications such as this aircraft turbine bearing, angular alignment is jeopardized by the out-of-square position the sideface assumes against a flange due to these asperities.
Image Description: At arrow, dark hand-written numerals are elevated above ring sideface. This is detected by placing the ring on a flat plate with this face down and measuring squareness on the opposite face.
Suspected Causes: The use of 'electric pencil' spark-erosion markers is common in serializing hardened parts. In some high-precision applications the resulting molten-metal asperities cause flatness tolerances to be exceeded and the use of electric pencil is prohibited.

DATA

Plate No: 4.2
Archive No: 093-005
Image type: a, b: light macro
Scalebar = 30 mm
(micros: ±20%, others: +100%, −50%)
Component: CRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.1 Local nick
Failure Code 2: 00.00.01 Defect by location: in fit surface
Failure Code 3: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 4: 21.9 Geometry or assembly defect in housing



DESCRIPTIONS

Failure Description: A chip trapped between housing and OR OD created a nick and local contact load concentration in the underlying roller path when overrolled. Fatigue spalling followed.
Image Description: The W image half shows the OR OD with a deep nick made by a machining chip near the E-W image centerline, just W of the E ring edge. The E image half shows the roller track directly underlying the nick. An extensive spall has formed in service, starting at the E side of the track, directly underlying the nick on the OD.
Suspected Causes: A machining chip was trapped between OR OD and housing bore, providing the primary load support in that area. During overrolling, this local support created a load concentration in the contact which then produced the spall.

DATA

Plate No: 4.3
Archive No: 087-115
Image type: light microgram
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Component: TRB; OR, mounted
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.1 Local nick
Failure Code 2: 00.01.1.1 Nick with raised edges
Failure Code 3: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 4: 00.09.1 Scoring from forcible assembly or mounting (no galling)
See also PLATE: 4.4

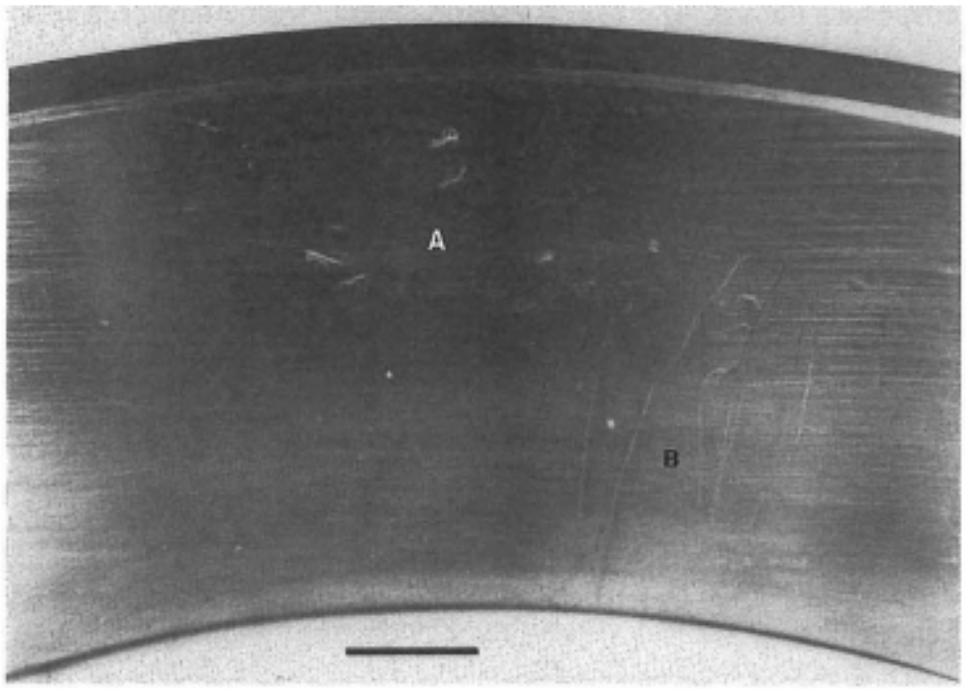


DESCRIPTIONS

Failure Description: A series of nicks (with raised edges) was created in the roller track by impact with a sharp-pointed tool.
Image Description: Nicks similar to those in Plate 4.4. The nicks cross finishing lines. At *A*, finishing lines remain visible within nick. Also at *A*, the nearest edge of nick is raised above the surrounding surface. The very bright appearance of the south edges of each nick is due to lighting.
Suspected Causes: These short, roughly parallel nicks are produced by repeated contact with the sharp edge of a hard tool. Scraping a tool over the surface by hand pressure may create such small nicks.

DATA

Plate No: 4.4
Archive No: 014-54
Image type: light macro
Scalebar = 100 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; OR, mounted
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.1 Local nick
Failure Code 2: 00.01.2 Scratch, toolmark, scuffmark
Failure Code 3: 00.00.02.1 Defect by location: in Hertz contact
surface
Failure Code 4: 00.09.1 Scoring from forcible assembly or mounting (no galling)
See also PLATE: 4.3

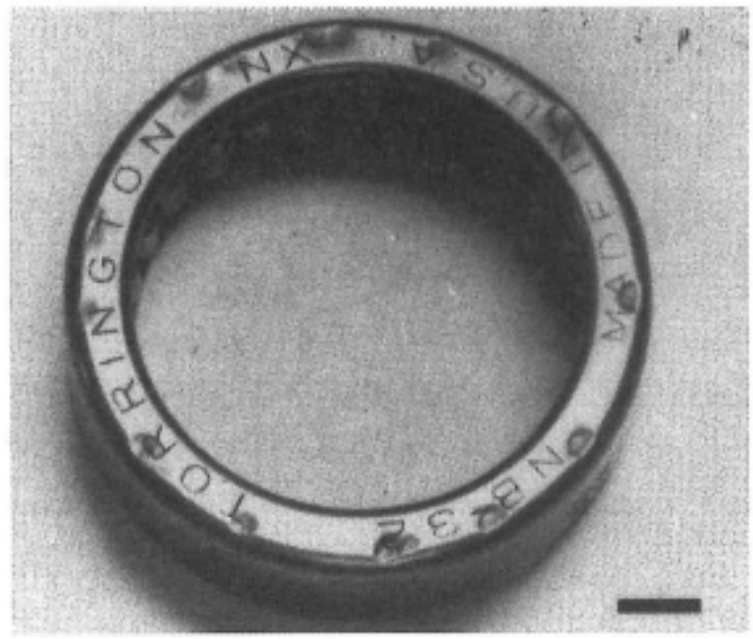


DESCRIPTIONS

Failure Description: Several local nicks and scratches on the roller track of TRB OR.
Image Description: This light macro shows a slightly enlarged portion of the roller track in a TRB cup (OR), with irregularly shaped depressed nicks at *A* and irregular cross-track scratches at *B.* For an enlarged view of assembly nicks see Plate 4.3.
Suspected Causes: In assembly, a punch-type tool (drift) was used on the narrow face of the cup. It slipped repeatedly into the roller track when struck with a hammer, making nicks (when impacting one point on the track) or scratches (when sliding across the track).

DATA

Plate No: 4.5
Archive No: 018-201
Image type: view
Scalebar = (micros: ±20%, others: +100%, −50%)
Component: NRB; OR & R, mounted
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.1.1 Nick with raised edges
Failure Code 2: 00.00.01 Defect by location: in fit surface
Failure Code 3: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 4: -

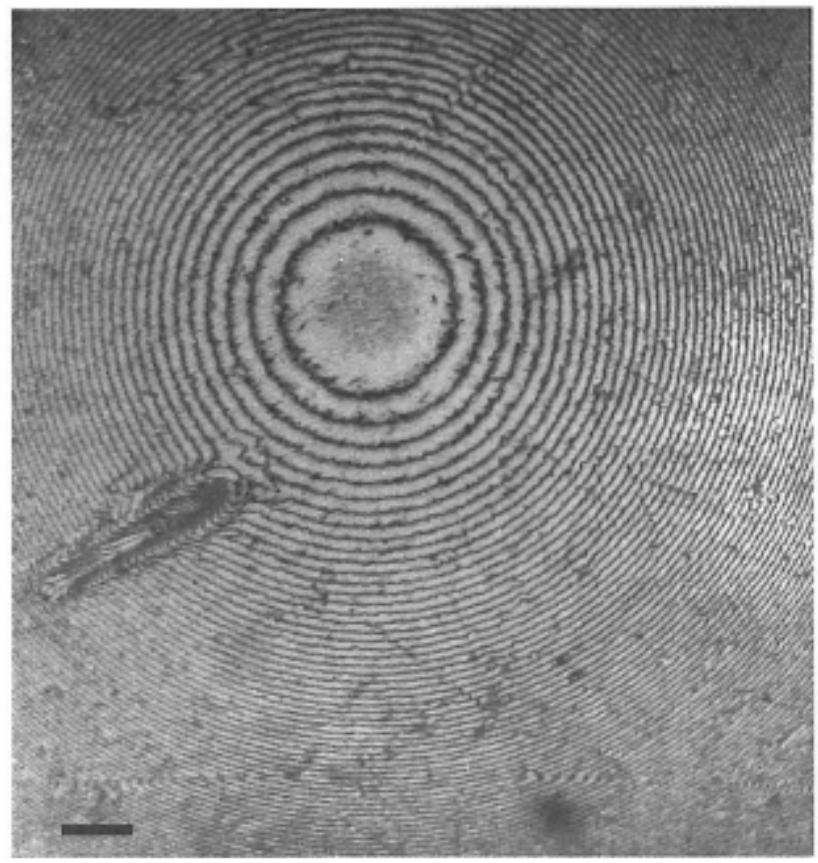


DESCRIPTIONS

Failure Description: Several deep nicks with raised edges (at OD chamfer) around the circumference of OR face, due to sharp plastic indentation. In the thin-walled deep-drawn sheet-steel cup, the indentation stoves in the sheet, creating a bulge in the inner surface facing the roller ends. Bearing may seize if run.
Image Description: Several half-moon shaped indentations spaced circumferentially near the OD edge of the face, with raised edges at the OD. Bottom of nicks is shiny.
Suspected Causes: Use of a hammer and punch to install the drawn needle roller bearing cup into the housing has led to plastic indentation under the impact of the punch. Bending of the thin-walled cup creates a bulge on the roller-end facing inner face of the cup and may distort the entire cup geometry.

DATA

Plate No: 4.6
Archive No: 093-1.1.2
Image type: light interference micro
Scalebar = 35 μm (micros: ±20%, others: +100%, −50%)
Component: BB; B, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.1.1 Nick with raised edges
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: A plastically formed nick or "gouge" in the ball surface, by indentation with a sharp-edged hard object under high normal pressure. Raised edges surround the nick. A ball with this damage runs noisily. The damaged surface may suffer surface distress (FC 00.17) and surface-origin spalling (FC.00.16) as a result of interrupted EHD film and stress concentration at the nick.
Image Description: The image is made by multiple beam interference microscopy, which creates narrow dark contour lines spaced 1/2 light-wavelength (about 0.2 μm) apart. On an undamaged ball surface the contours are circles (with small random excursions showing lapping marks). The lines show the depressed nick bottom (about 0.4 μm deep) and a raised rim (about 0.2 μm high) surrounding it.
Suspected Causes: In ball lapping a tool is used to extract the balls from between the lapping plates. If it is metal and develops a raised edge, it can mark the balls. The mark shown has raised edges, indicating that it must have been caused at the end of the finishing operation. Another source of nicks (less likely in view of the nick shape shown) is assembly of the bearing.

Failure Code: 00.01.1.1
Failure Code: 00.01.2

DATA
Plate No: 4.7
Archive No: 003-012 (a) & (b)
Image type: a: view, b: light micrograph
Scalebar = a: 10, b: 2 mm (micros: ±20%, others: +100%, −50%)
Component: BB; B, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.1.1 Nick with raised edges
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 4: -

DESCRIPTIONS
Failure Description: Straight boat-shaped plastic indentation in ball surface, made by a hard, straight-edged object pressed or impacted into the ball. A ball with this damage is noisy and is likely to spall early at surface defect. Raised edge of nick may damage ring ball-path.
Image Description: (a): View shows appearance of nick to the unaided eye. (b): Micrograph shows 5× magnification. In both images, bracket indicates nick. The boat shape, sharp points and straight edge along nick center indicate indentation by sharp straight edge. Surface of dent is shiny, same as undented ball surface. Dark color in image is due to light reflection.
Suspected Causes: During mounting of split-innerring ball bearing into machine, separator/ball complement may be displaced in OR so that IR, mounted on shaft, hits a ball during rotor insertion. As another cause: In ball manufacture or assembly into bearing, balls may drop from some height onto the sharp edge of a hard machine component. A drop of 20–40 cm suffices to cause a dent as shown.

a

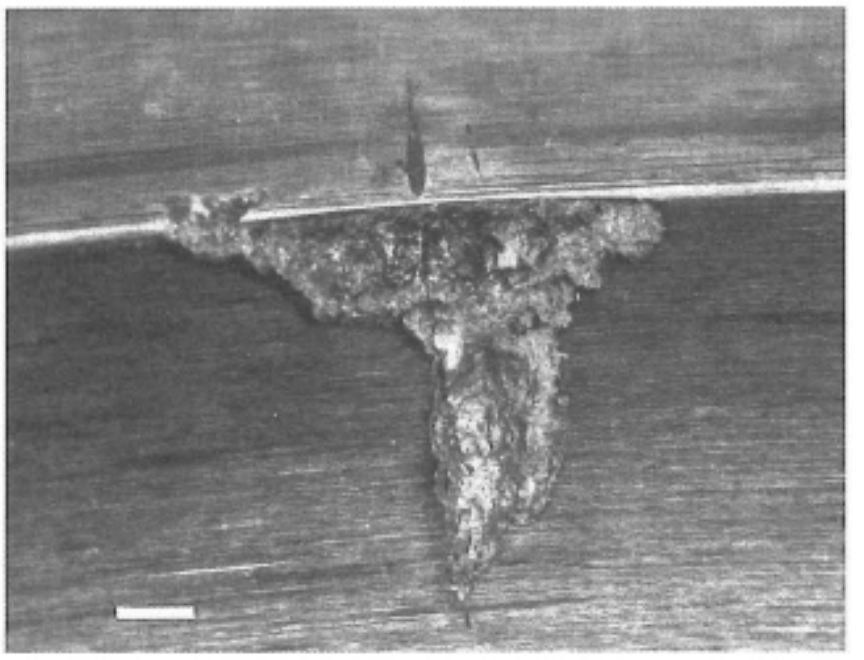
b

DATA
Plate No: 4.8
Archive No: 014-50
Image type: view
Scalebar = 100 mm
(micros: ±20%, others: +100%, −50%)
Component: TRB; OR (2), unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.2 Scratch, toolmark, scuffmark
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 4: 00.18.3 brinnelling

DESCRIPTIONS
Failure Description: Forcible assembly of tilted rollers into OR (cup) caused: (1) series of circumferential dents aligned axially (scuffmarks), (2) axial scoremarks and (3) brinnell marks. The damage causes a noisy bearing and is likely to lead to early spalling at the dents or brinnell marks.
Image Description: Dark-appearing broad fuzzy-edged axial scuffmarks on roller tracks (both OR-s). In OR at image E, also fine flared dark brinnell marks near both track edges, and axially aligned series of circumferential cuts or nicks in the N center portion of the track. The gouge marks and nicks are shiny, and may appear light or dark against the background depending on light incidence angle.
Suspected Causes: With the OR (cup) mounted in a housing and the IR (cone) and roller assembly on the shaft, assembly of the rotor into the machine stator with inadequate alignment can force contact between roller (end) and OR roller path. Stator weight or assembly forces provide the load that can cause scuffing, nicking and brinnelling.

DATA

Plate No: 4.9
Archive No: 001-12
Image type: light micrograph
Scalebar = 500 μm (micros: ±20%, others: ±100%, −50%)
Component: ACBB; IR, run
Speed: 1 MdN
Load: 0.7 GPa
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.01.2 Scratch, toolmark, scuffmark
Failure Code 2: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 3: -
Failure Code 4: -

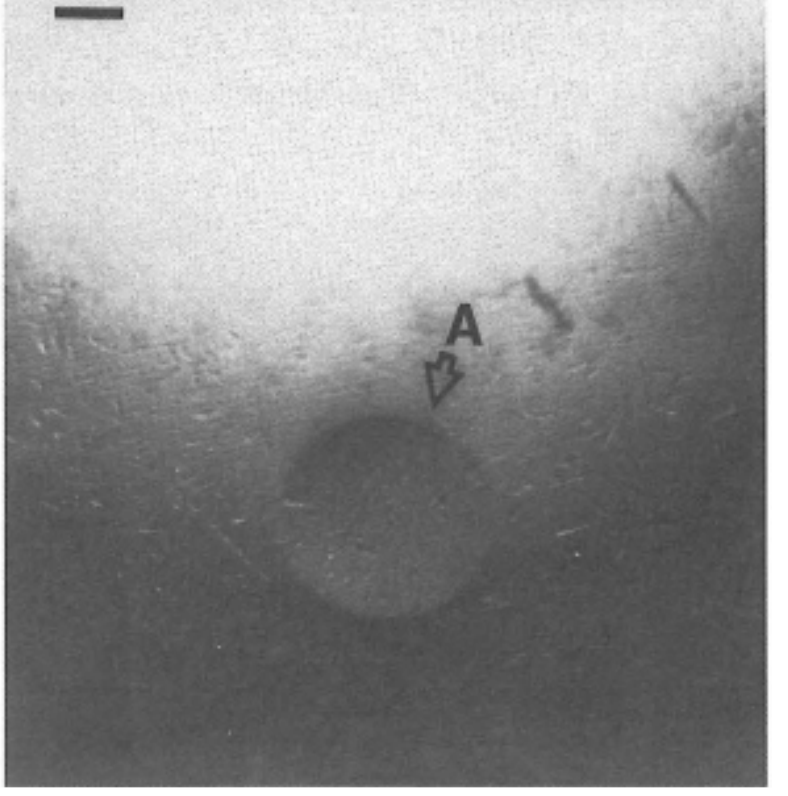


DESCRIPTIONS

Failure Description: Severe axial tool mark on land and ball groove, followed by spall in groove, extending to edge and chipping into land. Contact apparently extended to edge so that spall could form at edge. Ring has failed.
Image Description: N 1/3 of image is land, S 2/3 is ball groove; the two are separated by groove edge. Dark, teardrop-shaped gouge in land. Elongated scratch still visible in groove, just S of land edge, and near S image edge. Mushroom-shaped spall formed E of gouge (downstream in rolling direction) and broadened near land edge, from edge loading. Near land edge, spall crossed gouge and extended against rolling direction.
Suspected Causes: Severe nick or gouge in rolling surface is cause for early spalling. Broadening of spall toward land edge suggests that contact must have overrun the edge, so that substantial edge stresses existed. This is likely to cause early spalling even without the defect.

DATA

Plate No: 4.10
Archive No: 093-1.1.5
Image type: light micrograph
Scalebar = 70 μm (micros: ±20%, others: +100%, −50%)
Component: BB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.01.3 Circular flat nick on ball
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 4: -



DESCRIPTIONS

Failure Description: Circular flattened nick (commonly called a "flat") on ball surface, marked by arrow *A*. A slight bulge of displaced metal surrounds the edge of the flat. Multiple short, small scratches and dents on ball surface both inside and outside the flat, due to wear. A flat on a ball causes noisy running but is a serious spall originator only when severe. Scratched and dented surface is likely to cause noise.
Image Description: The ball surface is shaded by oblique lighting. The flat is outlined where the light and shadow blend, due to its differing orientation. (Unless highlighted by oblique light impinging at a grazing angle, such flats are invisible.) The flat's edge is surrounded by a slight bulge. Multiple dents and scratches appear as dark streaks in the lit area and as light streaks near the edge of the unlit area.
Suspected Causes: Flats are typical ball manufacturing defects caused by balls impacting against each other in a container or against a hard flat surface. Due to the small impact area, a ball surface is plastically deformed under a drop of as few as 20 cm onto a hardened flat surface. Balls packed in boxes suffer flats when the box is dropped from similar heights.

Surface Defects from Manufacturing 5

Failure Code 00.02–.04

General Description

This chapter comprises morphological manufacturing defects that are (or may be) visible on the finished surface of the component, become visible at failure (e.g., in a fracture) or upon sectioning. Not covered in this chapter are Nicks (FC 00.01). Many types of failure can occur in casting, sintering, forming, or finishing which are not visible either on the surface or in fracture (material composition and structure defects, dimensional errors, etc.). These are not covered in this chapter. Some of them, which can be diagnosed by visual means, are covered in Chapter 6. Defects such as incorrect material composition, which are inherently nonvisual, are not covered in the Atlas.

5.1 FINISHING MARKS — FAILURE CODE: 00.02

5.1.1 Definition

A finishing mark is defined as a mark of unintended shape or size left on the finished surface by the last sequenced (intended) operation in the manufacturing process. It is distinct from a nick (FC 00.01) and a gouge (FC 00.09) caused by surface contacts occurring accidentally prior to service.

5.1.2 Nomenclature

- Abrasively finished (ground, honed, lapped, or polished) surfaces show *finishing furrows, chatter,* or *wheel hits*. Some grinding methods may produce *shoe marks.*
- Turned, milled, hobbed, or shaved surfaces show gouges, tears, or chatter.
- Cold rolled, deep drawn, or other chipless finished surfaces show marks specific to the process.

5.1.3 Failure Process

When a finish-machining operation malfunctions, the tool may leave unintended marks on the surface.

Abrasively Finished Surfaces. Any bonded abrasive used for grinding or honing may detach a grit particle which is dragged over the surface and cuts a furrow that is deeper or more irregular than a normal finishing mark, or runs in a different direction. It may start or end abruptly and may retain particles of grit.

Lapping compound may contain oversize or aggregated particles which make an abnormally deep furrow in the surface.

Centerless grinding methods rely on supporting machine elements to position the workpiece. Some of these (shoes) are in sliding contact with the workpiece. These supports can wear, score, or polish the surface of the workpiece, producing a shoe mark.

A control error in the motion of the abrasive finishing tool may bring it into abrupt unintended contact with the workpiece, creating a surface patch with defective geometry or finish. This is a

wheel hit. Similar to a wheel hit is a mark left by a hand-held grinder used to remove a local spall or dent from the surface.

Turned, Milled, or Hobbed Surfaces. Tool edges may chip, with the broken-off piece caught against the workpiece and making a gouge. A tear can result from a chipped tool or a tool with a worn or improperly formed edge failing to cut cleanly.

Hard-turned surfaces are fully hardened surfaces finished by single-point carbide or ceramic tools. They show finishing marks of similar origin as do other turned surfaces, but these are on a roughness scale comparable to those on ground surfaces.

Chipless Finished Surfaces. A multitude of surface markings can result from malfunction in chipless finishing, depending on the nature of the process. Characterization requires specific information concerning the finishing process.

5.1.4 Distinctive Appearance

Finishing furrows typically are wider and deeper than the normal finishing lines. When caused by a detached piece of grit, they may show one blunt end and one tailing-off end (comet-tail), as the grit is caught, dragged, and expelled or shattered, or left embedded in the surface. On finely ground or honed surfaces, magnification is required to identify finishing furrows.

Chatter marks may be seen as periodic changes in the luster of the surface, as one proceeds around the circumference. Often, they become visible only after being highlighted by running. Occasionally, they are detectable only as waviness, by surface tracing. Chatter marking may produce grinding damage (FC 00.08), which may subsequently be obliterated by further finishing.

Wheel hits or hand grinder marks may show directions of grinding cuts that differ from other surface areas. Usually, a geometry error (depression) can be detected by surface tracing. Wheel hits may produce grinding damage (FC 00.08), which may be subsequently obliterated by further finishing.

Shoe marks are circumferential marks of wear, polishing, or scoring, on the ground surface. Shoe marks may produce grinding burns (see FC 00.08: Grinding Damage).

Gouges are deep or irregular tool marks. Tears are plastically deformed and microcracked surface irregularities.

Finishing marks on chipless finished surfaces require knowledge of the finishing process for identification.

5.1.5 Causes

Causes of finishing marks require specific information on the finishing process for their identification.

5.1.6 Effects of Finishing Marks

Finishing marks may have similar effects as nicks (FC 00.01) or dents (FC 00.18). Specifically:

- Marks representing depressions without raised edges (finishing furrows and some chipless finishing marks). If present on contact surfaces, they impair the EHD film, causing surface distress (FC 00.17) in a surrounding "halo."
- Severe finishing furrows represent surface defects (stress concentrations) for the initiation of surface–origin spalls (FC 00.16).
- Shoe marks, if galled, are defects that may cause further galling (FC 00.13) and spalling (FC 00.16). If grinding damage exists in the marks, rubbing cracks (FC 00.08), bulk cracks (FC 00.22), or spalls (FC 00.16) may form.

- Gouges and tears tend to have raised edges and show microcracking. They act as severe nicks and may cause wear, galling, spalling, or bulk fracture.
- The effects of finishing marks from chipless finishing require evaluation using the specifics of the finishing process.

5.2 PIT OR UNFINISHED AREA — FAILURE CODE: 00.03

5.2.1 Pit — Failure Code 00.03.1

5.2.1.1 Definition

A pit is defined as a void open to the surface, caused by a casting, or forming defect or chemical attack on the surface. All pitting, other than by chemical attack, predates service. Chemical attack (corrosion) pitting may occur at any time after final finishing throughout the life of the part. It is covered for all cases under FC 00.20.

5.2.1.2 Nomenclature

In the literature, the word 'pit' has been used to describe any sharp-edged depression in a surface, including a spall. In this Atlas, a pit is distinguished from several other types of manufacturing defects and from spalls.

Pits are distinguished *from finishing marks, nicks, dents,* and unfinished areas by the following:

- A void created on the surface by the finishing process is a finishing mark (FC 00.02).
- A void created by unintended indentation prior to service is a nick (FC 00.01). Indentation in service is a dent (FC 00.18).
- An unfinished area is a patch of surface where the second-last finishing operation has not been reworked by the last operation (see section 5.2.2).

Pits are distinguished from spalls, which are fracture craters caused by contact fatigue (FC 00.16).

5.2.1.3 Failure Process

Pits result from either manufacturing process failure or chemical attack.

Manufacturing process failures are exemplified by the following:

- In casting, pressing, forging, rolling, or other blank preparation processes, internal voids (porosity, FC 00.05) may unintentionally be created. A subsequent chip-removal process may cut into these voids, creating a pit open to the surface.
- Weak interfaces created by the forming operation may separate during finishing, leaving a pit.
- Inclusions in the material may be intersected in finishing and tear out, leaving a pit.
- Large carbides present in some steels, and ceramic grains in bonded ceramics may tear out in finishing, leaving a pit.

Chemical Attack. Any time during manufacture, mounting, storage, or service of the machine element, chemical attack (corrosion, FC 00.20) may occur at a surface, causing pits.

5.2.1.4 Distinctive Appearance

Pits typically appear as sharp-edged craters. The surface in the pit does not show the finishing marks of the surrounding surface (distinguishing it from a nick). The pit surface is not a transgranular crack. This distinguishes a pit from a spall.

Differentiation of a pit from an incipient spall may require microscopic or SEM examination to detect the presence or absence of typical spall-bottom surface features (FC 00.16).

5.2.1.5 Causes

For causes of casting or forming defects, inclusions, or large grains, each of which can generate a pit if intersected in finishing, see FC 00.04 through FC 00.07. Any chip-forming finishing process can intersect one of these defects and leave a pit. More severe processes (higher cutting forces, larger depths of cut) are more prone to generating pits.

For causes of corrosion pitting see FC 00.20.

5.2.1.6 Effects of Pits

- Pits represent depressions without raised edges. If present on contact surfaces, they impair the EHD film, causing surface distress (FC 00.17) in a 'halo' surrounding them.
- Pit surfaces are often microcracked or otherwise weak. They act as surface defects for the initiation of surface–origin spalls (FC 00.16).
- Sharp-edged pits in a contact surface are defects acting as stress concentrators for surface–origin spalls (FC 00.16).
- Corrosion pits promote further corrosion of the surface.

5.2.2 Unfinished Area — Failure Code: 00.03.2–4

5.2.2.1 Definition

An unfinished area is left on a surface if the manufacturing operation preceding the last finishing leaves insufficient stock for the last operation to perform stock removal, or if the last operation misses the area.

5.2.2.2 Nomenclature

Unfinished areas in abrasively finished (or hard-turned) surfaces are often dark due to heat treat oxidation and are then referred to as "black areas." Unfinished areas are also known as NCU (not cleaned-up), unground, or unhoned.

5.2.2.3 Failure Process

Casting, forging, cold forming, and all chip-removal operations may produce a surface area that is depressed relative to its nominal position. The last finishing operation may find the depression deeper than the stock allowed for finishing, so that, after completion, the surface condition created by the preceding operation effective in that area is left unchanged. Alternatively, the finishing operation may miss an area due to machine or cutting tool malfunction. The effect is as previously described, except that the surface is now raised rather than depressed.

5.2.2.4 Distinctive Appearance

Unfinished areas are identified by the difference in surface finish between that area and the surrounding surface.

- In a heat treated part, an area left in the 'as heat treated' condition is usually black or gray.

- Rough-ground areas in a finish-ground, honed, or polished surface may show grinding marks running in a different direction or deeper and sharper than the final finish. Surface tracing or microscopic examination may be needed for diagnosis.
- 'Lips' at edge reliefs, left when the finishing tool fails to reach the relief groove, may be visible under low magnification or detected by surface tracing.

5.2.2.5 Causes

- On a cold formed part with corner radii specified to be left as formed, the forming may fail to fill out the radius at some point, leaving a depressed area running into a contact surface. When the part is ground, no stock is available in the depression and it remains unfinished.
- Heat treatment or chucking of a part in the machine tool can cause distortion, leaving some surfaces lower than specified. Finishing to specification may leave these areas unfinished.
- Turning, prior to heat treatment and grinding, can leave gouges that are too deep for grinding to clean up.
- On surfaces that are rough ground and finish ground or ground and honed, the next-to-last operation may remove excessive material (or relieve residual stresses that cause distortion) so that the finish grinding or honing fails to find stock to remove. A rough-ground 'unfinished' surface is left behind.
- Components with integral flanges require finishing of the roller track and the flange. If grinding is the finishing method, a relief, i.e., a corner radius or undercut, is provided between track and flange, because the grinding wheel cannot reliably produce a sharp receding edge. If the wheel fails to find a wide enough relief, it may leave an unground lip at the beginning of the relief. A similar effect may be produced if the wheel geometry is in error (the wheel edge is rounded), leaving a lip near an undercut of correct width.

5.2.2.6 Effects of Unfinished Areas

Depressed unfinished areas are (large) nicks. They do not carry their share of contact load and edge stresses may develop at the boundary of the area.

- *Premature spalling* may result if the unfinished area falls within a Hertzian contact.
- *Galling* may result at locations where the edge of an unfinished area slides over a flange or a rolling bearing separator.

Lips are elevated above the finished surface and if contacted by a roller cause edge stresses, local plastic deformation, and a line of fine spalls in the roller, in the ring carrying the lip, or both.

High grinding stresses or grinding damage may be present at surfaces left unfinished after rough grinding.

5.3 FORMING DEFECTS — FAILURE CODE: 00.04

5.3.1 Definition

Forming defects are internal defects of a formed (forged, rolled, cold formed, pressed, deep drawn, or stamped) part, or of a part formed by powder compacting, resulting from the forming process. They may extend to the surface of the formed part.

- A *lap* is an unintended folded-over metal lip pressed into the surface with a weak interface to the bulk material.

- A *seam* is an unwelded interface in a formed part, often bearing a laminar inclusion of foreign material.
- *Defects in formed structure* consist of weak, brittle, or otherwise off-standard volumes of material caused by a faulty forming process, such as wrong forging temperature.
- *Pipe, porosity,* and *cracks* may be found in formed parts. Pipe and porosity are covered under FC 00.05; forming cracks under FC 00.07.

5.3.2 Nomenclature

Alternative nomenclature used in the forging, pressing, or extruding industries is not covered. The preceding is the usual nomenclature for contact machine elements.

5.3.3 Failure Process

- A lap forms if a volume of material is unintentionally folded over an adjacent volume during the forming operation and the fold is tightly pressed together. There may be partial welding at the interface, especially if the operation is hot forming.
- A seam forms if scale or other foreign material is unintentionally forged or rolled into the material where it forms a laminar discontinuity. Seams are interfaces extending radially inward from the surface.
- Defects in a (hot-)formed structure arise by processes of local melting, recrystallization, segregation, etc. Details of the processes depend on the material and specific forming method used.

5.3.4 Distinctive Appearance

Laps and seams are detected as nearly straight lines on the surface of the part. They may be obscured by plastically flowed surface material during finishing operations and reappear after running, or when a crack forms at them. A metallographic section shows oxide, voids, and/or irregular structure surrounding laps and seams. In a seam, the included foreign material is typically observable. Laps extend at a shallow angle to the surface, whereas seams run radially into the material.

Defective formed structure is detected in metals by metallographic examination, including etching. In other materials (ceramics), special microscopic techniques are required.

5.3.5 Causes

Identification of causes of forming defects requires specific knowledge of the forming method used.

5.3.6 Effects of Forming Defects

Forming defects are gross discontinuities which, under stressing, typically lead to

- Bulk cracking or fracture (FC 00.22);
- Spalling (FC 00.16).

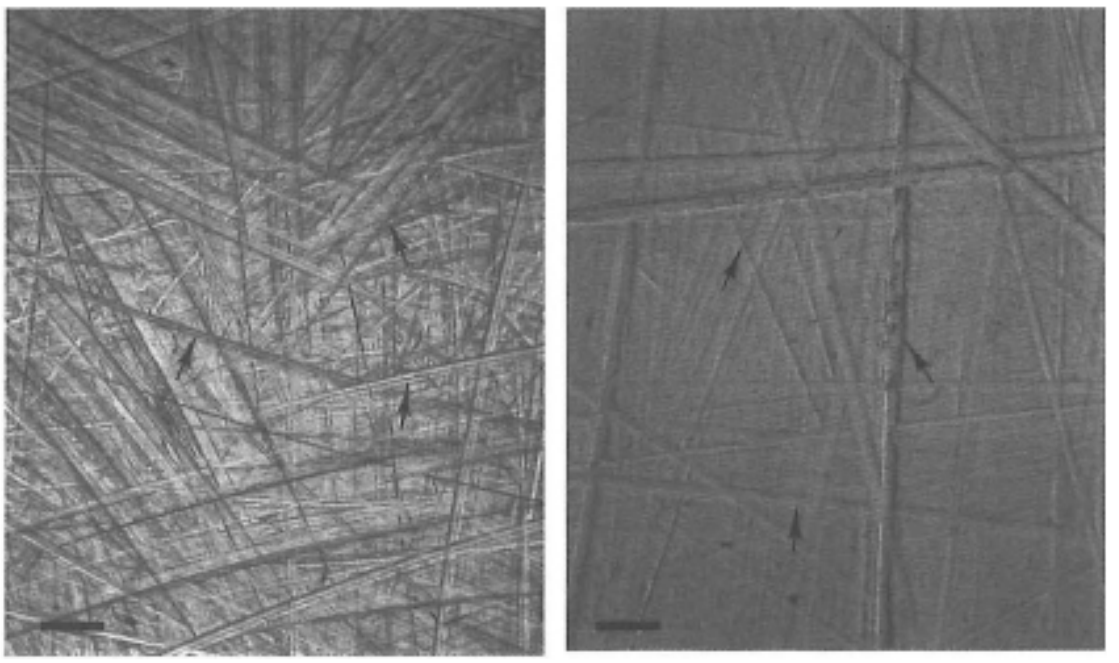
Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.02.1	5.19 8.20 10.68 10.69 11.24 11.25 11.26 12.13
00.02.2	6.23
00.03	5.11 19.10
00.03.4	7.12
00.04.1	8.13
00.04.2	5.23 10.45 15.28
00.04.3.1	6.15
00.04.3.1.1	10.34 10.53

PLATES

DATA

Plate No: 5.1
Archive No: 002-001b&d
Image type: SEM
Scalebar = (a) 100 μm; (b) 20 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, lapped, run
Speed: 1.5 MdN
Load: 0.75 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.02.1 Grinding, honing, lapping furrow
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



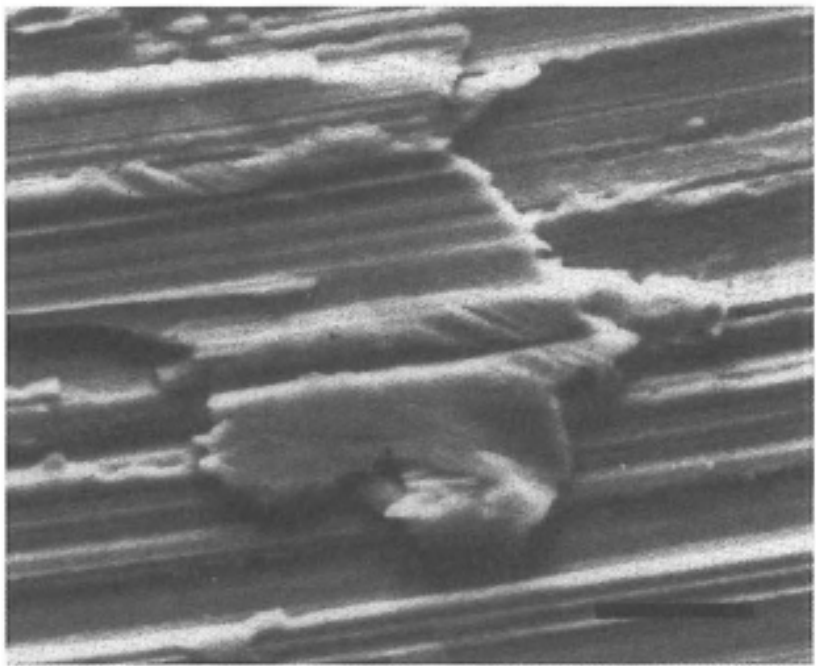
a b

DESCRIPTIONS

Failure Description: Smooth linear scratchmarks in random direction, generally uniformly distributed but of uneven depth, from ball manufacture. The deep marks qualify as lapping forrows. Marks of this depth may initiate surface distress in critical applications and somewhat wear separator pockets. Two distinct sets of marks (one from lapping the other from service) are not present, i.e., furrows not of service origin. See FC 00.12 for wear.
Image Description: (a): Dense pattern of randomly oriented smooth-ending scratchmarks. Some marks are deeper than others (arrows) and qualify as furrows. (b): Higher magnification shows the lack of sharp feather edges at all marks, indicating that they are likely to have undergone equal running times since scratching, i.e., none are of service origin. Arrows mark some deeper furrows.
Suspected Causes: The ball lapping process necessarily produces fine lapping lines. If the lapping compound is of uneven grain size, larger grains may produce the deeper furrows.

DATA

Plate No: 5.2
Archive No: 006-1
Image type: SEM
Scalebar = 10 μm (micros: ±20%, others: +100%, −50%)
Component: G, high hardness, ground, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.1 Grinding, honing, lapping furrow
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

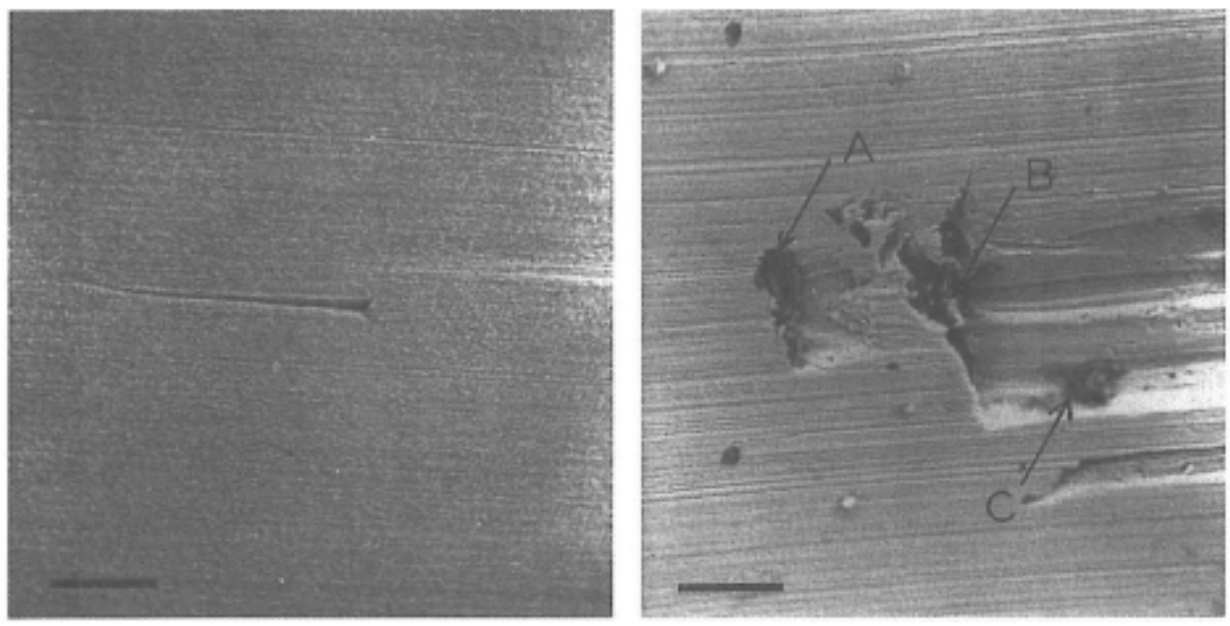


DESCRIPTIONS

Failure Description: As-ground gear tooth surface on which the grinding process has redeposited (welded) steel particles. This surface has poor resistance to wear or fatigue failure. The redeposited debris is heavily worked and heated material, welding to the surface entails high stresses and the debris increases roughness.
Image Description: Grinding lines run E–W in the image. A particle at least 50 μm long extends from NW corner to image center where it ends in a "peninsula." Some grinding took place after welding, as evidenced by grinding lines on the particle.
Suspected Causes: Insufficient flushing of grinding debris from the wheel/workpiece contact may cause debris to be redeposited from the grinding wheel and welded to the workpiece surface.

DATA

Plate No: 5.3
Archive No: 093-2.1.9&11
Image type: SEM
Scalebar = a, b: 50 μm (micros: ±20%, others: +100%, −50%)
Component: BB; IR, unrun, Nital etched
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.1 Grinding, honing, lapping furrow
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: -
Failure Code 4: -



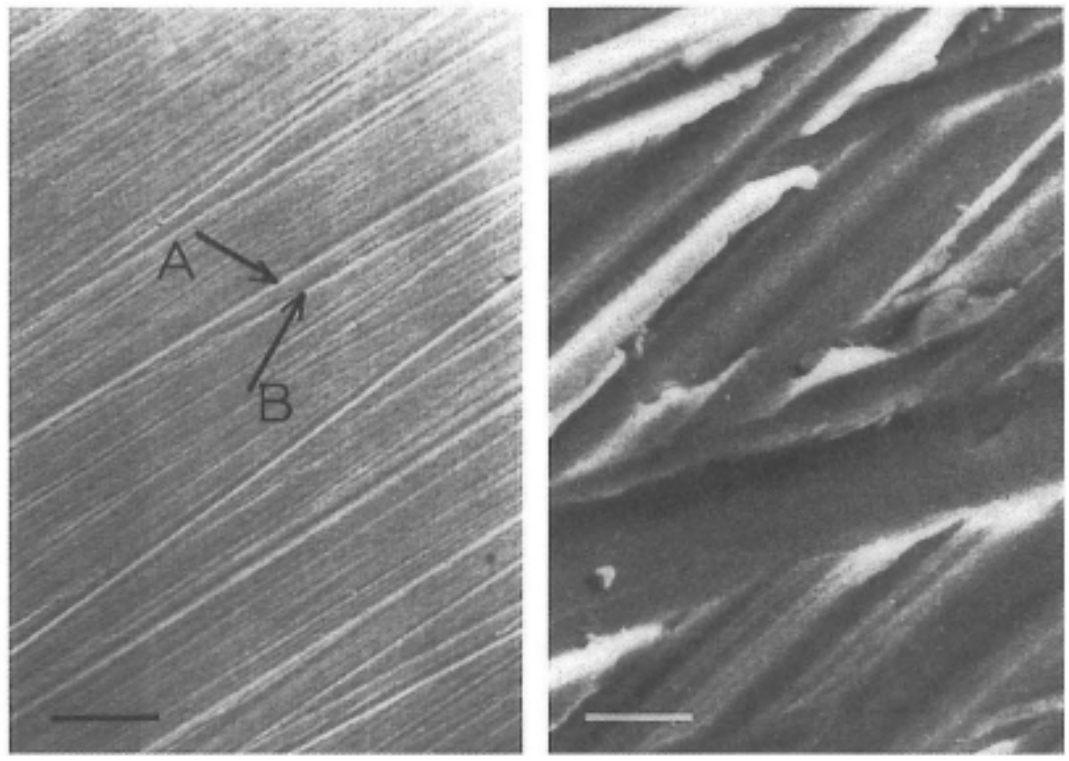
a b

DESCRIPTIONS

Failure Description: (a): 'Comet-tail'–shaped grinding furrow in the honed rolling track. The plowing contact started at the pointed, tail side of the furrow and ended abruptly at the blunt, head side. The furrow is too deep to be removed by subsequent honing. (b): Deeper furrow, with embedded grinding grit. Furrows are a source of surface distress upon running.
Image Description: (a): Fine E–W running honing lines. Mottling from Nital etch. Comet-tail (dark streak) at image W center is grinding furrow. Dark color in furrow center is a depression. Light outlines are sharp edges. (b): E–W honing lines cover background. Furrow head extends from E image edge to points *A, B,* and *C*, where dark grinding grit particles are visible.
Suspected Causes: A particle of grinding grit becomes detached from the wheel and is dragged along the surface being ground. As the wheel-to-workpiece contact builds up, the grit is pressed deeper into the workpiece, causing the widening furrow. The grit may shatter or be expelled and the furrow stops abruptly. Honing removes insufficient material to remove the furrow.

DATA

Plate No: 5.4
Archive No: 093-2.1.1&2
Image type: SEM
Scalebar = a: 60, b: 6 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.1 Grinding, honing, lapping furrow
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



a b

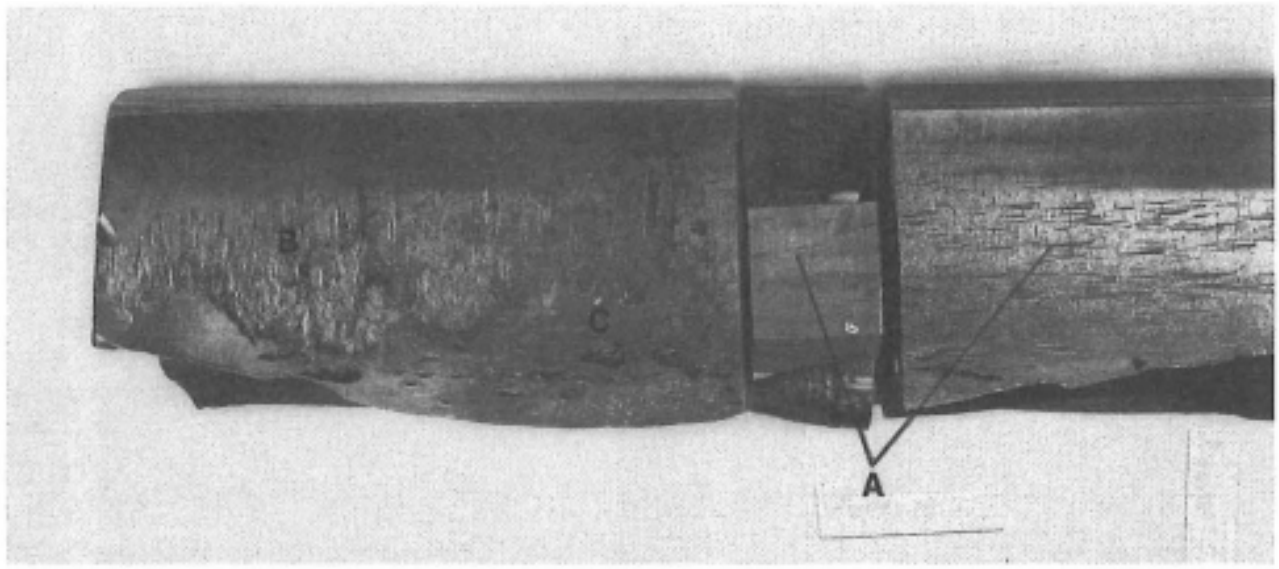
DESCRIPTIONS

Failure Description: Illustrations of unfailed honed ball groove surface, with normal honing lines including crosshatch. Sharp cutting action of honing grit is apparent from clean edges and absence of major tears. Note the "feather edges" in image (b) which will plastically deform. They may wear off rapidly in running and produce lubricant contamination. Honing produces much finer "feather edges" than does grinding.
Image Description: (a): At moderate magnification, shows even, fine honing lines running in two crossed directions (crosshatch) as at arrows *A* and *B*. (b): At high magnification, shows details of the honing action (not the same specimen). At the NW image corner, feather edges of material are shown on the light gray flank of a cut. SEM images exaggerate perceived depth. The slopes of the cut walls are not as steep as they appear.
Suspected Causes: The images show normal honing action.

Failure Code: 00.02.1
Failure Code: 00.02.2

DATA

Plate No: 5.5
Archive No: 099-235
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, 4350 steel, med. hard, run
Speed: 260 cm/sec
Load:
Lubrication: oil, ? °C
Failure Code 1: 00.02.1 Grinding, honing, lapping furrow
Failure Code 2: 00.13.2.1.2 Rolling surface galling, dent or nick visible
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: 00.22.01.4 Gear tooth crack or fracture

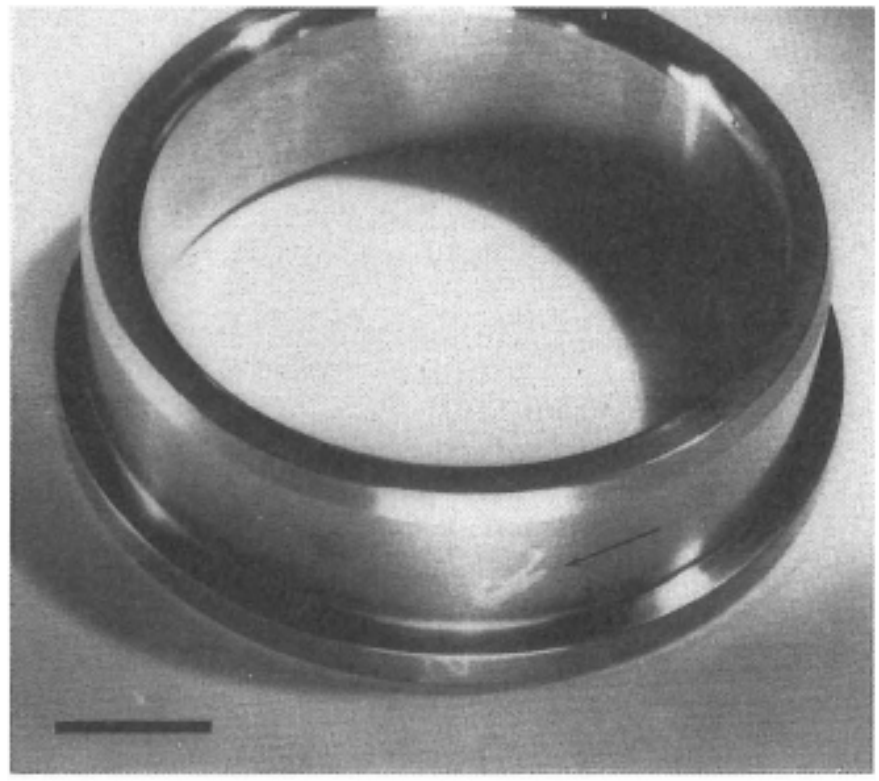


DESCRIPTIONS

Failure Description: Multiple, comet-shaped axial furrows, overlaid by patchy radial galling streaks. Local spalling. Tooth root bending fracture. An area on the tooth with pressure concentration was vulnerable to galling and spalling aided by the grinding furrows. Ultimately the tooth broke in bending fatigue in the overloaded area.
Image Description: Broken gear tooth, sectioned; sections placed side-by-side. N edge of the two large sections is the tooth tip. S edge of the image is the bending fracture surface. Furrows are comet-shaped axial dark lines at *A*; galling streaks run radially, at *B*; dark spall crater at *C*.
Suspected Causes: Geometry error may have caused concentrated contact on a very long (2 m) tooth. Presence of furrows from tooth grinding enhanced the risk of galling and spalling. Once surface-damaged, bending fatigue cracking fractured the tooth at the root.

DATA

Plate No: 5.6
Archive No: 087-005
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.2 Wheelhit
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

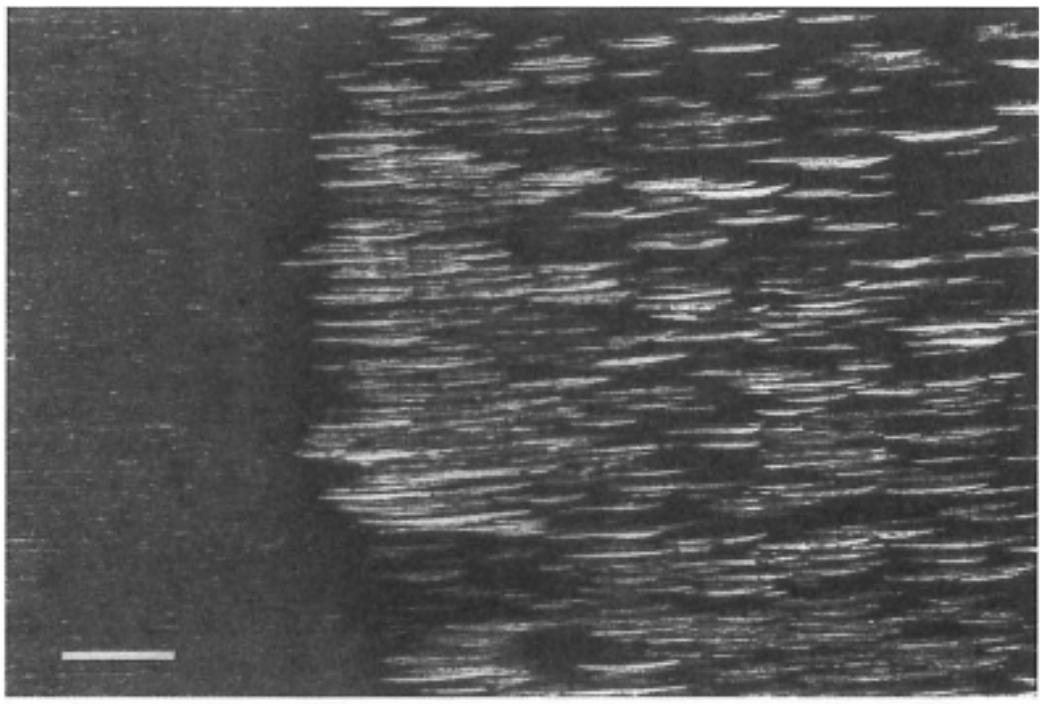


DESCRIPTIONS

Failure Description: Unintended local grinding wheel impact (wheelhit) on roller path and flange OD. A wheelhit on a contact surface causes edge loading at the rim of the depressed hit and may lead to spalling (FC 00.16). Due to disrupted contact, the wheelhit may cause running noise. In high-speed bearings it may cause roller skew with resulting failure. Wheelhits often produce grinding burns (FC 00.08) which lead to early spalling.
Image Description: At the arrow is a light-appearing irregular patch on the roller path. Below, similar patch on flange OD. If viewed in close-up, the grinding marks in the patches might run in directions other than circumferential.
Suspected Causes: This wheelhit was caused by a hand-held small grinder (may be used to engrave serial numbers on ring sideface). (Wheelhits by uncontrolled approach of the wheel in a specified grinding operation are more common.)

DATA

Plate No: 5.7
Archive No: 006-0b
Image type: light microgram
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, run, spot-ground
Speed:
Load:
Lubrication: mineral oil grease, ? °C
Failure Code 1: 00.02.2 Wheelhit
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

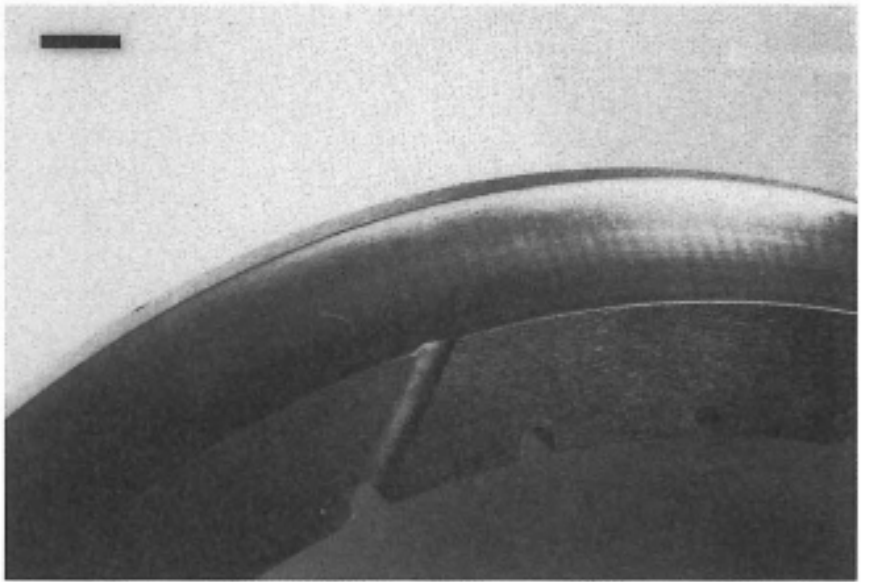


DESCRIPTIONS

Failure Description: Localized spall crater repaired by grinding with a hand-held grinder. The rough, reground surface is covered with deep furrows. The surface is depressed beneath the working contact path and thus stressed only at the edges of the re-grind where stress concentration exists and early spalling is expected. However, the stress concentration is probably less than at the edge of an unrepaired spall.
Image Description: Image W, to ⅓ width, is the original contact surface with multiple debris dents. Image center and E shows a hollow made by re-grinding. The light colored E–W lines are the grinding furrows of the last pass. In the dark background, N–S grinding lines from a previous pass are faintly visible.
Suspected Causes: As a cost-saving measure, rolling mills and other users of very large roller bearings may, upon finding small spalls in a ring contact path, use a high-speed hand grinder to remove the spall surface and create a relatively smoother and better blended hollow to prevent rapid spall propagation at spall edges.

DATA

Plate No: 5.8
Archive No: 018-623
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR (split), run
Speed: >1 MdN
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.02.3 Grinding chatter
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

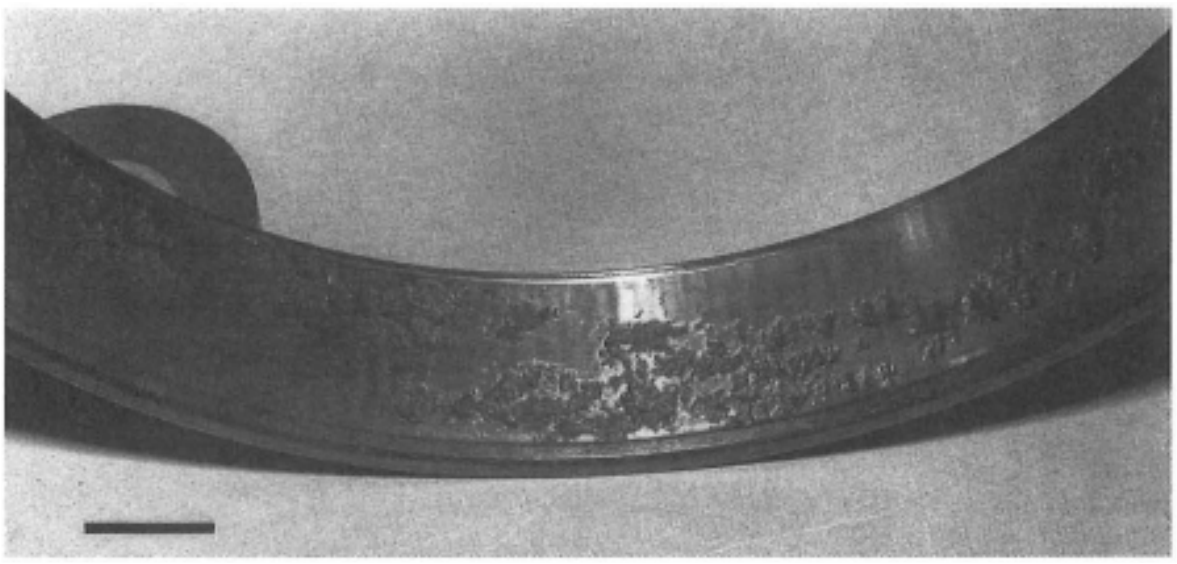


DESCRIPTIONS

Failure Description: Severe high-frequency circumferential waviness (grinding chatter) in ball track. Grinding chatter produces noisy and vibratory running. In high speed bearings, kinematic instability may result. Severe chatter may precipitate early spalling or galling failure.
Image Description: Along centerline of ball track, light and dark parallel axial marks, about 4 mm apart, highlight the high and low points in waviness (chatter). Unless severe, chatter is visible only after running, when uneven polishing wear caused by vibratory ball motion highlights it.
Suspected Causes: Machine vibrations in a grinding operation cause oscillatory wheel pressure and result in a wavy surface on the workpiece.

DATA

Plate No: 5.9
Archive No: 031-805
Image type: light macro
Scalebar = 20 mm
(micros: ±20%, others: +100%, −50%)
Component: CRB; OR, run
Speed:
Load:
Lubrication: grease, 100°C
Failure Code 1: 00.02.3 Grinding chatter
Failure Code 2: 00.00.02.1
Defect by location: in Hertz contact surface
Failure Code 3: 00.16.02.3 Incipient spalling, single spall
Failure Code 4: -

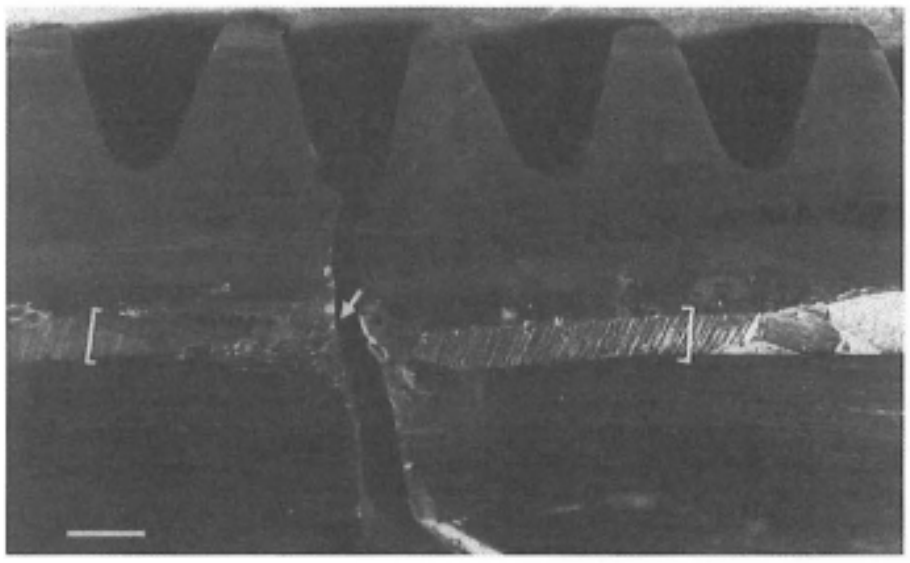


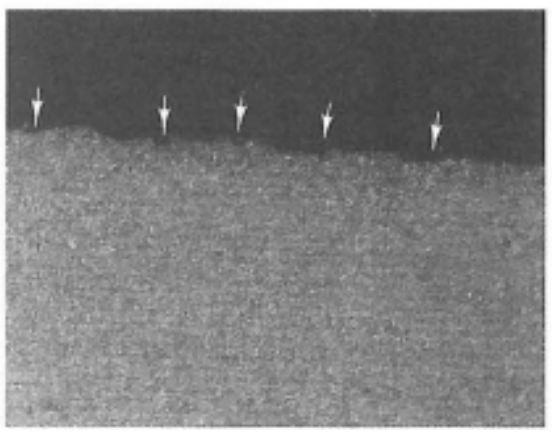
DESCRIPTIONS

Failure Description: Severe grinding chatter in unspalled region of OR roller track. Extensive spalling. Grinding damage to material from uncontrolled grinding resulting in chatter, may contribute to spalling. Bearing vibration due to chatter may be severe enough to accelerate spalling even in the absence of grinding damage. The bearing has failed.
Image Description: In the NE quadrant of the roller path shown, periodic light and dark axial lines show grinding chatter. Elsewhere in the track are extensive spalling craters. There is some indication that spalling is wider where it falls on the dark chatter bands.
Suspected Causes: Grinding chatter is due to vibrations of the grinding spindle during grinding, causing variable grinding pressure and circumferential waviness in the workpiece. Spalls may be due to normal service, with possible correlation with chatter as a result of (1) surface roughness changing on wave crests, (2) vibratory load components caused by chatter, or (3) possible grinding damage (see FC 00.08).

DATA

Plate No: 5.10
Archive No: 002-008c&d
Image type: a: light macro, b: metallogram, etched
Scalebar = a: 4mm, b: 200 μm
(micros: ±20%, others: +100%, −50%)
Component: BG; G, hobbed, run
Speed: 91 m/sec
Load: 0.6 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.02.4 Machining mark
Failure Code 2: 00.00.03 Defect by location: in free surface
Failure Code 3: 00.22.01.1 Axial cross section crack in ring
Failure Code 4: -
See also PLATE: 15.27





DESCRIPTIONS

Failure Description: Coarse machining marks at chamfer, as stress raisers. Cross-section fatigue cracking from bending stresses in service, raised by the machining marks. Machining marks are sharp-edged and about 20 μm deep, producing strong stress-raising effects. Highly stressed gear rings cannot tolerate machining as coarse as found here. See Plate 15.27 for fatigue failure.
Image Description: (a): Between brackets, rough machined chamfer area with angled machining marks. Cross-sectional crack originated at arrow, from stress concentration in these marks. (b): Arrows show roughly evenly spaced rectangular cross sections of machining marks in the sectioned free surface. The sectioned surface is etched.
Suspected Causes: Highly loaded bevel gear ring undergoes high alternating bending stresses. The machining marks acting as stress raisers precipitated bending fatigue. Off-specification machining operation on the chamfer has produced the deep marks.

DATA

Plate No: 5.11
Archive No: 080-101
Image type: light macro
Scalebar = 60 mm (micros: +20%, others: +100%, −50%)
Component: SG, high hardness, hobbed, shaved, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.4.2 Gear hobbing mark
Failure Code 2: 00.03 Pit or unfinished area
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Periodic, axial marks from gear hobbing, which subsequent shaving failed to remove. These marks are undesirable (may cause noisy running and poor EHD film condition) but rarely cause functional gear failure.
Image Description: Axially periodic, light and dark appearing patches along tooth flank. Color depends on light incidence.
Suspected Causes: Hobbing of gear teeth, if not followed by adequate finishing, may leave hob marks. These are variations in surface roughness and are usually removed in finishing operations. In the case shown, the shaving operation left uncleaned hob marks.

DATA

Plate No: 5.12
Archive No: 080-103
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SG, high hardness, shaved, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.4.3 Gear shaving mark
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Plastically displaced material from gear shaving forms raised "lips" at edges between both flanks and OD of gear tooth. Unless extreme, these lips do not interfere with functioning, but they do indicate an imperfect shaving operation.
Image Description: The surface at image NE is the gear OD. One tooth flank is visible at SW. A light-colored, raised lip appears at the edges, where each tooth flank meets the OD. The raised material at the two edges is similar in magnitude.
Suspected Causes: The gear shaving operation may, when performed with a dull cutter, plastically deform the tooth flank material, raising an edge where the face intersects the OD. Edges at the intersection of both flanks with the OD tend to be similarly raised.

Failure Code: 00.02.4.3
Failure Code: 00.03.1

DATA

Plate No: 5.13
Archive No: 064-1001
Image type: color macro (SEE IMAGE IN APPENDIX.)
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: HG, P, med. hard, shaved, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.02.4.3 Gear shaving mark
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: -
Failure Code 4: -

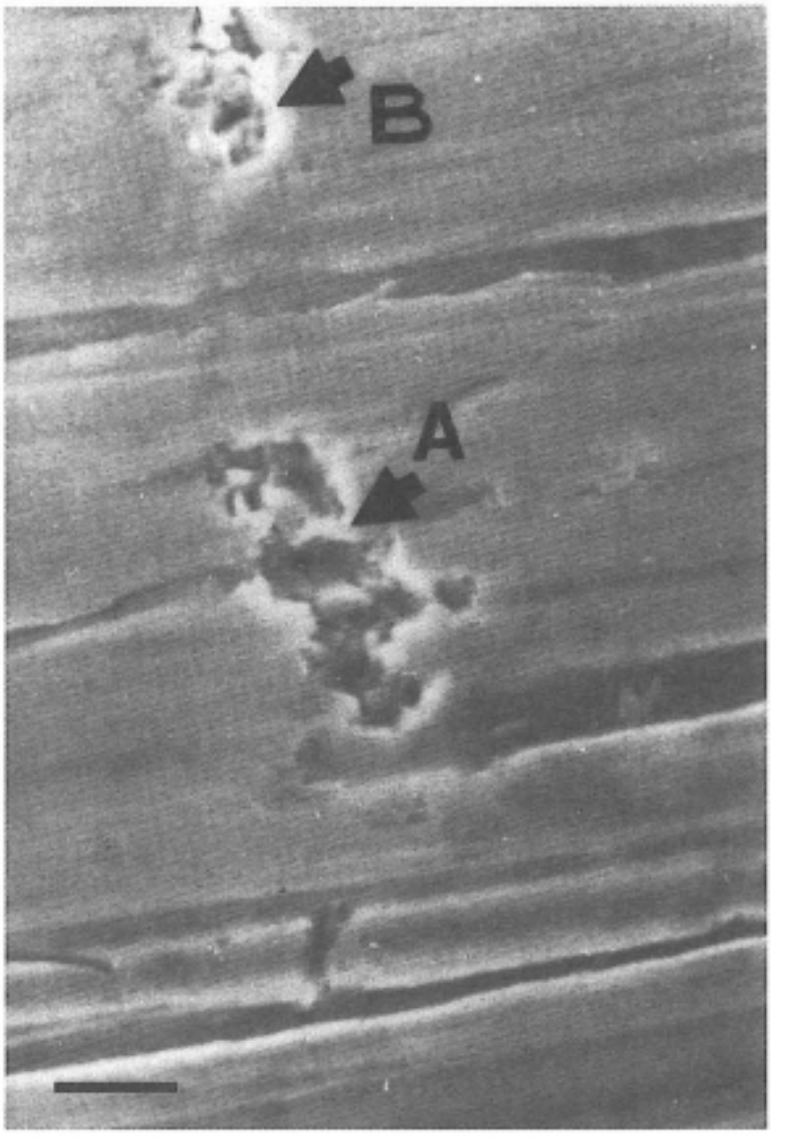
[See Image in Appendix]

DESCRIPTIONS

Failure Description: Shaving marks on gear tooth faces. In running, the marks were selectively discolored. Shaving marks may be harmless, unless deep enough to disrupt EHD film and/or pressure distribution.
Image Description: At about −20° angle to radial, dark brown and metallic light streaks alternate on tooth face, at about 3 mm spacing.
Suspected Causes: The shaving operation in tooth manufacture leaves this type of mark.

DATA

Plate No: 5.14
Archive No: 093-3.1.8
Image type: SEM
Scalebar = 8 μm (micros: ±20%, others: +100%, −50%)
Component: BB; IR, tool steel, honed, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.03.1 Surface porosity or pit
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: 00.06.1.3 Primary carbide
Failure Code 4: -

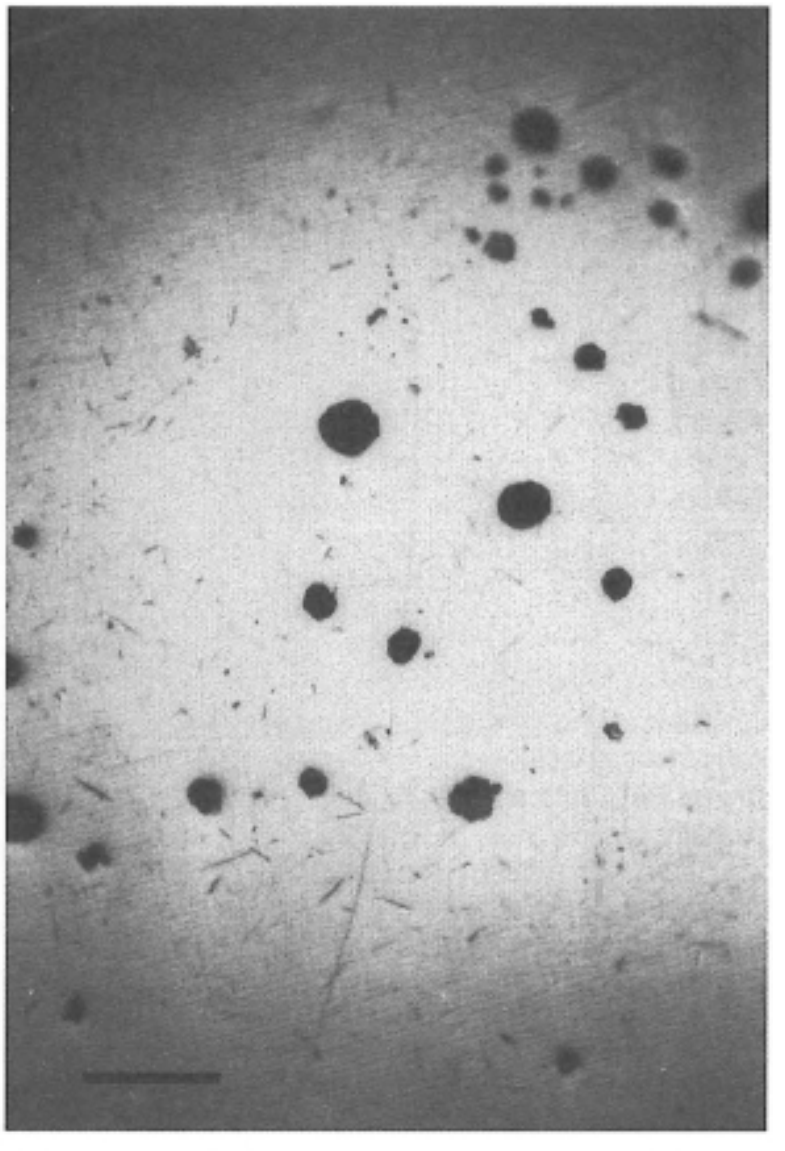


DESCRIPTIONS

Failure Description: Micropits formed during honing of tool steel surface. Pits of this small magnitude (about 10 μm long) are often harmless except in instrument bearings requiring extreme smooth operation. Surface distress (FC 00.17) may form at larger pits and initiate spalling failure (FC 00.16).
Image Description: Honing lines run E–W. At *A* and *B*, irregularly shaped sharp-edged angular depressions. At S end of pit at *A*, a deeper furrow emanates, and propagates to image E.
Suspected Causes: In tool steel (and stainless steel) bearing materials, relatively large carbides are common. During honing, such carbides may be torn from the surface and leave a pit. They may also be dragged along the surface, making a furrow.

DATA

Plate No: 5.15
Archive No: 093-3.1.6
Image type: light microgram
Scalebar = 150 μm (micros: ±20%, others: +100%, −50%)
Component: BB; B, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.03.1 Surface porosity or pit
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: 00.20.2 Corrosion pitting
Failure Code 4: -

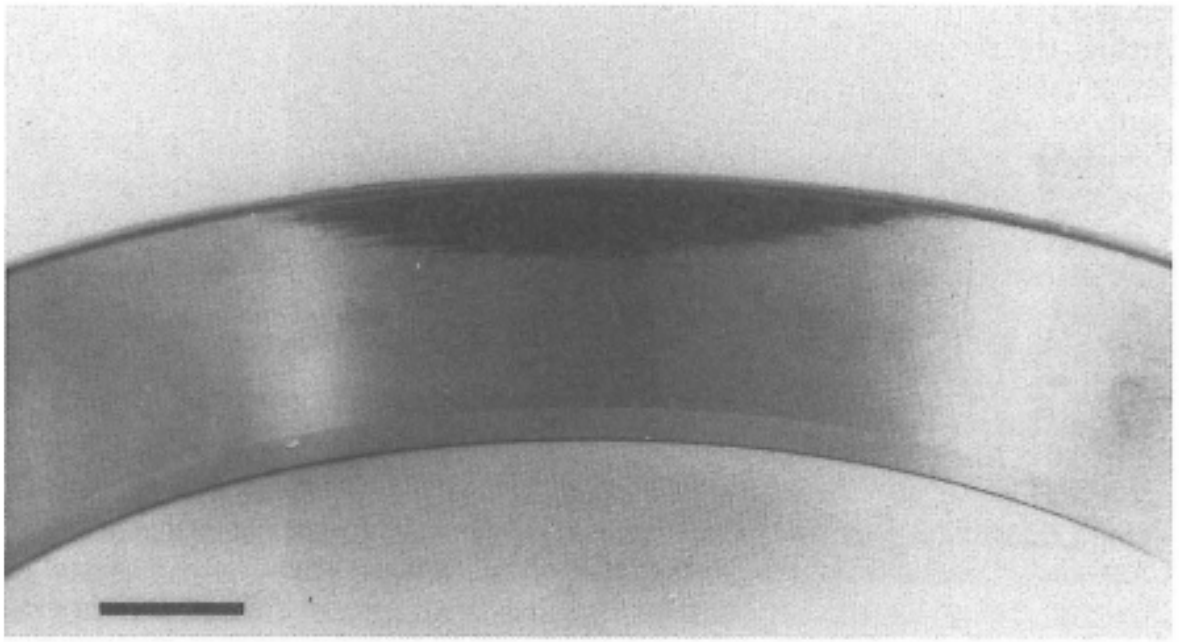


DESCRIPTIONS

Failure Description: Multiple pores in the surface, not removed in finishing. A ball operated with surface defects of this magnitude will fail rapidly in spalling fatigue. It may copy indentations onto the contacting part and it may run noisily.
Image Description: Round black spots of varying size on a background of fine short scratches in the lapped surface. Near the W edge of the image where light-incidence is grazing, the rim of the spots is seen to be depressed below the spherical ball surface.
Suspected Causes: A likely cause of the pits is corrosion of the hardened unfinished ball. The corrosion pits were too deep to be removed in the hard finishing operations.

DATA

Plate No: 5.16
Archive No: 093-3.1.4
Image type: view
Scalebar = 20 mm
(micros: ±20%, others: +100%, −50%)
Component: TRB; OR, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.03.2 Unground area
Failure Code 2: 00.00.02.1
Defect by location: in
Hertz contact surface
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

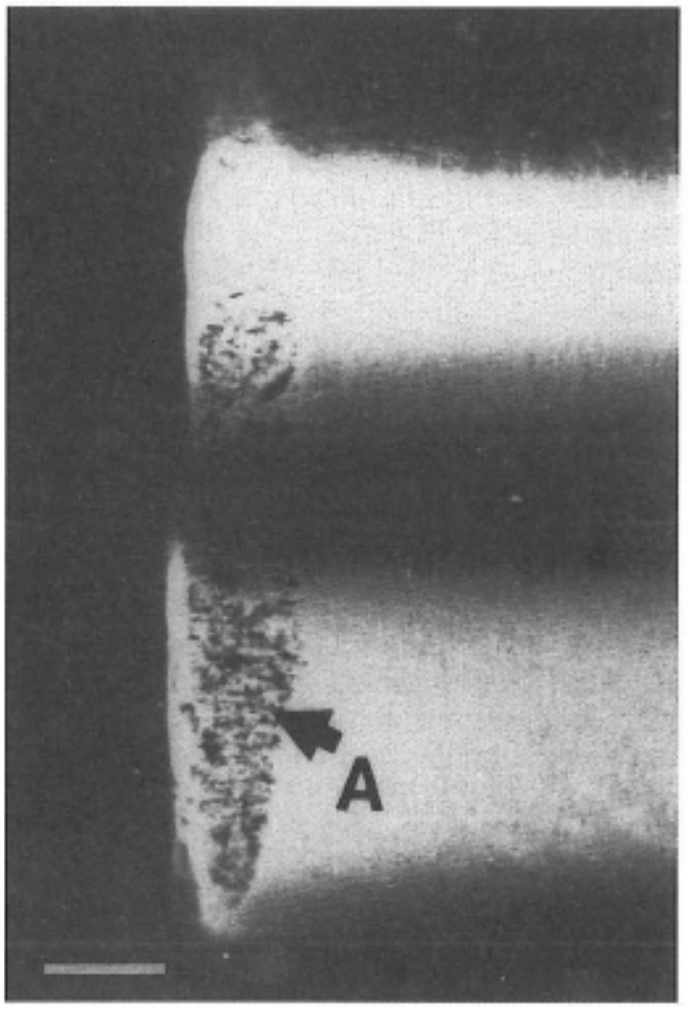
Failure Description: Unfinished surface at edge of TRB cup roller track. Surface is as heat-treated. This area is depressed below the finished contact surface and does not carry its share of load, leaving the contact area, especially the edge of the unground patch, overstressed. If the unground area should make contact, its rough surface and poor integrity (scale) will cause it to fail early in spalling fatigue.
Image Description: The shiny finished surface of the TRB cup roller path is interrupted at image N by a half-moon shaped black area with feathery border. In natural color, the black area is a dark gray (color of heat-treat scale).
Suspected Causes: The TRB cup shown is a case hardened thin-walled ring. Such parts may distort in quenching (fixture quenching is often used in larger rings). If sufficient grinding stock is provided, the grinding operation fails to reach the entire surface and unground patches remain.

DATA

Plate No: 5.17
Archive No: 093-3.1.1
Image type: light macro
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; R, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.03.2 Unground area
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Near roller end face, the rolling contact surface of this TRB roller shows a partially ground area at *A*. The grinding operation skimmed some high points but the valleys remain as heat-treated. Load carried by this partially ground area will be poorly distributed on a few high spots, leading to early spalling failure.
Image Description: Near W image edge, at *A*, a mottled dark crescent is the partially ground area. In natural color, the dark area is dark gray (heat treat scale).
Suspected Causes: TRB rollers are mostly cold headed from wire stock in automated headers. If the cutoff operation preparing the headed slug provides insufficient volume of material, an "underfill" is produced in the die, leaving a surface near the large end of the roller depressed. The grinding operation then fails to remove sufficient material to provide a clean ground surface.

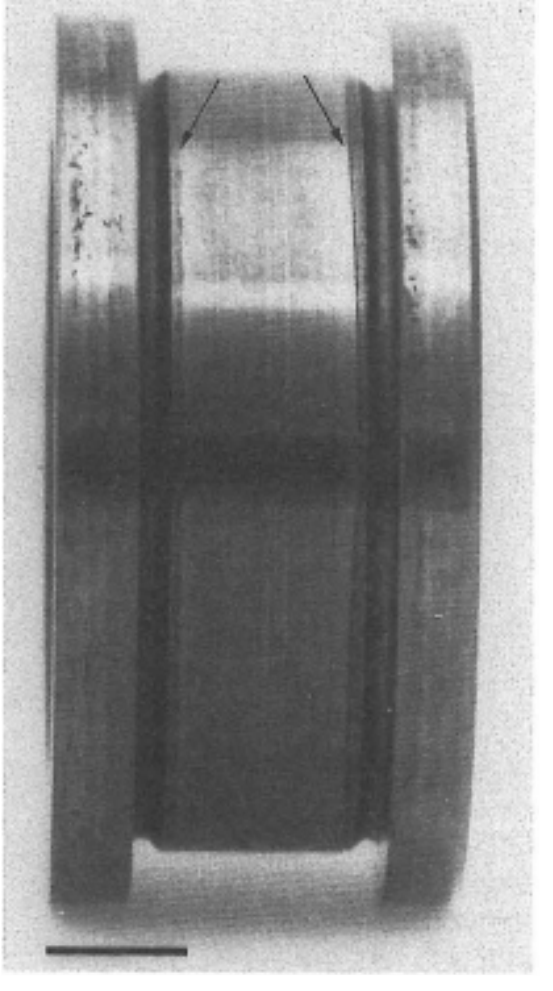


DATA

Plate No: 5.18
Archive No: 003-009
Image type: view
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed: 60 KdN
Load: 1.5 GPa
Lubrication: synthetic polyester oil, 110°C
Failure Code 1: 00.03.2 Unground area
Failure Code 2: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
Failure Code 3: -
Failure Code 4: -

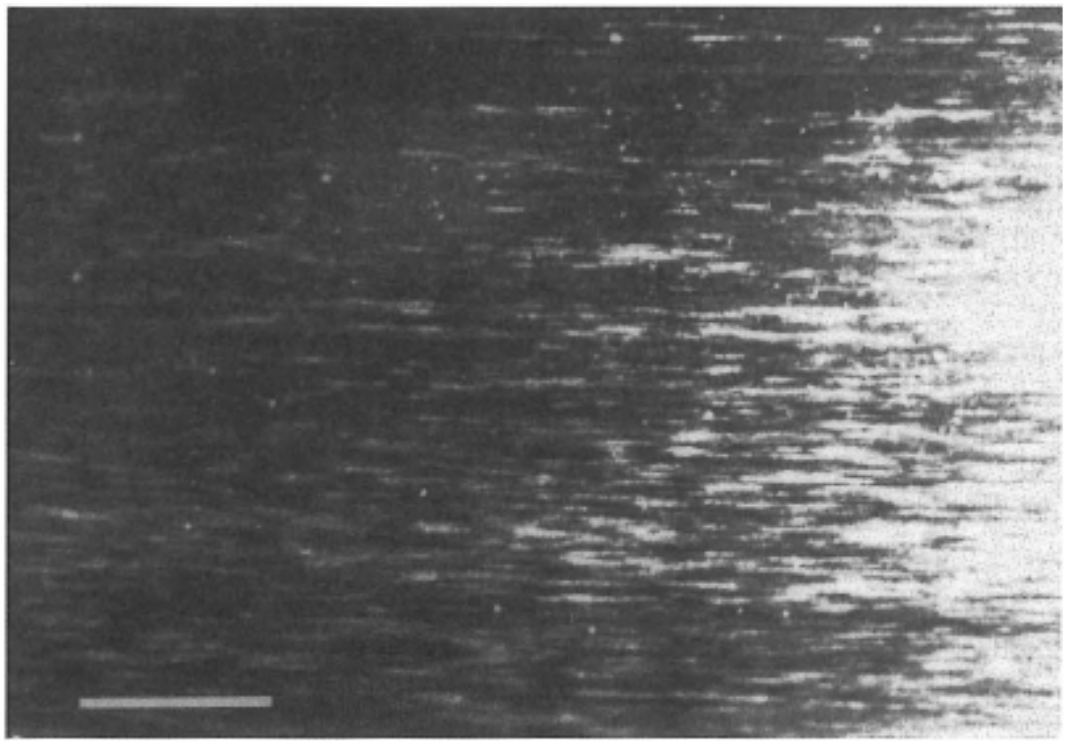
DESCRIPTIONS

Failure Description: Improperly machined undercuts at roller track edges (trail into roller track). Trailing edges not finished. Polishing of roller track by wear (where finished), during running. Excessive undercut deprives rollers of contact near their ends. Edge spalling may result.
Image Description: Roller track (light color) is flanked by (dark) undercuts, which, at arrows, extend into track (darker than polished track).
Suspected Causes: Improper machining of undercuts.



DATA

Plate No: 5.19
Archive No: 093-2.1.7
Image type: light micrograph
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: BB; IR, honed, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.03.3 Unhoned area
Failure Code 2: 00.02.1 Grinding, honing, lapping furrow
Failure Code 3: -
Failure Code 4: -

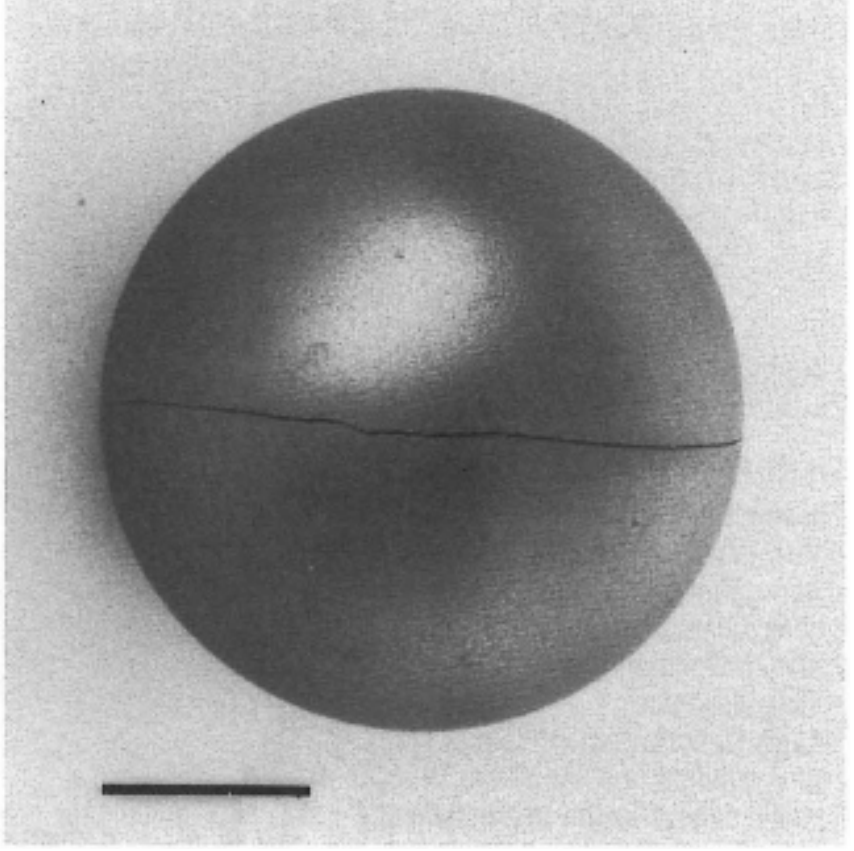


DESCRIPTIONS

Failure Description: Incomplete honing of ground surface, leaving numerous as-ground furrows. Intended EHD film thickness/roughness ratio, designed assuming complete honing, is not achieved when deep grinding marks remain on the surface.
Image Description: Grinding and honing marks run horizontally. Oblique lighting illuminates the (higher slope) valleys of remaining grinding marks. Honing, giving lower slopes, appears dark.
Suspected Causes: Higher than specified roughness after grinding, or insufficient material removal in honing can cause unhoned areas to remain on the surface.

DATA

Plate No: 5.20
Archive No: 087-112
Image type: light macro, hot acid etched
Scalebar = 4 mm (micros: ±20%, others: + 100%, −50%)
Component: BB; B, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.04.1 Forming lap
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

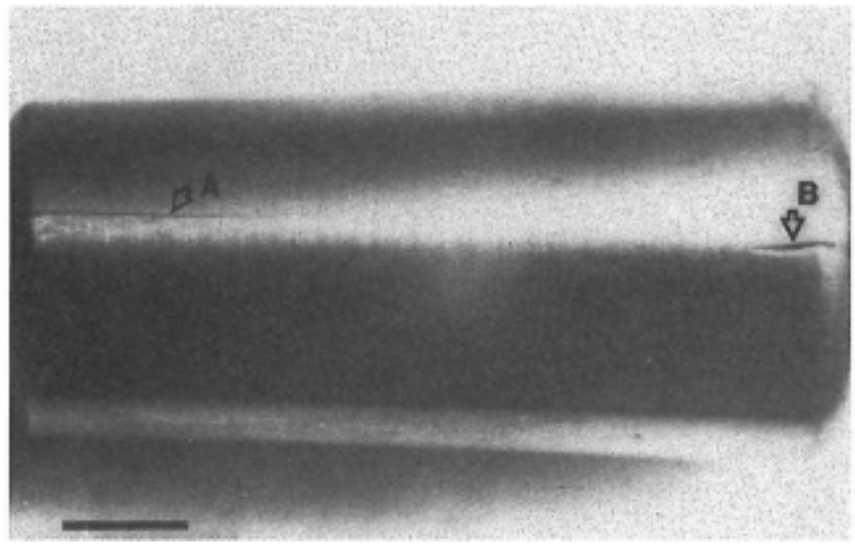


DESCRIPTIONS

Failure Description: During forming of the ball, a lap developed at the equator, encircling at least half the ball. A ball with a forming defect of this severity is likely to break in half upon running.
Image Description: Pebbled gray surface of the ball is due to hot acid etching. The etch has widened the lap to form the dark, open equatorial separation dividing two hemispheres.
Suspected Causes: Balls are cold or hot headed in dies divided at the equator. Normally a flash forms around the equator which is removed in soft finishing. Under deficient forming conditions or defective material, a fold may form at the flash. Finishing removes the outermost portions but, if deep, the fold persists as a lap in the finished ball.

DATA

Plate No: 5.21
Archive No: 093-4.1.1
Image type: view
Scalebar = 3 mm (micros ±20%, others: +100%, −50%)
Component: TRB; R, cold headed, finished, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.04.2 Forming seam
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

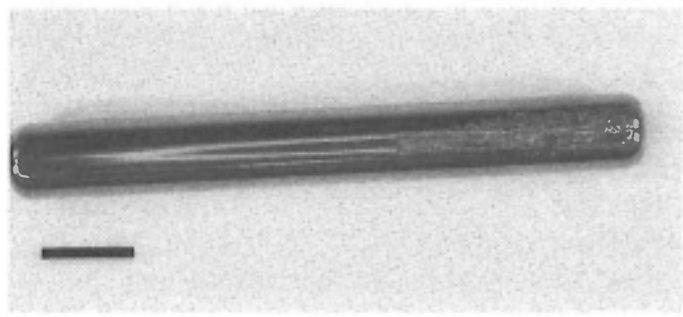


DESCRIPTIONS

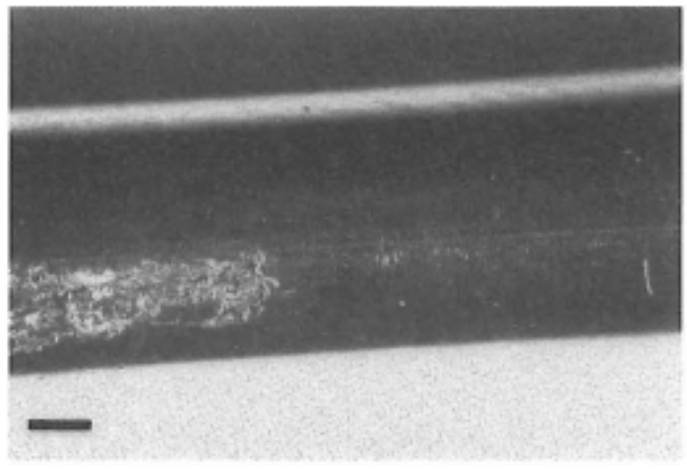
Failure Description: Axial seams at both ends of roller. A seam is a layer of oxide or other nonmetallic, sandwiched into the metal during bar or wire manufacture or forging, extending inward in roughly radial direction from the surface. Seams are severe forming defects which typically lead to fracture (FC 00.22) or spalling failure (FC 00.16) in operation.
Image Description: Seams are the dark, generally axial, lines at *A* and *B*, tapering off from roller ends toward center. They show appreciable width near both roller ends. Surface is depressed below normal surface at *B*. The seam extends onto the corner radius at the E of *B*.
Suspected Causes: Tapered rollers are often made from wire by cold heading. In the wire manufacturing process, seams occasionally form. During cold heading, seams are preserved and may open due to the plastic working.

DATA

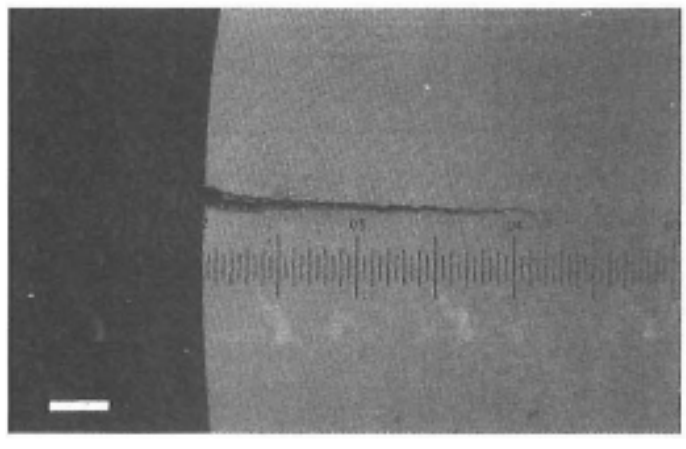
Plate No: 5.22
Archive No: 001-20&21&22
Image type: a,b: light microgr., c: light metallogr, etched
Scalebar = a: 10, b: 1 mm, c: 100μm (micros: ±20%, others: +100%, −50%)
Component: NRB; R, run
Speed: 25 KdN
Load: 1.5 GPa
Lubrication: synthetic polyester oil, 60°C
Failure Code 1: 00.04.2 Forming seam
Failure Code 2: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 3: -
Failure Code 4: -



a



b



c

DESCRIPTIONS

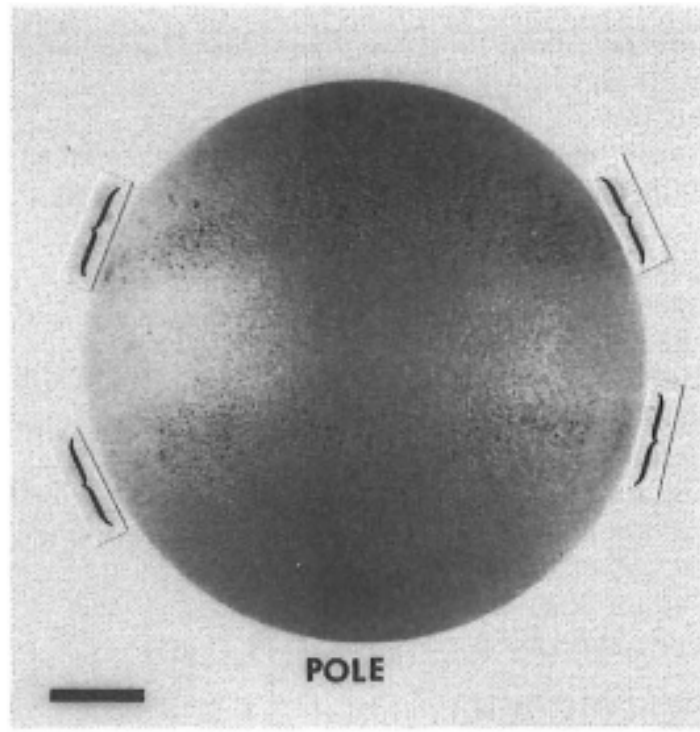
Failure Description: Forming seam in needle roller, extending virtually its entire length. Extensive spall originating from seam. A seam is a forming discontinuity, usually with non-metallics in the interface. A seam is a severe stress raising defect, which, when overrolled, leads to early spalling as in this roller. Note spall extending mostly to one side of the defect (behind, in the rolling direction).
Image Description: (a): Spall craters at E roller half. (b): Seam is E–W running white line. At image W, S of seam: multiple spall craters. Some carters extend to the seam, others leave a narrow band of unspalled surface. Spalling is down-stream from defect (in rolling direction, N to S). (c): In etched section, seam is dark, tapering streak running radially inward from the surface. Scale in image is 254 μm per numbered division.
Suspected Causes: In the rolling or drawing of wire stock for rollers, seams occasionally occur, when nonmetallics are rolled (drawn) into an interface running longitudinally and radially to the wire axis. Spalling is precipitated by the severe surface and subsurface discontinuity of the seam.

DATA

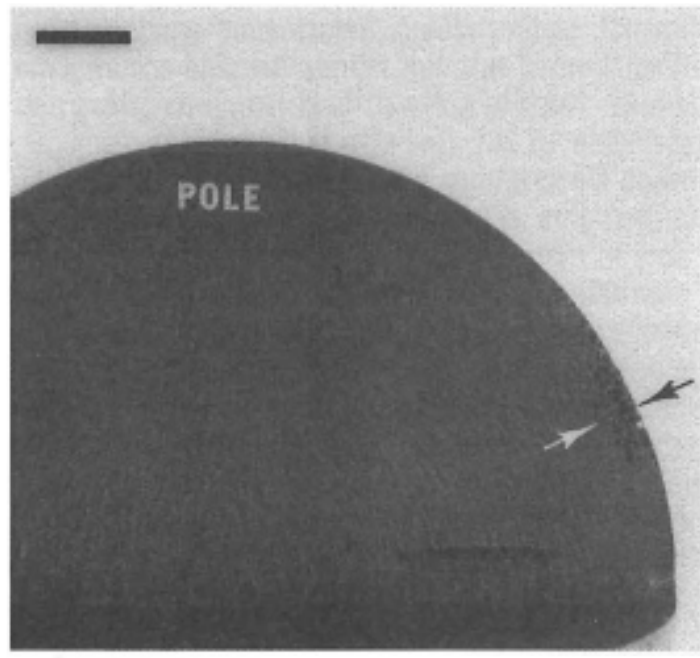
Plate No: 5.23
Archive No: 002-024c&d&e
Image type: a,b,c: light micrograph (a,b: hot etch)
Scalebar = a: 6, b: 3, c: 1 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.04.3.1.1 Incipient melting from forging at excessive temperature
Failure Code 2: 00.05.1 Micro-porosity
Failure Code 3: 00.04.2 Forming seam
Failure Code 4: 00.22.2 Bulk fatigue crack
See also PLATES: 5.24 and 15.28

DESCRIPTIONS

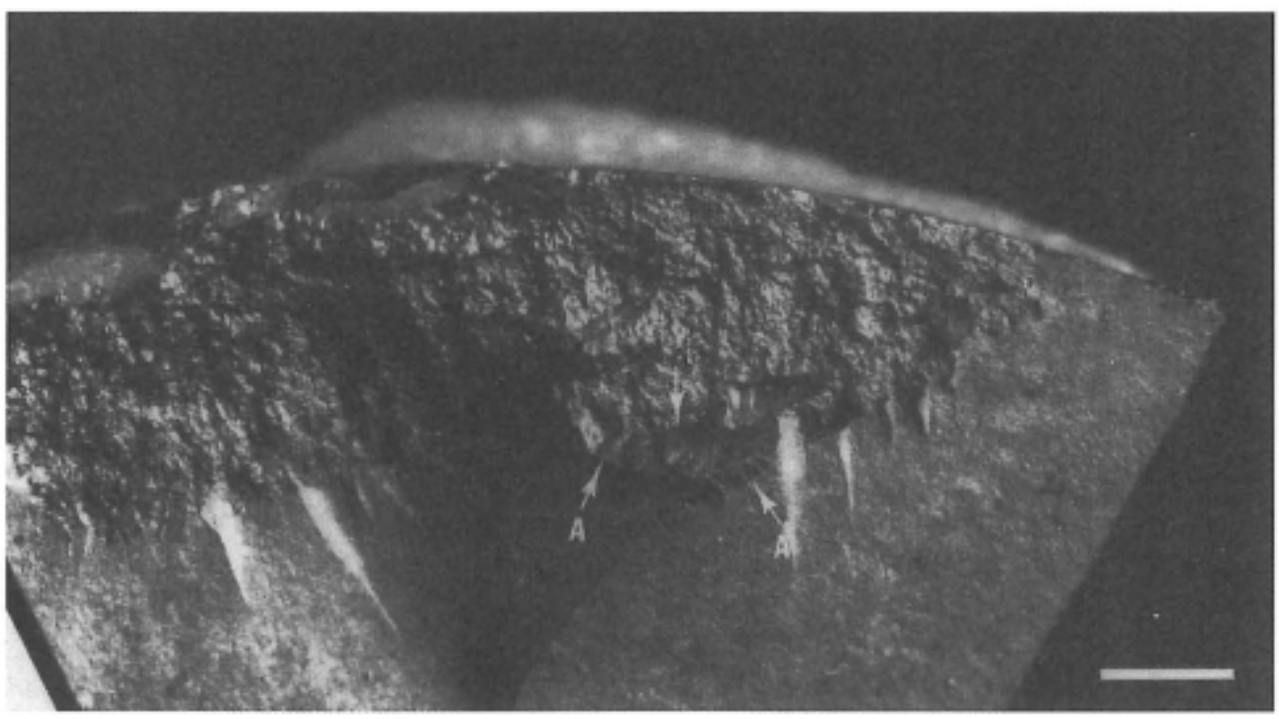
Failure Description: Improper forging has produced several defects: incipient melting and micro-porosity (a, b); a forming seam (c) and, upon running, a bulk fatigue crack and spall (see Plate 15.28). Forming defects in structure may cause early spalling. A seam is a severe defect. The ball has failed by spalling.
Image Description: (a): Two 'latitude' bands of deep etch pits (brackets) indicate altered material structure or micro-porosity. (b): Polar cross section through ball. At arrows, deep etch pits. (c): At image N, ball surface. Dark fatigue crack surface between arrows, *A*. Light-colored smooth fractures at image S are made for examination.
Suspected Causes: Forging at excessive temperature alters material structure by producing coarse grains or incipient melting. In this case, a seam also formed during forging and its surface oxidized at forging temperature. A radial bulk fatigue crack propagated during running from the discontinuity of the seam.



a



b



c

DATA

Plate No: 5.24
Archive No: 002-024g&h
Image type: a, b: light metallogram, Nital/Zephiran etch
Scalebar = a: 100, b: 20 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.04.3.1.1 Incipient melting from forging at excessive temperature
Failure Code 2: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 3: 00.16.02.1.1 Microplastic deformation bands or 'butterflies'
Failure Code 4: -
See also PLATES: 5.23 and 15.28

DESCRIPTIONS

Failure Description: Forging of the ball at excessive temperature has caused incipient melting to form pores in the material. Upon running, deformation bands (white etching areas) formed through fatigue damage accumulation at these defects. The ball suffered bulk fatigue cracking and spalling. (see Plate 15.28). See also Plate 5.23.
Image Description: (a): Section through spalled area. Dark mottled area at image S is etched matrix. Numerous black spots in matrix are pores. White irregular spots are deformation bands. Arrows labeled *A* indicate porosity, other arrows indicate deformation bands. (b): One pore with two deformation band "butterflies" at higher magnification.
Suspected Causes: Forging of material at excessive temperature during ball manufacture causes incipient melting which can result in porosity. The pores are severe stress raisers that tend to cause early fatigue damage as indicated by the deformation bands.

a

b

Material and Assembly Defects 6

Failure Code 00.05–09

General Description

This chapter encompasses a variety of visually identifiable manufacturing defects that are not covered in Chapter 5. The material defects covered here are typically not surface defects. However, the assembly defects often are. The division between Chapters 5 and 6 is not dictated by a sharp distinction in subject.

6.1 MOLDING, CASTING OR SINTERING DEFECTS — FAILURE CODE: 00.05

6.1.1 Definition

Morphological defects occurring in a casting, molding or sintering process include:

- *Porosity* (FC 00.05): macro- or microvoids in the cast, sintered or powder formed part.
- Defects of the *ceramic binder* in a sintered ceramic.

For porosity visible at the surface see FC 00.03.

- *Underfill*: failure of the cast material to completely fill the mold.
- *Pipe*: a central, empty or inclusion-filled thread in a cast ingot or rolled product made from the ingot.
- *Cracks (FC 00.07).*
- *Inclusions (FC 00.06).*
- *Casting structure defects (FC 00.07).*

6.1.2 Nomenclature

Alternative nomenclatures used in casting, molding or ceramic manufacturing industry are not covered. The cited nomenclature is usual for contact machine elements.

6.1.3 Failure Process

Casting, that is, forming from the liquid state, is the initial manufacturing operation for all (except powder processed) metal parts. Plastic components are molded or extruded. (In rolled metal products, casting produces the ingot.) Ceramic components are made by compacting, sintering and densification methods including hot isostatic pressing.

The morphological defects of as-cast material appear in original form in components used without subsequent forming. They are often carried, in modified form, into the semi-finished (rolled, forged, etc.) product.

In view of the wide variety of materials and casting processes used in Hertz contact machine elements, only the following generalities can be provided on the failure process:

- *Porosity* in cast parts may be due to release of dissolved gases from the solidifying melt.
- *Porosity* in powder processed parts including ceramics arises from incomplete densification.
- *Defects of the binder* in ceramic parts arise when the material used to consolidate the ceramic grains into a solid (the binder) fails to provide the required complete and strong matrix around the grains.

- *Forging porosity* may occur from local remelting of the as-cast structure under excessive forging temperature (FC 00.04).
- *Underfill* occurs when the molten material fails to reach all volumes in the mold before solidification.
- *Structure defects* may arise from a wide variety of chemical and/or physical processing errors specific to the manufacturing process and to the material. They are covered under FC 00.07.
- *Inclusions* are described under FC 00.06.
- *Cracks* (FC 00.07) may be due to internal stresses arising in solidification or phase transformation. Separations (weak interfaces) may be left where molten material reaches a cross section in the mold from two sides and fails to bond completely.

6.1.4 Distinctive Appearance

Porosity is visible as an open void:

- when it produces surface pits;
- when a crack failure intersects a pore;
- in a section of the component, made for examination purposes.
- An inclusion may be exposed at a surface and then torn away, leaving a pore.

Macro-porosity may be shown in a casting by X-ray or by ultrasound imaging.

Underfill is visible as a local deviation from intended shape.

For cracks, see FC 00.07; for inclusions, see FC 00.06.

Ceramic binder defects may be visible in sections, at fracture surfaces, or when grain boundary cracking arises.

6.1.5 Causes

Identification of causes of casting, molding or compacting defects requires specific information on the manufacturing process used.

6.1.6 Effects of Casting, and Molding, Compacting Defects

Casting and molding defects are gross discontinuities which, under stressing, typically lead to bulk cracking or fracture (FC 00.22) or to spalling (FC 00.16).

Porosity of some degree is unavoidable in ceramics; inclusions are unavoidable in wrought steel. Unless porosity is sufficiently low and fine, spalling (FC 00.16) and fracture (FC 00.22) of ceramic components will result.

Binder defects in ceramics lead to grain-boundary cracks and subsequent early spalling (FC 00.16).

6.2 INCLUSIONS — FAILURE CODE: 00.06

6.2.1 Definition

Inclusions are volumes of unintended foreign material embedded in the matrix of the component material. In metals produced by a casting process (including parts used as-cast, pressed, rolled, extruded or forged), inclusions are mostly nonmetallic. In powder metals and ceramics, inclusions may be either nonmetallics or foreign metals.

Notes:

1. Hardenable steels contain carbides as structural elements. These are not inclusions, defined as defects.

2. Some metals are precipitation hardened. The precipitates are not inclusions, defined as defects.
3. Cermets and some ceramics consist of (hard) grains embedded in a binder. An inclusion (defect) is a volume of material *other* than the intended grains or binder.

6.2.2 Nomenclature

In metals, inclusions may be referred to as nonmetallics or slag.
Macro-inclusions are large enough to be visible with the unaided eye (0.2–0.5 mm minimum).

- *Stringers* are strongly elongated macro-inclusions.
- *Globular inclusions* are roughly spherical macro-inclusions.

Micro-inclusions are similar to, but smaller than the above, and discernible by metallography.

6.2.3 Failure Process

An inclusion forms during melt (or powder) processing of the material, when a foreign substance agglomerates into distinct volumes and is enclosed in the matrix material.

In molten metals, indigenous nonmetallics may be generated during the melt processing (including slagging) or casting. Exogenous nonmetallics result from extraneous contamination of the melt (for example, from the furnace lining or ladle).

In powder-based material (powder-metal, cermets, ceramics), the powder may be externally contaminated, or contain slag from its own manufacture.

6.2.4 Distinctive Appearance

Macro-inclusions are directly visible if they extend to a surface or appear in a fracture as spots or (if stringers) as streaks in the otherwise uniform surface. If inclusions do not extend to the surface, they are observed in metallographic section, on an X-ray or ultrasound image or as eddy-current indications. Inclusions extending to a finished surface are often covered in the finishing operation by a thin layer of plastically flowed metal. During running under stress, this layer may be removed and the inclusion revealed.

Micro-inclusions are identified by examination (of sections) at high magnification.

Depending on material and its manufacturing process, a multitude of distinct inclusion classes and appearances occur. Their differentiation requires specific information on material manufacture and appropriate examination methods.

6.2.5 Causes

The material of inclusions is originally admixed to or generated in the melt (or powder) during processing of the raw material. Solidification (or sintering) forms them into distinct inclusion volumes. Subsequent forming steps may significantly change the size and shape of the inclusions.

Identification of the processing conditions conducive to each type of inclusion requires specific information on the material and its manufacturing process.

6.2.6 Effects of Inclusions

At the inclusion/matrix interface, stress concentrations arise. Both strong (high ultimate strength) and weak inclusions are detrimental due to these stress concentrations. Factors affecting the severity of the stress concentration are inclusion size, shape, interface (such as smooth or jagged, bonded or unbonded), elastic modulus difference from the matrix, brittleness and particulars of the macro-stress field.

Macro-inclusions are macroscopic weak volumes. They may cause failure by the following processes:

- Bulk cracking and fracture (FC 00.22), if located anywhere in a stressed cross-section.
- Spalling (FC 00.16), if located in the Hertz stress volume.
- Galling (FC 00.13), if extending to a contact surface.

Micro-inclusions are microscopic weak volumes which may cause failure through:

- Subsurface-origin spalling (FC 00.16), if located in the Hertz stress volume.
- Surface distress (FC 00.17) and surface-origin fatigue (FC 00.16), if located in the contact surface layer.
- Wear (FC 00.12), if extending to the contact surface.

6.3 MATERIAL STRUCTURE DEFECTS PRIOR TO, OR IN HEAT TREATMENT FAILURE CODE: 00.07

This section is included for completeness, to permit material-structure related morphological failures to be traced to this source. Diagnosis of structure defects requires laboratory methods of materials analysis, specific for the material, for its condition and for the defect that is to be diagnosed.

In metals, the examination methods are primarily hardness testing, fracture examination, metallography including appropriate etching, and X-ray diffraction. Ultrasound, magnetic or eddy-current methods may also be used. Some of these examination methods are also applicable to non-conductive, nonmagnetic materials such as ceramics.

6.3.1 Definition

Defects of material structure are those physical deficiencies in a structural material that impart to it less resistance to an imposed stress (mechanical, thermal or chemical) than the specified structure possesses.

The great majority of contact components are made of steel heat treated to optimal properties for the specific application (high hardness surface for most bearings, high or medium hardness surface for gears and cams). This section covers structure defects in these steels.

Other contact component materials, such as cast iron, nonsteel metals, ceramics, cermets or plastics have different structure requirements and defects but are not covered in this Atlas.

6.3.2 Nomenclature

Alternative nomenclature for structure defects is not covered.

6.3.3 High Hardness Steel Components

6.3.3.1 Definition

The following are common structural defects in high hardness (>50 RC) steel contact components.

Hardness defect. Most often, the part is softer than specified.

- *Carbon loss* (decarburization) at the surface of through-hardened parts.
- *Carbon gradient defect* in carburized parts.
- *Nitrogen gradient* defect in nitrided parts.

Defects in required constituents.

- Many hardened steels are *martensitic.* The morphology of the martensite needles may deviate from specification. *Untempered martensite* may be present from rehardening.
- Other hardened steels may be (lower) *bainitic.* The specific metallographic morphology of the bainite may deviate from specification.

Impermissible structural constituents. In fully hardened steels, these are generally soft constituents. Ferrite and upper bainite are recognizable soft constituents.
Retained austenite. Excessive quantities of austenite retained in the finished product.
Grain boundary defects. Weaknesses in the (prior austenitic) grain size of the material.
Carbide segregation. Carbides in the steel are too large, or segregated into bands, networks, etc.
Cracking due to excessive processing (casting, forming, heat-treating) stress.

6.3.3.2 Failure Process

Material structure defects in parts of hardened steel are the result of deficiencies in raw material composition; forming and/or heat treatment processes which interfere with the grain size control; recrystallization in hot forming; deviations from proper casing (carburizing or nitriding, flame or induction hardening); errors in austenitizing, quenching, tempering or other post-quench treatment.

6.3.3.3 Distinctive Appearance

Material structure defects are detected by materials laboratory methods.

6.3.3.4 Causes

Identification of the processes resulting in material structure defects in hardened steel requires detailed information on casting, hot forming and heat treatment methods for the material.

6.3.3.5 Effects of Defects in Material Structure

The material properties typically affected by defects in structure are:

- *Tensile strength* or *hardness*: the limit of plasticity under tensile stressing or indentation.
- *Ductility* or *toughness*: the ability to sustain plastic deformation without fracture.
- *Fatigue resistance.* Especially in Hertz contacts, fatigue resistance (resistance to spalling failure) does not uniquely correlate with other macroscopic strength parameters.
- *Temperature resistance.* Improperly heat treated steel may show dimensional instability or soften at operating temperatures.
- *Corrosion resistance.* In corrosion resistant steels, structure defects detract from corrosion resistance.

6.3.4 Medium Hardness Steel Components

Structure defects and their consequences in medium hardness steels are somewhat similar to those in fully hardened steel. However, the structure elements of lower-hardness steels differ quantitatively and qualitatively from fully hardened steels, as follows:

- The required and the impermissible structural constituents may be different from fully hardened steels.
- Metallographically identifiable carbides may not be present.
- Retained austenite may not be present.

6.4 FINISHING DAMAGE TO MATERIAL STRUCTURE — FAILURE CODE: 00.08

6.4.1 Definition

The last or near-last finishing processes of component surfaces may damage the subsurface material structure. This damage is defined as finishing damage to material structure. Classes of such damage are: grinding damage, coating damage and cold forming damage.

6.4.2 Grinding Damage — Failure Code: 00.08.1–3

6.4.2.1 Definition

Grinding damage is damage to the near-surface material due to aggressive grinding (or other abrasive finishing).

6.4.2.2 Nomenclature

The common designations for types of grinding damage are: grinding burns, grinding temper, and grinding cracks.

6.4.2.3 Failure Process

Grinding damage to subsurface material is the result of overheating of the surface under strong pressure and shear forces transmitted by the grinding wheel, honing or polishing tool. It typically affects hardened (martensitic, lower bainitic) steel components. The overheating results in three types of change in these components:

1. Grinding temper arises when the material is locally heated above its specified tempering temperature and thus becomes softer than the bulk material. Since tempering results in volume change, some residual stresses are set up.
2. Grinding burns occur when the overheating exceeds the austenitizing temperature of the steel and reaustenitizes a volume. The hot volume, being surrounded by cold steel is rapidly cooled and quenched but not tempered leading to a rehardened volume, surrounded by a tempered shell which was heated but not reaustenitized. Severe residual stresses are set up because the austenite/martensite transformation upon quenching results in great volume change. When grinding burns of substantial severity are created by the next-to-last finishing operation, it is possible for the last operation to remove the surface evidence of the damage (making it undetectable by Nital etching), but leave severe residual stresses which can lead to local cracking in service.
3. Grinding cracks are the result of the residual stresses described above, when they exceed the strength of the material.

6.4.2.4 Distinctive Appearance

- Grinding cracks may be discernible with the unaided eye or under low magnification. Magnetic particle, eddy current or dye-penetrant inspection provide more sensitive detection.
- Grinding temper and burns are detectable by Nital etching of the surface. The *tempered* volume etches dark, the *rehardened* volume etches lighter than normal. Eddy current methods for grinding damage detection are in limited use.

Notes:

1. In some steels, such as secondary-hardening tool steels, detection of grinding damage by etching is difficult.

2. Grinding burns obscured by refinishing are detectable only by a destructive etching method. Some success is claimed for eddy current detection.

6.4.2.5 Causes

- Excessive grinding parameters (high infeed); excessive pressure on honing or polishing tool.
- Inappropriate selection of grinding wheel or other abrasive.
- Insufficient or inadequate coolant.
- Sensitive material structure: Inadequately tempered material is easily damaged in grinding.
- High pressure, high sliding speed or unsuitable material of sliding support elements (shoes) in grinding.

6.4.2.6 Effects of Grinding Damage

- *Cracking* (either local, or bulk; (FC 00.22), as a result of residual stresses.
- *Surface distress* (FC 00.17) or *spalling* (FC 00.16). Damaged material has low Hertzian fatigue resistance.

6.4.3 Coating Damage — Failure Code: 00.08.6

6.4.3.1. Definition

Coatings commonly used on (metallic) contact surfaces are

- Chemical (oxide, phosphate, molybdenum disulfide) coatings for dry lubrication and rust protection purposes.
- Electroplating with tin or cadmium as a dry lubricant (in a few aerospace applications).
- Special (spheroidal) chromium plating in highly aggressive environments.
- Burnished-on, sputtered or chemically deposited solid lubricant coatings. (For the failure of lubricant coatings *in service*, see Chapter 18.)

The many experimental or developmental coatings that are applied to contact surfaces are not covered in this Atlas.

Coating of fit surfaces by hard chromium electroplating is common for the correction of dimensional errors in manufacture or the repair of wear.

Functionally, coatings may be divided into hard coatings aimed at protecting the weaker substrate; and soft coatings which act sacrificially, as solid lubricants or run-in aids, and additionally may also be corrosion protectors.

Coating damage is defined as defects in the coating, or deleterious interaction of the coating with the substrate.

6.4.3.2 Nomenclature

Alternative designations for coating damage are not covered.

6.4.3.3 Failure Process

Defects in coatings include:

- Improper coating composition for a solid lubricant or rust protector.
- Microcracking.
- Improper structure.

- Incomplete surface coverage.
- Inadequate bonding.
- Off-specification hardness.
- Chemical decomposition due to high temperature or in interaction with the environment.
- Foreign material in the coating.

Deleterious interactions of coating and substrate include:

- Hydrogen embrittlement from electroplating.
- Attack on surface microgeometry or grain boundaries of the substrate from chemically formed coatings.
- Residual stresses at the interface between coating and substrate.

6.4.3.4 Distinctive Appearance

Improper composition may be revealed functionally by wear or seizure of the substrate or the mating surface. It may be visible as a discoloration.

Visual inspection (with or without magnification) will reveal microcracking and, by showing islands of uncovered substrate, incomplete surface coverage.

Improper structure or foreign material in the coating may be discernible by metallographic examination or by gross appearance (color, gloss, etc.) and requires specific information as to the type of coating.

Inadequate bonding or improper hardness may be detectable by laboratory scratch tests, but is more often diagnosed from inadequate wear performance.

Hydrogen embrittlement is diagnosed from the cracking or flaking it causes in the substrate.

Residual stresses at the coating to substrate interface are generally detectable only from their effect on fatigue.

Diagnosis of chemical attack requires specific information as to the type of coating. In coatings that can be chemically stripped without damage to the substrate:

- *Damage to surface microgeometry* is diagnosed by increased roughness, pit formation or waviness observed on the stripped substrate.
- *Intergranular attack* is detected metallographically as differential etching of grain boundaries or microcracks in the substrate.

6.4.3.5 Causes

Identification of the causes of coating failure requires specific information on the coating process.

6.4.3.6 Effects of Coating Failure

Hard coating defects promote component failure by these processes:

- Inadequate wear resistance.
- Inadequate corrosion protection.
- Surface origin spalling, which may initiate in the coating or at the interface and propagate into the substrate.
- Detached flakes of coating cause denting of contact surfaces.

Soft coating defects manifest themselves as

- Inadequate solid lubricating performance.
- Inadequate corrosion protection.

6.4.4 Cold Forming Damage — Failure Code: 00.08.7

6.4.4.1 Definition

Cold forming damage is defined as damage to the subsurface structure due to a cold-forming finishing operation.

Cold forming as a finishing operation for contact components is used in the following examples:

- *Deep drawing* is the finish-forming method for drawn needle roller bearing cups.
- *Shot peening* has been used as a second-last or last finishing operation on working surfaces, with the intent of providing work hardening of the near-surface material.
- *Roll burnishing* or ball burnishing has been used to work-harden blend radii subject to heavy bending stresses.

6.4.4.2 Nomenclature

There are no other common designations for cold forming damage.

6.4.4.3 Failure Process

- Structure damage due to *deep drawing* of needle bearing cups has not been identified. The work hardening effect of cold drawing is generally considered advantageous. (Cracks, folds, surface defects can occur. See FC 00.02 and FC 00.04.)
- *Shot peening* of surfaces in Hertz contact as the last finishing operation leaves considerable roughness and waviness. If run in Hertz contact, such surfaces experience high asperity stresses. The work hardening and compressive stress formation in the near-surface material achieved by shot peening is beneficial to bulk fatigue. It is questionable whether resistance to Hertz contact fatigue is improved by the work hardening and compressive residual stress, or impaired by microscopic damage to the material. The outcome may depend on processing conditions, raw material and operating conditions.
- *Roll* or *ball burnishing* of blend radii as used in highly stressed shafts and similar components is intended to strengthen the blend radius by smoothing the surface (reduce stress concentrations) and work-harden and compressively prestress the near-surface material. The high Hertzian pressures needed to produce the required plastic deformation may cause cracking, leading to premature bending fatigue.

6.4.4.4 Distinctive Appearance

- No visible damage to subsurface material is expected in *deep drawing*.
- The appearance of a *shot peened* surface shows the surface roughness. Subsurface material damage is typically not visually observable and is diagnosed by early contact fatigue.
- Cracks in *roll burnished* blend radii may be visible or can be diagnosed by magnetic particle or dye-penetrant inspection.

6.4.4.5 Causes

Identification of shot peening parameters (shot size, impact energy, duration of peening) conducive to subsurface damage requires specific knowledge of material and processing conditions.

6.4.4.6 Effects of Material Damage by Cold Finishing

The effects of material damage by cold forming are contact fatigue as a result of diminished integrity of the near-surface material, and bulk fatigue arising from cracks in cold finished (roll burnished) material.

6.5 GEOMETRY, ASSEMBLY OR MOUNTING FAILURE — FAILURE CODE: 00.09

6.5.1 Definition

- *Assembly* is defined as the combination of parts into a Hertz contact machine element. Example: the assembly of components into a bearing.
- *Mounting* is defined as the installation of the Hertz contact machine element into the machine in which it will operate. Example: the placement of a gear set in the gearbox.

Failures covered in this section encompass geometry errors; and score marks, gouges and cracks due to assembly or mounting.

6.5.2 Nomenclature

Alternative designations of these failures (other than geometry defects) are 'assembly (mounting) error' and 'assembly (mounting) damage'.

6.5.3 Geometry Defect — Failure Code 00.09.0

6.5.3.1 Definition

A geometry defect is defined as off-specification geometry of the component or the mounting, through manufacturing error, assembly or mounting error, including use of wrong parts or omission of parts.

6.5.3.2 Nomenclature

Alternative designations of this failure are 'geometry error' and 'dimensional error'.

6.5.3.3 Failure Process

Depending on the machine element and its assembly or mounting method, geometry errors can arise at any point in manufacture of the components, their assembly into a machine element or in mounting the element into the machine.

Specific causes of mounting geometry errors are

- Mounting with off-specification shaft or housing.
- Excessive fastening forces.
- Misaligned mounting.
- Mounting on a debris-contaminated surface.
- Inadvertent omission of a part, misplacement of a part or use of the wrong part.

6.5.3.4 Distinctive Appearance

- Gross geometry defects are visually detectable by comparison of the machine element or mounted assembly with the product drawing.
- Moderately out-of-tolerance manufacturing geometry requires metrological examination.
- In as-run components, geometry defects are often detectable by incorrect wear patterns, such as edge contact, improper load distribution, etc. (See FC 00.12.)

6.5.3.5 Causes

Causes of geometry defects require specific information on the manufacturing, assembly or mounting process for diagnosis.

6.5.3.6 Effects of Geometry Defect

The range of possible effects from defective geometry encompasses virtually every in-service failure mode. The principal mechanisms through which geometry errors produce failure are

- Maldistribution of load among contacts or of pressure within a contact.
- Parasitic loads from lack of internal looseness.
- Excessive or insufficient fit interference to mounting parts.
- In rolling bearings, incorrect separator clearances, producing excessive separator loads or unintended contacts.
- Lubrication failure from excessive surface roughness.
- Gross malfunction from missing, improper or misassembled parts.

6.5.4 Scoring, Galling or Cracking in Assembly or Mounting — Failure Code: 00.09.1–3

6.5.4.1 Definition

- *Scoring*, in assembly or mounting, arises from ploughing of the surface by a hard, sharp implement, in a process of *wear* (FC 00.12).
- *Galling* in assembly or mounting occurs from *material transfer* in high-pressure sliding contact of ineffectively lubricated surfaces on each other. (See FC 00.13.)
- *Cracks* and *fracture* of components, in assembly or mounting, arise from excessive stresses imposed on a component, which are the result of assembly or mounting geometry errors. (See FC 00.22.)

6.5.4.2 Nomenclature

Nomenclature for assembly scoring and galling is unsettled. 'Scuff marks', 'scratch marks', and 'gouges' are used for either failure. 'Smear marks' designate galling. There is no alternative nomenclature for cracks or fracture.

6.5.4.3 Failure Process

The failure processes in this category are identified in the Definitions. More details are given in the Failure Codes listed there.

6.5.4.4 Distinctive Appearance

- Scoring is a ploughing mark with a shiny bottom and sharp, often raised, edges. The position and orientation of the score mark on the component may serve to distinguish it from a finishing furrow (FC 00.02) or service wear (FC 00.12). Score marks from tool impact tend to be on free surfaces which may suffer hammer blows or scraping by a 'drift'. Axial score marks in the bore of a bearing innerring or gear, or on the OD of a bearing outerring may arise from mounting on the mating shaft or housing with interference fit or over a sharp edge. Light score marks may alter only the surface asperity tips, resulting in a stippled mark.

- Galling marks in assembly arise under similar conditions as score marks, but galling marks show signs of metal transfer. Differentiation may require magnification. Galling in assembly is distinguished from in-service galling (FC 00.13) in the same way as for scoring.
- Cracks and fractures are material separations. Their origin in assembly or mounting is usually diagnosed form their location (example: chipping at a flange edge), accompanying impact marks, score or galling marks or geometric distortion.

6.5.4.5 Causes

The causes of scoring, galling and cracks differ only in severity, which increases in the order listed. The principal causes are

- Improper use of assembly or mounting tools, leading to slippage of the tool over a component surface, scratches, galling marks, impact damage, chipping or fracture.
- Sliding of working or fit surfaces over each other during assembly or mounting, when: (a) the interference fit is excessive, (b) there is excessive interface load, (c) surface roughness is excessive or sharp edges exist, (d) mounting is attempted under misalignment, (e) lubrication is inadequate, and/or (f) solid contaminant is present in the interface.

6.5.4.6 Effects of Scoring, Galling or Cracks in Assembly or Mounting

- *Scoring* or *galling* on *fit* surfaces during assembly or mounting may lead to cracking under service loading (FC 00.22).
- *Scoring* or *galling* in *contact* surfaces during assembly or mounting may lead to bulk cracking (FC 00.22), surface distress (FC 00.17), surface-origin spalling (FC 00.16), wear (FC 00.12) or in-service galling (FC 00.13).
- *Cracks* and *fracture* during assembly or mounting represent gross failure, making the machine element unserviceable either immediately or after further crack propagation.

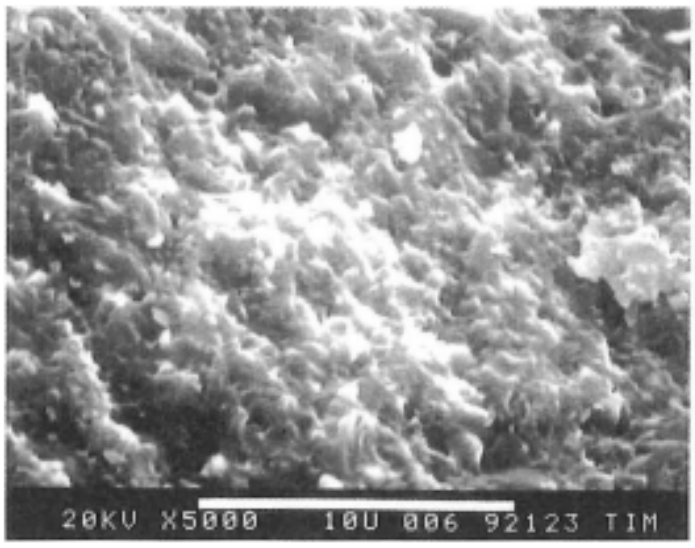
Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.05.1	5.23 10.44 11.10 18.18
00.05.4.1	10.48
00.05.4.2	10.43 10.48
00.06	18.18
00.06.1.1	10.30 10.46
00.06.1.3	5.14 6.5 9.14 11.4 11.20
00.06.2	6.5 10.42 15.19
00.07.1.1	15.41
00.07.5.01	15.13
00.07.5.02	6.19 15.8 15.29
00.07.5.1	15.30
00.08.2	6.22 10.49 15.31
00.08.3	6.24
00.08.4	19.6
00.09	15.20 16.17
00.09.0	7.9 7.11 15.32
00.09.01	4.3 4.4 4.5 4.7 4.8 6.36 6.38 12.14 16.18
00.09.2	6.32 6.33 8.5 15.11

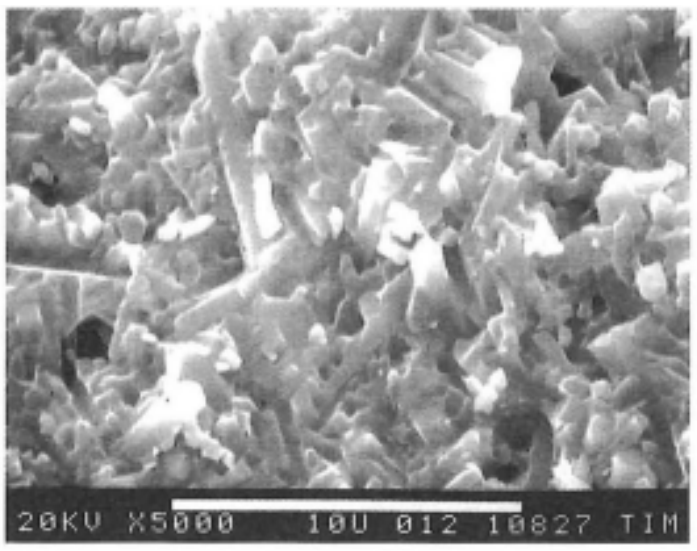
PLATES

DATA

Plate No: 6.1
Archive No: 014-B007&B009
Scalebar a, b: 10 μm (micros: ±20%, others: +100%, −50%)
Image type: SEM
Component: O; RC test rig rod fracture specimen; silicon nitride
Speed:
Load:
Lubrication:
Failure Code 1: 00.05.4 Structure defect in ceramic
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 10.5, 10.36, 10.48 and 11.29



a



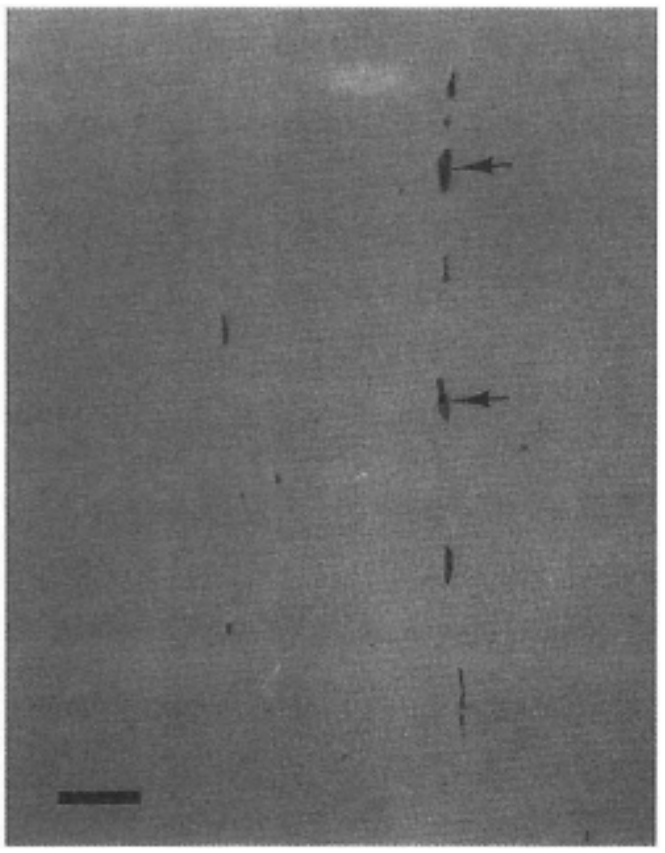
b

DESCRIPTIONS

Failure Description: Bulk fracture surfaces of long lived (a) and short lived (b) silicon nitride ceramic tested as on the Plates referenced below. Fine equiaxed grains with normal binder in long lived material (a); coarse, acicular grains in short lived material (b).
Image Description: (a): Fine fracture surface without sharply delineated large, sharp-edged grains appears in various shades of gray. Small white patches are well distributed binder. (b): Large grains with sharp straight edges appear in shades of gray. Small white patches are well distributed binder.
Suspected Causes: These images illustrate ceramic structures which are, respectively, long lived (a), and short lived (b) in rolling contact fatigue. DP hardness of material (a) is 18.73 GPa (at 2.94 N load) and of material (b) is 14.38 GPa (at 4.90 N load), measured under the highest indenter load not causing a crack. The long lived material cracked under lower indenter load. Accordingly the long-lived material was harder but with lower fracture toughness than the short-lived material. The materials may have contained different types and percentages of binder and different silicon nitride grain sizes.

DATA

Plate No: 6.2
Archive No: 002-016h
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Image type: light metallogram, unetched
Component: CRB; OR, run
Speed: 0.9 MdN
Load: 0.8 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.06.1.1 Hard micro-inclusion
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 15.32

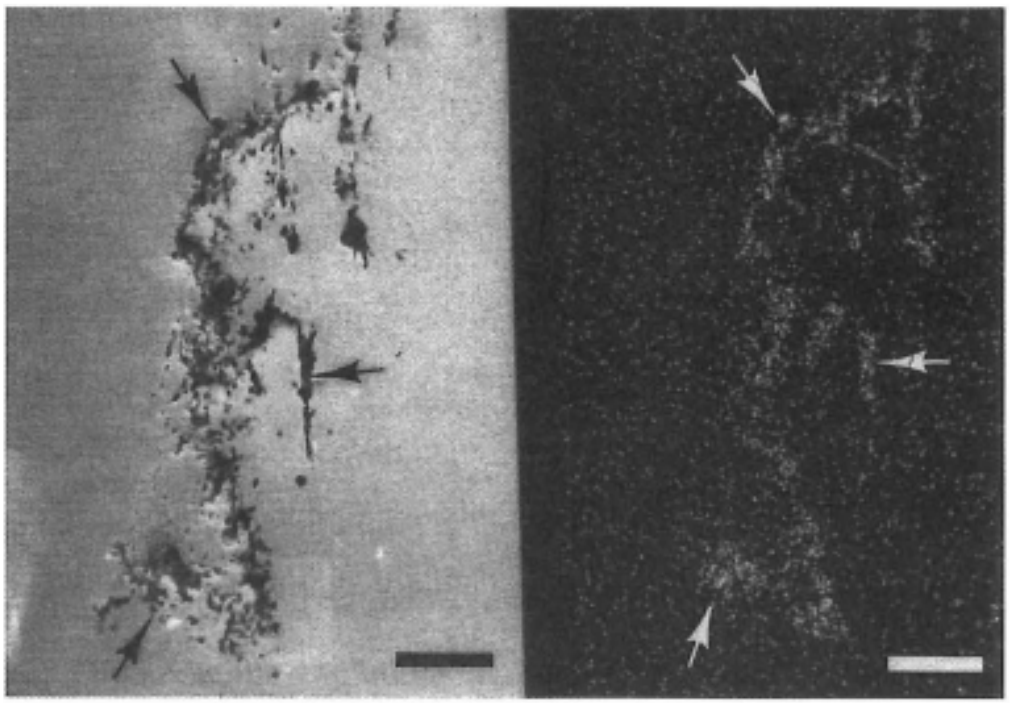


DESCRIPTIONS

Failure Description: Multiple silicate micro-inclusions in the steel, which are rated as exceeding limit for this application. Silicate inclusions are hard and represent subsurface defects of severity depending on size and frequency, and generally lead to spalling. In this case, bulk fatigue of a retaining lug resulted. See Plate 15.32.
Image Description: In unetched gray background of metallographic cross section, inclusions form dark dashes, most of which are in a line. Two are indicated by arrows.
Suspected Causes: Silicates are constituents of slag in steelmaking. Occasionally, some of the silicate is entrapped in the melt to form inclusions. During rolling of the bar product, reduction of the cross-section elongates the initially globular inclusions.

DATA

Plate No: 6.3
Archive No: 002-017b
Image type: (a) SEM; (b) X-ray image for aluminum
Scalebar = a, b: 50 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; OR, 52100 steel, run
Speed: 0.9 MdN
Load: 0.8 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.06.1.1 Hard micro-inclusion
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 15.32



a b

DESCRIPTIONS

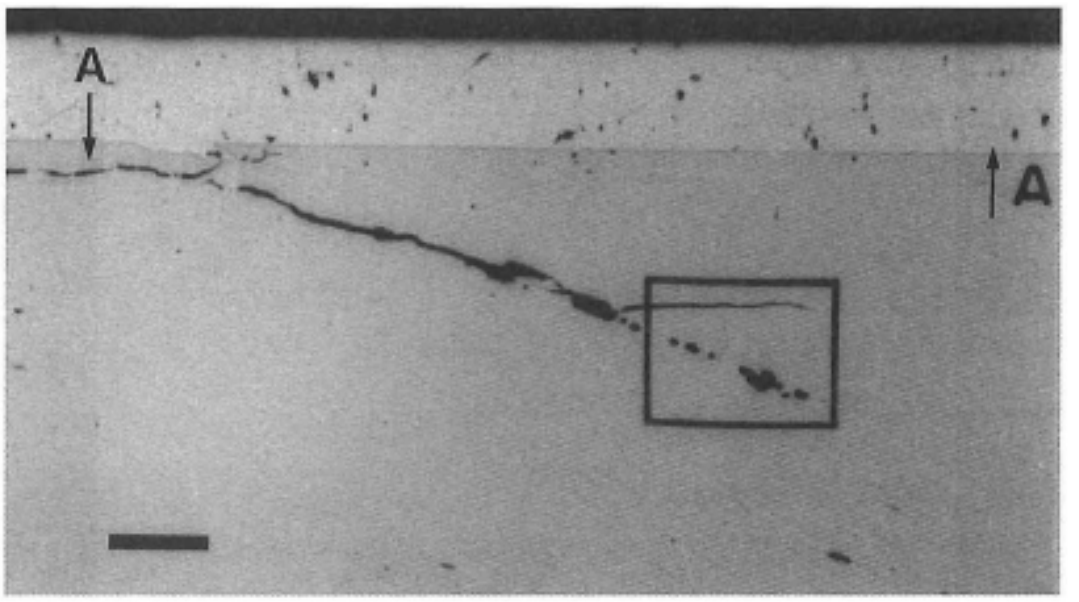
Failure Description: Cluster of alumina micro-inclusions in axial/radial
section of outerring. Aluminum content confirmed by X-ray analysis. Alumina are hard non-metallics representing significant stress raising defects. They typically lead to spalling. In this case they led to antirotation lug bulk cracking. (See Plate 15.32 for fatigue failure.)
Image Description: (a): SEM of polished metallographic cross section (light) containing a cluster of dark inclusions, several of which are marked by arrows. (b): X-ray energy dispersive image, in which aluminum appears white. Inclusions are outlined by cluster of white dots.
Suspected Causes: Non-metallics are steelmaking defects. Aluminum is used in steelmaking as a deoxidizer. Aluminum oxide (alumina) is removed by slagging, but micro-inclusions of it are never wholly absent from melted steel. A cluster of inclusions is an unacceptable accident of steelmaking.

DATA

Plate No: 6.4
Archive No: 014-136&137
Image type: light metallogr., a: unetched, b: etched
Scalebar = a: 100, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, carburized steel, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.06.1.1 Hard micro-inclusion
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: 00.16.02.1.1 Microplastic deformation bands or 'butterflies'
Failure Code 4: -

DESCRIPTIONS

Failure Description: (a): Nonmetallic inclusion *stringer* extending in the "fiber flow" direction (the direction of elongation during tube rolling) has initiated a spalling fatigue crack progressing upward to the surface. (b): Fatigue damage indicated by the microplastic deformation zones ('butterflies') forming around the inclusion. Deformation zones indicate high local stress but not necessarily the initiation of a fatigue crack.
Image Description: (a): In rectangle at image E, angled line of black globules is an inclusion stringer. The line of uneven width extending NW from there is a crack. Surface is *A–A*. (b): Section of volume within the rectangle of *A*. Etched martensitic matrix. Inclusions: wavy black line at N and black patch at center. To both sides of the latter, at about −20° to surface, white etching wing-like 'butterfly.'
Suspected Causes: Nonmetallic inclusion particles form during the steelmaking process. During rolling, they are often strung out in a line in the fiber flow direction, forming a stringer. Spalling fatigue cracks arise at such stress concentrating defects. Deformation bands are an altered matrix structure and may, in some steels, be accompanied by lenticular carbides formed during the deformation process.



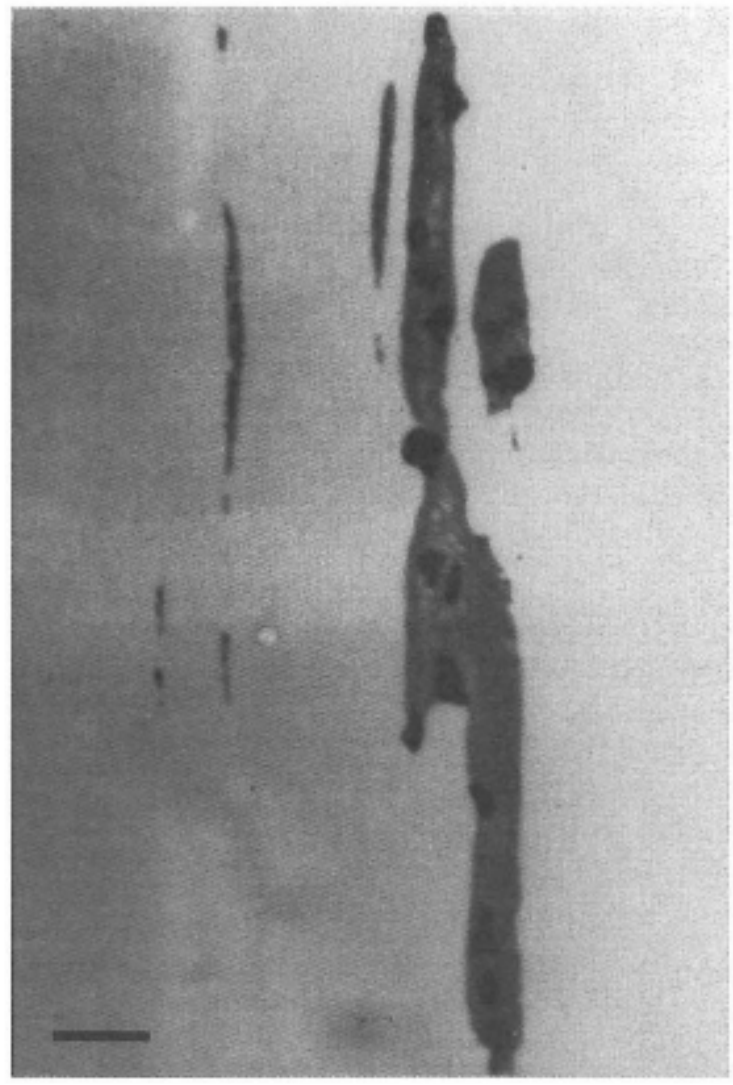
a



b

DATA

Plate No: 6.5
Archive No: 093-6.1.2
Image type: light metallogram
Scalebar = 10 μm (micros: ±20%, others: +100%, −50%)
Component: 8620 steel raw material specimen
Speed:
Load:
Lubrication:
Failure Code 1: 00.06.1.2 Sulfide inclusion
Failure Code 2: 00.06.2 Inclusion stringer
Failure Code 3: 00.06.1.3 Primary carbide
Failure Code 4: -

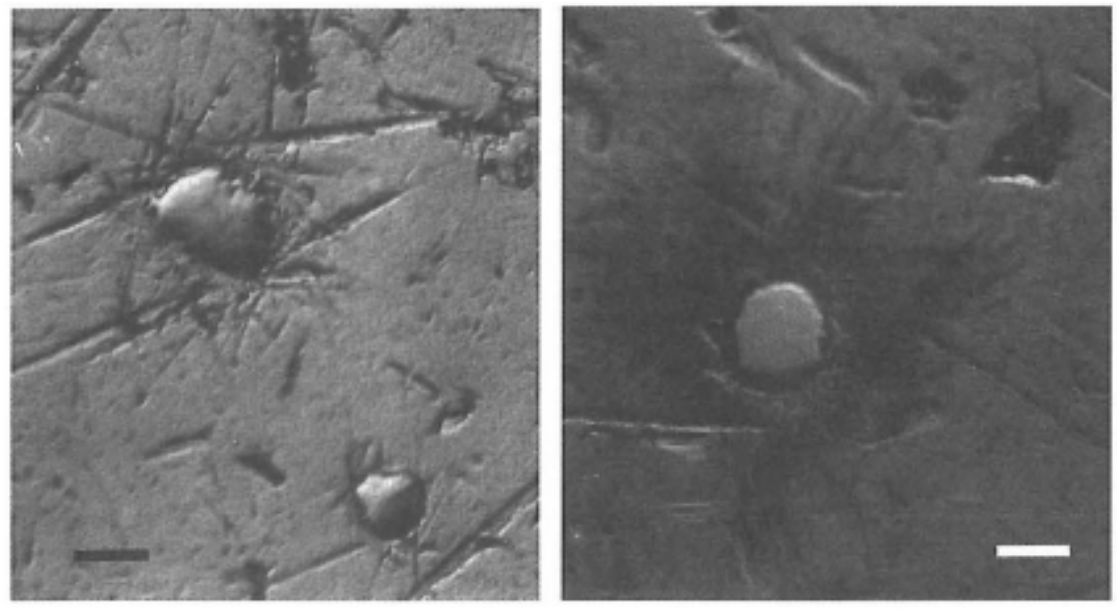


DESCRIPTIONS

Failure Description: Elongated sulfide inclusion 'stringer' formed parallel to the rolling direction of the material. Inclusion stringers form subsurface defects at which spalling fatigue (or bulk cracking) may initiate. Size for size, sulfide inclusions are believed to be less severe defects than hard (alumina, silicate) inclusions, presumably because they are soft and smooth-surfaced.
Image Description: Dark streaks running N–S on the unetched light background are sulfide inclusions. Note smooth boundaries. The black round spots are primary carbides (not a defect).
Suspected Causes: Sulfur is a natural contaminant present in melted steel and must be reduced to specified limits. (Intentionally 'resulfurized' steel is rarely used in rolling bearings.) Residues of sulfur contamination may form globular sulfide inclusions in the ingot which, during material rolling, elongate into stringers.

DATA

Plate No: 6.6
Archive No: 018-309&310
Image type: SEM
Scalebar = a, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel; (a): unrun, (b): run
Speed: 1.125 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 150°C
Failure Code 1: 00.06.1.3 Primary carbide
Failure Code 2: 00.17.2 Localized surface distress (halo at defect)
Failure Code 3: -
Failure Code 4: -



a **b**

DESCRIPTIONS

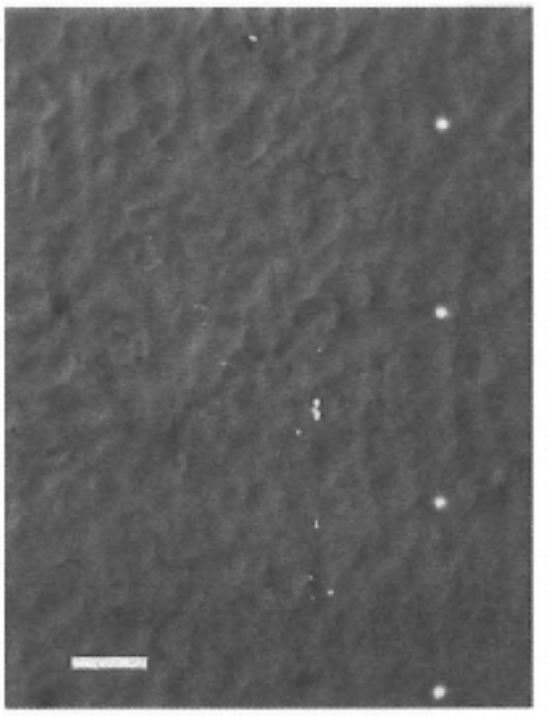
Failure Description: (a): Hard primary carbides of tool steel (or stainless steel) bearings are exposed at the ball surface, protruding above (unrun) matrix surface. (b): On run surface, hard carbide is surrounded by surface distress halo. Protruding carbides may damage the mating surface, cause torque irregularity in instrument bearings, and surface distress in any bearing. The latter may lead to premature spalling.
Image Description: (a): Two round, protruding carbides are exposed on the lapped surface of an unrun ball. The scratch marks are normal for this high magnification SEM, but do appear to cluster around the carbides. (b): The lighter-colored round carbide is flattened in running (by wear?); halo of dark-colored burnish marks surrounding it indicate surface distress glazing.
Suspected Causes: Hard alloy carbides are intrinsic to high-carbon, high-alloy tool steels and martenistic stainless steels as used in aerospace and instrument bearings. Finishing by lapping (loose abrasive) may remove matrix faster than carbides, causing them to protrude. In operation, the Hertzian pressure may deform and the sliding may wear the protruding carbide. The disruption of the EHD film around the carbide may promote surface distress.

DATA

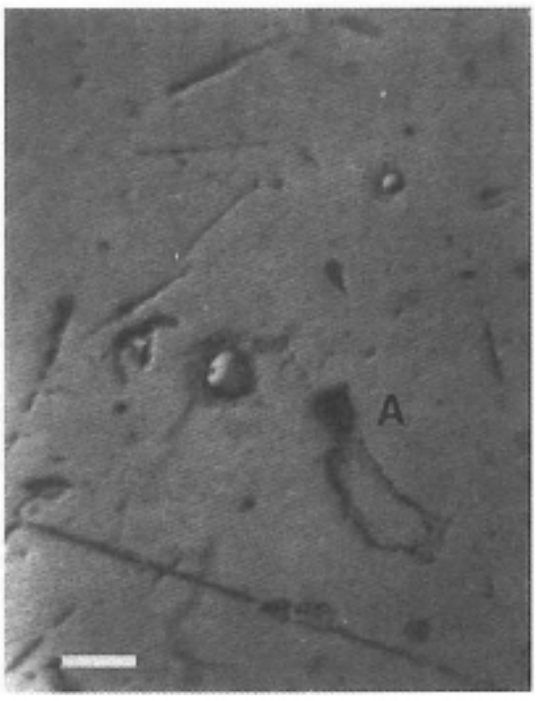
Plate No: 6.7
Archive No: 003-013a&b&014
Image type: a, b: SEM; c: light macro
Scalebar = a, b: 25 μm c: 5 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; (a,c: OR; b: B) tool steel, run
Speed: 1 ? MdN
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.06.1.3 Primary carbide
Failure Code 2: 00.18.2.2.2 Stippled line(s) or band(s) from rolled-in debris
Failure Code 3: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 4: -

DESCRIPTIONS

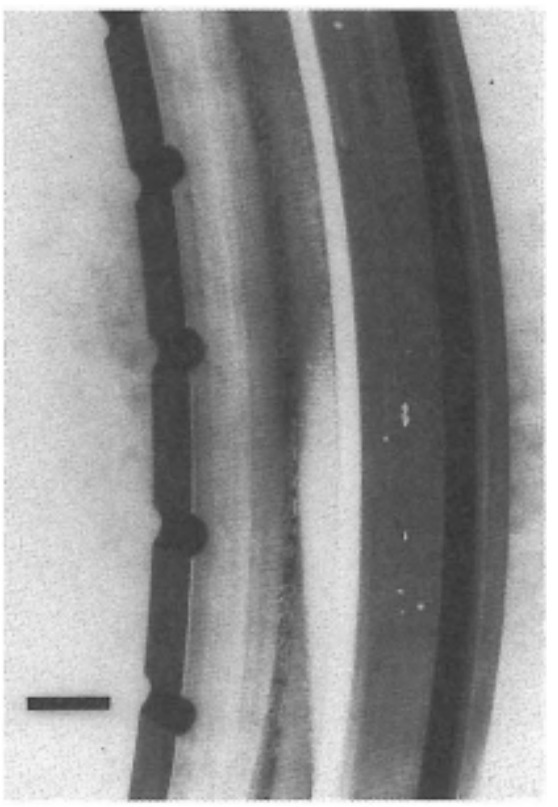
Failure Description: Tool steel balls of this bearing contained hard Vanadium carbides (15 μm diameter), which created a profusely dented IR surface. During running, a band of this damaged surface failed in a line of spalls. The bearing has failed.
Image Description: (a): Surface of OR in ball path, completely covered with rolled-over rounded dents from contact with spherical hard carbides in balls. (b): Ball surface. At image center and 1/2 to NE corner, spherical hard carbides. Elsewhere, dents and scratches, perhaps a microspall at *A*. (c): OR, with ball path between white circle and scalloped edge, mottled by dents. A band of dark spalls in center of ball path.
Suspected Causes: Tool steels may contain hard primary carbides, which remain prominent during ball lapping. When rolled against ring surface, carbides create profuse dents, eventually 'peening' the surface. Plasticity is exhausted and surface forms spalls upon further running.



a



b



c

DATA

Plate No: 6.8
Archive No: 075-201&202&204
Image type: a: light macro, b: SEM, c: SEM composite
Scalebar = a: 5 mm, b: 200, c: 100 μm (micros: +20%, others: +100%, −50%)
Component: CRB; IR, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.06.2 Inclusion stringer
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Inclusion stringer totaling 10 mm in length or more, open to the rolling surface is determined by X-ray spectrum to be a layered stringer of largely alumina inclusions. A stringer so located as to be open to the surface, and of this great length, is an imminent source of spalling failure.
Image Description: (a): On the as-ground surface, grinding lines run N–S. A 10 mm long interrupted wavy black line running E–W is the inclusion. More nonmetallics show as fine black points at W end and to the N of the stringer. (b): Intentional fracture along stringer. Rolling surface is N section edge. Parallel white E–W lines are the inclusion. (c): Layout as in (b). 3 or more E–W layers of light-color inclusion "pebbles" in fracture surface.
Suspected Causes: Alumina inclusions may be exogenous (emanating from the refractory used in steelmaking equipment), or endogenous (from aluminum added for deoxidizing). In view of its large size, this stringer is believed to be exogenous. It assumes its elongated shape parallel to the direction of material elongation during tube rolling or forging.

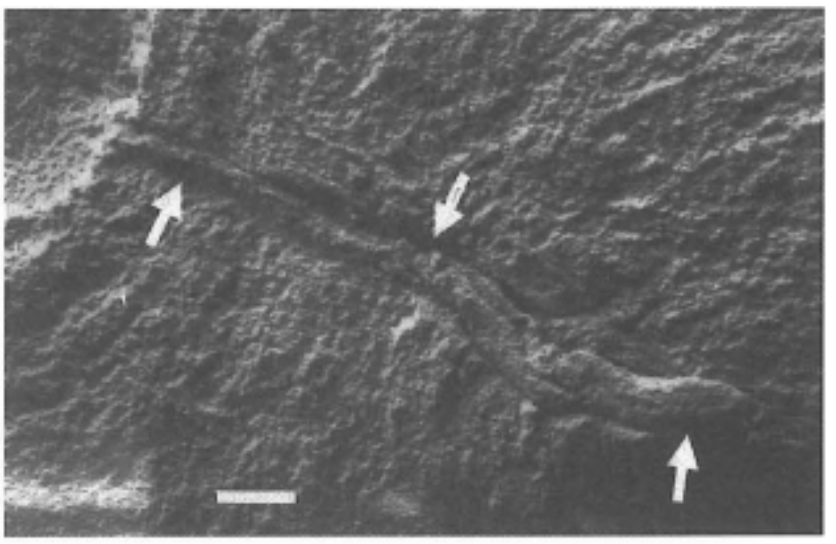
a

b

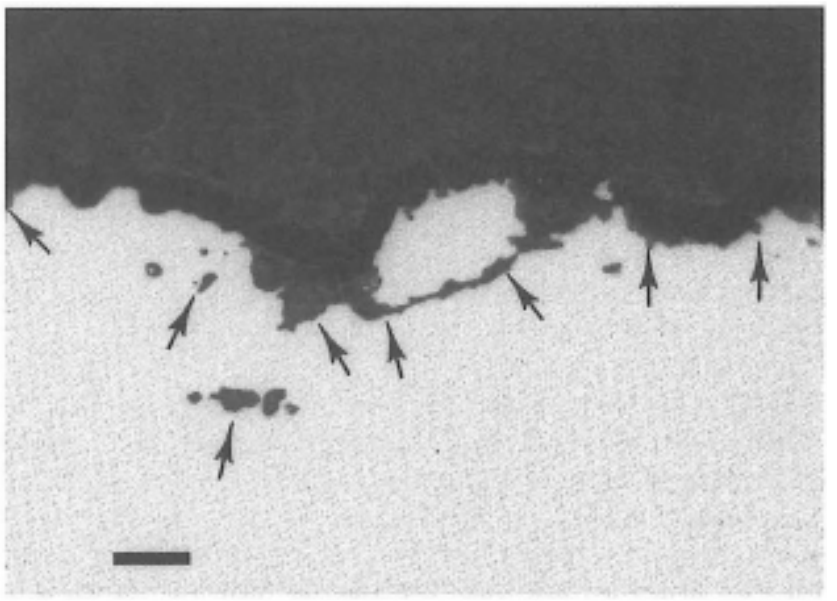
c

DATA

Plate No: 6.9
Archive No: 002-004d&g
Image type: a: SEM, b: light metallogram, unetched
Scalebar = a: 200, b: 20 μm (micros: ±20%, others: +100%, −50%)
Component: BG; G, carburized AISI 4310 steel, run
Speed: 106 m/sec
Load: 0.5 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.06.2 Inclusion stringer
Failure Code 2: 00.22.01.4 Gear tooth crack or fracture
Failure Code 3: 00.22.2 Bulk fatigue crack
Failure Code 4: -
See also PLATE: 15.19



a



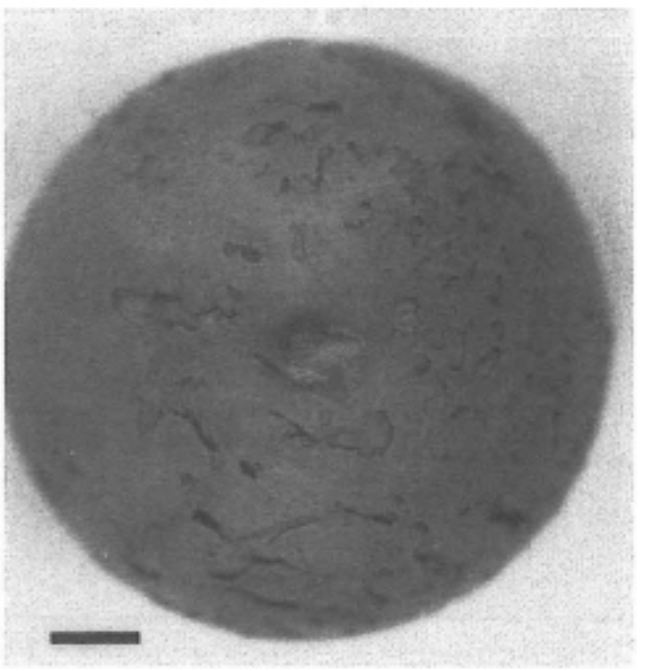
b

DESCRIPTIONS

Failure Description: Alumina inclusion stringer in gear tooth material has caused tooth bending fatigue fracture. Alumina inclusions are hard and brittle and represent severe stress-raising defects. This stringer is at least 2 mm long, giving it direct macroscopic effect on fatigue strength. (See Plate 15.19 for the gear tooth fatigue caused by this stringer.)
Image Description: (a): The image background is the fracture surface. The three arrows bracket a long, fragmented stringer of alumina non-metallic. (b): White S image half is tooth cross-section. Fracture surface forms N boundary of section. (Black mottled N half is mounting.) Arrows show gray alumina inclusions at and beneath fracture surface.
Suspected Causes: Non-metallics are steelmaking defects. Aluminum is used in steelmaking as a deoxidizer. Large aluminum oxides (alumina) are removed by slagging, but micro-inclusions of it are never wholly absent from melted steel. A macroscopic stringer (elongated, often multiple inclusions) as shown, is an accident of the steelmaking process.

DATA

Plate No: 6.10
Archive No: 018-603
Image type: light macro
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: BB; B, 52100 steel, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.1.1 Insufficient bulk hardness
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: -



DESCRIPTIONS

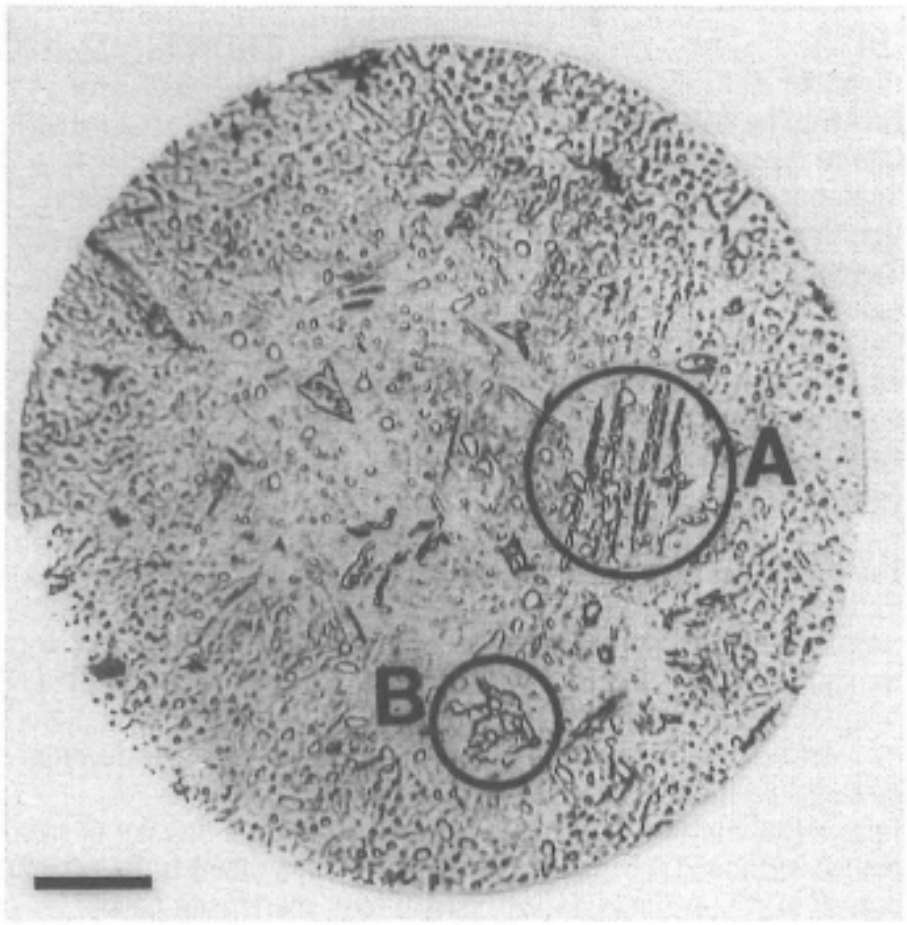
Failure Description: Hardness of ball was 21 HRc throughout, compared to approx. 60 HRc specified. Generalized spalling and heavy wear resulted from inability of soft material to carry load.
Image Description: Light macrograph shows entire ball with extensively spall-cratered surface. Between craters, the surface is streaked and matte, due to wear. No sign of original surface is left. The low hardness was established by hardness testing.
Suspected Causes: Through handling error a ball may avoid heat treatment and be placed with heat treated balls to be finished. While ordinarily such a ball is conspicuous by a diferent luster, it may be overlooked. The soft material cannot carry normal ball loads and spalls and wears extensively under them.

DATA

Plate No: 6.11
Archive No: 093-7.1.2
Image type: light metallogram, Nital etch
Scalebar = 8 μm (micros: ±20%, others: +100%, −50%)
Component: 52100 bearing steel raw material
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.1.2 Ferritic constituent
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Excessive soft ferritic constituent in hardened 52100 steel. This structure has less resistance to fatigue spalling than properly hardened structure.
Image Description: Background is finely distributed martensitic matrix with small carbides (dark dots). Streaky constituent is soft ferrite, as in circles at *A* and *B*.
Suspected Causes: Soft constituents in a hardened structure may arise if the austenitizing temperature is insufficient.

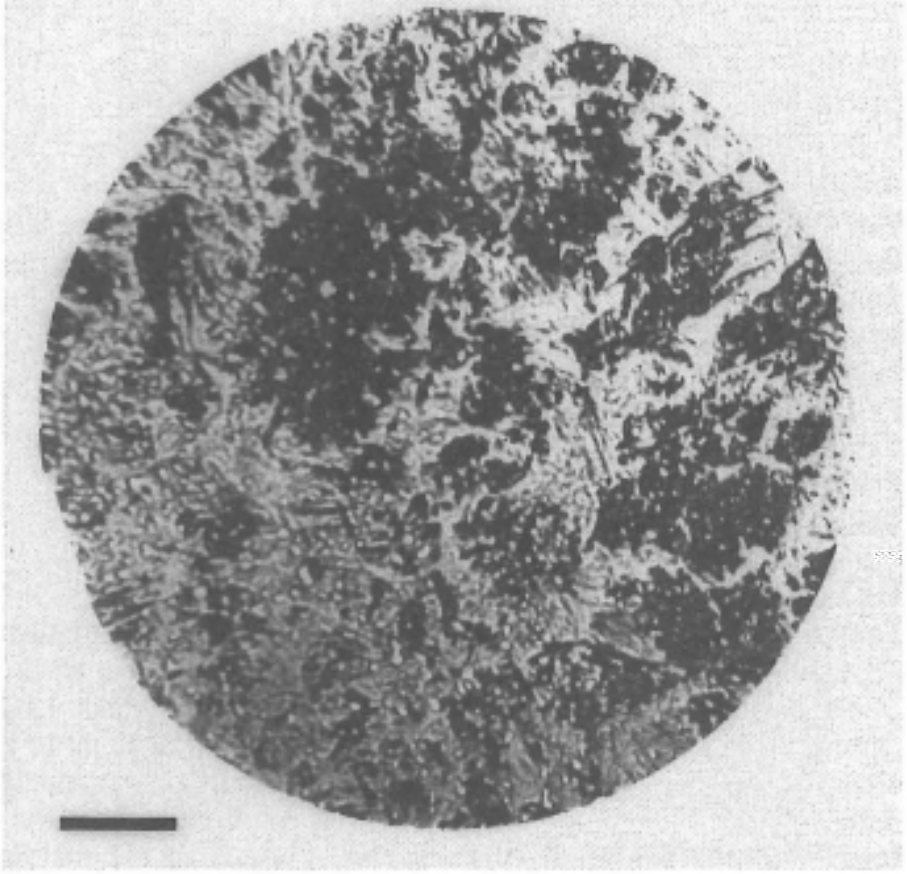


DATA

Plate No: 6.12
Archive No: 093-7.1.4
Image type: light metallogram, Nital etch
Scalebar = 8 μm (micros: ±20%, others: +100%, −50%)
Component: 52100 steel raw material
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.1.3 Upper bainitic constituent
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

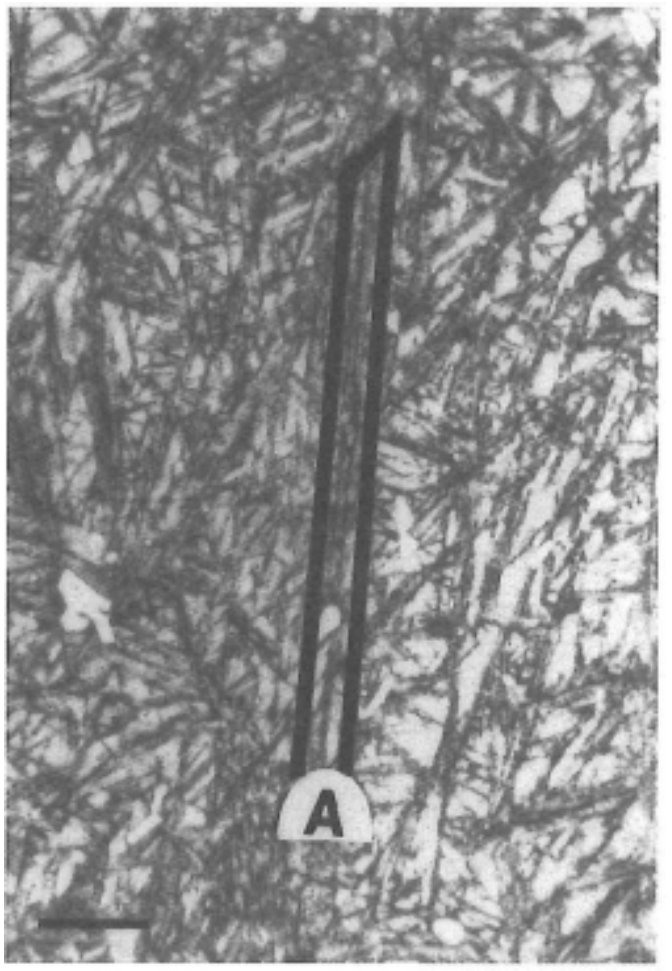
DESCRIPTIONS

Failure Description: Soft constituent formed by insufficient quenching is 'upper bainite' believed to be detrimental to fatigue resistance. It is distinct from 'lower bainite' obtained by a special high-temperature quench and used for improved toughness compared to conventional martenistic quench.
Image Description: Gray background is martenistic structure. Dark areas are upper bainite.
Suspected Causes: If quenching is performed too slowly or is interrupted before completion, upper bainite can form.



DATA

Plate No: 6.13
Archive No: 093-8.1.2
Image type: light metallogram, Nital etch
Scalebar = 10 μm (micros: ±20%, others: +100%, −50%)
Component: M50 tool steel specimen
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.2 Off-specification martensite platelet size
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

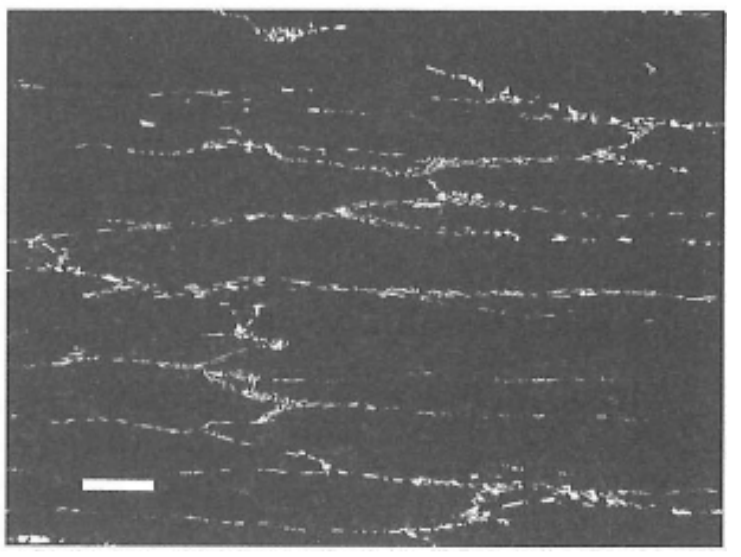


DESCRIPTIONS

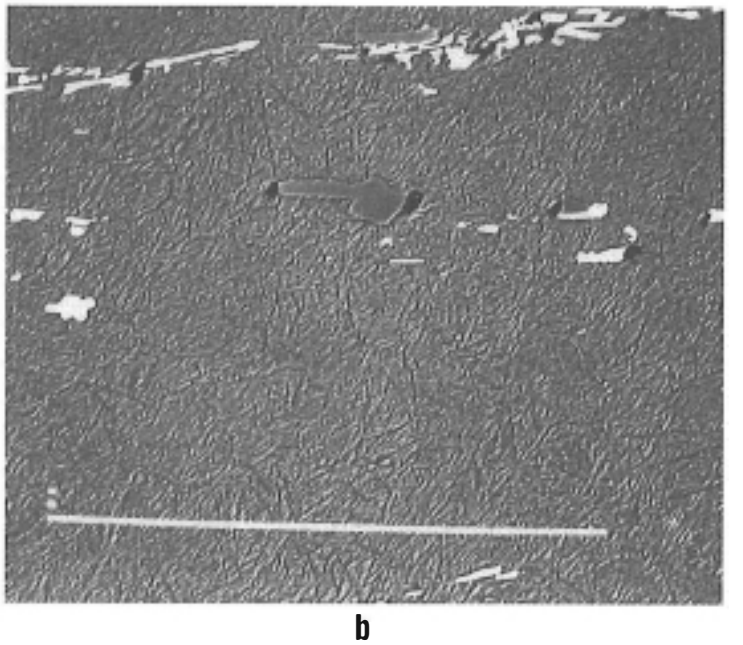
Failure Description: Martensite platelets formed in hardening may develop excessive size if heat treatment conditions are improper. This condition is thought to increase brittleness and lead to cracking, especially under high hoop stress. (It is not established whether the large platelets are the cause or merely an indication of increased brittleness.) Limits are often set for permissible martensite platelet size.
Image Description: Martensite platelets appear as streaks or needles in the etched section. Their size is too large (for this steel) to be accepted. The outline at *A* surrounds an excessively long martensite needle.
Suspected Causes: Austenitizing at excessive temperature during heat treatment causes large martensite needle size.

DATA

Plate No: 6.14
Archive No: 018-320&321
Image type: a: light metallogram, etched; b: SEM
Scalebar = a, b: 100 μ (micros: ±20%, others: +100%, −50%)
Component: heat-treated M50 steel, 100×100 mm billet
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.3.1 Carbide segregation
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



a



b

DESCRIPTIONS

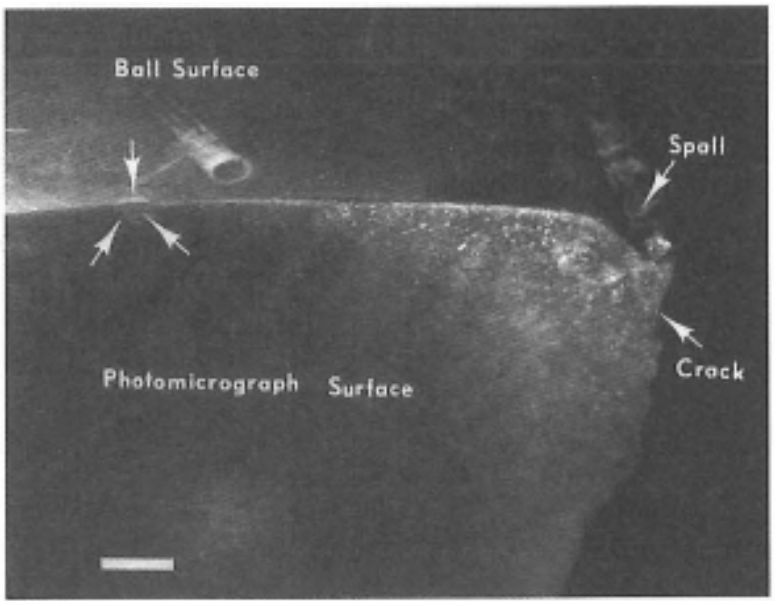
Failure Description: (a): Segregated primary carbides in high-alloy tool steel. (b): Sizeable primary carbides in M50 tool steel. Two types (molybdenum-rich and vanadium-rich) are arrayed in streaks. Large carbides may impair surface finishing. Segregation is thought to reduce resistance to cracking. Requirements exist for limits on carbide segregation in steels used in bearings.
Image Description: (a): Dark background is heavily etched matrix. White linear design consists of segregated primary carbides. (b): Gray patterned background is etched, hardened matrix. At image N is a string of molybdenum-rich carbides, shown white in the SEM. Slightly N of image center is a keyhole-shaped, large vanadium-rich carbide shown gray in the SEM.
Suspected Causes: High alloy tool steels tend to develop carbide segregation during ingot processing. Degree of segregation depends on processing method.

DATA

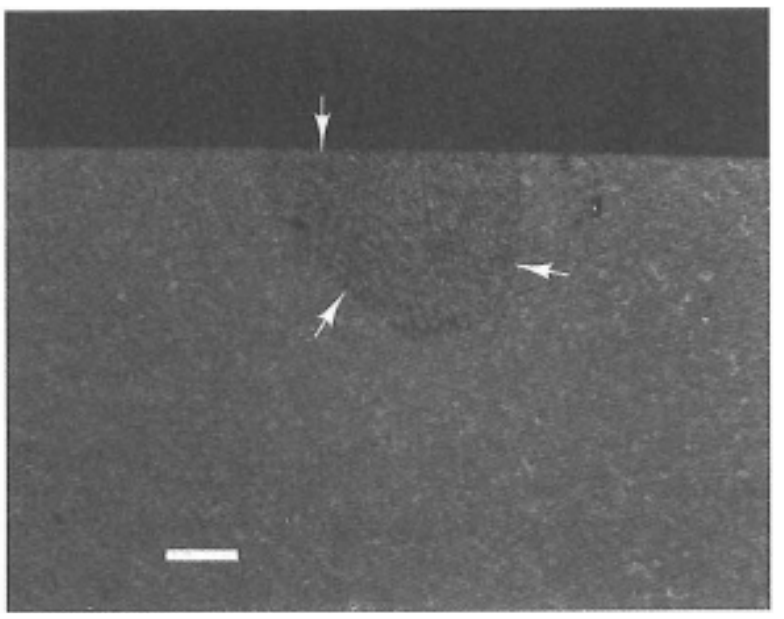
Plate No: 6.15
Archive No: 002-002i&j&f
Image type: a, b, c: light metallogram, Nital/Zephiran etch
Scalebar = a: 1 mm; b, c: 100 μm
(micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 0.8 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.07.3.2 Lamellar carbide
Failure Code 2: 00.04.3.1 Forging at excessive temperature
Failure Code 3: 00.16 Spalling Hertzian contact fatigue
Failure Code 4: 00.22.01.3 Rolling element (ball, roller) crack

DESCRIPTIONS

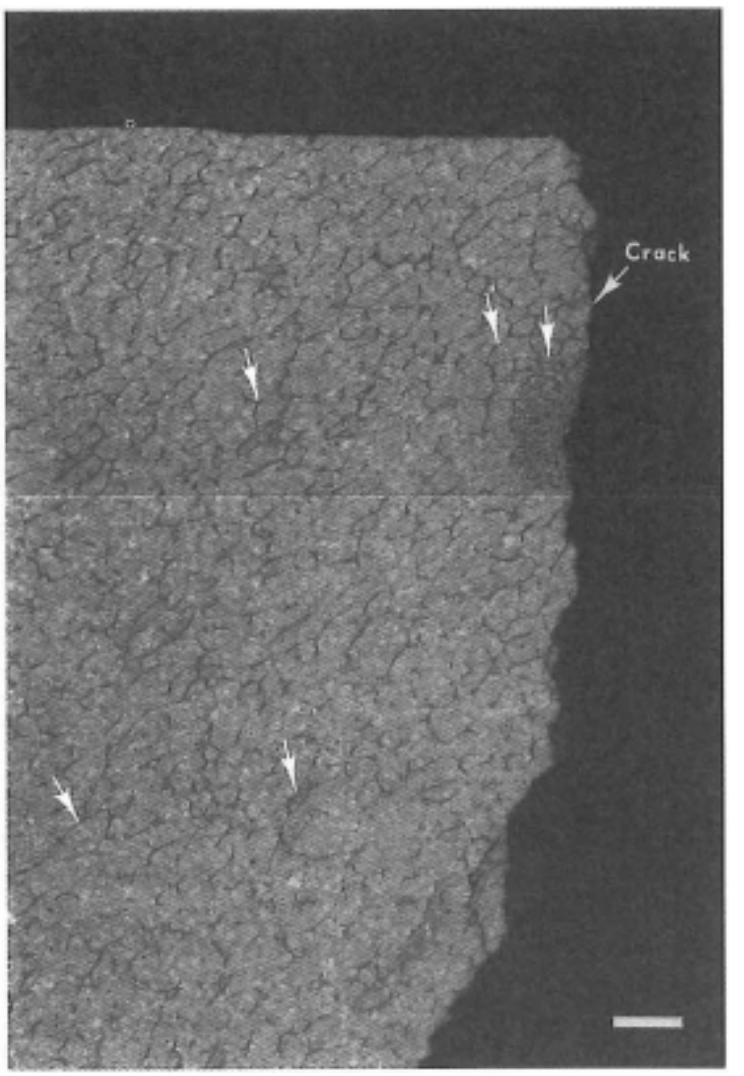
Failure Description: Island of defective structure characterized by lamellar carbides due to forging at excessive temperature with recrystallization. Bulk fatigue crack, spalling. Material volumes with recrystallized structure are weak volumes, at which spalls may form prematurely. This ball also shows incipient melting. A spall has formed from one of the material defects. Bulk cracking has resulted.
Image Description: (a): At image NW, material with lamellar carbides extending to ball surface (3 arrows). Spall and crack marked by arrows at E edge. The white, keyhole-shaped mark on surface is an artifact. (b): At N center, recrystallized zone (arrows) etches dark and shows lamellar carbide striations. (c): Jagged E boundary of etched section is bulk crack (labeled). Lamellar carbides throughout section (arrows).
Suspected Causes: This tool steel ball was forged at excessive temperature which has caused incipient melting and recrystallization producing the lamellar carbides. Spalling and subsequent cracking occurred in the weak structure. Incipient melting was also observed.



a



b



c

DATA

Plate No: 6.16
Archive No: 093-10.1.2
Image type: light metallogram, Nital etch
Scalebar = 6 μm (micros: ±20%, others: +100%, −50%)
Component: 8620 steel specimen
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.4 Visible retained austenite
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

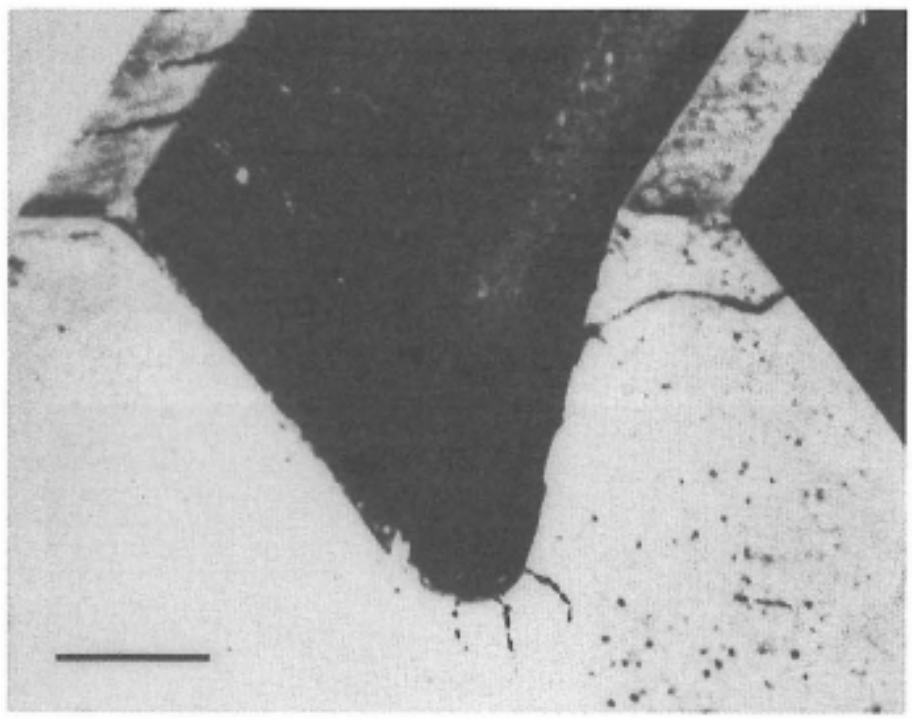


DESCRIPTIONS

Failure Description: Microscopically visible retained austenite in excessive amount. Depending on steel analysis and heat treatment, varying percentages of austenite are retained after tempering. Austenite retained beyond specification suited to the application causes dimensional instability due to gradual transformation in service. It may increase wear and indentation sensitivity.
Image Description: Dark "needles" in the image are martensite. White angular patches are retained austenite. The percentage of retained *visible* austenite can be estimated from such images but is usally less than the true percentage measurable by X-ray diffraction.
Suspected Causes: Austenite retention depends on steel analysis and numerous heat treatment variables (austenitizing time, temperature, quench conditions, tempering temperature and time, special cold treatments, etc.).

DATA

Plate No: 6.17
Archive No: 099-142
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: SG; P, med. hard, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.5.02 Heat treat crack
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

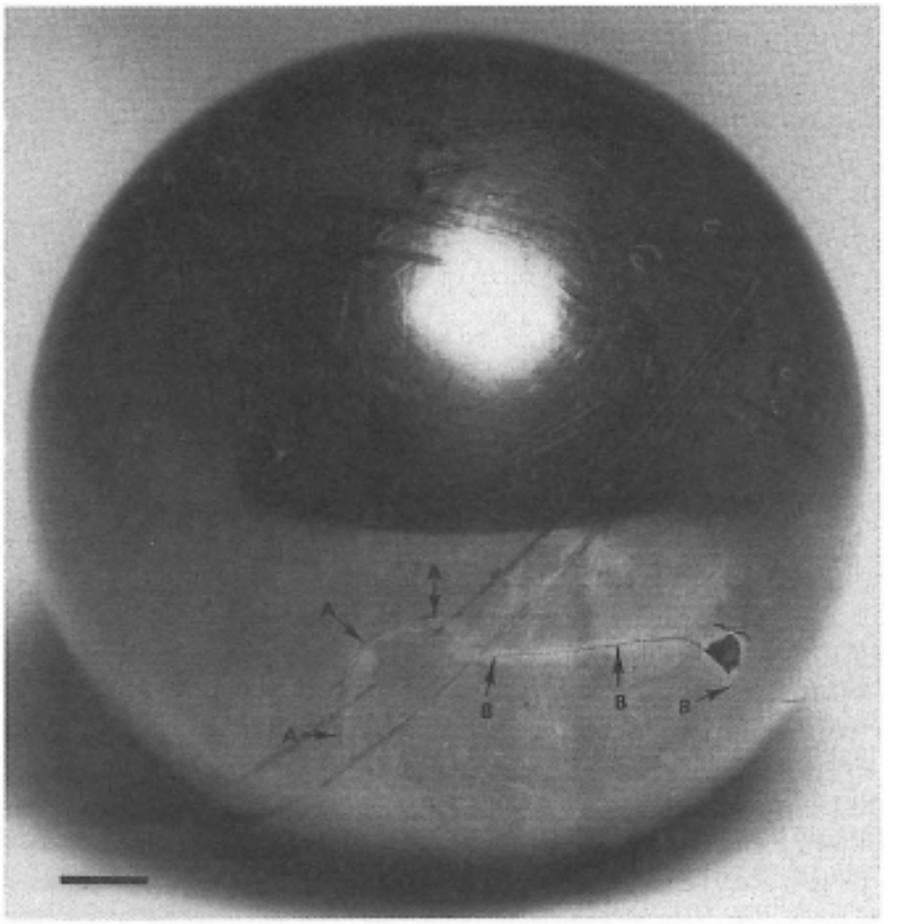
Failure Description: In through hardened gears (generally about 40 HRc hardness), quenching cracks may occur as a result of mismatched material and heat treatment procedure, excessive or uneven quenching. Quenching cracks are likely to lead to early tooth bending fatigue and/or spalling.
Image Description: At the side face of the gear, a crack crosses the tip of the tooth at image E. Three cracks extend into the root fillet. From the top land of the tooth at image W, two crosswise-directed cracks extend down to the tooth flank.
Suspected Causes: Mismatched material and heat treat practice, excessive quenching, uneven quenching or quenching in too-cold medium may precipitate quenching cracks.

DATA

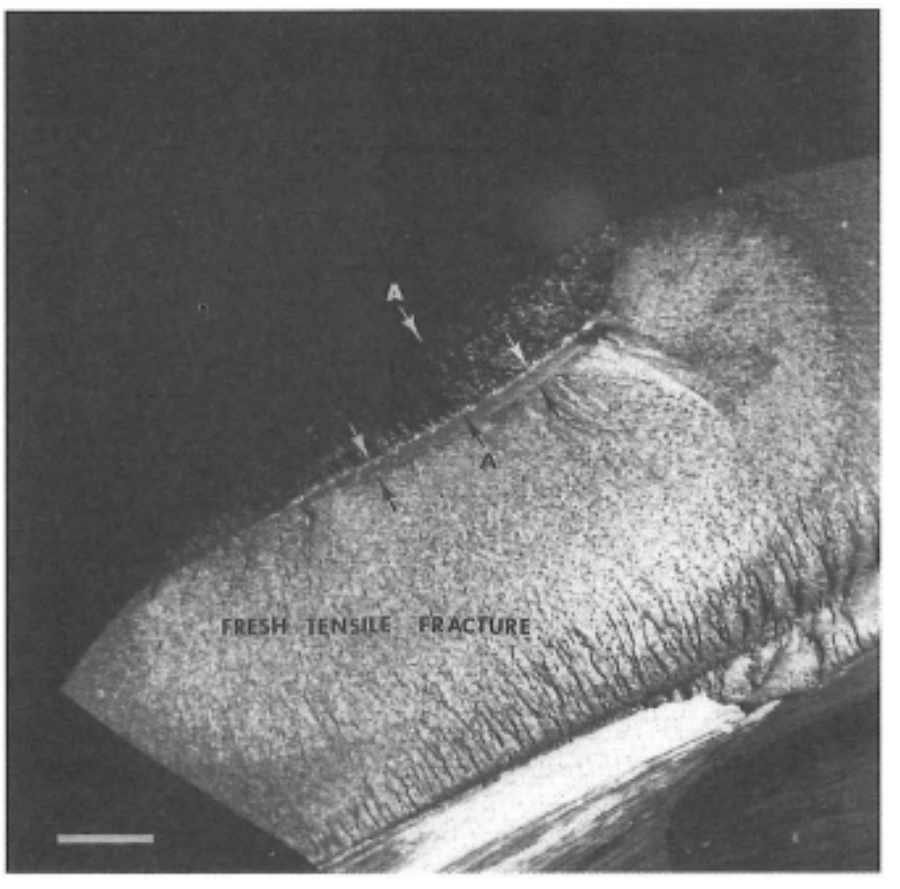
Plate No: 6.18
Archive No: 002-007a&c
Image type: a: light macro, b: fractured specimen macro
Scalebar = a: 3, b: 1 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.07.5.1 Crack with oxidized surface
Failure Code 2: 00.16.1.1.2 Spall from subsurface defect
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
See also PLATE: 15.30

DESCRIPTIONS

Failure Description: (a): Two adjacent cracks with oxidized surfaces formed, probably, in heat treatment of the ball. Incipient spall at one crack. Bulk fatigue crack propagation. Scratch marks, some probably from separator contact. (b): Oxidized radial heat treat crack, extended by unoxidized bulk fatigue crack. Heat treat cracks are severe defects that lead to fracture. See also Plate 15.30 illustrating crack propagation by fatigue.
Image Description: (a): Two cracks are marked with *A* and arrows and *B* and arrows. Small spall at crack *B* (bracket). Two major-circle scratch marks from SW to NE. Many shallower wear marks in N polar region. (b): In NW, dark crescent-shaped, oxidized heat treat crack (*A*–*A*). Central portion of crack extended inward by fatigue (unlettered arrows). This crack face is unoxidized (gray). "Fresh tensile fracture" was made for examination.
Suspected Causes: The tortuous path and oxidized surface of the initial crack suggests a heat treat crack. Fatigue spalling and cracking extended original failure in running. Scratch marks are due to service wear, perhaps aggravated by spall debris.



a



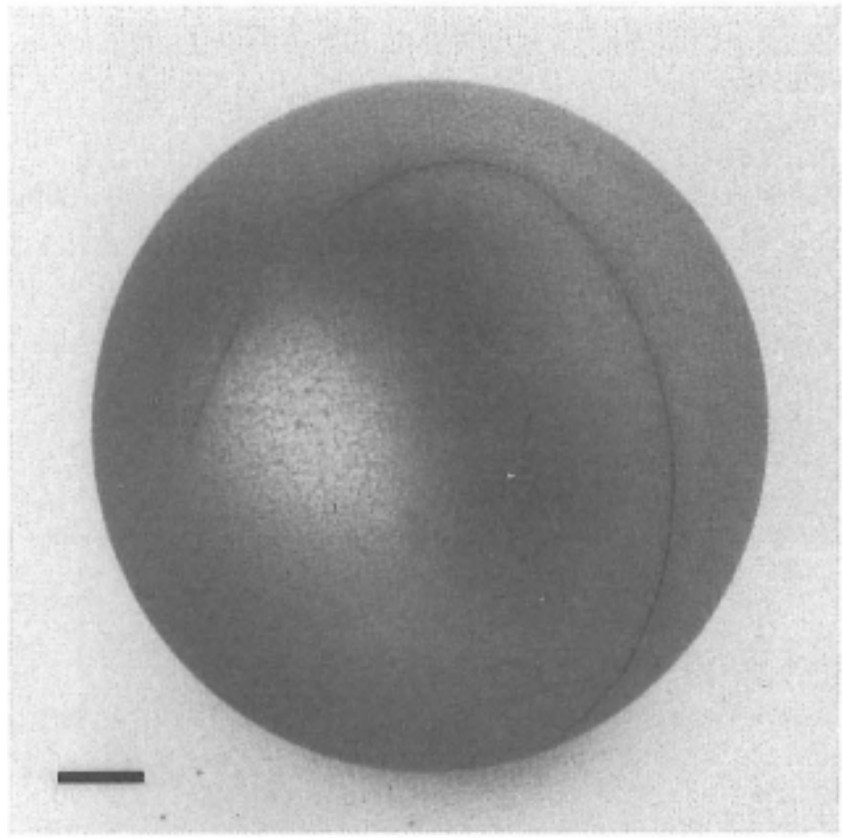
b

DATA

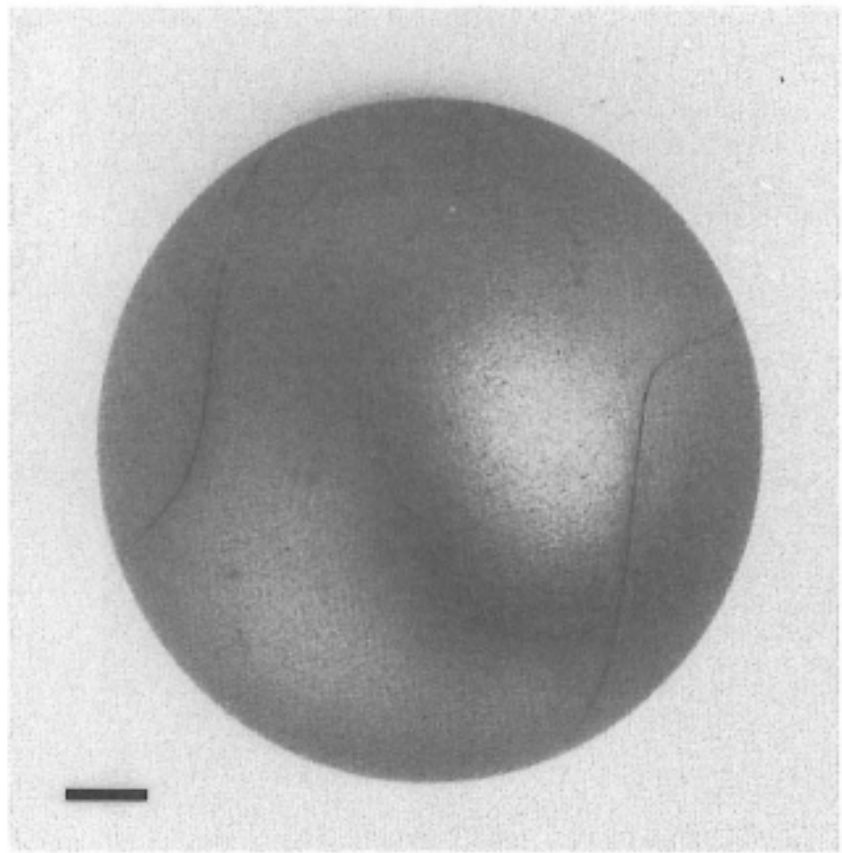
Plate No: 6.19
Archive No: 087-106&108
Image type: a, b: light marco, hot acid etched
Scalebar = a, b: 2 mm (micros: ±20%, others: +100%, −50%)
Component: BB; B, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.07.5.2 Twisted (baseball) crack
Failure Code 2: 00.07.5.02 Heat treat crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Typical heat treat crack in a ball, designated as a 'baseball crack' because the crack follows the pattern of the seam in a baseball. The crack is widened by hot acid etching. Such cracks result from excessive thermal stresses formed in heat treatment due to uneven or too-rapid quench. The cracks may form after hardening, especially if tempering is delayed.
Image Description: Background surface is pebbled from hot acid etch used in examination. (a): One loop of the crack is visible as a black line. (b): The ball is turned 90° (S to N) to reveal part of both loops of the crack.
Suspected Causes: Quenching of through-hardened balls will produce high thermal stresses that are reduced to acceptable level in tempering. Causes such as improper material and quenchant combination, uneven quenching, too-cold quenchant or delay between quench and temper may allow the stresses to initiate a crack, which, in a ball, tends to assume this characteristic shape.



a



b

DATA
Plate No: 6.20
Archive No: 002-021d
Image type: light metallogram, Nital-Zephiran etch
Scalebar = 40 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.5 MdN
Load: 0.8 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.08 Material structure damage, post-heat treatment
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

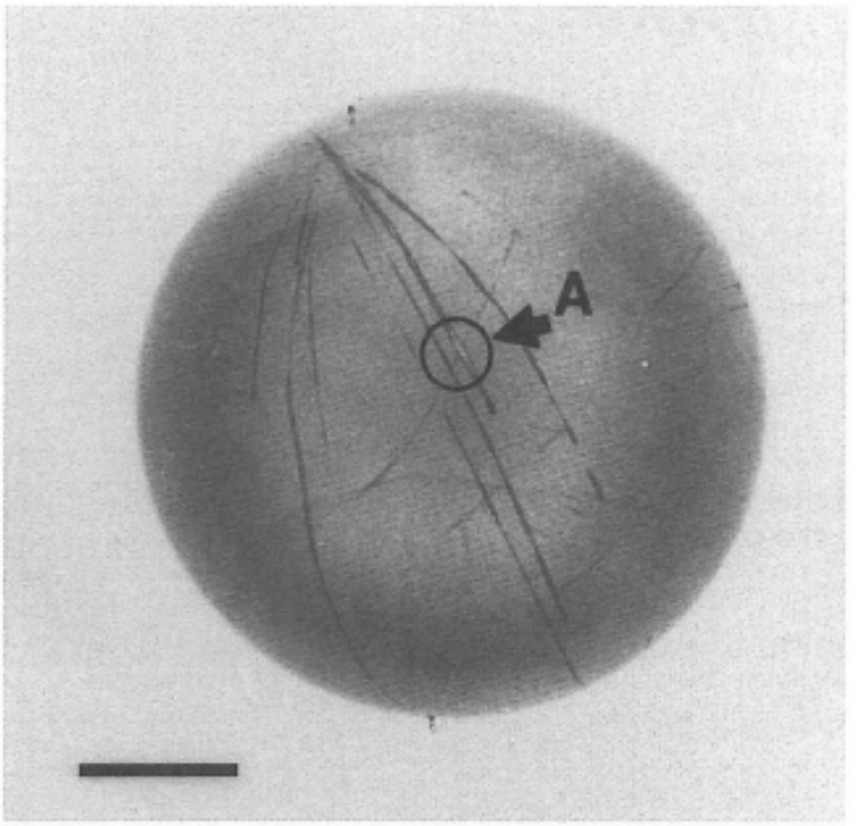
DESCRIPTIONS
Failure Description: Thin surface layer of material showing etching difference. Assumed to be a sign of cold plastic working in finishing. These balls suffered early wear marking in service, which is attributed to weakened surface material.
Finishing of bearing rolling surfaces for sensitive aerospace applications must be free from such surface damage, which is conducive to surface distress.
Image Description: Etched section is mottled structure in S 3/4 of image. Surface is a S-pointing arrow. Between 2 arrows, thin (2 μm thick) surface layer etches lighter than bulk material. Cold worked material shows this property.
Suspected Causes: In lapping of bearing balls, considerable contact pressure and sliding are applied. If the cutting action of the lapping compound is slow and the pressure too high, the process degenerates into burnishing, that is, it constitutes predominantly a cold rolling of the surface. The result is a damaged surface material layer.

DATA
Plate No: 6.21
Archive No: 002-028a
Image type: light microgram of section
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR
Speed: 2.5 MdN
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.08 Material structure damage, post-heat treatment
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Heat-damaged surface of oil hole initiated a fatigue crack which led to bulk cracking of IR under high centrifugal stress during running. Ultrahigh speed bearing innerrings are at great risk of hoop stress failure. Oil holes are potential sources of stress concentration. The bearing has failed.
Image Description: Bore of IR is at image E (light-colored area). Oil hole runs E–W and connects the bore with the undercut at roller path to flange intersection. (Half of the oil hole is visible in this fractured ring section.) The surface of the oil hole is very rough and shows galled or melted metal. At arrow is initiation of fatigue crack that led to bulk fracture.
Suspected Causes: Oil holes in aircraft engine mainshaft bearing innerrings are often hard-drilled following heat treatment. (Spark erosion machining is generally prohibited.) Hard drilling with a dull or broken drill may damage, gall and overheat the metal, thus leaving residual stresses and gouges as failure initiation points.

DATA

Plate No: 6.22
Archive No: 093-11.1.5
Image type: light macro, Nital etched
Scalebar = 7 mm (micros: ±20%, others: +100%, −50%)
Component: BB; B, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.1 Grinding temper
Failure Code 2: 00.08.2 Rehardened grinding burn
Failure Code 3: -
Failure Code 4: -

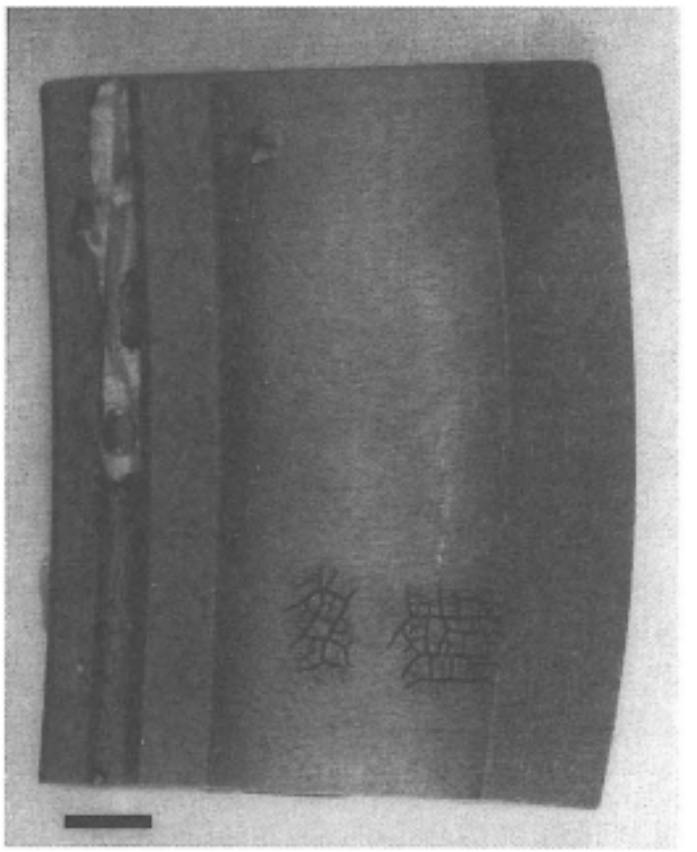


DESCRIPTIONS

Failure Description: Grinding temper and rehardened grinding burn lines on lapped surface of a ball ('Hoffman lines'). Rehardened Hoffman lines lead to early spalling. Lines that are not rehardened may reduce spalling resistance.
Image Description: Numerous dark great-circle lines on the gray etched ball surface represent grinding temper without rehardening. In the circle at *A*, the line has a white center with dark edges. The center is rehardened.
Suspected Causes: In ball lapping (and grinding), balls may be pressed against each other as they travel through the grooves of the lapping plate. There is sliding in that contact. If the contact occurs under sufficient pressure, it locally overheats, creating the Hoffman lines. Moderate overheating causes overtempering, higher overheating causes rehardening.

DATA

Plate No: 6.23
Archive No: 018-627
Image type: light macro, hot acid etched
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, tool steel, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.2 Rehardened grinding burn
Failure Code 2: 00.02.2 Wheel hit
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Two confined patches of grinding burn in the ball track, with cracks formed under hot etch. The localized nature of the patches indicates a wheel hit. Grinding burns severe enough to crack under hot etch are likely to cause early spalling and/or bulk fatigue cracking. A wheel hit, aside from causing structure damage, may also form a geometric imperfection and cause vibration on running.
Image Description: Mottled darkened background as a result of hot acid etch. In the ball groove (second N–S band from image E), two adjacent rectangular patches of dense surface cracking shown by etching as black line mesh on a darker gray background. This darkening upon etching indicates the altered structure at the grinding burn.
Suspected Causes: Grinding burns arise in grinding with too-severe parameters of speed, feed, improper wheel or cooling, causing overheating of the material so that it is locally reaustenitized and immediately self-quenched by cold metal. High residual tensile stresses develop from the material volume change. These may lead to cracking during grinding, or in sevice (or upon hot etching). A wheel hit is an unintended severe grinding event.

DATA

Plate No: 6.24
Archive No: 001-36
Image type: light macro, Nital etched
Scalebar = 2 mm (micros: +20%, others: +100%, −50%)
Component: CRB; IR, run
Speed: 1 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.08.2 Rehardened grinding burn
Failure Code 2: 00.08.3 Grinding crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Grinding burns containing a rehardened structure and multiple surface cracks. Grinding cracks cause surface-initiated failure: for example, spalling or bending fatigue. Rehardened grinding burns containing altered structure and high stresses are sources of early spalling.
Image Description: At image N, the dark zone is the IR roller track (labeled "raceway"). The radial plane surface S of it is a roller guide flange. Dark radial lines (at arrows) are grinding cracks revealed by the etch. Two oblong light patches with dark borders are grinding burns. The light area is rehardened, untempered martensite (labeled "rehardening"), the dark border is overtempered original martensite.
Suspected Causes: Grinding operations using too-severe parameters of speed, feed, improper wheel or cooling cause excessive heating of the material so that it is locally re-austenitized, and immediately self-quenched by the adjacent cold metal, producing untempered martensite. On the borders of the rehardened area heating is less, and material is overtempered but not rehardened. Stresses due to structure changes may lead to cracking.

DATA

Plate No: 6.25
Archive No: 002-022c
Image type: light macro, section, Nital etch
Scalebar = 5 mm (micros: +20%, others: +100%, −50%)
Component: ACBB; split IR, run,
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.08.2 Rehardened grinding burn
Failure Code 2: 00.16.1.2 Surface origin spall
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.49

DESCRIPTIONS

Failure Description: Extensive spalling has resulted from rehardened grinding burn in groove. A grinding burn contains modified structure and high residual stresses, possibly cracks and is a source of early spalling failure. The initiation area of the spall shown is lined up with the grinding burn. This spall is also shown in Plate 10.43.
Image Description: Cut innerring pieces. A portion of the ball groove, with a large spall, is at the image center; the land is to the N thereof. Matching, etched circumferential section is placed directly S of groove. Deep grinding damage area underlying spall shows light patches (burn), measured 200 μm deep, surrounded by dark margins (temper) between three arrows. Spall initiation area in groove at *A*, above grinding burn, shows deep, smooth oval exfoliation.
Suspected Causes: Abusive grinding causes grinding burns. A burn 200 μm deep is of unusual severity. Spalling-out of rehardened grinding burn occurs due to high residual stresses and weakness of rehardened and overtempered layers.

DATA
Plate No: 6.26
Archive No: 099-301
Image type: light macro of dye-penetrant tested part
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: SG; G, high hardness, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.3 Grinding crack
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Multiple surface cracks on the tooth contact surface. The cracks typically form from a rehardened grinding burn with high residual stresses. Grinding cracks cause surface-initiated failure, such as spalling or bending fatigue. Rehardened grinding burns, containing altered structure and high stresses, are early spalling sources.
Image Description: The block is a section of a gear tooth. The narrow N surface is the tooth tip land. S of it, the wide rectangle is part of the tooth flank. The S-most surface was made in sectioning. The many forking cracks on the tooth flank are highlighted in white by a penetrant dye.
Suspected Causes: Grinding operations using too-severe parameters of speed, feed, improper wheel or cooling cause excessive heating of the material so that it is locally re-austenitized and immediately self-quenched by the adjacent cold metal. High residual stresses develop from the material volume change resulting from structural phase transformation and these may lead to cracking.

DATA
Plate No: 6.27
Archive No: 099-143
Image type: light macro
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: SG; G, high hardness, ground, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.3 Grinding crack
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Multiple surface cracks on the tooth flank. The cracks form typically in a rehardened grinding burn with high residual stresses. Grinding cracks cause surface initiated failure, for example, spalling or bending fatigue. Rehardened grinding burns, which contain altered structure and high stresses, are early spalling sources.
Image Description: Flanks (dark gray) and tip lands (light gray) of several teeth in a spur gear. On the flanks, light-colored radial lines are cracks highlighted by a penetrant dye.
Suspected Causes: Grinding operations using too-severe parameters of speed, feed, improper wheel or cooling cause excessive heating of the material so that it is locally re-austenitized and immediately self-quenched by the adjacent cold metal. High residual stresses develop from the material volume change and these may lead to cracking.

DATA

Plate No: 6.28
Archive No: 087-003
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, 52100 steel, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.4 Hydrogen embrittlement cracking or flaking
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

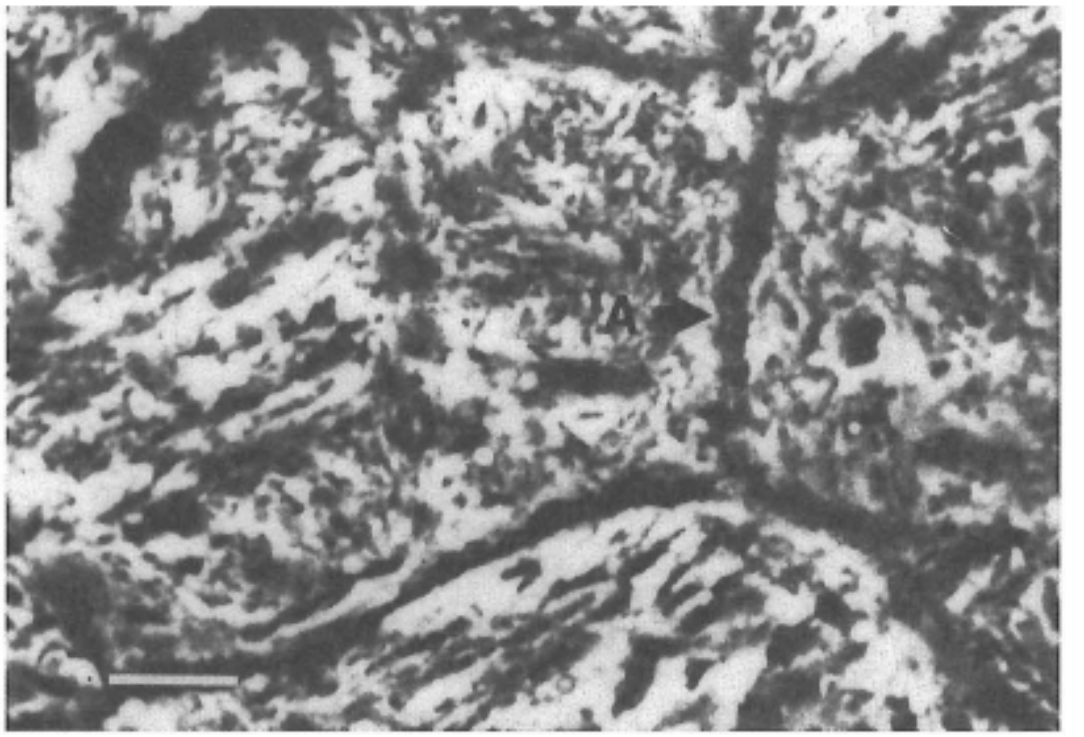


DESCRIPTIONS

Failure Description: Hydrogen embrittlement cracking from improper electroplating of bore. Electroplating of hardened components without proper heat treatment thereafter dissolves hydrogen in the steel, which creates residual stresses sufficiently high to cause cracking after varying time periods. This is gross failure.
Image Description: Two images of ring show extensive and erratic cracking in ball groove and on side face. The cracks have opened due to remaining residual stress. Black pen marks at various points of the surface are not defects.
Suspected Causes: To repair oversize bores or undersize OD, electroplating (mostly with chromium) can be used. Unless properly heat treated afterwards, this method can leave dissolved hydrogen in the steel, causing very high residual stresses resulting in severe cracking.

DATA

Plate No: 6.29
Archive No: 093-20-1.5
Image type: SEM
Scalebar = 4 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, black oxide coated, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.5 Chemical attack during manufacture
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

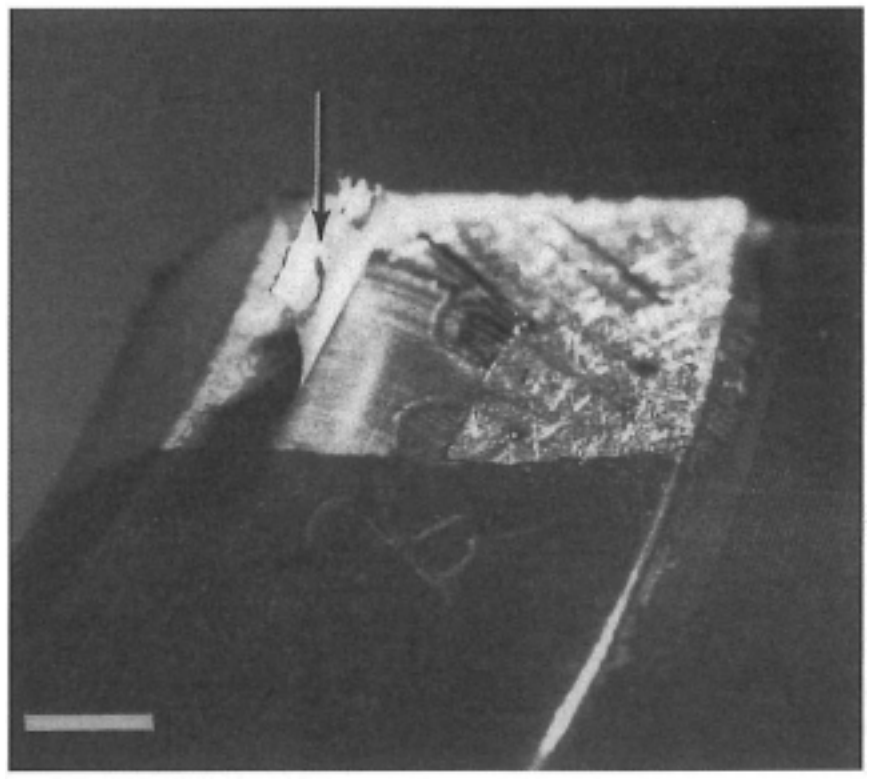


DESCRIPTIONS

Failure Description: Microscopic preferential attack by black oxide surface treatment on prior austenitic grain boundaries. This degree of preferential attack is harmless. Other surface treatments (for example, certain phosphate coatings) may produce sufficient grain boundary attack to reduce fatigue resistance of the surface.
Image Description: In this high (×4000) magnification SEM, three prior austenitic grains in the hardened steel are outlined by curving, dark 'canyons': (1) crossing N image edge, (2) N–S at *A,* (3) E–W in S image half. Black oxide coat was chemically removed, leaving striated-appearing etched surface under the coating, with prior austenitic grain boundaries preferentially attacked by the oxide coating process to form canyons.
Suspected Causes: Black oxide treatment properly applied is an acceptable running-in aid in rolling bearings, e.g., for some aerospace uses. It also apparently mitigates the tendency of low EHD film to cause surface distress. Improper chemical surface treatments can have serious degrading effect on surface integrity, and thus contact fatigue resistance, by creating more severe surface attack.

DATA

Plate No: 6.30
Archive No: 001-28
Image type: light macro
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, copper plated, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.08.6 Coating damage
Failure Code 2: 00.00.01 Defect by location: in fit surface
Failure Code 3: -
Failure Code 4: -

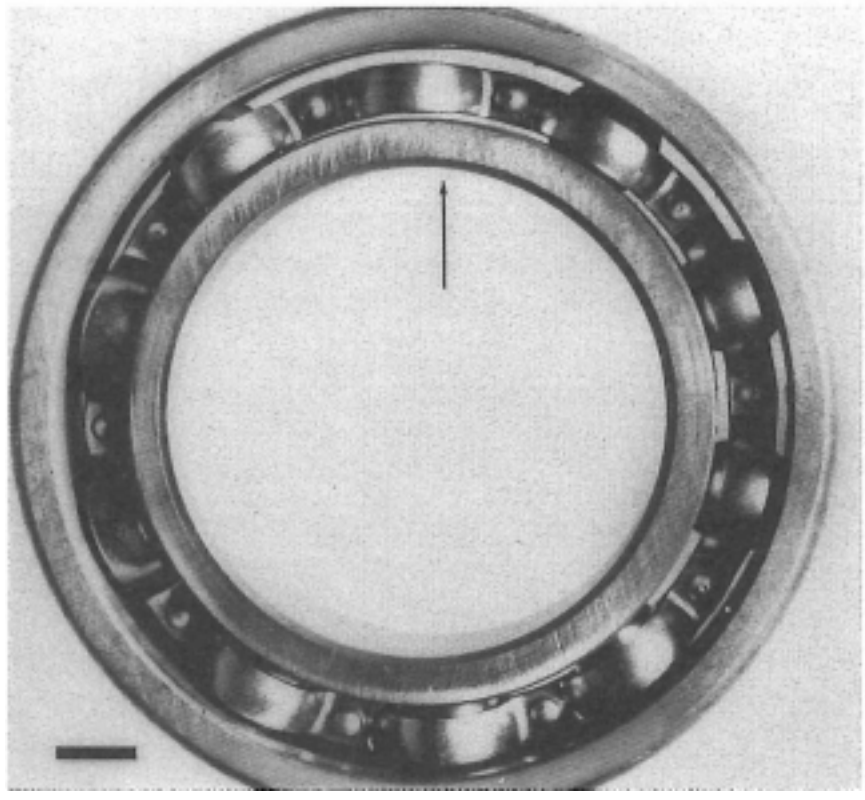


DESCRIPTIONS

Failure Description: Copper plating on fit surface has lifted off (during adhesion test). Unless plate adheres properly, intended anti-fretting effect is not realized.
Image Description: Cut IR segment viewed on side face. At arrow, peeled copper plating on ground side face of ring. Light/dark radial dividing line is an artifact.
Suspected Causes: Processing error in copper plating.

DATA

Plate No: 6.31
Archive No: 087-028
Image type: view
Scalebar = 8 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB, assembled, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.09 Geometry, assembly or mounting defect
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

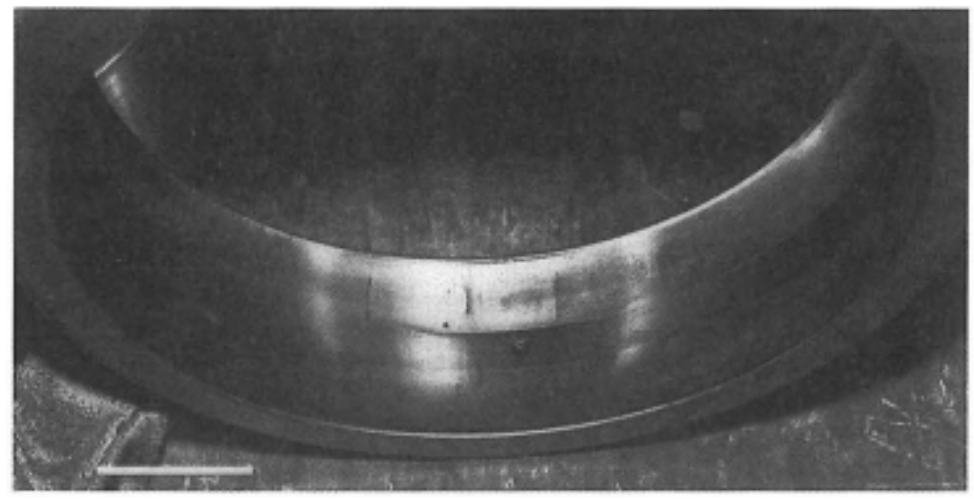


DESCRIPTIONS

Failure Description: One missing ball, omitted in assembly. A bearing with this defect is (a) vibratory, (b) of lesser load carrying capacity, and (c) unbalanced. Condition (a) may be objectionable in quiet running applications, (b) will spall in highly loaded applications, and (c) is likely to suffer separator failure in high speed applications.
Image Description: The ball marked by arrow is missing. While the ball regions protruding from separator are visible in the other balls, light shines past separator at arrow. Balance testing or suitable vibration testing can be used for detection in sealed or shielded bearings. Manufacturers use special magnetic sensors.
Suspected Causes: Most ball bearings are automatically assembled. Balls are metered in, distributed and the separator is then put in place. A ball may fail to feed and the bearing is assembled with a missing ball unless a sensor for missing ball detection is present.

DATA

Plate No: 6.32
Archive No: 031-703
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 2: 00.00.02.1 Defect by location: in Hertz contact surface
Failure Code 3: 00.09.2 Galling from forcible assembly or mounting
Failure Code 4: -

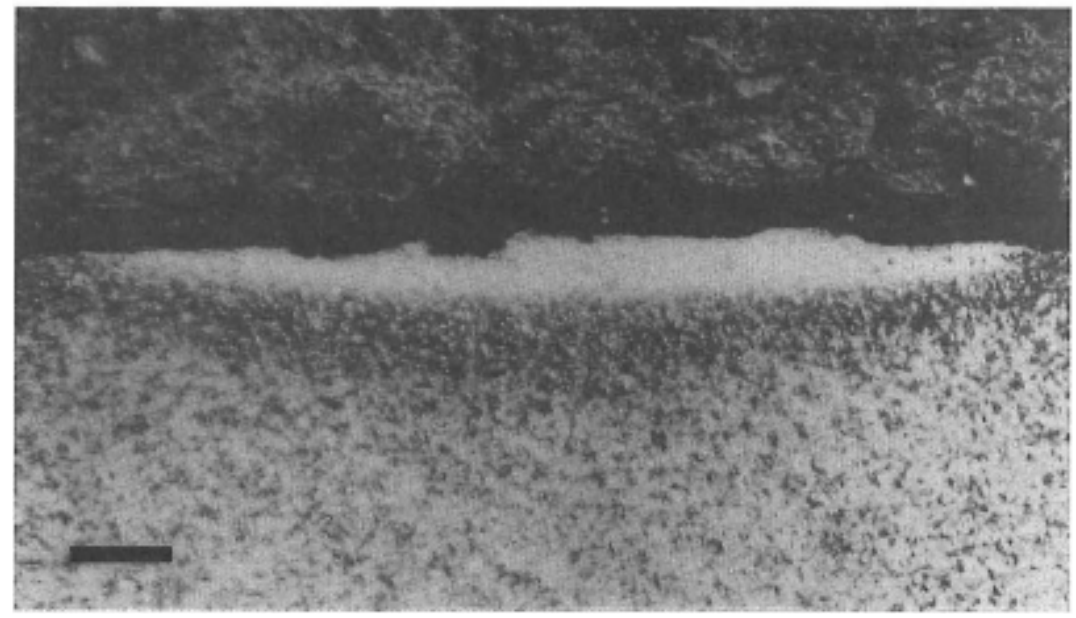


DESCRIPTIONS

Failure Description: Axial scuffmarks at roller spacing in the spherical roller path of a SRB OR, caused by sliding of the rollers, under pressure, across the OR surface of the stationary bearing. The marks are asperity-scale plastic flow with a suspicion of incipient galling.
Image Description: Score marks are dark, axial, fuzzy-edged lines across both roller tracks. The marks become more visible as the bearing is run. The running tracks show a different luster from the center band, because the bearing was operated. The fuzzy, faint scoring marks are probably not galled; the W-most mark in the N roller path is sufficiently sharp to suggest that it is galled. Microscopic examination is needed for differentiation.
Suspected Causes: Spherical roller bearings are assembled with the OR placed out of the plane of the IR and the separators to permit roller insertion. Having completed roller assembly, the OR is swiveled into the bearing plane. Inattentive handling, lack of lubrication or sharp roller edges can cause excessive roller to OR contact pressure producing the scuffmarks. They may or may not contain galling streaks, depending on contact severity.

DATA

Plate No: 6.33
Archive No: 018-113
Image type: metallogram
Scalebar = 40 μm (micros: ±20%, others: +100%, −50%)
Component: metallographic section, etched
Speed:
Load:
Lubrication:
Failure Code 1: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 2: 00.09.2 Galling from forcible assembly or mounting
Failure Code 3: 00.19.5 Local structure damage from frictional heating
Failure Code 4: -
See also PLATES: 4.8 and 6.31



DESCRIPTIONS

Failure Description: An incipient galling event produced by scuffing. The scuffed surface is gouged (probably with material transfer). A shallow layer beneath the scuffmark was heated to austenitizing temperature and self-quenched by the surrounding cold steel. It etches light. Below is a band of less heated, tempered dark-etching material. See Plates 4.8 and 6.31 for other views of assembly scoring.
Image Description: Metallographic section is the S half of the image (the N half is the plastic mount). The black/light-gray interface line is the rolling surface, showing depressed and elevated elements in the scuffmark due to plastic flow, wear, and possible galling. The featureless light layer (20 μm deep) is reaustenitized self-quenched martensite. The dark etching substrate blending into unaltered material below is over-tempered martensite.
Suspected Causes: Scuffing at sufficient pressure and speed produces localized plastic flow, wear and probably galling, with overheating of material leading to the structural changes observed. Structure change of this magnitude is rare in an assembly mark. A more common source of such damage is a grinding burn (FC 00.08).

DATA
Plate No: 6.34
Archive No: 027-262
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; OR, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 2: 00.12.1 Fit surface wear
Failure Code 3: -
Failure Code 4: -
See also PLATE: 6.37

DESCRIPTIONS
Failure Description: Axial scoremarks on the OD of the outerring. Marking to the extent shown here is due to mild wear and is generally harmless. More severe scoring may represent galling (FC 00.13) and may lead to subsequent cracking (FC 00.22).
Image Description: The scoremarks are thin axial lines with luster different from that of the undisturbed OD surface. They are distributed around the circumference of the ring OD. When examined under magnification, the grinding lines are interrupted by the marks. The marks show no material transfer (as distinct from galled scoremarks which do).
Suspected Causes: Assembly into a housing, either without adequate corner break or with excessively tight fit and/or rough surface. Assembly in the presence of solid contaminant in the fit.

DATA
Plate No: 6.35
Archive No: 002-023d
Image type: SEM
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.09.1 Scoring from foricible assembly or mounting (no galling)
Failure Code 2: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 3: -
Failure Code 4: -

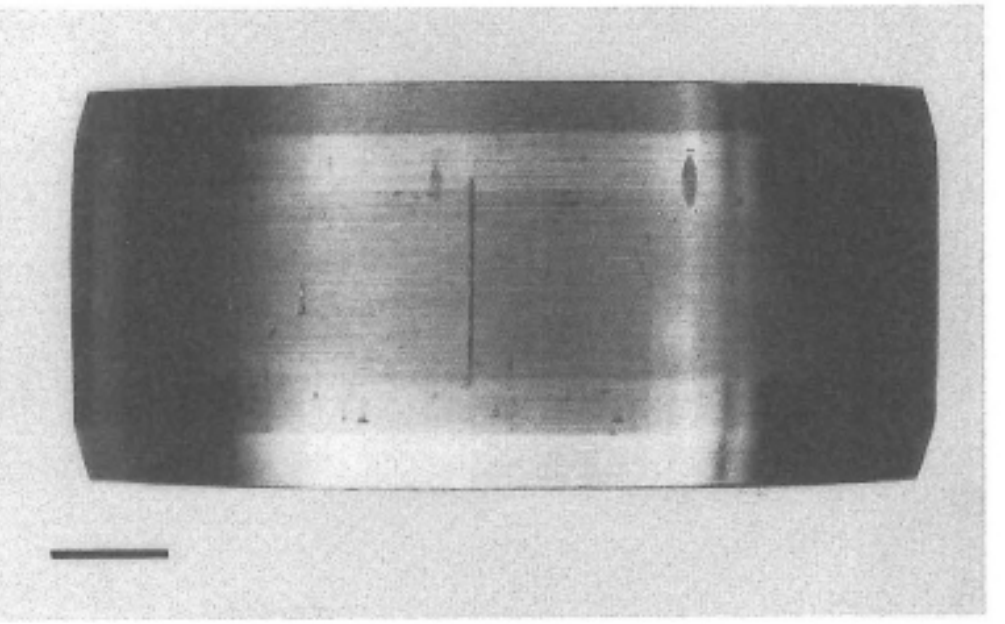
DESCRIPTIONS
Failure Description: Several gouges, presumably from bearing assembly, have damaged the ball surface and initiated a spall. The gouges are indentations and not wear marks, and have damaged the material to significant depth as shown by radial cracks in the spall. The ball has failed.
Image Description: Background is ball surface with varying gray hue due to viewing angle change. At *A*, remaining ends of crossing indentations made by edges of mating parts. Irregular spall crater indicates multiple initiations from these nicks. Surface cracks extend the spall at N and W sides. A radial crack face is between opposing arrows.
Suspected Causes: Indentation of ball surface by foricible assembly, such as into the pocket of "snap-through" separator design, or interference with a ring edge, can cause static cracking (especially in crack-sensitive tool steel) in addition to initating spalling.

DATA

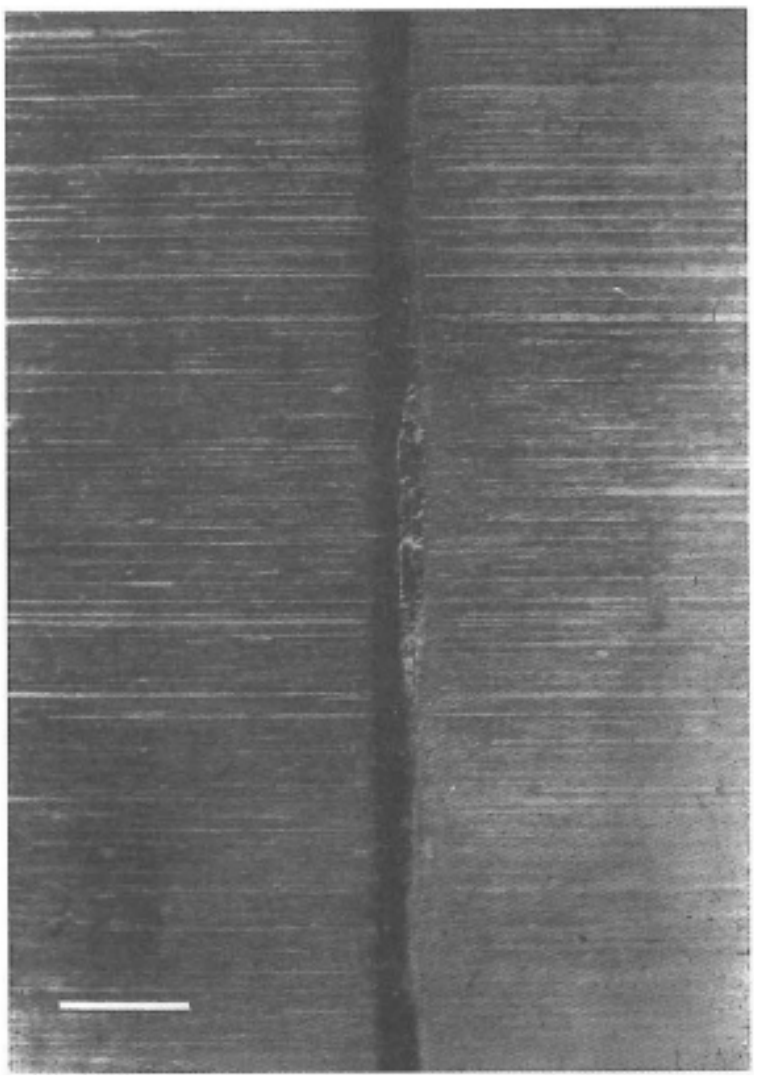
Plate No: 6.36
Archive No: 093-015&16
Image type: a: view; b: light macro
Scalebar = a: 25, b: 3 mm (micros ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.09.2 Galling from forcible assembly or mounting
Failure Code 2: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Two axial score (wear) marks, and, adjacent to one, a galling streak on IR roller path, from sliding of roller over IR during assembly, without rolling, under high contact load. A rolling path with a galled score mark from assembly fails early in spalling or from additional galling during operation.
Image Description: (a): Roller path showing circumferential running track across the contact width. One long, dark straight score (wear) mark at image center. Another, shorter mark just W of the lighting change from bright to gray. (b): Center mark enlarged. Dark uniform line is a score (wear) mark; dark-pitted oblong island with white border in image center, at E edge of dark mark, is material transferred in galling.
Suspected Causes: Careless insertion of CRB innerring, which is mounted on a shaft, into OR/roller assembly which is mounted in a housing, especially when rotor weight loads rollers. This is a common source of axial scoremarks with or without galling.



a



b

DATA

Plate No: 6.37
Archive No: 027-128
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; assembly, run
Speed: 180 KdN
Load: 3 GPa
Lubrication: synthetic grease, 60°C
Failure Code 1: 00.09.2 Galling from forcible assembly or mounting
Failure Code 2: 00.13.1 Fit surface galling
Failure Code 3: 00.15.1.1 Generalized fretting, radial fit surface
Failure Code 4: -
See also PLATE: 6.34

[See Image in Appendix]

DESCRIPTIONS

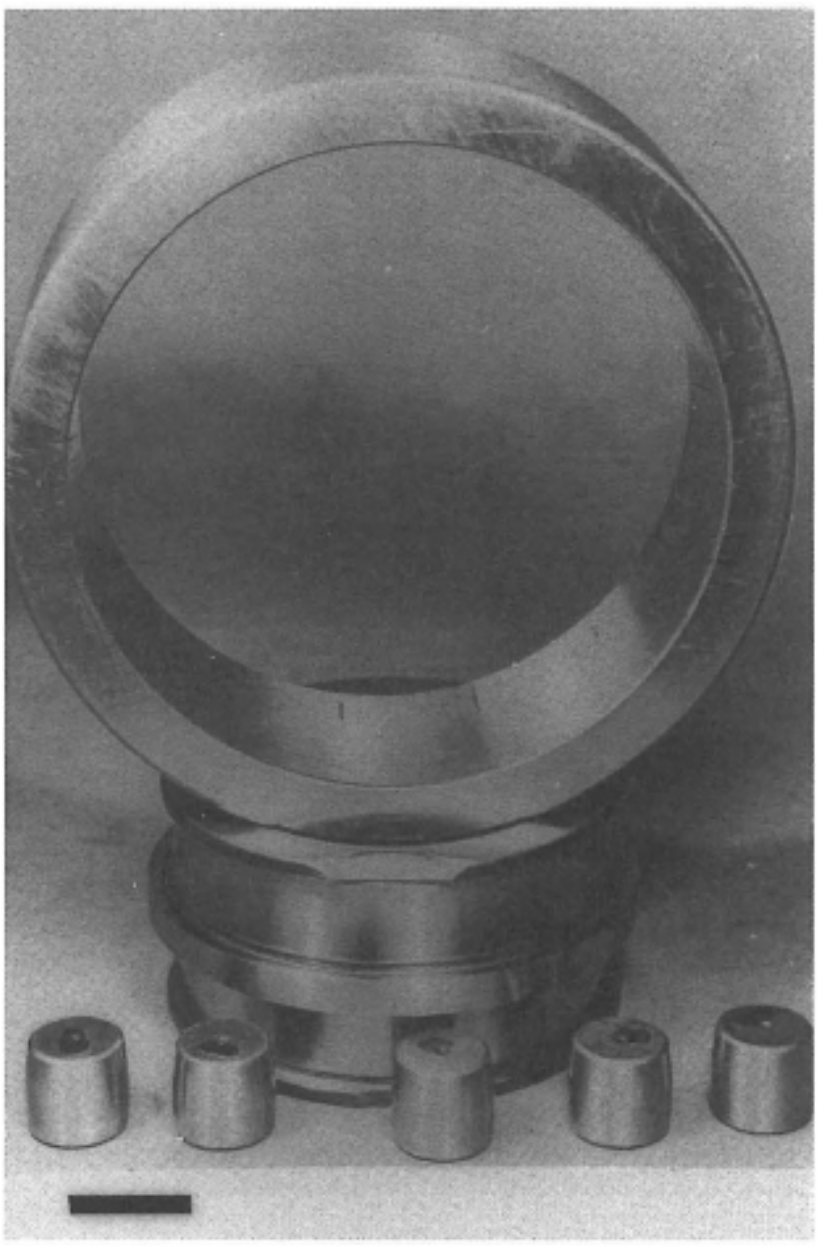
Failure Description: Axial galling streaks in IR bore from forcible assembly. Fretting corrosion in bore during running. Galling in bore may lead to bulk cracking of ring during cyclic stressing under high hoop tensile stress from tight intereference fit. Fretting to the extent shown is not a failure.
Image Description: Narrow bright axial bands of galling metal transfer between bearing bore and shaft (arrows). Brown, streaky fretting corrosion in bore, highlighting waviness ('chatter') on shaft (or in ring).
Suspected Causes: Galling streaks result from high interference between IR bore and shaft seat combined with rough shaft surface or a sharp edge at the lead-in to the seat, over which the bearing was pressed in assembly. Fretting is not uncommon in IR bores under rotating load.

DATA

Plate No: 6.38
Archive No: 018-110
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; OR&IR&R, mounted
Speed:
Load:
Lubrication:
Failure Code 1: 00.09.3 Cracking (fracture) from forcible assembly or mounting
Failure Code 2: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 3: -
Failure Code 4: -

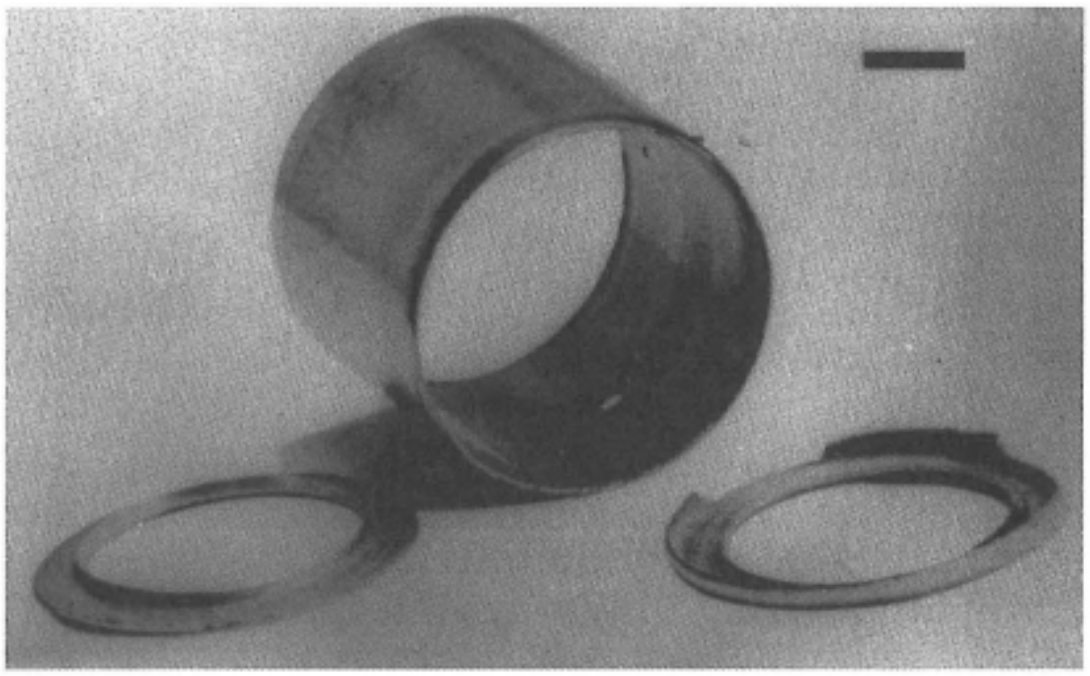
DESCRIPTIONS

Failure Description: Chipped side flange on IR from hammer blow during mounting. Axial scoremarks in OR roller path and on roller OD from relative axial motion of stationary bearing during mounting. The bearing is unusable.
Image Description: OR at image N, standing on IR. Rollers near S image edge. Dark axial lines on far side of OR roller path, at roller spacing, are scoremarks. Axial scoremarks (mostly light-colored) on roller OD-s. IR side flange facing image N severely chipped near ring centerline.
Suspected Causes: Assembly of bearing using hammer blows or other heavy impact, especially if applied to flange edge, are likely to fracture the part. The scoremarks arise from hammer blows transmitted through rolling contacts in the stationary bearing.



DATA

Plate No: 6.39
Archive No: 018-203
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: NRG; OR (drawn cup), mounted, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.09.3 Cracking (fracture) from forcible assembly or mounting
Failure Code 2: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Mounting damage from defective tool shape caused one folded-over end flange to break off by circumferential cracking. (The other end flange broke in dismounting.) Running tracks are visible in the contact paths, showing the bearing was (briefly) run, but it is not serviceable now.
Image Description: Cylindrical OR (drawn cup) in image center. Two broken-off end-flanges SW and SE. Separation of flanges along circumferential crack (smooth on SW flange, jagged on SE flange). Polished roller paths from two rows of needle rollers in cup bore.
Suspected Causes: Closed-end needle roller cup must be mounted using a piloted tool with a back-angled flange which bears near OD of end-flange when pressing the cup into housing. The tool used here had a forward angle and pressed against the bore diameter of the end-flange. Bending stresses on the flange were excessive and it cracked around the OD radius.

MILD WEAR 7

Failure Code 00.12

7.1 Definition

Wear (of a contact component) is defined as the removal of component surface material in the form of loose particles by the application of high tractive forces in asperity dimensions during service. It is distinguished from:

- *Surface distress* (FC 00.17), defined as surface material plastic flow and micropitting by the application of high *normal* forces in *asperity* dimensions;
- *Galling* (severe wear) (FC 00.13), defined as removal of surface material in the form of material transfer to distant surface areas by the application of *tractive* forces in *multi-asperity* dimensions;
- *Fretting wear* (FC 00.15), defined as removal of surface material, often with oxidation of debris, as a result of microscopic surface-parallel relative movement of surfaces in nominally static contact under normal load.

7.2 Nomenclature

Mild wear is generally designated in industry as just 'wear'. Often, a distinction is made between *adhesive* (or *two-body*) and *abrasive* (or *three-body*) wear, with the former taking place in the absence of extraneous solid particles in the interface, and the latter caused by such particles.

Occasionally the term *wear* is used loosely to designate all modes of surface material removal, including the other modes listed in Section 7.1. In the Atlas, wear always designates mild wear, but includes two- or three-body wear.

In some gear failure literature [9, 10], the term *adhesive wear* is used to denote galling (FC 00.13). In this Atlas, that use is consistently avoided.

7.3 Failure Process

Several theories exist to describe the micro-scale mechanism of wear particle formation in mild wear. For the Atlas, it suffices to define the macroscopic circumstances causing mild wear. If: 1) two solid surfaces are in contact under normal load (i.e., not fully separated by an intervening fluid film), 2) sliding takes place between the surfaces, and 3) the normal pressure and the sliding velocity in combination are less severe than the threshold condition for galling—then, under the conditions and for the materials used in Hertz contact machine elements, removal of loose particles of asperity dimensions may take place from one or both surfaces. It is assumed that the tractive forces operating between asperities sliding over each other are the cause of the particle removal. A *wear rate* is associated with the wear process; the rate is higher for more severe stress conditions, and usually higher for 'less wear resistant' materials, rougher surfaces, and higher friction coefficients. The wear rate may be speed-independent under conditions where temperature and lubrication parameters do not change with speed.

Nonzero wear rates vary over many orders of magnitude for realistic operating contacts. For low enough severity of the contact (especially for low slide/roll velocity ratios and/or low tractive stresses) the wear rate may be zero (as observed on a macroscale) throughout the entire life of the contact, or may "run in" to zero after an initial period during which the surfaces become smoother through wear.

Boundary lubrication, defined as the provision, in the interface, of low-shear strength solid films (including some oxides of the surface material) or adsorbed fluid films, generally reduces both wear and the friction coefficient, but the two effects are generally not functionally related.

Solid particles, often designated *contaminants* or *debris*, present in the contact interface either from extraneous sources or as a result of the wear process itself, modify the wear process into the variant designated three-body wear.

7.4 Distinctive Appearance

Wear may be identified morphologically: from the morphology of a worn surface, or from the appearance of loose 'wear particles' in or near the contact or in the lubricant. The appearance of wear particles is described under FC 11 and FC 12 (Lubricant Failures).

In contact components, a worn surface can have several distinct appearances depending on the conditions of the wear process. They are described below. In differential diagnosis of wear, it is critical to observe that the characteristic appearance of the other material removal modes—surface distress (FC 00.17), galling (FC 00.13), or fretting (FC 00.15)—is *not* present.

Smooth Wear. When smooth wear is advanced, then the worn surface, under low or no magnification, appears featureless, matte and nondirectional. The characteristic finishing marks of as-manufactured surface have been worn away.

In the initial stage of smooth wear, finishing marks are gradually ablated, and the matte worn surface is interspersed with remnants of the (deeper) finishing marks.

The *matte* featureless surface of a worn component must be distinguished from the *burnished*, i.e., glossy, featureless surface of a 'glazed' surface-distressed component (FC 00.17).

Under the microscope, preferably the scanning electron microscope, a smoothly worn surface shows a pebbly appearance, which under high magnification resolves into random-length short scratches in the sliding direction.

Smooth wear is most commonly observed in the presence of *fine*, hard contaminant particles (including oxide particles from the surface).

Characteristics specific to the smooth wear of bearings and gears:

In *bearings*, light smooth wear, alone or in combination with light surface glazing (FC 00.17), produces visible contact paths which distinguish a surface swept over by Hertz contacts from adjacent surfaces outside the contacts. The distinction is one of changed luster, and may require experimentation with lighting direction to be revealed. Contact path shape and position are prime indicators of load distribution, especially in ball bearings.

In *gears*, the axially locked relative position of meshing surfaces produces several types of smooth wear (i.e., wear without individual visible wear scratches), which may vary from point to point in the contact:

- *Polishing* and *smooth tooth wear* are increasing degrees of uniform wear of the tooth profile, short of the severity that renders the gearing unserviceable.
- *Destructive tooth wear* may be two-body or three-body wear and, in distribution, may be: or *uniform*; *wavy*, with wave crests running laterally across the contact width; *bumpy*, with mating macroscopic hills and valleys across the contact; or *furrowing*, with narrow, short radial furrows clustered in axial bands, crossing finishing lines.

Kinematic Wear Marks. The wear process is precipitated by sliding in the contact. Therefore, an asperity on one surface, or an abrasive particle imbedded in one surface, travels a prescribed kinematic path over the contacting surface. The process begins when the asperity (particle) enters the contact and ends when it exits. (Earlier if the asperity breaks off or the particle shatters.) The track of the asperity on the opposite surface can often be seen as a scratch designated a *kinematic wear mark*. Such marks have distinctive geometries, depending on the kinematics of the machine element and the location of the asperity in the contact area.

In *roller* bearings with *cylindrical, needle* or *tapered* rollers:

- Marks on *rolling* surfaces are circumferential scratches. Such marks *may* arise in the Hertz contact or in the contact between roller and separator pocket. In a Hertz contact, a few degrees angle deviation may exist if the roller has skewed. The length of the scratch is generally short if it arises in a Hertzian contact, since the asperity is rolled out of contact (unless the roller skidded). Scratches from a separator contact may run the entire circumference of a roller.
- Marks on flange or roller-end surfaces are epicycloidal arcs if they arise in roller to flange contacts. On roller-end surfaces, concentric circular arcs arise in roller to separator pocket contacts.

In *roller* bearings with *spherical* rollers the marks are similar to those in other roller bearings, but the length of scratches arising from Hertzian contacts varies with position. At two axial positions where sliding is zero ('Heathcote bands'), the scratch length is near zero, and progressively increases as the location moves away from the Heathcote bands.

In *ball* bearings:

- Marks arising in the Hertzian contacts are parabolic arcs for which the aspect ratio and orientation depend on location relative to the momentary spin pole of the ball. The parabola is concave as viewed from the spin pole.
- Marks on balls arising from a separator contact are concentric circular arcs.

In *gears*, kinematic wear marks may produce a type of uneven wear designated as ridging. Their geometry is determined by the kinematics of the tooth mesh, namely:

- In *spur* gears, marks follow a gear tooth profile line.
- In *helical* gears, *bevel* and *hypoid* gears, marks follow the local sliding direction.

Marks on *cams* with *rolling followers* are similar to those in cylindrical roller bearings, but sliding may be considerable and accordingly, marks may be long. Marks on *cam* and *tappet* contacts, in which the tappet spins around its longitudinal axis, are parabolic arcs.

Step Worn In. When wear occurs in a contact bounded by edges (line contact), extends to the edge and is substantial, then a discontinuity in the profile may appear at the contact edge and is designated a *step*.

Pitting Wear. Pits can form during wear of a surface, if:

- Weak material volumes (mostly inclusions or large carbides) are present at or near the surface. Ablation of the surface by wear may expose these weak volumes to tractive forces and tear them out, leaving a pit (see also FC 00.03).
- Microporosity exists in the material just below the surface, which may be opened to the surface by wear, to form pits.

These wear pits differ from:

- *Spalls* (FC 00.16), by the surface character of the crater, which, in pits, is *not* a fracture surface. The appearance of a pit is described under FC 00.03.
- *Corrosion pits* (FC 00.20) which show an oxidized surface.
- *Electric erosion pits* (FC 00.21) which show a molten surface.

7.5 Causes

The common causes of mild wear are

- Excessive sliding in the contact;
- Excessive surface roughness;
- Insufficient boundary lubrication;
- Insufficient EHD lubrication;
- Insufficient wear resistance of material due to low hardness, wrong structure or wrong material combination in the contact. In ceramics or cermets: binder defects contribute to low wear resistance;
- Chemically aggressive environment (lubricant or atmosphere);
- Contamination by solid (three-body wear);
- The presence of weak material volumes near the surface (pitting wear).

Causes of Mild Wear Specific to Rolling Bearing Contact Components

In rolling contact:

- Edge contact due to geometry error;
- Excessive skewing of roller;
- Excessive spin of ball;
- Excessive separator friction;
- Excessive angular acceleration, especially at load zone entrance.

In *roller-end* to *flange* contact:

- Edge contact due to geometry error;
- Excessive normal stress due to axial load or roller skewing;
- Excessive sliding velocity due to geometry error;

In *Hertz contact element* to *separator* contact:

- Edge contact due to geometry error;
- Excessive separator forces in contact with support element;
- Insufficient separator clearance to contact element.

Causes of Mild Wear Specific to Cams. Cams and cam followers or tappets suffer the general causes of mild wear listed above. Of these, they are particularly vulnerable to the following:

- *Sliding*. Cam and rolling follower systems undergo high angular accelerations once every cycle as the cam and follower make contact at the start of the lift phase. Cam and tappet systems operate with continuing relative spin.
- *Edge contact*. Rolling cam followers are difficult to maintain in precise alignment and edge relief is difficult to provide. Tappet wear may eliminate edge clearance.
- *Contamination*. Cam systems are often lubricated from general circulating oil systems which carry combustion products (in internal combustion engines) and wear products.
- *Rough surfaces*. Camshafts often are large components; cam geometry is complex and machinery for cam finishing may not permit as good a finish as in smaller, simpler components.

Causes of Mild Wear Specific to Gears

- *Initial wear* (running-in) is an expected phenomenon in many gear systems, due to forced sliding of teeth at all locations away from the pitchline, and limitations to surface finishing imposed by the complex tooth shapes, especially in medium-hard hobbed gears.

- *Continuing wear* damages the geometry and finish of the teeth. It is often abrasive, that is, it brings on three-body wear by contamination with extraneous hard particles or wear debris.
- *Two-body mild wear* (not to be confused with the galling designated as adhesive wear in [8, 9]) may occur due to the several general wear causes listed earlier, such as rough surfaces, insufficient wear resistance of (one or both) gears, inadequate lubrication, and misalignment leading to edge load.

Note: Gear sets are characterized by the laterally locked relationship between contacting surfaces, leading to a tendency for wear to become localized (wavy, bumpy, ridged).

7.6 Effects of Mild Wear

Mild wear has damaging effects on contact components, if it is not self-limited (run-in). The damage occurs primarily through the following mechanisms:

Material removal distorts component geometry. As a result, surface pressures are often redistributed unfavorably. In addition, geometric relationships that influence machine accuracy, backlash, quietness and so on, may be impaired.

Surface finish is modified, which may either improve or destroy as-made surface microgeometry. If material removal is substantial, bulk strength of components (gears) may be impaired. Finally, components which have been surface-treated for wear-, fatigue-, galling- or corrosion-resistance, or for solid lubrication, may lose some or all of these layers.

Cross-Index of Secondary Failure Codes

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00.12.1	6.34
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00.12.3.2.1.4	13.3 15.38
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PLATES

DATA

Plate No: 7.1
Archive No: 093-020
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.1.1 Fit surface polishing
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

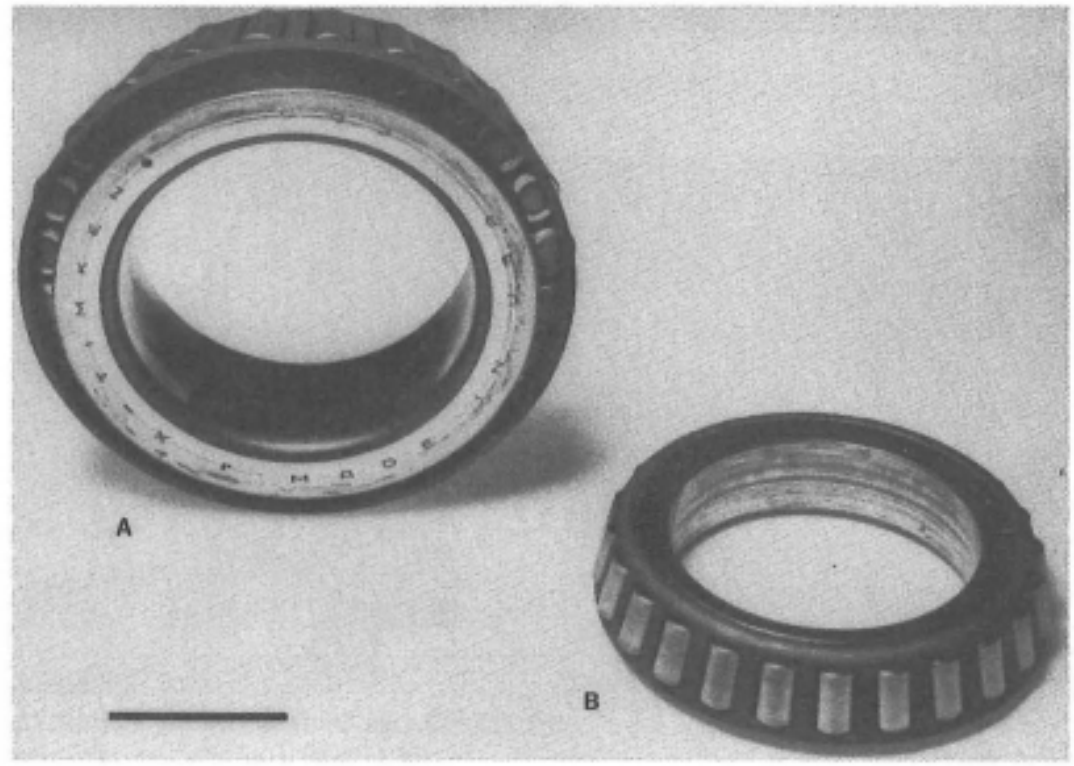


DESCRIPTIONS

Failure Description: IR bore highly polished by rotation in loose fit under rotating load. Such rotation can lead to galling and subsequent cracking, or to progressive wear. Noise (squealing) is also possible.
Image Description: The IR bore surface is burnished to mirror finish. Grinding lines are largely obliterated.
Suspected Causes: Radial load of rotating direction with respect to the innerring ('rotating load') causes relative rotation of ring and shaft if the fit interference is insufficient. Microscopic relative motion causes fretting; more rapid motion produces polishing or wear. In more severe cases (higher load, rougher surface, higher speed and poor lubrication), it produces galling.

DATA

Plate No: 7.2
Archive No: 014-60
Image type: a, b: view
Scalebar = a, b: 40 mm (micros: ±20%, others: +100%, −50%)
Component: TRB, IR assembly, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.1.2 Advanced mild wear of fit surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: (a): A groove is worn in the large sideface of an IR (cone). (b): Circumferential marks are worn in the bore of a cone. Progression of sideface wear leads to excessive axial looseness of bearing assembly. Progression of bore wear aggravates spinning of cone on shaft and eventually may lead to galling and fracture or seizure.
Image Description: (a): Large sideface of a TRB IR (cone) with a circular groove worn through the lettering. The rest of the sidetrack is smoothly worn. (b): Several circumferential grooves (dark circles) and smooth wear in the bore of a cone.
Suspected Causes: When the radial load rotates with respect to the IR, an interference fit between bore and shaft is required to prevent epicyclic rotation of the ring on the shaft. The interference must be higher for higher load. If it is insufficient, the ring rotates and wears in the bore. In a TRB, an axial load component always exists and causes wear of the large sideface against the support shoulder when the IR rotates on the shaft.

Failure Code: 00.12.3.2.1.1
Failure Code: 00.12.3.2.1.2
Failure Code: 00.12.3.2.1.4

DATA

Plate No: 7.3
Archive No: 093-03a..i
Image type: a..i: drawing
Scalebar = -
Component: DGBB; IR & OR, run
Speed:
Load:
Lubrication:

a

Image (a):
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: 00.12.3.2.0.1 Wear track when load rotates over innerring
Failure Description: Rolling track when normal magnitude radial load rotates with respect to innerring.
Image Description: Wear marks (polishing or scratches) in ball paths, away from both edges. The OR track is angularly confined to a load zone of less than 180° in circumference. The IR track extends through 360°.

b

Image (b):
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: 00.12.3.2.0.2 Wear track when load rotates over outerring
Failure Description: Rolling track when normal magnitude radial load rotates with respect to outerring.
Image Description: Wear marks (polishing or scratches) in ball paths, away from both edges. The IR track is continued to a load zone of less than 180° in circumference. The OR track extends through 360°. Both tracks centered in their grooves.

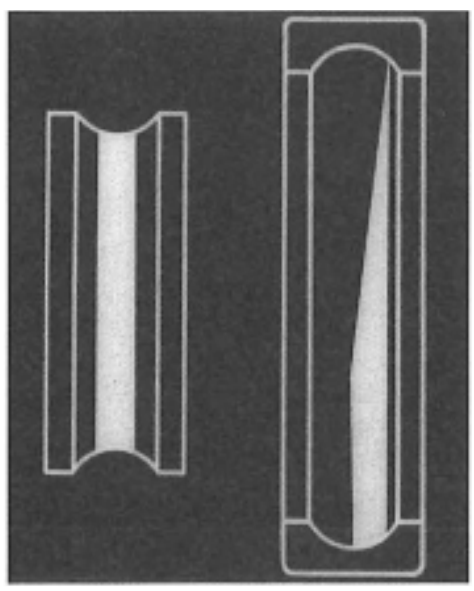
c

Image (c):
Failure Code 1: 00.12.3.2.1.2 Wear track off-center in contact
Failure Code 2: 00.12.3.2.0.5 Wear track for centered axial load
Failure Description: Illustration of rolling track when normal magnitude centered axial load is applied. Off-center, uniform width 360° load track on both rings. There may be a great circle track on the ball if the load is uninterrupted in time. Otherwise several tracks, or no discernible track on the ball.
Image Description: Wear marks (polishing or scratches) in ball paths, shifted toward opposite edges on IR and OR, but not reaching either edge. Both tracks extend through 360° circumferentially.

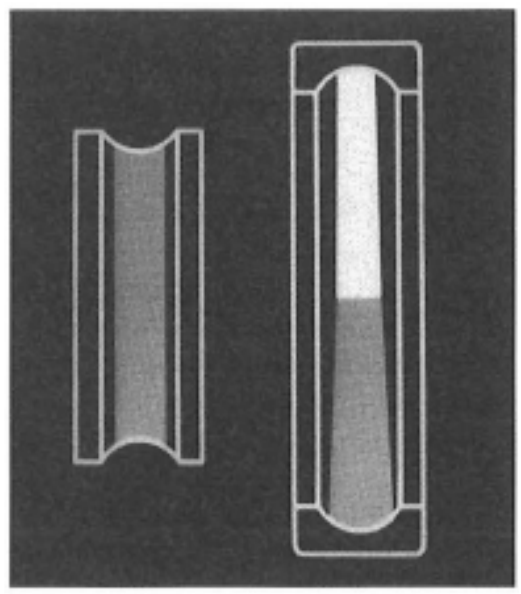
d

Image (d):
Failure Code 1: 00.12.3.2.1.4 Wear track at contact edge
Failure Code 2: 00.12.3.2.0.5 Wear track for centered axial load
Failure Description: Rolling track when excessive magnitude of centered axial load is applied. Tracks extend to a groove edge in one or both rings. This condition may precipitate early spalling failure on ring or balls, from edge stresses, depending on the degree of overload.
Image Description: Wear marks (polishing or scratches) in ball paths, shifted toward opposite edges on IR and OR, reaching at least one groove edge. Both tracks extend through 360° circumferentially.

Plate No. 7.3, continued



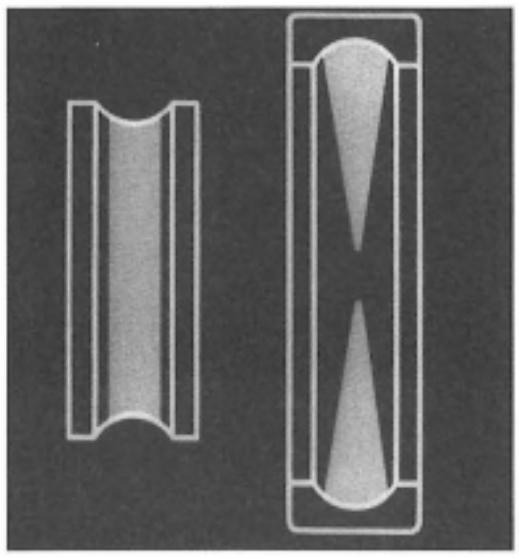
e



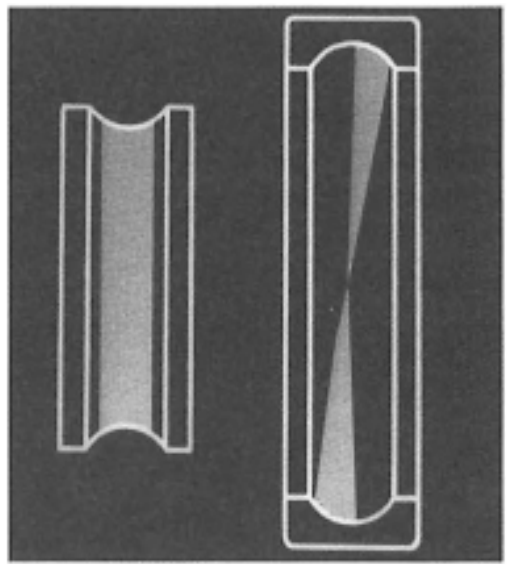
f

Image (e):
Failure Code 1: 00.12.3.2.1.2 Wear track off-center in contact
Failure Code 2: 00.12.3.2.0.6 Wear track for combined radial/axial load
Failure Description: Rolling track when normal magnitude axial load is combined with normal magnitude radial load rotating over the IR. In DRBB, load zones of different angles, (incl. 0 in one track), occur for combined load.
Image Description: Wear marks (polishing or scratches) in ball paths, away from both edges. For single-row gearings, the OR track is confined to a load zone ranging from 180° to less than 360° in circumference. The IR track extends through 360°. For double-row bearings, OR track may be less than 180° in one row.

Image (f):
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: 00.12.3.2.0.3 Wear track for radial preload
Failure Description: Rolling track for normal magnitude radial load rotating over innerring, with radial preload from negative internal looseness; wider on the radial load action side. Unintended radial preload may cause overheating and early spalling (FC 00.19 and FC 00.16).
Image Description: Wear marks (polishing or scratches) in ball paths, away from both edges. Load zone on both rings is centered; on IR, it is uniform around 360°; on OR, it is >180°, wider on the radial load action side.



g



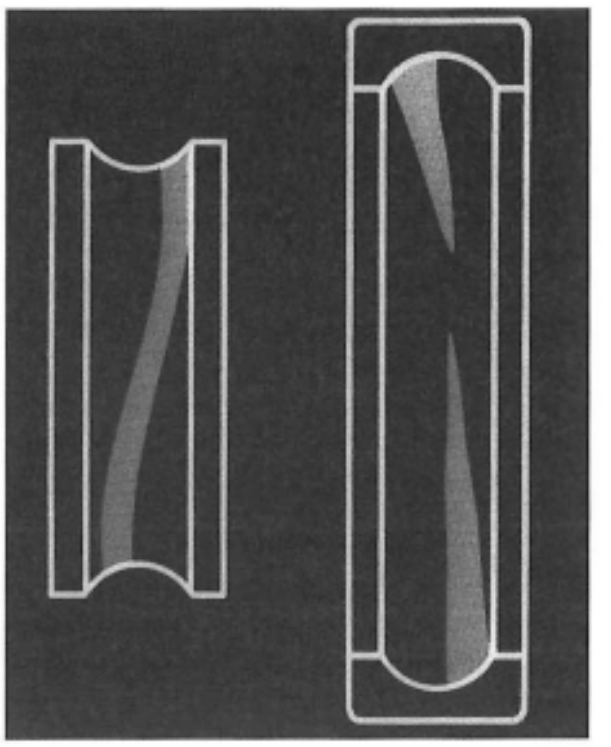
h

Image (g):
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: 00.12.3.2.0.4 Wear track for out-of-round ring
Failure Description: Rolling track in an out-of-round OR.
Image Description: Wear marks (polishing or scratches) in ball paths, away from both edges. The OR track is confined to two opposite load zones of less than 180° each in circumference. The IR track extends over 360°. If radial load rotating against the innerring is added, then one of the two load zones will be wider.

Image (h):
Failure Code 1: 00.12.3.2.1.3 Wear track shifts in contact
Failure Code 2: 00.12.3.2.0.7 Wear track for misaligned innerring
Failure Description: Rolling track for a misaligned OR.
Image Description: Wear marks (polishing or scratches) in ball paths. The OR track is confined to two opposite load zones of less than 180° each in circumference, axially off-center in opposite directions. The edge of one or both load zones may reach the groove edge. IR load track extends uniformly through 360° and is wider than OR load zones. If radial load rotating against the innerring is added, then one of the two load zones will be wider.

Plate No. 7.3, continued

Image (i):
Failure Code 1: 00.12.3.2.1.3 Wear track shifts in contact
Failure Code 2: 00.12.3.2.0.8 Wear track for misaligned innerring



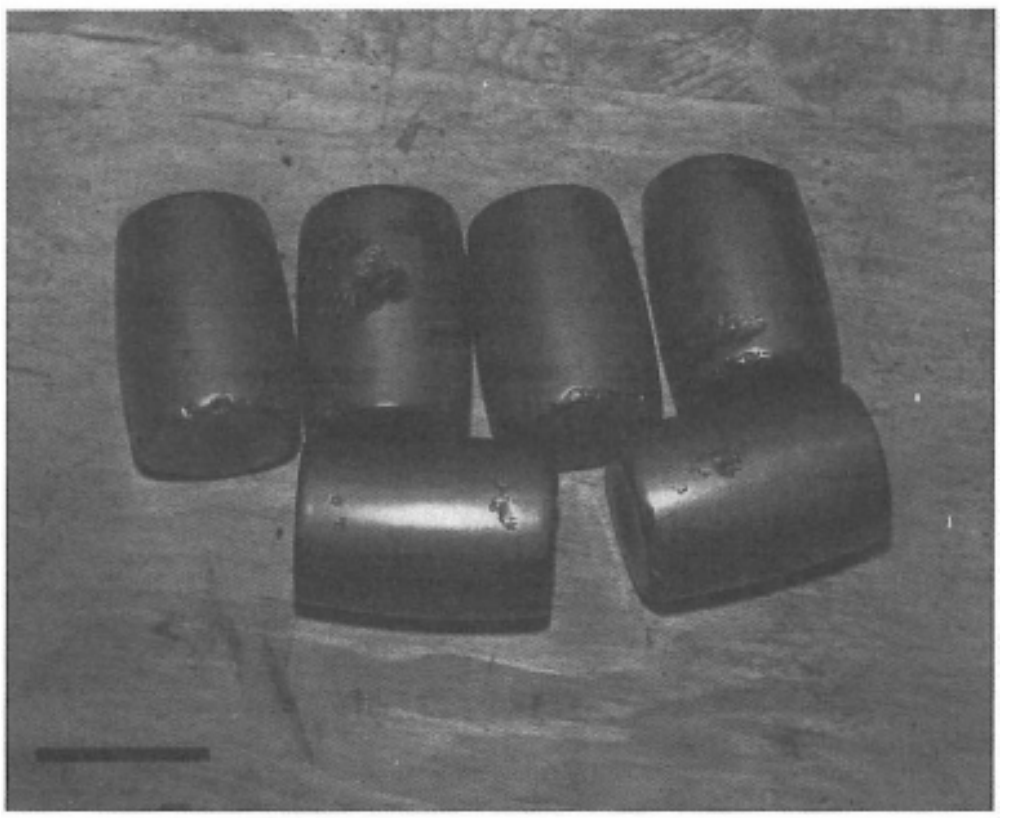
i

DESCRIPTIONS

Failure Description: Rolling track for a misaligned IR.
Image Description: Wear marks (polishing or scratches) in ball paths. OR ring track is confined to two opposite load zones of less than 180° each in circumference, off-centered in opposite directions. IR track shifts from side to side of the groove and runs 360°. The edge of either load zone may reach the groove edge. If radial load is added, one of the OR load zones is wider than the other.

DATA

Plate No: 7.4
Archive No: 031-007
Image type: view
Scalebar = 30 mm (micros: +20%, others: +100%, −50%)
Component: SRB; R, run
Speed: 25 KdN
Load: 1.4 GPa
Lubrication: mineral oil, 150°C
Failure Code 1: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
Failure Code 2: 00.12.3.3.2 Wear, centered in sliding contact
Failure Code 3: 00.16.02.5 Advanced spalling
Failure Code 4: 11.3.3 Abrasive contaminant in oil

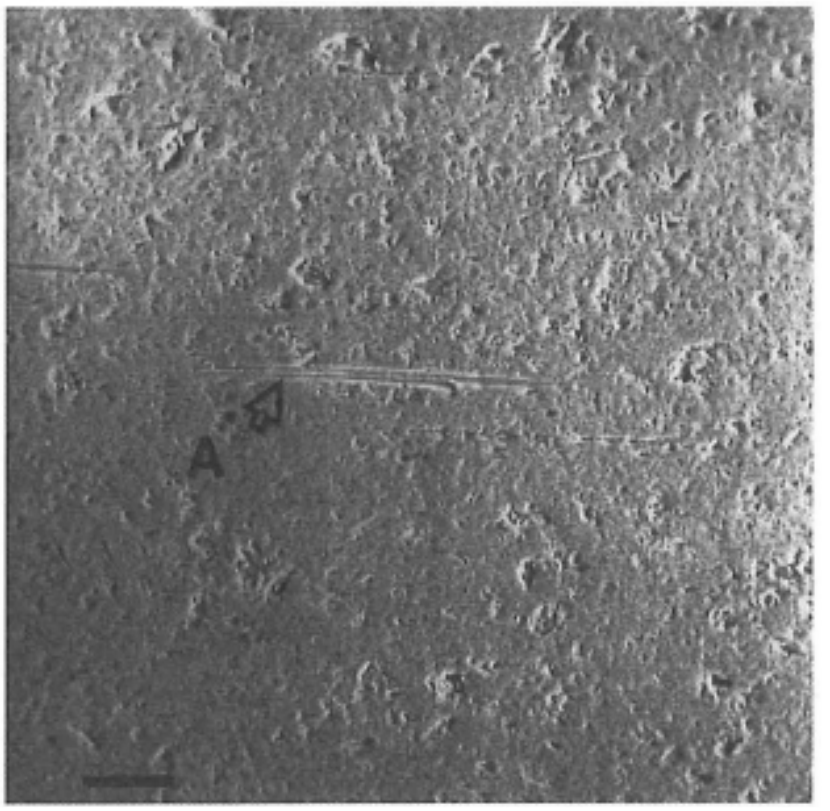


DESCRIPTIONS

Failure Description: Smooth wear on all (rolling and sliding) contact surfaces of rollers. Deep spalls both within and at the extreme edges of the rolling contact. Probable failure progression: (1) abrasive wear; from contamination carried in the lubricant, (2) spalling, (3) indentations by large spall debris (not visible); (4) deep spalling at track center from dents. Edge spalls from dents or edge contact.
Image Description: All rolling surfaces and all but the center circle of the visible roller end surfaces are worn to a matte satiny finish with most finishing lines obliterated. Extremely deep spall craters centered in contact and at edges, extending onto corner radii.
Suspected Causes: This bearing operated in a contaminated environment, causing abrasive wear. Spalling progressed extensively, creating large debris which made dents, causing extremely high local stresses leading to deep spalls. Spalling at the track edges and corner radii may be due to geometry error (too wide guidering) or skewing of rollers, resulting in edge contact.

DATA

Plate No: 7.5
Archive No: 093-12.1.3
Image type: SEM
Scalebar = 30 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, honed, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral (turbine) oil, 100°C
Failure Code 1: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
Failure Code 2: 00.18.1.4 Multiple irregular denting from fine, loose hard debris
Failure Code 3: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 4: -

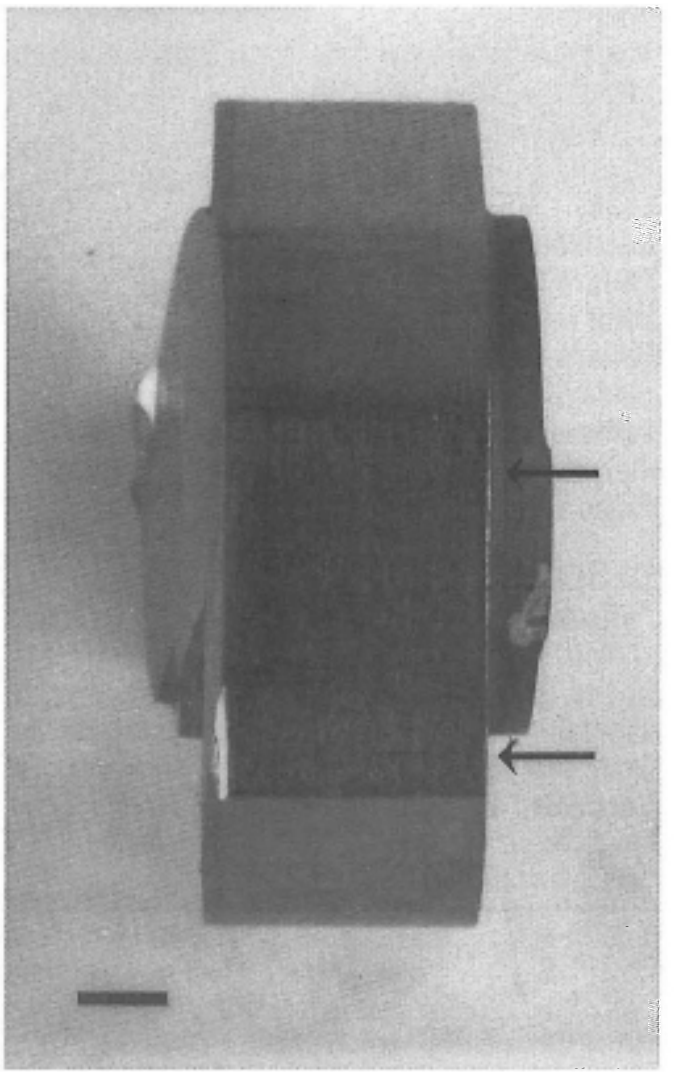


DESCRIPTIONS

Failure Description: Uniform mild wear of rolling surface with multiple very small non-directional dents from fine solid contaminant. Few long scratchmarks from sliding. All finishing marks are obliterated, by general ablation of the surface ("sandblasted" micro-appearance). A few surface distress microspalls (FC 00.17) may be present. Minimal wear may permit long life (with progressively impaired shaft support accuracy).
Image Description: The image background is a featureless gray surface covered with very fine (2–10 μm dia.) smooth-bottomed dents. Some dark-bottomed craters, probably microspalls from surface distress. One long E–W wear scratch at *A*. Others faintly visible elsewhere. No finishing lines visible.
Suspected Causes: Operation in lubricant carrying very fine solid contaminant causes uniform slow wear. In pure rolling, debris cause multiple dents. With the small sliding component existing in DGBB, wear also occurs. Individual wear events are not discernible (except few scratches such as at *A*). The EHD film was thick enough to prevent generalized surface distress.

DATA

Plate No: 7.6
Archive No: 005-12
Image type: light macro
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: C; CM (carburized), run
Speed:
Load: 2.1 GPa
Lubrication: Diesel fuel, ? °C
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Wear marks at end of the ramp part of a cam lobe, from sliding between cam and follower. If wear becomes excessive, galling or spalling failure may follow or cam geometry is lost.
Image Description: Sectioned cam is viewed from OD. Descending ramp (between arrows) is in S image half. On ramp, circumferential, light-colored wear marks. Wear marks are densest near the exit point of the (descending) ramp.
Suspected Causes: Pressure between cam and follower varies sharply by angular position, peaking on ascending ramp and dropping to zero along descending ramp. Friction on pin retards follower. When contact pressure to lobe is insufficient to provide necessary driving force, slip occurs, which may result in wear.

DATA
Plate No: 7.7
Archive No: 093-004
Image type: view with mirror image
Scalebar = 30 mm (micros: +20%, others: + 100%, −50%)
Component: SRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: 00.12.3.2.0.4 Wear track for out-of-round ring
Failure Code 3: 21.6 Housing deformed
Failure Code 4: -

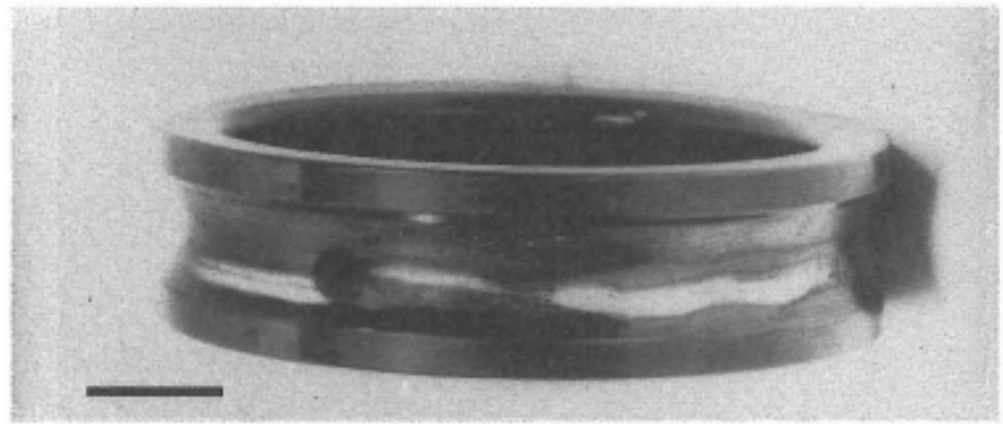
DESCRIPTIONS
Failure Description: Bearing shows two, diametrally opposite load zones in both roller tracks indicating out-of-round condition of housing. The condition causes parasitic overloading and may lead to early spalling and hot operation.
Image Description: In this image, the W half of the roller path is seen in direct view, and its E half in a mirror placed behind the ring. In both halves, light-colored contact tracks show a load zone in both roller paths. The two sets of load zones are 180° apart indicating out of roundness.
Suspected Causes: Out of roundness is likely in the housing (out of roundness of this magnitude in the ring proper is a rare occurrence). The housing deflects the outerring elastically, causing reduction in radial looseness along one direction, resulting in parasitic radial loading.

DATA
Plate No: 7.8
Archive No: 031-102
Image type: view
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: SRB; IR, run
Speed: 25 KdN
Load: 1.4 GPa
Lubrication: mineral oil, 120°C
Failure Code 1: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 2: 00.12.4 Wear of guiding-component support surface
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: 11.2 Water in oil

DESCRIPTIONS
Failure Description: Both roller tracks extensively worn. Solid contaminant abrasion probable. Separator support surface worn in sliding contact in the presence of contaminant. Some local denting of roller track by contaminant particles.
Image Description: Both roller tracks show dark, matte, slightly pebbled surface from abrasive wear. Center flange supporting separator is burnished and circumferentially scratched by abrasive wear. Roller track in S image half shows a dent near its center, from a large contaminant particle. Dark discoloration of roller paths and side flanges suggests water in the oil.
Suspected Causes: This bearing operated in a contaminated and possibly wet environment. The solid contaminant precipitated abrasive wear; water in the oil contributed to the dark discoloration of rolling surfaces and side flanges. Oil carbonization may also take place at high temperature.

DATA

Plate No: 7.9
Archive No: 087-036
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.3.2.1.3 Wear track shifts in contact
Failure Code 2: 00.09.0 Geometry defect
Failure Code 3: -
Failure Code 4: -

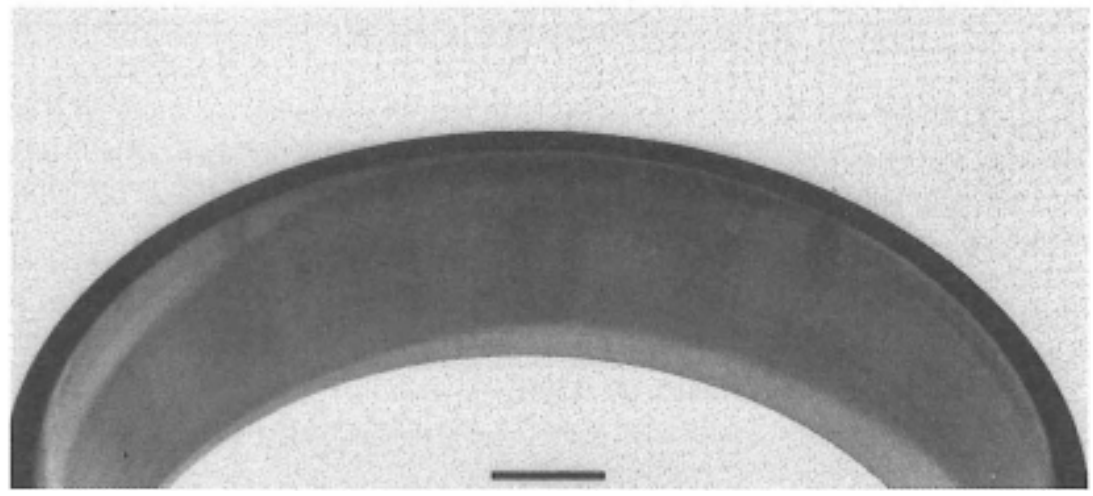


DESCRIPTIONS

Failure Description: Ball track in the groove of this IR weaves laterally. Effective contact angle varies around circumference, causing cyclic ball orbital speed variation resulting in high separator stresses. Noisy operation and early separator failure are likely.
Image Description: The black oxide coated ring shows a (bright) wavy wear band in the groove half located S of the image center.
Suspected Causes: Distortion from relaxation of stresses or poor fixturing during manufacture may cause circumferential waviness in the ball groove. If extreme, this may lead to observable contact angle variability as in this case.

DATA

Plate No: 7.10
Archive No: 014-35
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.3.2.1.3 Wear track shifts in contact
Failure Code 2: 00.12.3.2.0.7 Wear track for misaligned outerring
Failure Code 3: 00.20.1.3 Contact corrosion
Failure Code 4: 00.20.2 Corrosion pitting



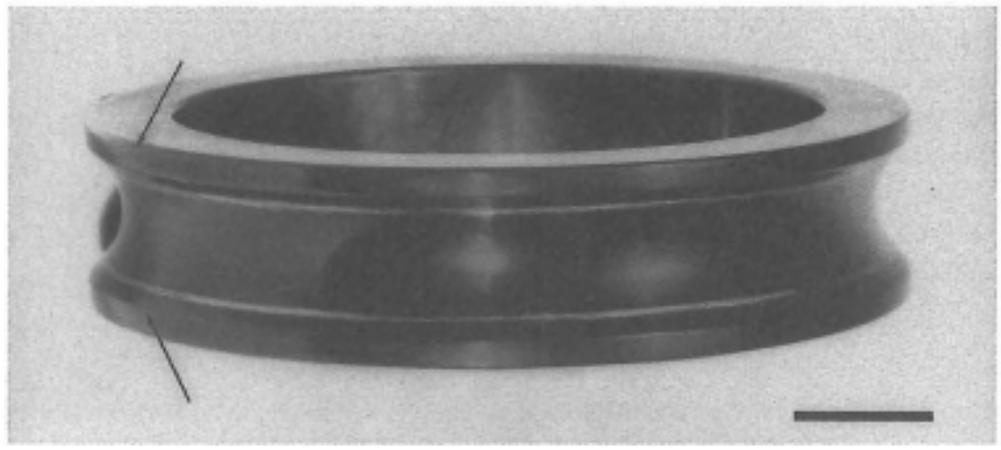
DESCRIPTIONS

Failure Description: Laterally shifting contact pattern in misaligned outerring, ranging from no contact at the large roller end to no contact at the small end. Axial streaks of contact corrosion. Misalignment produces serious edge loading at roller ends and may cause early spalling. High tractive forces act on the separator from roller orbital speed variations and may cause fracture. Incidental corrosion.
Image Description: The contact path of the rollers on the OR appears darker gray than the un-contacted track. The contact concentrates at the small roller end (at image W) and shifts to the large roller end at the image center and E. Darker axial streaks in the contact area indicate contact corrosion. 1/4 image width from W edge are two clusters of corrosion pits.
Suspected Causes: The shifting contact path indicates a misaligned innerring due to machine geometry error or mismounting of ring in housing. Contact corrosion may arise from water in the lubricant (see FC 00.20.1.3).

Failure Code: 00.12.3.2.1.4
Failure Code: 00.12.3.2.2

DATA

Plate No: 7.11
Archive No: 087-035
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.3.2.1.4 Wear track at contact edge
Failure Code 2: 00.09.0 Geometry defect
Failure Code 3: -
Failure Code 4: -

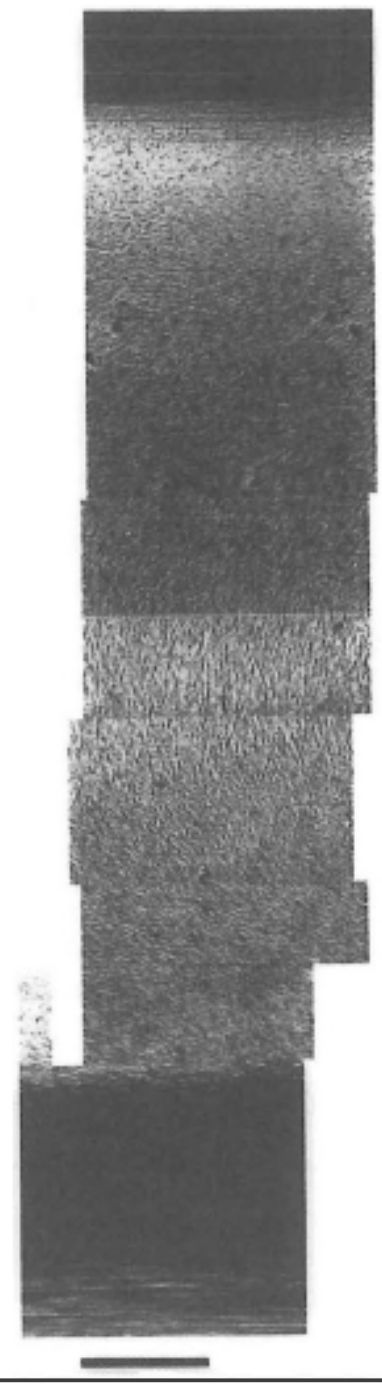


DESCRIPTIONS

Failure Description: Narrow wear bands near both edges of the ball path, due to mismatch of ball and groove profile radius and groove profile error. The bearing had no appreciable load carrying capacity.
Image Description: Black oxide coated innerring shows two narrow white wear bands near, but not at, both groove edges (inboard of arrows).
Suspected Causes: Mismatch between groove profile radius and ball diameter (conformity <50%, ball radius exceeded groove profile radius) caused two-point contact near groove edges. Since contacts are not precisely at the edges, groove profile must be noncircular (widened) at the edges.

DATA

Plate No: 7.12
Archive No: 018-302
Image type: light microgram (composite)
Scalebar = 400 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, tool steel, run
Speed: 1.125 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 150°C
Failure Code 1: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 2: 00.12.0.2 Abrasive mild wear
Failure Code 3: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 4: 00.03.4 Lapping imperfection

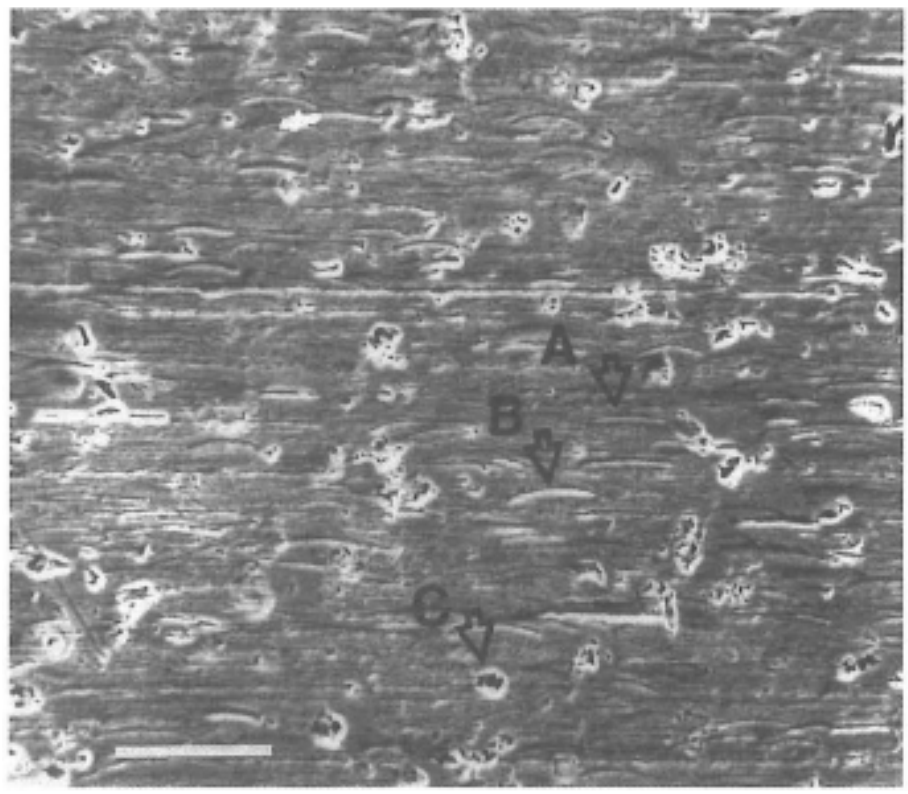


DESCRIPTIONS

Failure Description: Ball track marked by a dense pattern of kinematic wear marks from spinning ball with protruding carbides produces unacceptable shortening of fatigue life.
Image Description: This composite image of IR ball path shows swirl pattern of short kinematic wear marks running NE to SW at image N, N to S in center, and NW to SE at image S. Black irregular spots may be microspalls of incipient surface distress. Rolling direction is E to W. Unworn groove areas at N and S image edges show E-W finishing marks.
Suspected Causes: The balls were observed to have hard carbides protruding about 1 μm above surface, presumably as a result of differential stock removal in lapping the tool steel material. The carbides penetrate the (much thinner) EHD film and scratch the ring surface. A finishing process leaving protruding carbides is unacceptable.

DATA

Plate No: 7.13
Archive No: 093-12.1.8
Image type: SEM
Scalebar = 35 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, honed, operated
Speed: 450 KdN
Load: 3.3 GPa
Lubrication: synthetic polyester oil, 38°C
Failure Code 1: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: -
Failure Code 4: -

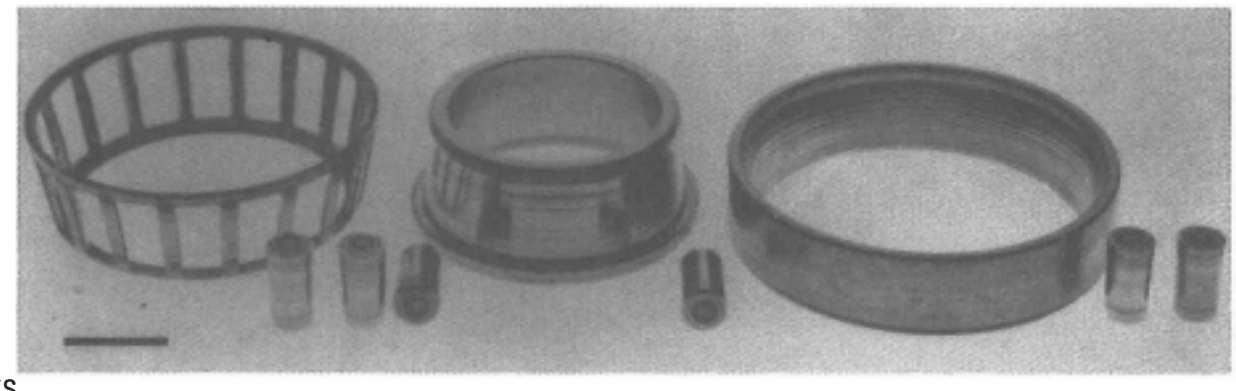


DESCRIPTIONS:

Failure Description: Mild wear events in asperity dimensions cause short scratch marks on the contact surface which trace the relative motion of the contacting surface. In a BB with curved contact interface, ball motion has a spin component at most points, and the kinematic marks are fingernail or horseshoe shaped parabolas. Surface distress microspalling is also present. The damage promotes spalling and (if wear progresses) impairs precision.
Image Description: Original finishing lines run straight E-W. They are covered with layers of generally E-W oriented, curved 'fingernail marks' convex from above: the kinematic wear marks. A recent sharp mark is at *B*, a partly worn-off mark at *A*. Micropalls, i.e., small dark craters with fracture surface bottoms and a white rim ('halo') are scattered on the surface. Example at *C*.
Suspected Causes: Kinematic wear marks occur in the presence of sliding (spin) in addition to rolling, under EHD film conditions insufficient to prevent asperity contact. *Small* amounts of fine solid contaminant, embedded in one of the contact surfaces may produce kinematic wear marks by acting as a temporary asperity. Surface distress is asperity scale contact fatigue (FC 00.17).

DATA

Plate No: 7.14
Archive No: 014-9
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; all components, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 2: 00.18.2.2 Rolled-in line inside contact
Failure Code 3: 01.13 Separator wear
Failure Code 4: 12.5.1 Steel contaminant in grease



DESCRIPTIONS

Failure Description: Steel contamination in the lubricant carried by the separator caused circumferential wear marks in the rollers. Rollers transferred rolled-in lines to the ring roller tracks. Additional contaminant wore circumferential lines on the separator OD. A bearing this severely worn has lost precision, is noisy and may soon seize when the worn separator jams between rollers and ring.
Image Description: Circumferential scratches on separator bar OD and roller OD. Rolled in lines on the roller tracks of both rings.
Suspected Causes: Steel contaminant was found in the grease, initiating the wear process. The contaminant may arise from contaminated assembly, contaminated housing or the wear of moving parts, other than the bearing, in the same chamber.

Failure Code: 00.12.3.2.2
Failure Code: 00.12.3.2.3

DATA

Plate No: 7.15
Archive No: 004-14
Image type: color microgram [SEE IMAGE IN APPENDIX.]
Scalebar = 200 μm (micros: ±20%, others: +100%, −50%)
Component: BB; IR, tool steel, solid tube coat
Speed: 840 KdN
Load:
Lubrication: GA-In-WSe burnished film; <315°C
Failure Code 1: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 2: 13 Solid or gas lubricant failure
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: The ball path in this tool steel bearing is solid-lubricated with a burnished-on composite film. During operation, the film wears away exposing underlying metal. Parabolic marks are the tracks of asperities on the balls, made on the solid lubricant coating of the ring (kinematic wear marks). At maximum test speed, this bearing failed due to retainer wear (not solid lubricant depletion on the surface shown).
Image Description: In this micrograph, the surface near the horizontal centerline of the image reflects specularly where metal is exposed (light color). The lubricant coat is dark. Near the N and S edges, lighting is low. The horizontal dark lines are remnants of burnished-on lubricant. The parabolic dark lines with apex to the W are kinematic wear marks.
Suspected Causes: This is natural wear in an experimentally solid lubricated high speed, high temperature bearing. It illustrates solid lubricant depletion and kinematic wear marks. It is not a failure image.

DATA

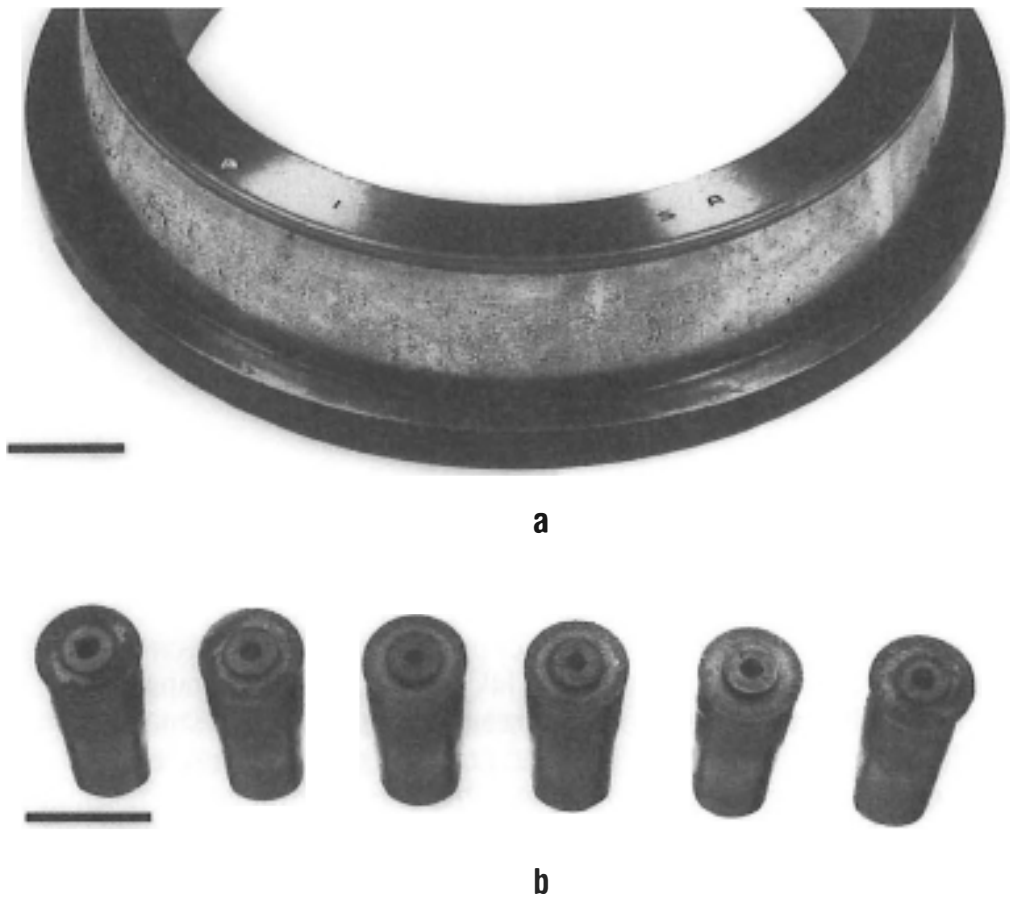
Plate No: 7.16
Archive No: 018-131
Image type: view
Scalebar = 60 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR & OR, run
Speed: 180 KdN
Load: 1.7 GPa
Lubrication: grease, 60°C
Failure Code 1: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 2: 00.12.0.2 Abrasive mild wear
Failure Code 3: 00.12.4 Wear of guiding-component support surface
Failure Code 4: 00.15.1.2 Localized fretting, radial fit surface

DESCRIPTIONS

Failure Description: Deep weardown of both OR contact paths, matte wear surface. Fluted wear of both IR contact paths. Sliding wear of IR center flange from separator contact. A few small fretting corrosion spots on OR OD. Grease was contaminated by abrasive material. Abrasive wear of this magnitude severely impairs shaft support accuracy. Separator failure is likely. Bearing is very noisy.
Image Description: The spherical contact surface of the OR shows a centered band with original finishing marks. To both sides, the roller contact paths are worn down to a matte surface, with a sharp step between them and the center area. The IR roller paths are worn matte, with periodic depressions. The center flange shows circumferential wear marks. The OR OD shows a few patches of dark fretting corrosion.
Suspected Causes: This bearing operated in a shaker screen, under severe vibratory load and in abrasively contaminated grease. All wear observed is abrasive; the fluted IR wear pattern is related to the vibratory load.

DATA

Plate No: 7.17
Archive No: 014-1&3
Image type: view
Scalebar = a, b: 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR & R, case hard., run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 2: 00.12.3.3.2 Wear, centered in sliding contact
Failure Code 3: 00.12.0.2 Abrasive mild wear
Failure Code 4: 00.16.02.3 Incipient spalling, single spall



a

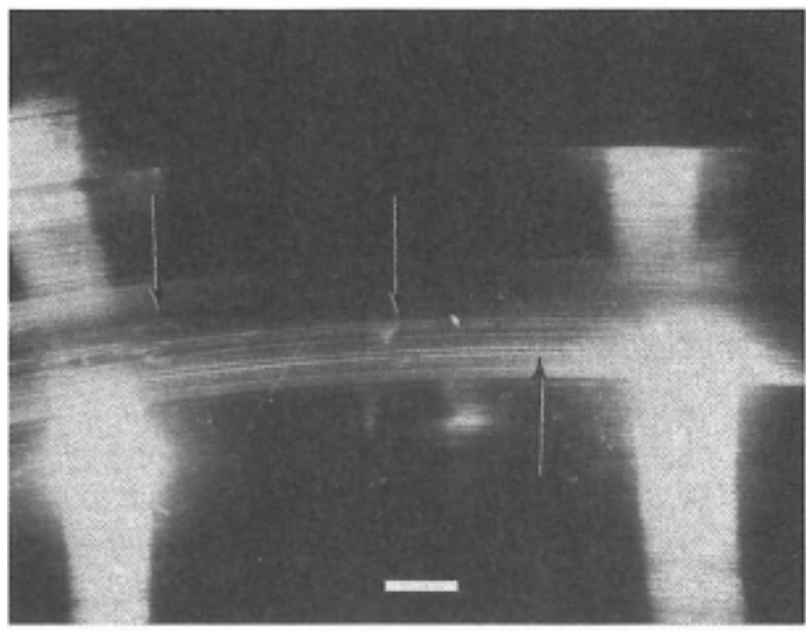
b

DESCRIPTIONS

Failure Description: Heavy abrasive wear of: IR thrust flange ('rib'); IR roller path; roller thrust face; roller OD. Multiple debris dents on IR roller path. Wear of this magnitude has removed most of the carburized case, causing severe loss of fatigue resistance. Spalling has begun of IR. Geometry on bearing is destroyed.
Image Description: (a): IR ('cone') with thrust flange ('rib') surface worn down to bottom of undercut. Rolling track worn, showing lip at small end and loss of undercut at large end. Multiple debris dents on rolling track. Spall crater at image E. (b): Step worn on roller thrust faces where flange contacted, with epicyclic kinematic wear marks. Rolling surface is worn to matte finish.
Suspected Causes: Abrasive contaminant in lubricant has produced the heavy wear and debris denting. Spalling is secondary to this damage.

DATA

Plate No: 7.18
Archive No: 027-154
Image type: light macro
Scalebar = 50 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 270 KdN
Load:
Lubrication: Grease, 60°C
Failure Code 1: 00.12.3.2.4 Scoring wear (macroscopic gouging without galling)
Failure Code 2: 00.18.1.1 Rounded dent (from soft contaminant)
Failure Code 3: 12.5.02 Severe grease contamination
Failure Code 4: 12.5.4 Soft contaminant in grease



DESCRIPTIONS:

Failure Description: Multiple circumferential scoremarks in IR groove from *sliding* contact in the presence of large, hard contaminant particles. Rounded dents arise from a soft contaminant, in *rolling*. The scoremarks will cause early surface distress (FC 00.17), galling (FC 00.13) or spalling (FC 00.16). The dents may accelerate spalling. The sliding shown by the scoremarks indicates separator or ball malfunction.
Image Description: On a shiny background, light-colored horizontal lines (E arrow) are scoremarks. They could be felt when tested with a scriber. Center and W arrows point to large, smooth dents. Vertical light streaks are artifacts of lighting.
Suspected Causes: Contamination may jam a ball in the separator, which then slides on track and with contaminant, causes scoremarks. Off-center separator may contact groove and score it but probably *not* near center plane, as here. Large dents arise from deformable contaminant trapped in rolling contact where it indents the steel due to hydrostatic pressure condition preventing lateral extrusion.

DATA
Plate No: 7.19
Archive No: 011-006
Image type: light macro
Scalebar = 500 μm (micros: ±20%, others: +100%, −50%)
Component: O; character typeface
Speed: impact & sliding
Load: impact
Lubrication: ribbon ink, 20–40°C
Failure Code 1: 00.12.3.3 Sliding contact wear
Failure Code 2: 00.12.7 Impact wear
Failure Code 3: 00.12.0.2 Abrasive mild wear
Failure Code 4: -

DESCRIPTIONS:
Failure Description: In impact printers, laterally moving character typeface of metal strikes a ribbon. Sliding under impact produces wear marks on character due to abrasive elements in ink. Ink and ribbon debris transfer to typeface. Edges of character are rounded, wear across surface is smooth. Eventually, character geometry is destroyed and type must be replaced.
Image Description: Letter "O" typeface, elevated above surrounding metal, is bordered by white metallic edge. Dark E–W abrasion marks within the letter face. Black fringes surrounding letter are ink residue and ribbon debris. Edges are rounded by wear. Inner edge shows apparent chipping at SE and S, which are actually residual finishing marks.
Suspected Causes: Impact loading against moving ribbon causes operational wear of character typeface requiring eventual replacement. The wear is primarily abrasive, as a result of abrasive impurities or components in the ink. Chemical effects from the ink may also occur.

DATA
Plate No: 7.20
Archive No: 003-004 & 005
Image type: light macro
Scalebar = a: 10, b: 3 mm (micros: +20%, others: +100%, −50%)
Component: CRB; R; G, run
Speed: 2.15 MdN
Load: 1.7 GPa
Lubrication: synthetic polyester oil; 120°C
Failure Code 1: 00.12.3.3.1 Wear at edge of sliding contact
Failure Code 2: 01.11.2 Separator fracture, cracking
Failure Code 3: 01.13.1.4 Roller separator, pocket bottom worn
Failure Code 4: 00.12.4 Wear of guiding-component support surfaces

a

DESCRIPTIONS
Failure Description: In high-speed cylindrical roller bearing, excentric heavy wear on endface of one roller; high roller/separator forces from skewing; separator ring wear and separator bar fracture. This is gross bearing failure.
Image Description: (a): Roller W of arrow shows half-moon shaped endface wear. Roller W of arrow and roller E of arrow show rubbing marks on the OD from separator contact. Wear marks on W-most roller endface. The separator bar at arrow is missing (broken). Separator rail worn at both sides of arrow. (b): Dark, excentric wear band with epicyclic marks, from flange contact inboard of corner radius. Further inboard, circumferential marks from separator.
Suspected Causes: In high-speed CRB excessive wobble of roller endface or roller unbalance produces high roller/flange forces creating skewing. The separator suffers very high roller contact forces and wears. Ultimately, a separator bar may break.

b

DATA

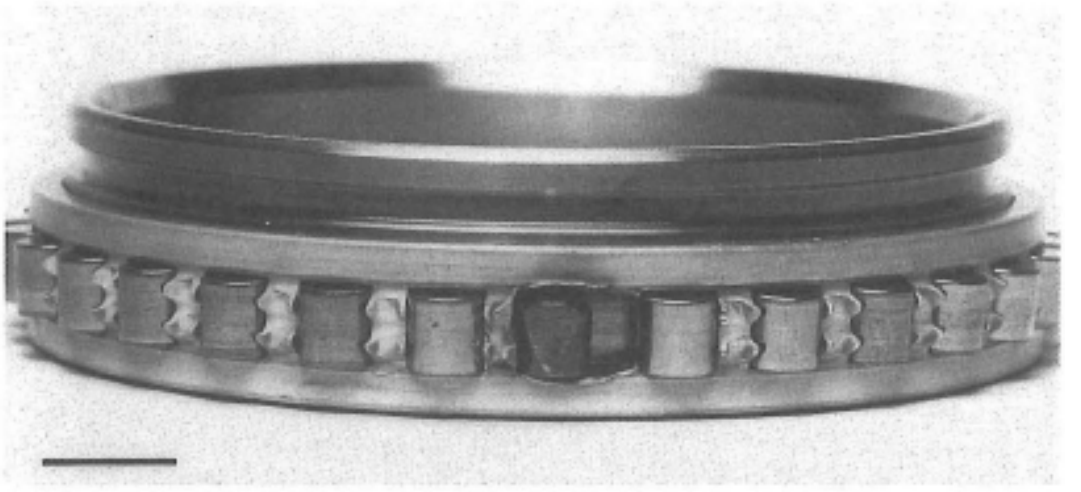


Plate No: 7.21
Archive No: 002-027a
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR & G & R, tool steel, run
Speed: 3.0 MdN
Load: 1.2 GPa
Lubrication: synthetic polyester oil, 204°C
Failure Code 1: 00.12.3.3.1 Wear at edge of sliding contact
Failure Code 2: 01.13.1.3 Roller separator, diagonal crossbar wear
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: 00.19.2 Hot plastic flow

DESCRIPTIONS:

Failure Description: One roller underwent severe end wear, resulting in skewing, separator wear, plastic flow and fracture. The roller turned crosswise in the pocket and slid along the IR rolling path wearing a flat on its OD. The damaged roller, the IR track and the separator pocket all show overheating. The bearing has failed.
Image Description: One roller at image center is dark discolored. The N-facing end face of the roller is worn conical. A separator bar is missing E of this roller. Separator pocket and bar W of this roller are peened with raised edges. The damaged roller jammed in the pocket before destroying the bar, and wore a flat on its OD (see sloping wear mark direction on flat, indicating skewed roller position). It was found turned 90° in the pocket.
Suspected Causes: In this extreme speed application, roller unbalance creates large skew forces, resulting in roller end wear. The friction at the roller end is self-aggravating; the roller destroys the separator pocket and eventually jams, overheating in the process and wearing a flat on its rolling surface.

DATA

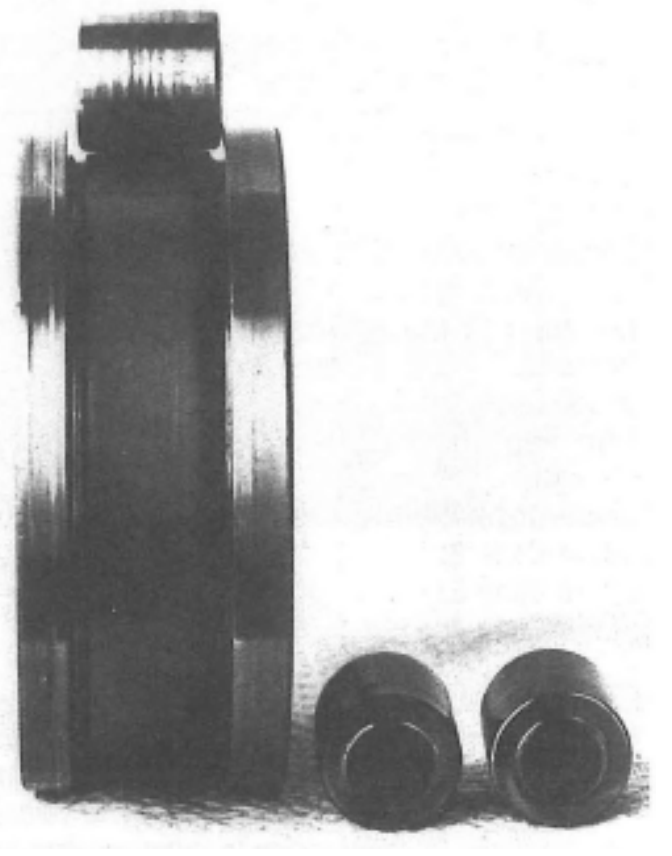


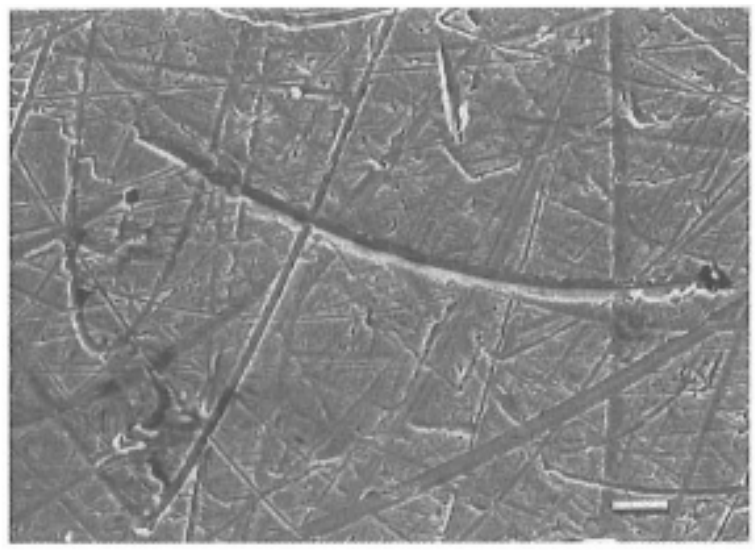
Plate No: 7.22
Archive No: 093-031
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR & R, run
Speed:
Load:
Lubrication: mineral oil, ? °C
Failure Code 1: 00.12.3.3.2 Wear, centered in sliding contact
Failure Code 2: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 3: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
Failure Code 4: 11.3.02 Severe oil contamination

DESCRIPTIONS

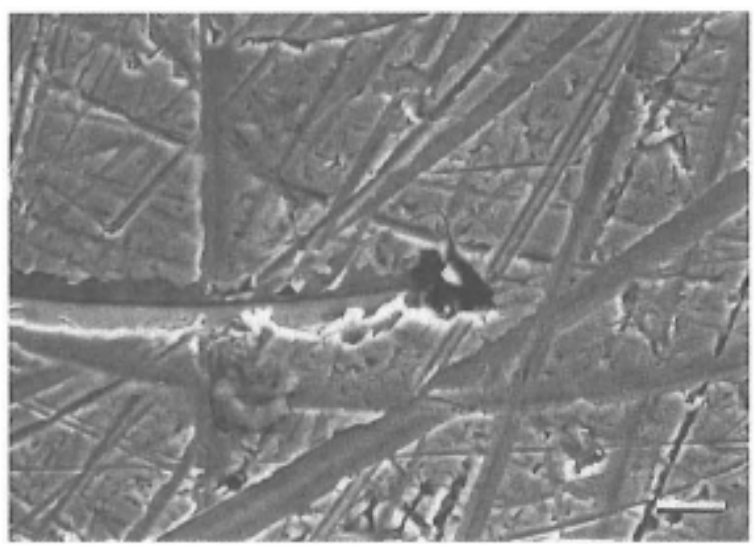
Failure Description: The roller end faces show a step worn in by flange contact. Flanges are worn down to match. Roller OD shows worn grooves. Ring roller track shows matte worn surface with finishing lines removed. Severe roller/flange contact wear causes roller skew, heavy separator pocket forces, high friction. Rolling surface wear impairs contact geometry and bearing precision.
Image Description: On the two rollers at image E, end faces show worn down annular step of width equal to flange height. Roller placed in IR is too short for flange spacing due to roller and flange wear. Flange wear visible at image W, under the roller contact, as step outboard of undercut. OD of roller placed on IR shows circumferential streaks indicative of grooving. Surface texture of IR is matte with no finishing lines.
Suspected Causes: Heavy lubricant contamination is most likely cause of all observed wear phenomena. Flange geometry error (negative flange angle), or incorrect roller axial looseness leading to skewing, or bearing misalignment may also cause roller end wear. Wear debris can then act as contaminants and cause grooving wear and matte surface in rolling tracks.

DATA

Plate No: 7.23
Archive No: 107-009 a & b
Image type: SEM
Scalebar = a: 20, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; R, run
Speed:
Load:
Lubrication: oil, 50°C
Failure Code 1: 00.12.3.3.3 Scratch marks in sliding contact
Failure Code 2: 00.12.0.2 Abrasive mild wear
Failure Code 3: 12.5.3 Abrasive contaminant in grease
Failure Code 4: -



a



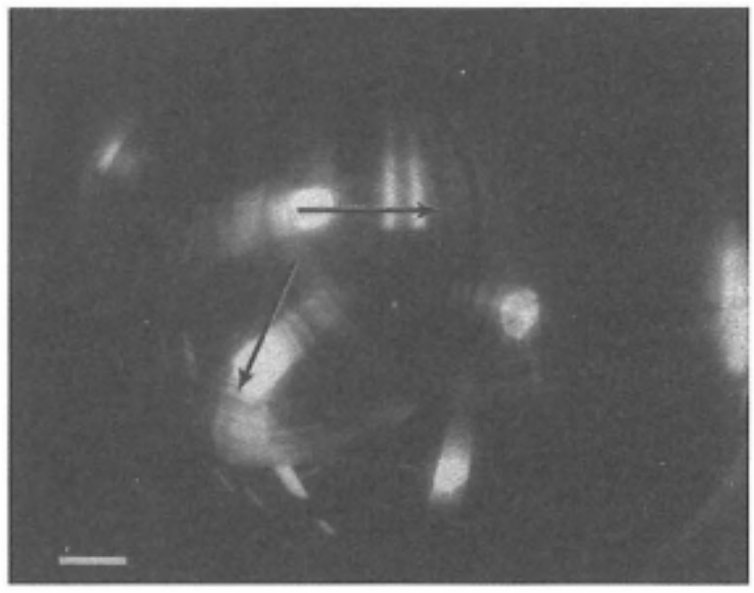
b

DESCRIPTIONS

Failure Description: Multiple scratchmarks (kinematic wear marks) on roller thrust face. Embedded abrasive particles (silicates) in some furrows. A point on the ring thrust flange describes epicycloid curve on the roller end, with a cusp if it ends at the rolling track and a tip radius if it ends away from the track. Different epicycloids cross. This abrasive wear causes friction, roller skew, and high separator forces, which may result in heat imbalance.
Image Description: (a): Overview of several kinematic wear marks. In NW quadrant, the radiused tip of an epicycloidal scratch. A mark runs from N center to SW corner, another from NW corner to E center. Many scratch lines, partly worn off, in background. Dark, embedded grit in SW and E. (b): The E center part of (a). Just E of image center is a dark abrasive grain at the end of the scratch it made. X-ray spectrum showed silicon.
Suspected Causes: Contamination of lubricant (oil) with abrasive material (sand or silicon carbide grinding grit) brings grains into the sliding/rolling roller-end/flange contact and produces the abrasive wear. The grit embeds in one or the other surface and marks the mating surface. Occasionally, as in (b), the grit changes place between surfaces.

DATA

Plate No: 7.24
Archive No: 027-180
Image type: light macro
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB, B, run
Speed: 130 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.12.4 Wear of guiding-component support surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

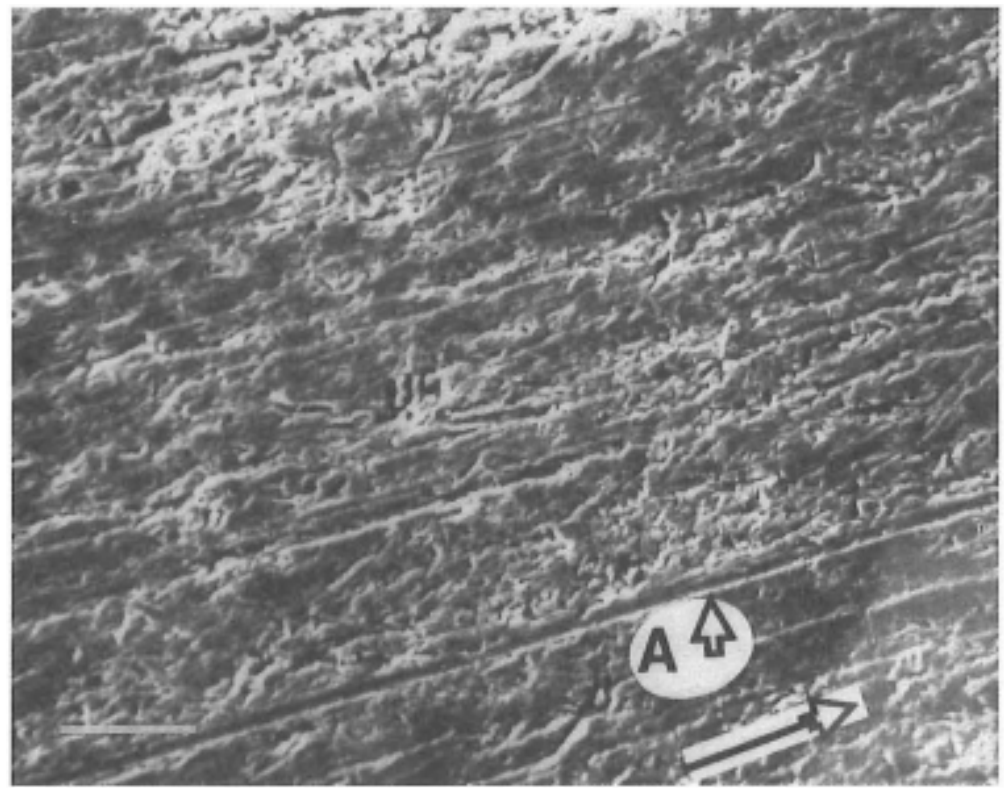


DESCRIPTIONS

Failure Description: Minor-circle scratch marks on ball from separator contact in the presence of contamination or sharp edges. Operation under this condition may cause high separator friction resulting in departure of ball rotation from epicyclic velocity, sliding in the rolling contact, wear, galling and noisy operation. The scratched balls are likely to cause noise in quiet running applications.
Image Description: Two overlapping minor-circle scratch patterns are shown on the ball surface (one marked with two arrows). These wear marks are made by a stamped steel (ribbon type) separator within which the ball has indexed to two different axes of rotation.
Suspected Causes: The most likely cause of the scratch marks is solid contaminant in the grease, entrained into the ribbon-separator/ball contact, where it is embedded in the separator and scratches the ball. Scratch marks may also form if a separator manufacturing error leaves sharp edges on the separator pocket.

DATA

Plate No: 7.25
Archive No: 093-12.1.11
Image type: SEM
Scalebar = 25 μm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.4 Wear of guiding-component support surface
Failure Code 2: Abrasive mild wear
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Uniform "mild" (non-galling) abrasive wear of guidering support land by fine solid contaminant. Multiple small pits and long scratch marks, directional in sliding direction. All finishing marks are obliterated by ablation of the surface. At high magnification, fine abrasive wear produces this pitted appearance, with the sliding direction identified by scratches. Wear of this severity destroys geometry and may cause seizure.
Image Description: Uniformly worn sliding surface shows sliding direction rising at about 20° from SW to NE (arrow). Multiple wear events have left most of the surface a jumble of overlapping short marks. Some recent deeper scratches, as at *A*.
Suspected Causes: Severe contamination of lubricant has introduced abrasive particles between guidering and IR land of this spherical roller bearing. The contaminant produced advanced abrasive wear.

DATA

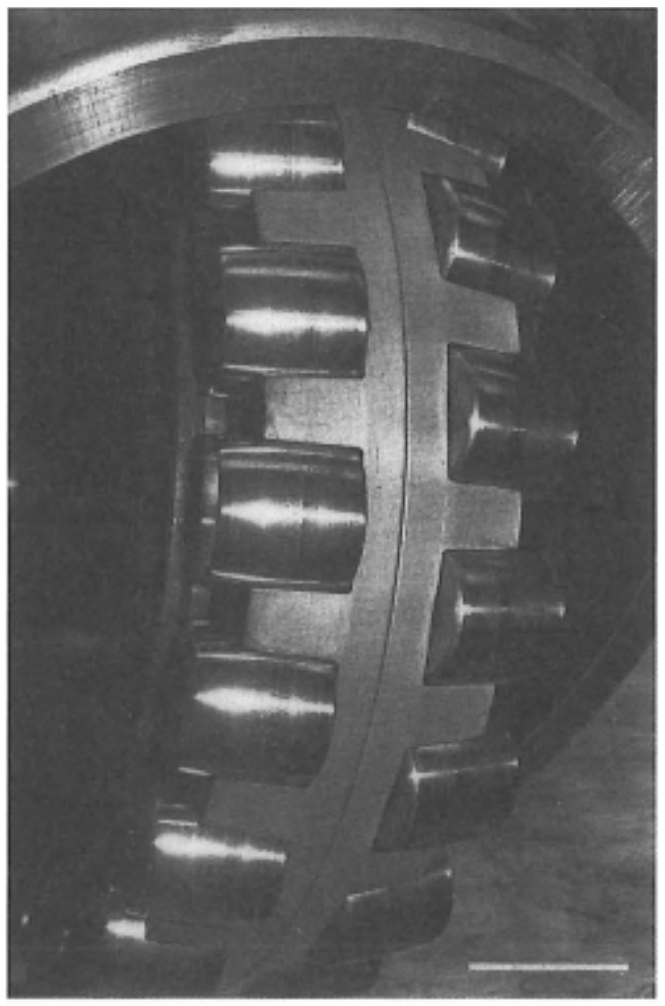
Plate No: 7.26
Archive No: 031-901
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed: 25 KdN
Load: 1.4 GPa
Lubrication: mineral oil, 150°C
Failure Code 1: 00.12.4 Wear of guiding-component support surface
Failure Code 2: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 3: 00.15.1.1 Generalized fretting, radial fit surface
Failure Code 4: 11.3.3 Abrasive contaminant in oil

DESCRIPTIONS

Failure Description: Innerring land riding retainer produced circumferential wear marks at two sides of roller track. Roller track shows matte featureless worn surface from over-rolling with contamination. Bore shows generalized fretting corrosion, to normal degree. The bearing is not failed, but may fail by separator wear (FC 01.13), heat imbalance failure (FC 00.19) or spalling (FC 00.16) in continued running with contamination.
Image Description: Two polished and circumferentially scratch marked sliding wear bands outside roller track edges, where separator contacted. Roller track is matte, somewhat pebbly from abrasive wear and possible denting. In bore, patchy, black-appearing fretting corrosion marks.
Suspected Causes: In the presence of solid contamination, sliding contact between (machined) separator and innerring produces wear. Same contamination produces denting and wear in roller contact. Microscopic motion in bore under load causes (normal) fretting corrosion.

DATA

Plate No: 7.27
Archive No: 031-008
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SRB assembly, run
Speed: 25 KdN
Load: 1.4 GPa
Lubrication: mineral oil, 130°C
Failure Code 1: 00.12.4 Wear of guiding-component support surface
Failure Code 2: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: 11.3.01 Incipient oil contamination

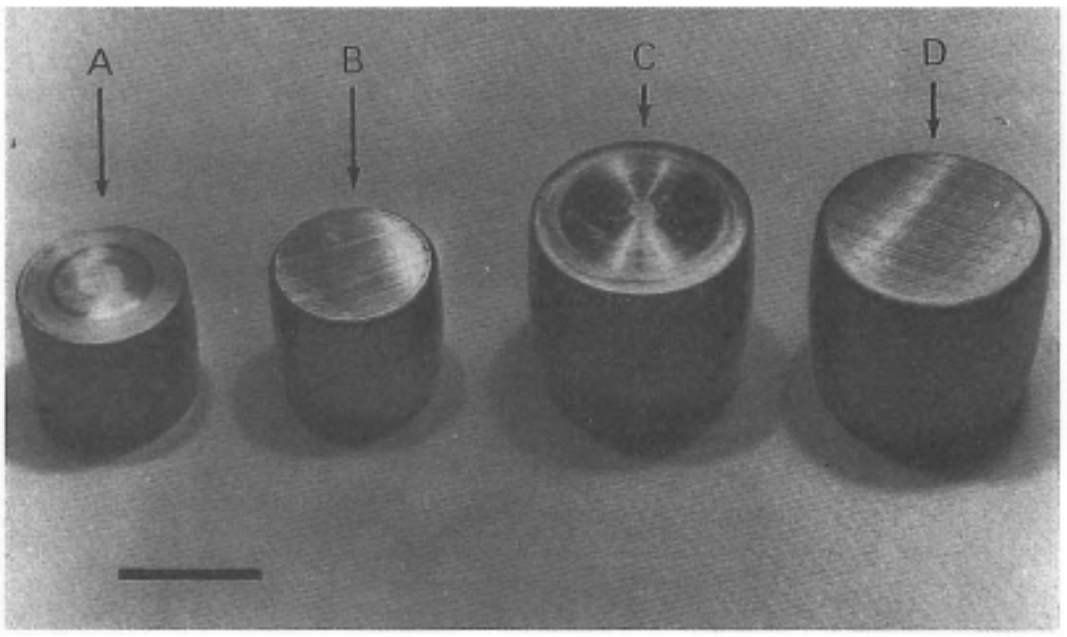


DESCRIPTIONS

Failure Description: Spherical roller bearing operated in somewhat contaminated lubricant. Circumferential wear marks on rollers from separator to roller contact. Matte wear from roller OD to ring contact. Moderate contaminant denting of roller OD. Such contamination limits the wear life and fatigue life of the bearing and seriously limits grease life.
Image Description: Image shows IR/separator/roller assembly pivoted out of OR plane. On the matte background of the roller OD surface worn in rolling contact, bright circumferential streaks show separator contact wear (note streaks are in surface areas contacted by separator prongs). Several small dents on each roller OD from rolled-over hard contaminant.
Suspected Causes: This bearing operated in a moderately contaminated environment which had contaminated the oil. Contaminant is carried into the separator/roller contact where it may lodge in the softer separator and scratch the rollers. Matte wear also occurs in the roller/ring contacts where there is Heathcote sliding with the rolling. Contaminant particles trapped in the rolling contacts form the dents.

DATA

Plate No: 7.28
Archive No: 018-132
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; R, unrun & run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.4 Wear of guiding-component support surface
Failure Code 2: 00.12.3.3.1 Wear at edge of sliding contact
Failure Code 3: 00.12.3.3.2 Wear, centered in sliding contact
Failure Code 4: 00.12.0.2 Abrasive mild wear

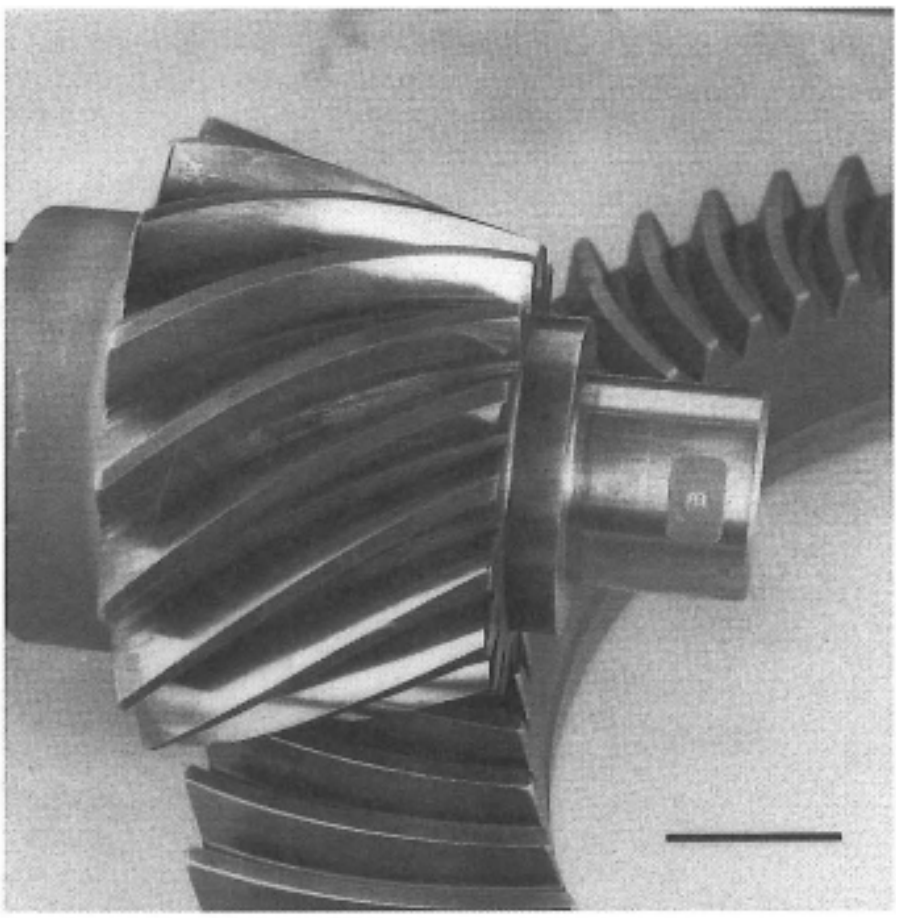


DESCRIPTIONS

Failure Description: Wear of roller thrust surface by separator pocket, with abrasive. Contact with IR thrust flange modifies wear pattern. Contamination leading to thrust surface wear produces high friction resulting in roller skewing with possible separator wear, galling or fracture (FC 01.1). Eventually, heat imbalance failure (FC 00.19) may occur.
Image Description: At *A*, roller thrust surface. From OD to half diameter epicyclic marks from flange contact and circumferential separator wear scratches. Next in, shiny band at flange edge, then separator wear scratches. Center: unworn. At *C*, same as *A*, but separator contact wear area is shiny throughout, with circumferential scratches. At *B* and *D*, new rollers, only faint circular contact marks, arising from manufacturing.
Suspected Causes: Separator pocket contact with roller thrust face, with abrasive contaminant. Position of wear marks in *A* suggests flange edge contact, in *C*, full flange contact.

DATA

Plate No: 7.29
Archive No: 099-118
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: BG, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.1 Tooth polishing
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Slow, smooth wear of entire contact area with gradual removal of finishing marks, during operation at low EHD film thickness, especially in high hardness (case hardened) gears. Tooth polishing is not a failure, unless it progresses to more serious wear.
Image Description: Spiral bevel gear set. Tooth contact surfaces have uniform, smooth appearance; finishing marks largely obliterated. Polishing during running is seen as lighter surface color extending near, but not up to, W edges on the flanks of the four S-most pinion teeth.
Suspected Causes: Normal operation of gear set, under low EHD film thickness condition (slow speed operation) produced polishing as a (desirable) run-in phenomenon.

DATA

Plate No: 7.30
Archive No: 009-123
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, high hardness, ground, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.2 Smooth tooth wear
Failure Code 2: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 3: 00.12.0.2 Abrasive mild wear
Failure Code 4: -



DESCRIPTIONS

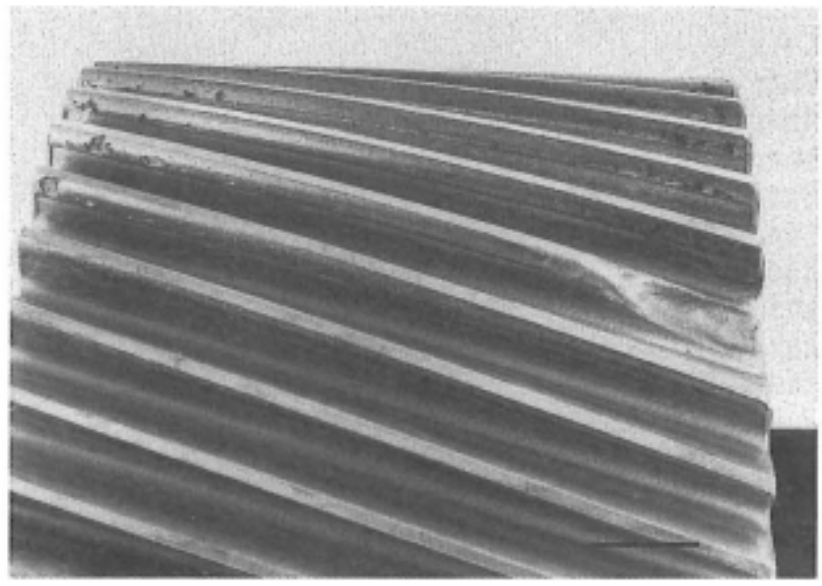
Failure Description: Scratch marks in contact surface, in the direction of sliding, caused by low concentration of hard contaminant in the lubricant. If clean lubricant is substituted, gears with this level of scratch-marking generally remain serviceable.
Image Description: Many small patches of fine, arced scratch marks from abrasive wear of tooth contact surface run E to NW, the direction of sliding in this helical gear. Underlying, less pronounced marks running SW to NE are grinding lines. Black stain on tooth tip of some teeth is marking compound ('bluing') used in examination.
Suspected Causes: Moderate level of fine solid contamination in lubricant produces fine scratch marks in wear. If the lubricant is replaced by a clean supply, the wear is arrested, otherwise it progresses and may become destructive of a finely ground gear.

DATA

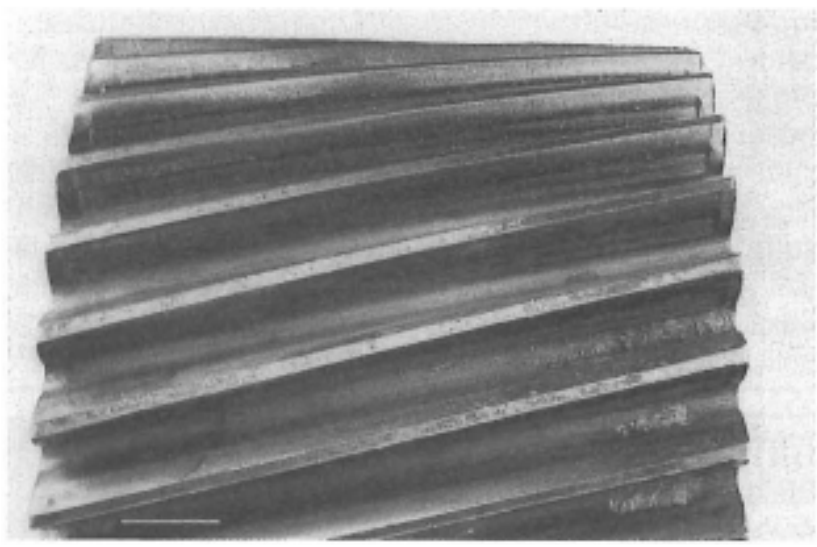
Plate No: 7.31
Archive No: 099-119 a & b & c
Image type: light macro
Scalebar = a,b,c: 30 mm (micros: ±20%, others: +100%, −50%)
Component: HG, W; med. hard, (a): 1 (b): 1.5 (c): 4 year run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.2 Smooth tooth wear
Failure Code 2: 00.16.01.3 Tooth spalling
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: -

DESCRIPTIONS

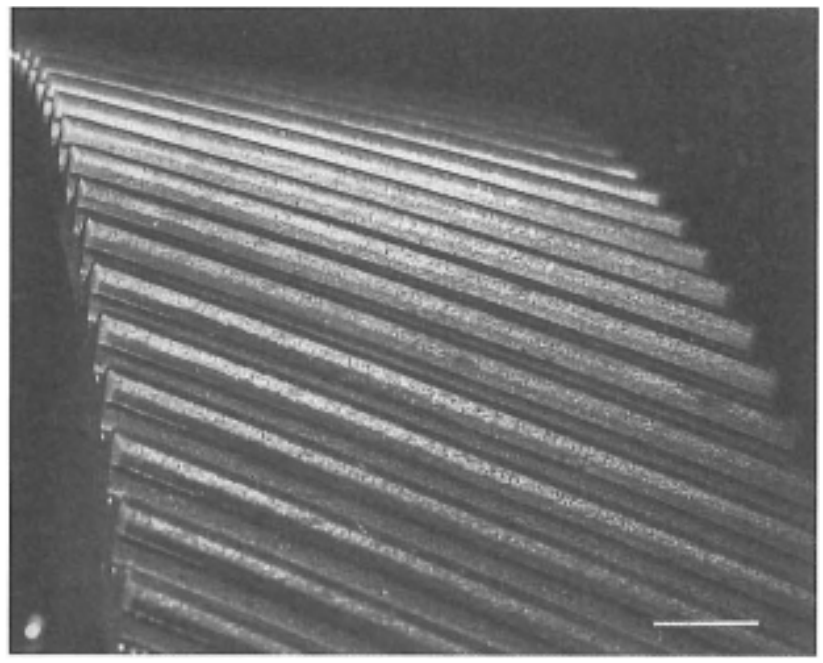
Failure Description: Progressive wear of medium-hard ('through hardened') gears, with initial spalls, subsequently worn off and steps worn into tooth face. In slow speed industrial gears, this degree of wear is often acceptable. Change in backlash and possible destructive wear may fail gear during further running.
Image Description: (a): Smooth wear on tooth contact surfaces, interspersed with dedendum micropitting (NE quadrant) and some spalling (near both ends of teeth at N). One tooth chipped at E end. (b): Steps produced by wear visible near tooth ends; copious micropitting. Loose contaminant at tooth roots. (c): Uniform, somewhat rough wear across entire tooth; deepest in dedendum.
Suspected Causes: Progressive wear from operation in low EHD film thickness regime with possible abrasive contamination from gear wear and/or other sources. Some spalling in low sliding areas, no large-scale craters. One tooth chipped (from passage of a large piece of debris?).



a



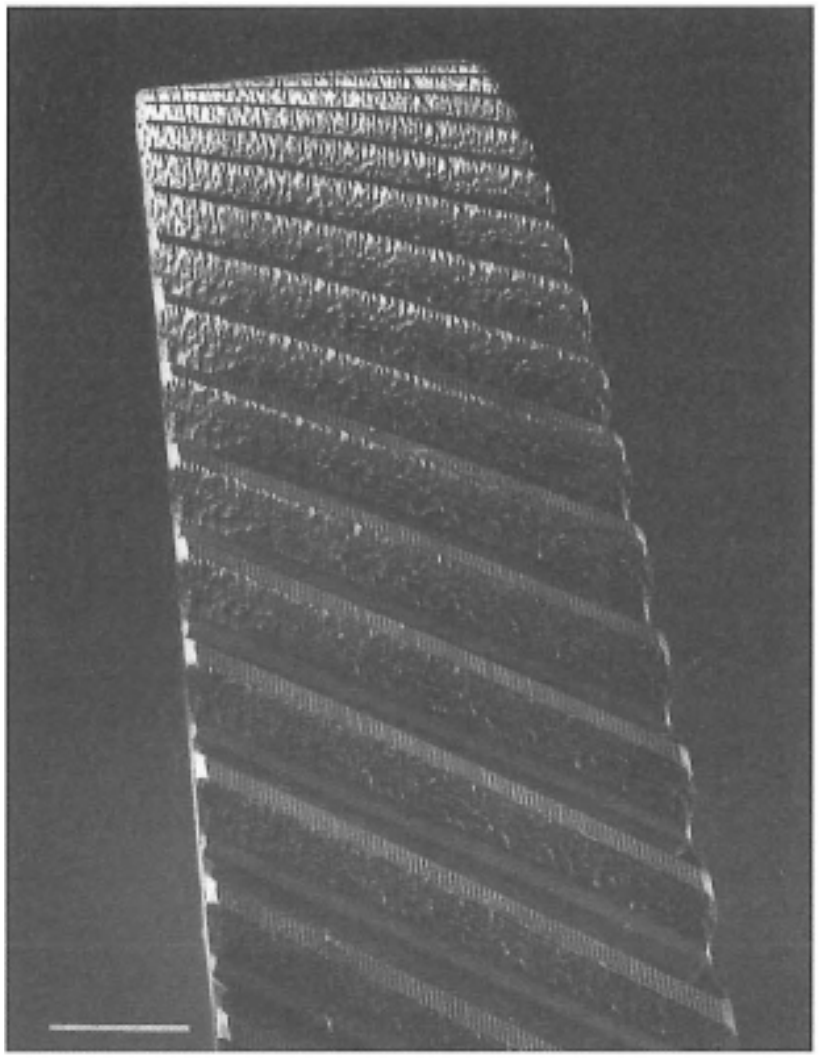
b



c

DATA

Plate No: 7.32
Archive No: 099-121
Image type: light macro
Scalebar = 25 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.1 Abrasive (destructive) tooth wear
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

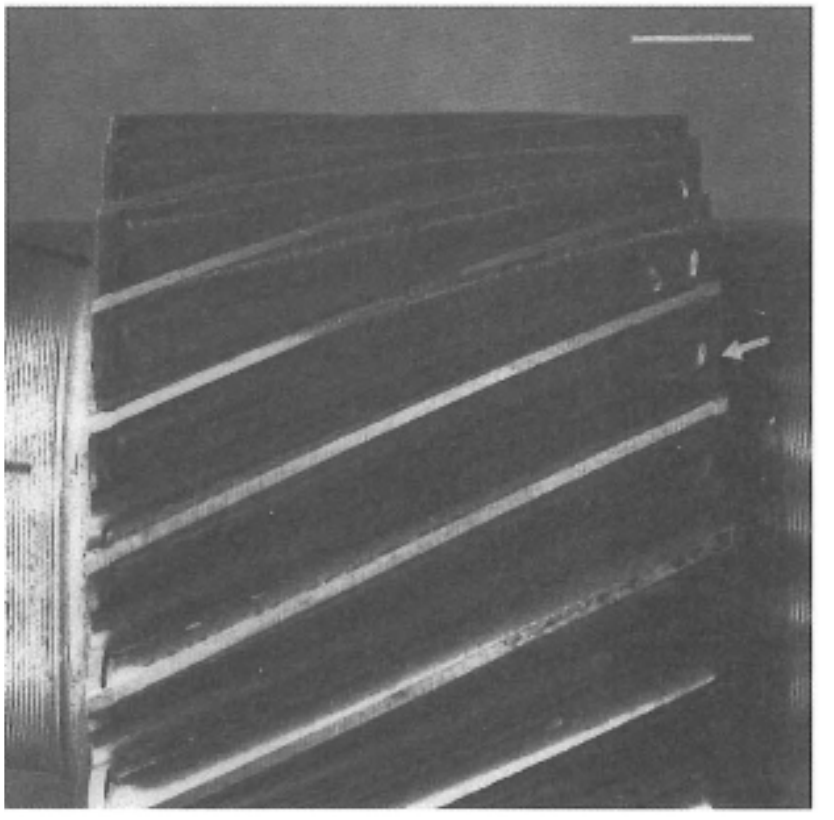


DESCRIPTIONS

Failure Description: Abrasive wear of gear contact surfaces by contaminated lubricant. Surface finish is destroyed and heavily grooved surface created, with grooves predominantly in the sliding direction. Gearing with wear of this severity is generally not serviceable.
Image Description: Entire contact area on surfaces of loaded flanks is heavily grooved in radial direction. Grooves vary in depth and length, as if produced by hard particles of varying dimensions.
Suspected Causes: This gear is known to have operated in a chamber where lubricant was severely contaminated by spalling debris from case hardened bearings. The debris are much harder than the gear material and of widely varying size. The debris operate as a coarse abrasive in the gear mesh.

DATA

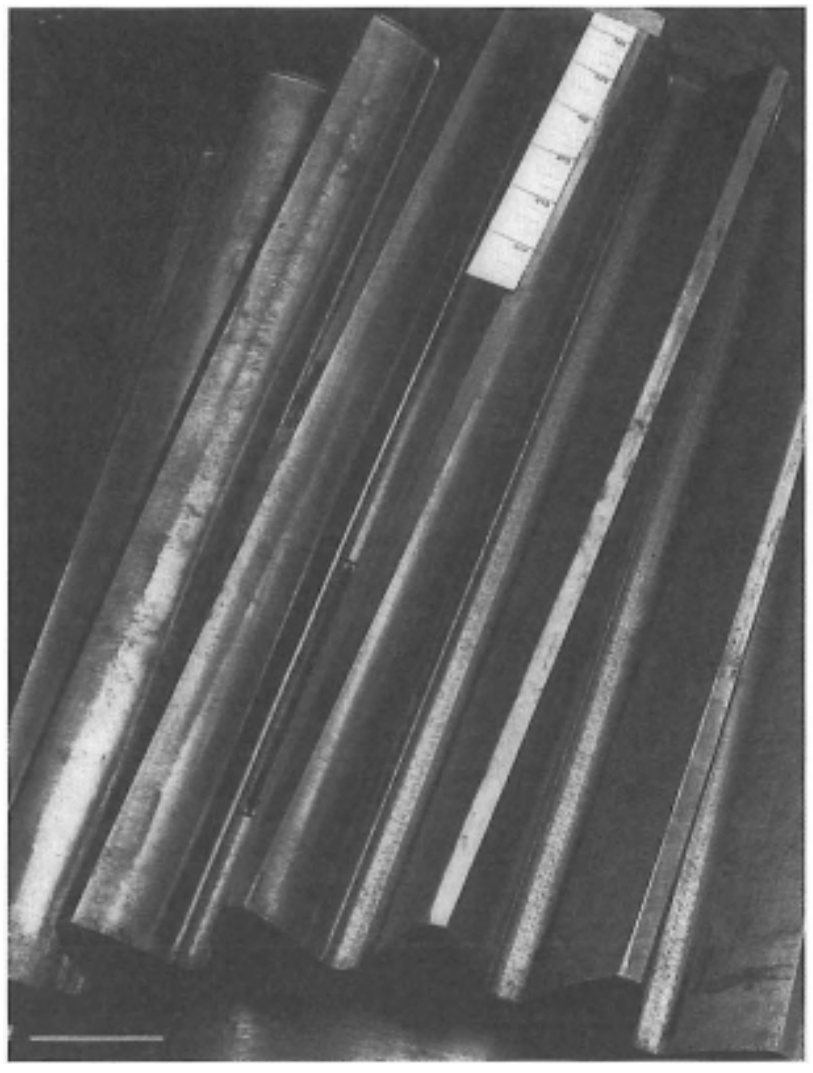
Plate No: 7.33
Archive No: 099-129
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.4 Adhesive (destructive, non-galling) tooth wear
Failure Code 2: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

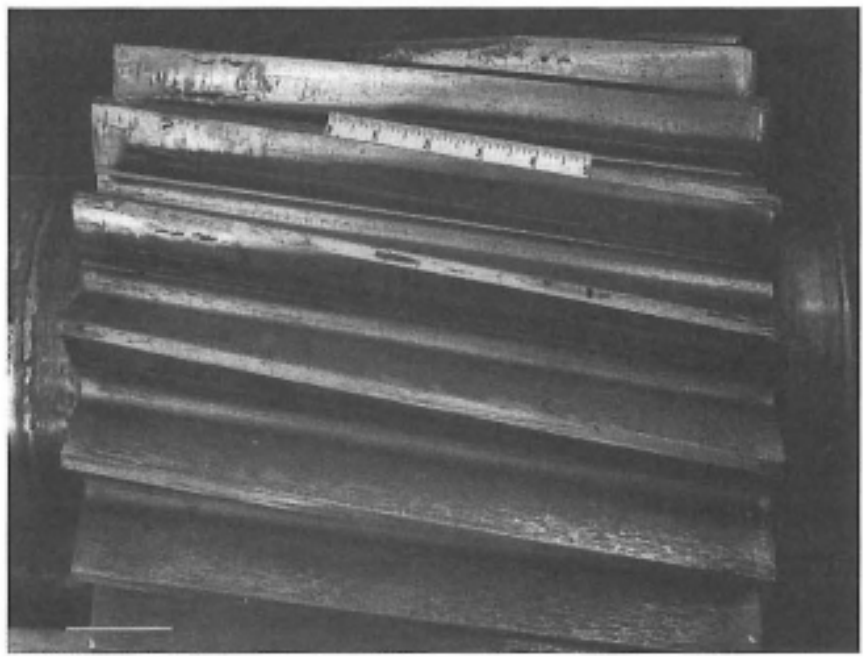
Failure Description: In contact of wider pinion with narrower wheel, in the presence of progressive wear, the pinion wear does not extend over the entire tooth length, leaving 'pads' of unworn material at the tooth ends. If during maintenance or operation, the contact pattern is shifted axially, edge contact between the 'pads' and the corner of the wheel teeth may occur, leading to fracture or other failure from edge loading.
Image Description: Worn step in contact area of teeth, heaviest in dedendum. At both tooth ends, step leads to unworn material outside contact area (arrows).
Suspected Causes: Progressive wear condition in the presence of pinion/wheel combination of unequal width.

DATA
Plate No: 7.34
Archive No: 099-230
Image type: view
Scalebar = 60 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.2 Adhesive (destructive, non-galling) tooth wear
Failure Code 2: 00.12.5.2 Smooth tooth wear
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: 00.16.02.4 Incipient spalling, multiple spalls



DESCRIPTIONS
Failure Description: Deep wear step in dedendum of gear, with spalling ("pitting"). The deep local wear suggests geometry error (misalignment?). The wear has led to a tooth fracture (not shown).
Image Description: W-facing tooth flanks are not worn (show hob marks). E-facing flanks show generalized smooth wear, with step worn in at N edge. W of line with arrowheads is a wide wear trough with sharp demarcation lines at E and W boundaries. Line of fine spall craters just W of line with arrowheads.
Suspected Causes: Geometry error is suspected cause of heavy wear zone. Spalling resulted from high local loading. Smooth wear (including wear step) is expected after long operation in this environment.

DATA
Plate No: 7.35
Archive No: 099-237
Image type: view
Scalebar = 50 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.2 Adhesive (destructive, non-galling) tooth wear
Failure Code 2: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: 00.22.01.42 Tooth corner fracture



DESCRIPTIONS
Failure Description: Generalized wear of tooth contact surface including step at one edge. Galling (FC 00.13) and incidental spalling (FC 00.16) in addendum near other edge. The damage has led to a tooth fracture (FC 00.22). The gear has failed.
Image Description: N-most fully visible tooth is fractured at left. Tooth flanks reached first when traveling S on the image are named *north* flanks, the others: *south* flanks. *North* flank surfaces are as machined (see image S). *South* flanks (see image N) are worn, with step at E contact edge (wear marks run radially). W image quarter shows plastic flow and galling over much of addendum. Axial elongated spall craters in galled area.
Suspected Causes: Overall wear from low EHD film. Heavy wear and galling from uneven loading (misalignment?). Spalls result from galling damage. Fracture is end result of galling and spalls.

DATA
Plate No: 7.36
Archive No: 099-127
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.2.1 Wavy tooth wear
Failure Code 2: 00.22.01.44 Tooth tip chipping
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Radially progressing waviness on tooth surfaces, with wave crests parallel to contact. The waviness is believed produced by wear, probably under vibratory operating conditions. The wear does not represent immediate failure but may aggravate the vibration and ultimately lead to failure. Some tooth tips are (incidentally) chipped.
Image Description: The luster of the contact surface shows inclined axial streaks (arrows), indicating wavy wear, with crests parallel to the contact in this helical gear. The waviness is identifiable by profile tracing. Two tooth tips near image N are chipped.
Suspected Causes: The engineering cause of wavy wear is not firmly established. Vibratory operating conditions are suspected.

DATA
Plate No: 7.37
Archive No: 099-303 & 302
Image type: a: view, b: light macro
Scalebar = a: 75, b: 15 mm (micros: +20%, others: +100%, −50%)
Component: HG; W, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.2.2 Bumpy tooth wear
Failure Code 2: 00.12.5.3.1 Abrasive (destructive) tooth wear
Failure Code 3: 00.16.02.3 Incipient spalling, single spall
Failure Code 4: 00.22.01.4 Gear tooth crack or fracture

DESCRIPTIONS
Failure Description: Elevated 'bumps' extending in the direction of the contact line on the tooth flank, formed by material removal in the surrounding area, appearing in similar form on several consecutive teeth, on *both* contact ends. Abrasive environment likely. Spalls on 'bump.' The 'copying' of bumps on several teeth suggests a self-reinforcing vibratory activity. Mating gear believed to show corresponding depressions. (Mating gear is lost.)
Image Description: (a): 'Bumps' of similar shape at both ends of all four S-facing tooth flanks (visible best in N half of gear). N-facing flanks (visible in S half of gear) are undamaged. One tooth tip in E is fractured. (b): Tip area of a tooth flank (section cut from a tooth). Wear pad leads to original tooth surface at W edge. Elongated 'bump' extends axially across smoothly worn tooth flank. Few small spall craters.
Suspected Causes: Self-reinforced vibratory motions in tooth mesh are conjectured as cause of mirror-image wear on mating teeth (bumps on this gear, hollows on mating gear) which copies same wear pattern on many teeth in sequence. No metallurgical deviation (e.g., hard areas) are present. Abrasive contamination is assumed to enhance deep wear. Precise causation mechanism not known.
The mating gear is unavailable for examination.

a

b

Failure Code: 00.12.5.3.2.3
Failure Code: 00.12.5.3.2.4

DATA

Plate No: 7.38
Archive No: 064-101
Image type: light macro
Scalebar = 50 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.2.3 Ridging tooth wear
Failure Code 2: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: -

DESCRIPTIONS

Failure Description: On addendum of teeth, ridging wear consisting of destructive adhesive removal of substantial material, to uneven depth, forming radial ridges. At contact edge, wear step. In dedendum, fine spalling. Wear of this severity, and spalling, impairs tooth geometry, causing noisy running and eventual failure by deep spalls or tooth fracture.
Image Description: Gear shown in chamber, with lubricant (thick black oil) still present. Near S image edge, gear OD, then two tooth flanks clean of oil. On both flanks: radial-running ridges worn into addendum, and step at W end of contact. Wear diminishes at pitchline, and a band of small spall craters and dents is visible in dedendum. N-most tooth of foreground gear and all of background gear carry dark tarry oil.
Suspected Causes: High-load, slow speed operation of medium-hard gears may result in ridging wear where sliding is substantial. Concurrently, spalling near pitchline may arise in dedendum.

DATA

Plate No: 7.39
Archive No: 099-130
Image type: light macro
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: SG; P, med. hard, hobbed, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.12.5.3.2.4 Furrowing tooth wear
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Furrowing wear occurs in large, rough-finished gear. Fine, short radial wear marks (furrows) cross the finishing lines of hobbing. Numerous axial bands composed of furrows may arise. The origination of furrowing wear is not clearly established. For slow speed, heavy gears, furrowing is not an immediate cause of failure.
Image Description: On the gear flank surface, N of the (artificial) fracture, axial bands of radial wear marks which decorate hobbing lines. If viewed under magnification, they are round-bottomed furrows. This "furrowing" has no relation to grinding furrows (FC 00.02).
Suspected Causes: The engineering cause of furrowing wear of gear teeth is not clearly established. It is observed as a wear phenomenon in coarse-finish large gears operating under low EHD film thickness, and may be related to rough surface finishes.

DATA

Plate No: 7.40
Archive No: 011-001
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: 0; impact printer hammer, run
Speed: impact
Load: impact
Lubrication: scant mineral oil, 50°C
Failure Code 1: 00.12.7 Impact wear
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 7.41

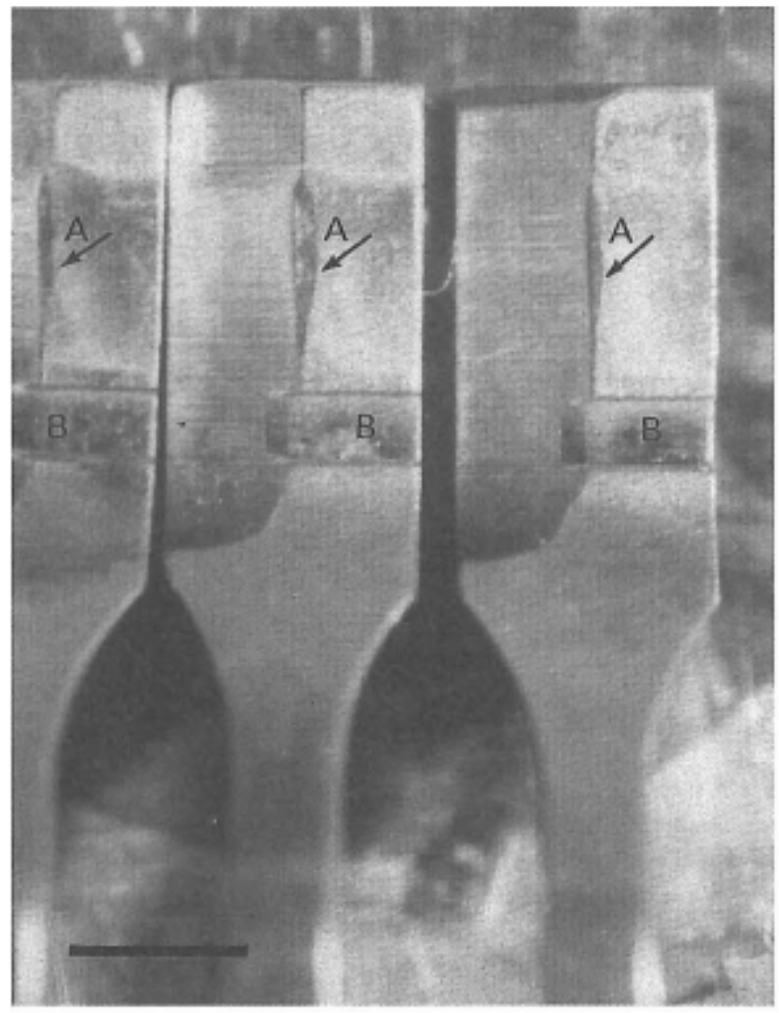
[See Image in Appendix]

DESCRIPTIONS

Failure Description: Wear of impact printer hammer surface against elastomeric pushrod tip. Hammer surface burnished. Transferred elastomer and other adhering debris. This degree of wear is not a hammer failure. The elastomeric pushrod usually fails first.
Image Description: The four gray/yellow rod-shaped elements are metal hammers from a data processing impact printer. At the broadened anvil area, an elastomer-tipped pushrod hits during operation (dark-rimmed oval with streaky green interior). Slight burnishing wear of metal, where yellow patch appears. Adhesion of elastomer debris (green) and oil (dark).
Suspected Causes: Some data processing impact printers transmit type-carrier forces through a pushrod to a hammer. The pushrod/hammer impact, which is essentially of normal incidence with a small sliding component, transfers some elastomer to the hammer, while inflicting mild wear on its metal surface.

DATA

Plate No: 7.41
Archive No: 011-002
Image type: light macro
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: 0; type element
Speed: impact & slide
Load: impact
Lubrication:
Failure Code 1: 00.12.7 Impact wear
Failure Code 2: 00.12.3.3 Sliding contact wear
Failure Code 3: -
Failure Code 4: -
See also PLATE: 7.30



DESCRIPTIONS

Failure Description: Impact wear with slding on rear of impact printer type-element. One wear scar from impact between the type element and a hammer. The other is at type/backstop contact and due to vibration and impact. As wear continues, dimension is lost, resulting in printing degradation.
Image Description: Three type-carriers are viewed from the back face. The averted face carries characters at the tip (image N). The thinned shank is elastic. Widening of sharp N–S edge at *A* is from hammer impact. Some E–W wear marks E of edges. E–W running rectangles at *B* are fretting marks, from backstop contact under vibration.
Suspected Causes: Impact printer type carriers have characters on their tip. The back face slides past a backstop when not printing and is hit by a metal hammer to make the imprint. Lubrication is marginal. Misalignment may exist. Impact wear and some sliding wear occur at the hammer contact; fretting and some impact wear at the backstop contact. Eventually geometry is destroyed sufficiently to require replacement.

GALLING, SKID MARKING 8

Failure Code 00.13–14

8.1 GALLING FAILURE CODE: 00.13

8.1.1 Definition

Galling (of a contact component) is defined as the transfer of component surface material in macroscopic patches from a location on one contacting surface to a location on the other contacting surface, and possibly back onto the first surface, by the action, in service, of high tractive forces in multi-asperity dimensions. Galling requires surface-parallel relative motion (sliding) in the contact. Galling is distinguished from:

- *Mild wear* (FC 00.12), defined as removal of surface material as loose particles by the action of tractive forces in asperity dimensions;
- *Surface distress* (FC 00.17), defined as surface material plastic flow and micropitting by the action of high *normal* forces in asperity dimensions;
- *Fretting wear* (FC 00.15), defined as removal of surface material, often with oxidation of debris, as a result of microscopic surface-parallel relative movement of surfaces in nominally static contact under normal load;
- *Skid marking* (FC 00.14), defined as material transfer between surfaces in *single-asperity* dimensions.

8.1.2 Nomenclature

Galling is also designated as severe wear, smearing, or scuffing. The term *'scoring'* may designate galling or alternatively, the formation of a scratch by plastic plowing. Occasionally the term *'wear'* is used loosely to designate all modes of surface material removal, including galling, as well as the other modes listed under Definition. In this Atlas, 'galling' is only used to designate severe wear, which is always two-body wear.

In some gear literature [8, 9] galling is called *adhesive wear*, although this term is generally reserved to describe two-body mild wear (FC 00.12). In this Atlas, galling is never designated as adhesive wear.

8.1.3 Failure Process

The mechanism of galling in a *rolling* contact is visualized in the following steps.

1. Sliding takes place in the contact, usually in addition to rolling, through the action of sufficient tractive force.
2. The combination of operating parameters such as normal pressure, sliding speed, temperature, micro-topography, lubrication and others, is sufficiently severe that welding of asperities occurs in macroscopic dimensions.
3. The surface-parallel displacement of the surfaces in the contact plastically transposes some welded material from either or both surfaces.
4. If the conditions change to less severe (e.g., by reduction in sliding velocity), then the welding of further asperities stops.
5. As the rolling contact area travels on, the welded asperities become separated in the surface-normal direction, leaving behind a patch of transferred metal on one or both contact surfaces. The material may have originated from either of the surfaces, regardless of the surface to which it is finally welded.

Many common theories describing the micro-mechanism of galling hark back to the Blok *flash temperature model* [13], according to which two asperities contacting under severe conditions heat up momentarily to a temperature which (a) vaporizes the lubricant and (b) welds the asperities together. More recent theories have added the conjecture that local heating causes thermal distortion of the surface, in effect creating a ''transient asperity'' which becomes overloaded by being higher than the surrounding surface.

It is believed that galling requires an 'avalanche' process, whereby a small patch of welded surface material is moved along the surface by sliding, then welded onto a next asperity, thereby increasing in area. This process continues until it is externally interrupted. It is believed that for the macroscopic material transfer process to take place, a galling event *must bridge more than one asperity* so that material dragged from one welded asperity is welded onto a second asperity, is further dragged to a third, etc. This sequence explains the cascading nature of a galling failure, which is its most significant characteristic.

Neither the flash temperature, nor any single macro-variable of operation (speed, load, roughness, lubricant, etc.) controls the onset of galling over a broad range of contact configurations. At present, the effect of the parameters influencing galling is known only for fixed configurations. Thus, there are experimental data on threshold values for speed, load, temperature and lubricant combinations that do not precipitate galling in a *precisely defined* contact configuration including defined contact material and surface finish. However, extrapolation to untested configurations is reliable only over small incremental configuration changes.

Galling is a welding phenomenon, that is, of adhesive bonding between material volumes. Accordingly, it is primarily a failure mode of metal or thermoplastic surfaces. Surfaces that resist welding (such as ceramics) and layers of lubricant or hard coating that combat welding, all resist galling.

It is believed that asperities must deform plastically in order to initiate the welding needed for galling. Therefore the slope angle (or tip curvature) of an asperity must exceed the limit of plastic flow under the operating conditions in order to initiate galling.

The cascading nature of galling explains the tendency of galling failures to be catastrophic. A galling event, once started, tends to continue and spread the transferred metal patch in the sliding direction as long as the contact lasts. For this reason, galling does not take place in *pure* rolling, since there is no surface-parallel relative motion to spread a welded patch to multi-asperity dimensions. Galling in combined rolling-and-sliding contact increases in severity as the slide/roll velocity ratio increases. Galling in simple sliding is particularly severe as there is no surface-normal motion component to separate the contact.

Galling is a threshold event, such as cracking. If contact conditions are made progressively more severe, a regime of mild wear will *abruptly* convert to one of galling. However, since many variables influence the threshold severity, some of which vary pointwise on a surface (roughness), galling occurrences show considerable scatter in repeated experiments.

Galling is self-aggravating. The transferred metal patch is higher than the ungalled surface and acts as a large and high asperity on which load concentrates. Therefore galling tends to propagate *very rapidly* by incremental transfer of more material onto the galled patch of origin. If galling is not arrested, it can rapidly lead to gross failure by bulk fracture or seizure of parts as the transferred patch of material becomes too high to pass through the contact without destruction.

In contrast to the self-aggravating nature of galling is its ability to ''heal.'' If a (temporary) external change drops the severity of the operating conditions below the galling limit, the galled patch may gradually wear down (''heal'') and the galling can be arrested. Among the many possible service changes that may arrest galling are: (a) termination of contact by surface separation in rolling; (b) arrival of a fresh local supply of cool lubricant; (c) cessation of a momentary overload or impact load; (d) a small change in the relative position of contacting parts during the next overrolling; and

(e) a deliberate or coincidental reduction of speed or load, or an increase in cooling lubricant flow by the operator.

The most significant operating variable controlling galling is *sliding speed.* Galling occurs above a fixed sliding speed limit for any given set of operating conditions and configurations. However, sliding motion in a Hertzian contact takes place only if sufficient tractive forces are applied to balance the sliding friction in the contact. The friction in a contact undergoing galling is usually higher than in an ungalled identical contact and must also be overcome to sustain galling. Therefore *tractive force* and *friction* in the contact are, in turn, the controlling variables of sliding speed.

Other significant operating variables controlling galling are: temperature, contact load, surface micro-geometry and boundary lubrication.

8.1.4 Distinctive Appearance

Galling is recognized by observation of the contact surfaces and, if necessary, the immediate subsurface material. Distinctive appearances are described below. In differential diagnosis of galling, it is important to observe that the distinctive appearance of other surface material removal failure modes (mild wear, fretting, surface distress) is *not present.* Depending on the severity of a galling occurrence, the appearance can be recognized on three levels.

Gross seizure. Advanced galling can lead to seizure of relatively moving parts (especially, confined parts such as those of a rolling bearing), producing bulk fracture, bulk plastic deformation and/or gross overheating failure. The most destructive failures in *rolling bearings* tend to arise from galling. In these cases, detection of the initiating galling event may be difficult or impossible, having been obliterated by subsequent destruction of surfaces. If it is observed, that no other obvious initiating failure is present in a seized assembly (such as a large spall, or loose chunks of material from a major fracture), then this strongly suggests that galling caused the seizure. The reverse, however, is not the case—fractures can well be secondary to galling events.

In an operating machine, a gross seizure event is often accompanied by violent vibrations, loud noise, rapid temperature rise, slowdown or uneven motion of the moving part, loss of positioning accuracy, etc.

Macroscopic galling. Galling in multiple-asperity dimensions appears as a raised patch of transferred metal "smeared onto" a contact-, or fit-surface. Profile tracing over the galled patch shows raised material. The surface topography of the transferred material is often rough and scored in the sliding direction, as the opposing part surface is forced over it. There are no finishing marks on the transferred patch as it covers over the finishing marks on the underlying original surface. The transferred material is often piled up at the end of the galled patch, where it is left when the galling event is terminated by surface-normal separation of the rolling contact surfaces.

Macroscopic galling in progress in a machine tends to create clicking or hammering sounds, high-pitched "screams" or deep "rumbles," depending on operating conditions.

Microscopic appearance of galling. A SEM image of the galled surface shows transferred material plastically smeared onto the original surface. The transfer patch bridges several (up to a great many) asperities. The transferred material is pressed into original surface furrows, may show plastic flow marks, lifted-off edges where welding was incomplete, or cracks where the plasticity of a material volume was exhausted by the smearing. Since galling marks are most often observed following further running after termination of the galling event, the galled material may be rolled down, smoothed or burnished as a result of being rolled over.

Microhardness of the transferred metal is generally higher than the original surface as it is heavily worked (but subsequent tempering is possible).

A (Nital-etched) metallographic section through a transferred metal patch generally shows the welded interface and may show off-specification material structure and/or plastic flow lines.

8.1.5 Causes

General Causes of Galling

- Susceptible material class (metal, thermoplastic polymer).
- Insufficient galling resistance of material due to low hardness, ease of welding, lack of protective surface layer, etc.
- Severe sliding in contact (in excess of critical value) caused by excessive tractive force and *maintained for sufficient time* to permit material transfer in multiasperity dimensions.
- Severe normal load (in excess of critical value).
- Overheating.
- Unfavorable surface microgeometry (local damage, general roughness).
- Inadequate boundary lubrication.
- Chemically aggressive environment (lubricant or atmosphere) removes protective layer.

Galling Causes Specific to Rolling Bearing Contact Components. The following circumstances tend to activate some of the general causes of galling:

In the rolling contact:

- Excessive angular acceleration.
- Excessive separator friction.
- Sudden heat imbalance.
- Nick or dent with raised edge.

In roller-end to flange contact:

- Edge contact due to geometry error.
- Excessive normal stress and/or sliding velocity due to axial load or roller skewing.

In Hertz contact element to separator contact:

- Edge contact due to geometry error.
- Excessive separator forces in contact with support element.
- Insufficient clearance between separator and contact component.

Causes of Galling Specific to Cams. Cams and cam follower rollers or tappets suffer the general causes of galling listed above, of which they are particularly vulnerable to the following:

- *Sliding.* The roller in cam and rolling follower systems undergoes high angular accelerations in every cam cycle as the roller attempts to follow the varying linear velocities encountered along the cam profile. Angular oscillations in the camshaft may add further accelerations. The contact between cam and follower roller must transmit the traction needed for (high, and possibly oscillatory) roller accelerations and to overcome the friction between roller and roller support elements. Contact pressure available to generate tractive forces varies from zero to maximum values along the cam circumference. Friction on the roller support elements may be erratic and high. All this can lead to intermittent sliding in the contact. If the sliding takes place with a velocity/pressure combination that exceeds the galling limit of the system, then galling results. Cam and tappet systems are designed to operate with continuing relative spin which is tolerated under design conditions. These systems may suffer galling if operating conditions are more severe than designed for.
- *Edge contact.* Rolling cam followers are difficult to maintain in precise alignment. Profile crowning needed to avoid edge stresses is not always provided. Tappet wear may eliminate edge clearance.

- *Contamination.* Cam systems are often lubricated from general circulating oil systems which carry combustion products (in internal combustion engines) and wear products.
- *Rough surfaces.* Camshafts often are large components; cam geometry is complex and the specialized machinery for fine cam finishing may not be available.
- *Nicks.* Cam surfaces are external and camshafts are often large components difficult to handle protectively.

Galling Causes Specific to Gears

- High, kinematically forced sliding speeds in high-velocity gears, at tip, root, nick or edge.
- Overheating.

8.1.6 Effects of Galling

Galling is often the primary cause of gross seizure of a machine element, due to severe geometric alteration, high normal and tractive contact forces and extreme overheating.

Early stages of galling create operating malfunctions, as follows:

- Clicking, hammering or rumbling noise.
- Radial or angular vibrations.
- Positioning inaccuracy in cam systems.

Early stages of galling make the machine element vulnerable to deterioration from small causes:

- Excessive and time-variable forces arising in the galled contact reduce overload safety margin.
- The rough surface of transferred metal is vulnerable to further galling whenever lubrication is impaired.
- Particles worn off the (fast wearing) transferred metal contaminate the lubricant and may precipitate galling at other surface points.
- The transferred material has low resistance to spalling and surface distress. This, combined with local overloading from excess height of transferred material may cause early spalling failure.

Machine elements with controlled clearance (rolling bearings, gears) may lose all clearance over the transferred material, resulting in parasitic loads and failure from that cause.

Rolling bearing separator galling against rolling elements or ring guide surfaces cause these failure risks:

- Separator material transferred onto rolling elements is not contact-fatigue resistant, but can raise the surface causing local overloading.
- Tractive forces exerted on the separator during the galling process may cause separator failure (see FC 01).

8.2 SKID MARKING — FAILURE CODE: 00.14

8.2.1 Definition

Skid marking is asperity-scale surface material transfer. It is *analogous* to the macroscopic process of galling (FC 00.13), but *distinct* from galling in which the elementary material transfer event takes place on a multi-asperity scale. Galling is a cascade process bridging several asperities by transferred material, whereas in skid marking no cascade of transfers takes place. In some cases, galling streaks are so small that the distinction between them and skid marks cannot be made with certainty.

8.2.2 Nomenclature

Skid marking is a recognized failure mode of (high-speed) rolling bearings, where it is also called *skidding* or *frosting.* A similar (or identical) failure mode in gears is designated in *some* gear literature as *scuffing,* whereas the term ''scuffing'' in rolling bearing technology is synonymous with galling. Skid marking failure has been identified in cam and roller follower systems, where it is usually designated as micro-galling. In this Atlas, the term 'skid marking' is adopted, as distinguished from 'skidding,' which is also used in bearing technology to describe the kinematic condition of gross sliding in the contact, as, when a rolling element fails to maintain epicyclic speed of rotation. 'Frosting' has been used to describe an advanced degree of surface distress (FC 00.17) and therefore is not used in this Atlas to describe skid marking.

8.2.3 Failure Process

A skid mark appears as a multitude of asperity-scale spots of transferred material on the contact surface. It can arise when high sliding velocity is imposed on a Hertzian contact for a self-limited, very brief period, during which the relative surface-parallel displacement of the contacting components on each other is less than a typical asperity spacing, so that the cascading transfer of material characterizing galling has no opportunity to develop.

In *rolling bearings,* this circumstance can arise if a rolling body (ball, roller) orbits without maintaining epicyclic rolling velocity (as, when contact loads are small and separator friction high) and is then suddenly accelerated to epicyclic velocity upon the onset of sharply increased contact load. The tractive forces necessary for the high acceleration may cause skid marking. Once the rolling body is up to speed, the high tractive forces promptly disappear. If their duration is short enough, skid marking can result; for longer durations (heavy rolling elements, persistent high cage friction), macroscopic galling may take place.

In *gears,* skid marking (scuffing) may occur in the sliding zones of the tooth contact for slide/roll ratios insufficient to cause galling.

In *cam/roller* systems, skid marking can appear at specific positions on the cam circumference, where conditions require particularly high traction to maintain rolling contact. A complex of operating variables, including (momentary) inadequate lubrication, torsional cam vibrations, and torque excursions in the roller support elements can contribute to skid marking.

Visible skid mark areas build up gradually as opposed to galling, which can occur as a single catastrophic event. Individual marks are of asperity dimensions. If the precipitating condition repeats itself (typically once per separator revolution in a bearing, once per cam cycle in a cam/roller system), a pattern of skid marks develops.

An existing skid mark is a natural starting point for a new mark during the next cycle. Therefore, skid marks tend to line up in rows in the sliding direction. Because the elementary skid mark is small, further extension of a row of marks is easily halted by a scratch or furrow in the surface which crosses the sliding direction.

8.2.4 Distinctive Appearance

To the unaided eye, skid marks appear as individual fine streaks or circumscribed macroscopic areas on the contact surface, having a distinctive ''frosted-glass'' appearance. Under high magnification, skid marks are asperity-size weld spots lined up in streaks running in the sliding direction. Individual skid marks may cluster in narrow cross-track bands on cams. In a rolling bearing, the edge of a skid marked area may be feathered if it extends on an uninterrupted surface, or cut off sharply by a surface furrow (common on balls which have furrows running in random directions).

In an etched metallographic section (prepared after overplating of the surface for the preservation of a sharp edge at the intersection of section and surface), skid marks may appear as rehardened

welded-on material overlaying a tempered surface. Aside from its small scale, this appearance is similar to that of galling (FC 00.13), *but not of surface distress* (FC 00.17), which shows no sign of welding.

8.2.5 Causes

Skid marking, like galling, is caused by the application of high tractive forces *to an asperity contact* so as to cause sliding at a speed sufficient to induce welding of surface material under existing conditions of material, temperature, lubrication and surface microgeometry. For skid marking to occur as opposed to galling (FC 00.13), the duration of the high tractive force must be too short to develop a multi-asperity cascade of welding.

Effect of galling sensitivity factors (such as roughness, boundary lubrication and temperature) upon skid marking are not well documented, but likely.

In *rolling bearings,* skid marks are the consequence of kinematic anomalies in the motion of rolling bodies. Examples:

- Slowdown of rolling body autorotation under low contact load (and significant separator friction), followed by a *brief* acceleration when load steps up.
- In a high-speed bearing, abrupt change of epicyclic rolling body speed upon a step load change.

In *cam and roller-follower* systems, skid marking arises as a result of momentary sliding under high contact pressure, at the entrance to the lift lobe where the follower must rapidly accelerate, and at other angular locations if rapid rolling-speed changes are forced by the cam profile, by angular oscillations or special operating conditions of the cam system. At angular location where contact pressure is sufficiently high, *momentary* high torque demand of the roller support system can precipitate skid marking. *Galling* (FC 00.13) may occur if the sliding under high pressure is of longer duration.

In *gearing,* skid marking (scuffing) has been observed in slow-speed, smooth-surface, substantially loaded gears operating *below* the galling limit.

8.2.6 Effects of Skid Marking

In rolling bearings and cams:

- Skid marked surfaces are rougher than as-manufactured surfaces, and the transferred metal structure is defective. These factors accelerate failures influenced by EHD film ratio, such as surface distress, surface initiated spalling and wear. They are, for the same reason, more prone to gross galling.
- The material in a skid mark is severely plastically worked, rehardened and probably microcracked, making it much less resistant to surface-origin contact fatigue (surface distress and surface-origin spalling).
- A skid marked high-speed bearing is more noisy and vibratory than an intact bearing.
- Friction between a skid marked rolling body of a bearing and the separator may be greater than normal. Separator wear, or overheating or both may result.

In *gearing,* skid marking (scuffing) is not considered catastrophic failure. However, it may act as precursor to more severe failure by wear, galling or contact fatigue.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.13.01	8.12 8.14
00.13.02	8.2 8.6 8.7 8.15 13.2 13.13
00.13.1	6.37 10.7 15.37
00.13.2.1	8.22 13.12 13.15 15.34
00.13.2.1.1	7.35 13.5
00.13.2.1.1.2	10.37 15.38
00.13.2.1.2	5.5 8.2 10.7
00.13.2.3	8.2
00.13.3	10.18

PLATES

DATA

Plate No: 8.1
Archive No: 093-019
Image type: view of sectioned ring
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB, IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.1.2 Galling from rapid motion origin, fit surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Multiple circumferential galling streaks cover an IR bore due to rapid sliding on shaft under load. Galling of this magnitude destroys bore dimension and may initiate bulk cracking. Rapid rotation in an unlubricated bore may cause overheating.
Image Description: On gray-appearing original bore surface, a dense overlay of light-colored circumferential streaks with ragged edges. These are the galling marks. On closer inspection, patches of transferred metal would be visible.
Suspected Causes: Insufficient interference fit between IR bore and shaft seat in a bearing operating with radial load rotating with respect to the innerring, causes epicyclic rotation of ring on shaft. The higher the load and the looser the shaft fit, the more rapid is the rotation. When the sliding velocity becomes excessive, galling sets in.

DATA

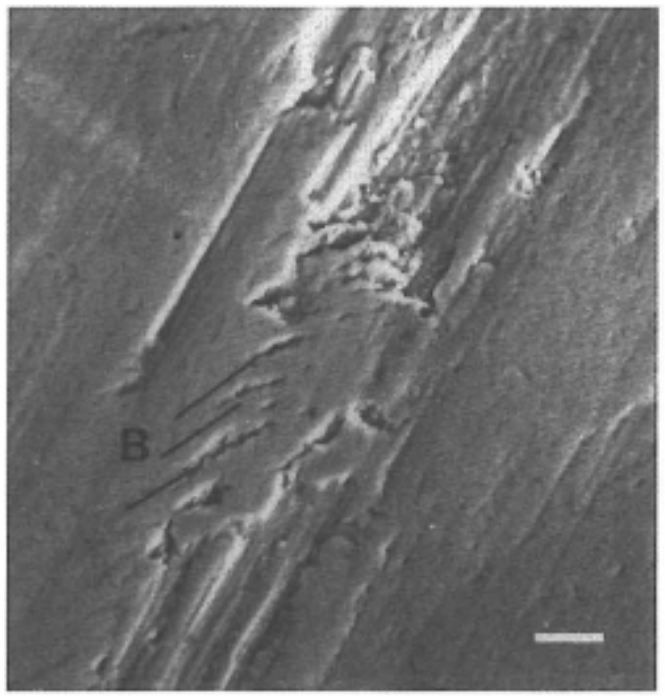
Plate No: 8.2
Archive No: 027-152
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 100 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.13.2.1 Rolling surface galling
Failure Code 2: 00.13.02 Extensive galling
Failure Code 3: 00.18.3 brinnelling
Failure Code 4: 00.13.2.3 Galling at guiding-part contact surface

DESCRIPTIONS

Failure Description: Massive galling seizure, possibly due to lubrication failure. Groove shows extensive material transfer, rolldown, brinnell marks at ball spacings and galling on lands from separator contact. This is a gross failure.
Image Description: At extreme S, ring was cut, presumably for dismounting. Ball groove is rolled out to irregularly larger radius. In W groove half, extensive deposited laminae of transferred metal. In groove bottom, several elliptical depressions are brinnell marks from wedged balls. Land surfaces near groove show circumferential streaks of transferred material from separator rubbing after deformation.
Suspected Causes: Loss of lubricant, galling, separator deformation and rubbing on lands, separator fracture, wedging of separator elements under balls, and brinnelling of groove are the likely failure sequence.

Data

Plate No: 8.3
Archive No: 093-13.1.8
Image type: SEM
Scalebar = 30 μm (micros: ±20%, others: +100%, −50%)
Component: CRTB; IR, run
Speed: 150 KdN
Load: 2.0 GPa
Lubrication: mineral turbine oil, 100°C
Failure Code 1: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

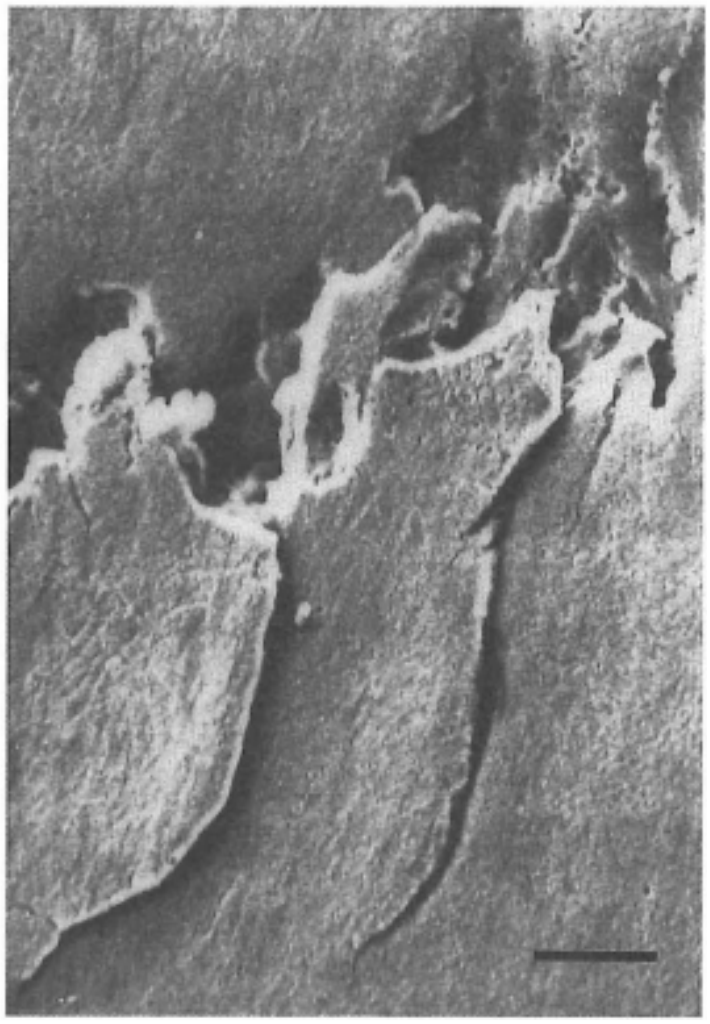


DESCRIPTIONS

Failure Description: Microscopic galling event. A gouge created by an asperity or debris particle sliding over the surface is filled by plastically flowed, microcracked and welded-on material. An isolated microscopic galling event may "heal" by further over-rolling. Often, however, it initiates additional meterial transfer and fails the bearing by heat imbalance failure, seizure, possibly spalling.
Image Description: Wear marks (and finishing lines) are straight lines running SW to NE. A wear gouge (50 μm wide) runs diagonally SW to NE, to the E of marker lines *B*. It is filled by almost featureless material containing microcracks (at lines *B*) due to heavy plastic working. The deposited material results from the galling event. Faint wear lines on galled material suggest that it was rolled over.
Suspected Causes: Galling requires a sliding velocity component. (In a CRTB, the sliding component is large over most of the contact width.) A high asperity or debris particle gouges a wear mark in sliding. Subsequently, material brought from upstream in the sliding direction is rolled into the gouge and welded on.

Data

Plate No: 8.4
Archive No: 093-13.1.11
Image type: SEM, Nital etch
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: CRB, IR, tool steel, run
Speed: 180 KdN
Load:
Lubrication: synthetic polyester oil, 38°C
Failure Code 1: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

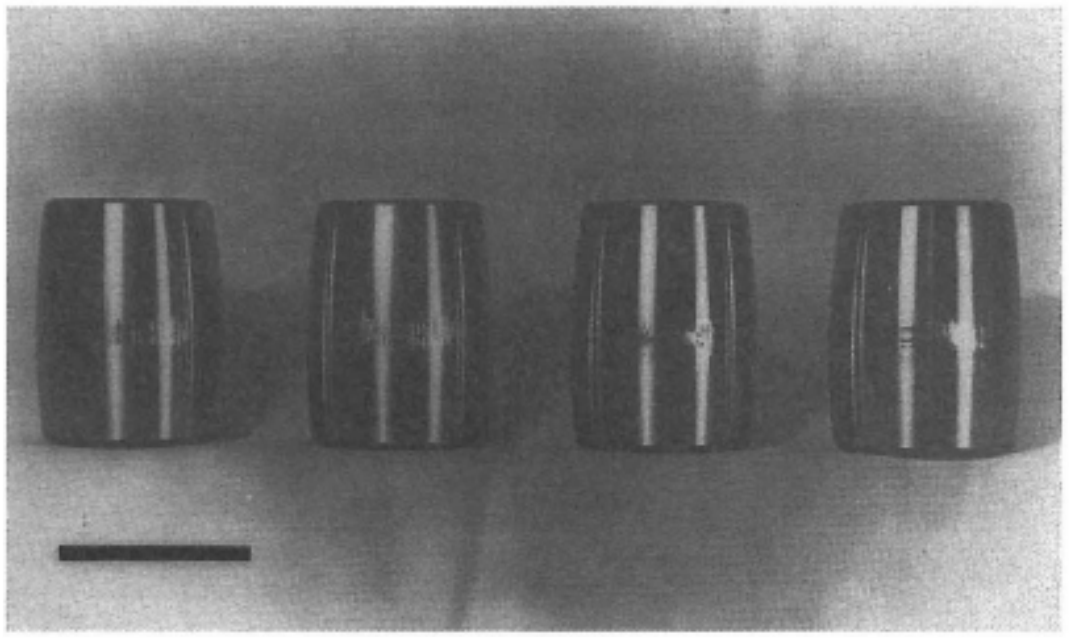


DESCRIPTIONS

Failure Description: Laminae of material transferred onto a surface by galling contain high residual stress from cold working. Upon Nital etch, some residual stresses were relieved by microcracking. The underlying surface is visible and heavily worked. Microscopic galling, as shown, may heal. More often, it initiates large-scale galling, heat imbalance failure, seizure or spalling.
Image Description: Matte, pebbly gray surface is the etched surface of the transferred material. At image N, a valley of presumably original surface. In SW quadrant, two curved surface cracks lift off laminae of transferred metal.
Suspected Causes: Galling requires a sliding velocity component. Material brought from upstream in the sliding direction is rolled onto the surface and welded on. The cold working is severe, leaving high residual stresses making the material vulnerable to cracking. The material is often raised above the surrounding surface, causing stress concentration and initiating further galling.

Data

Plate No: 8.5
Archive No: 018-111
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; R, transported
Speed: 0
Load:
Lubrication:
Failure Code 1: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 2: 00.09.2 Galling from forcible assembly or mounting
Failure Code 3: -
Failure Code 4: -

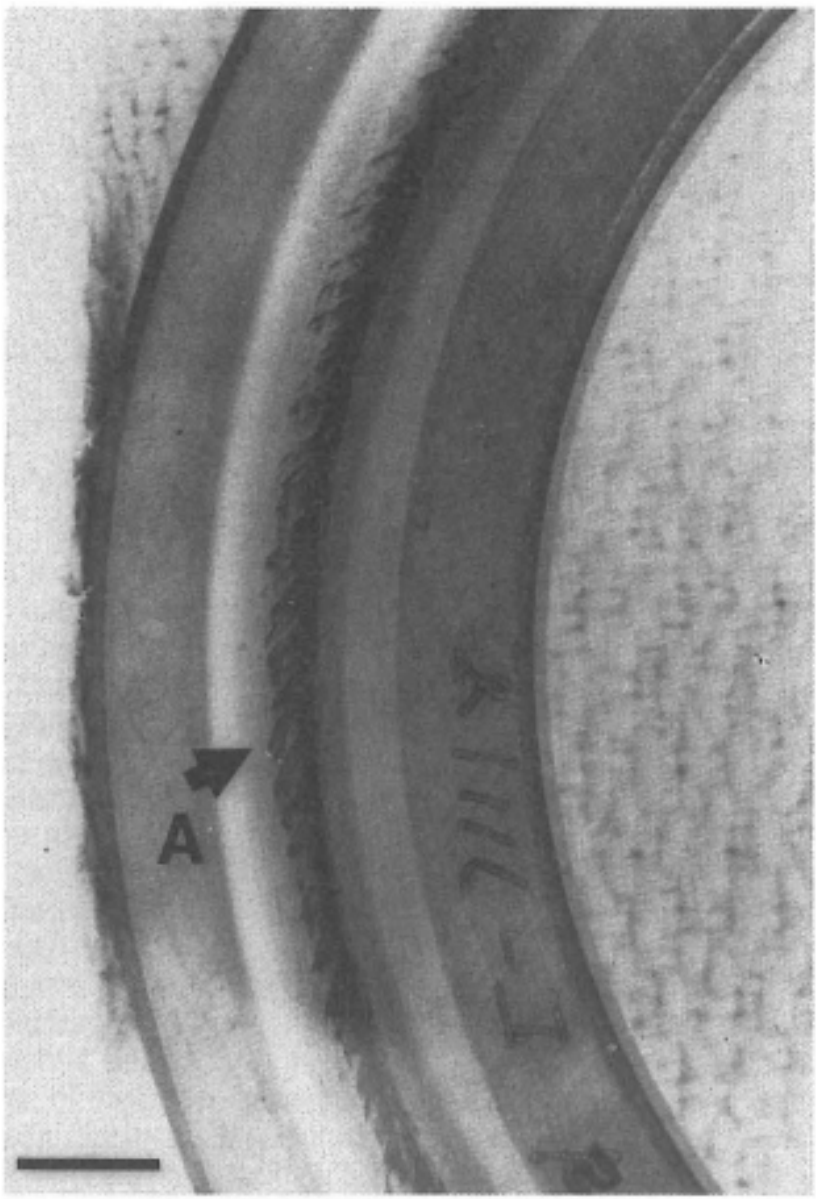


DESCRIPTIONS

Failure Description: Galling streaks on roller OD's, from axial motion of rollers against rings under load without rotation. Such motion may occur in transporting a bearing mounted in a machine. If there is no axial motion, false brinnelling might result; with dominant axial sliding, galling streaks are generated. The bearing is noisy when run and likely to fail in galling or spalling.
Image Description: Near maximum diameter of rollers, short sharp axial lines are galling ('scoring') marks. Metallographic examination would show transferred material.
Suspected Causes: Transportation of machinery with bearings mounted, may expose the bearings to relative motion without rotation. The most common resulting failure mode is false brinnelling (FC 00.15). However, in the present case, the axial motion was of large enough amplitude to cause galling (scoring) marks by material transfer between the contacting surfaces.

Data

Plate No: 8.6
Archive No: 093-13.1.1
Image type: light macro
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: TBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 2: 00.13.02 Extensive galling
Failure Code 3: -
Failure Code 4: -

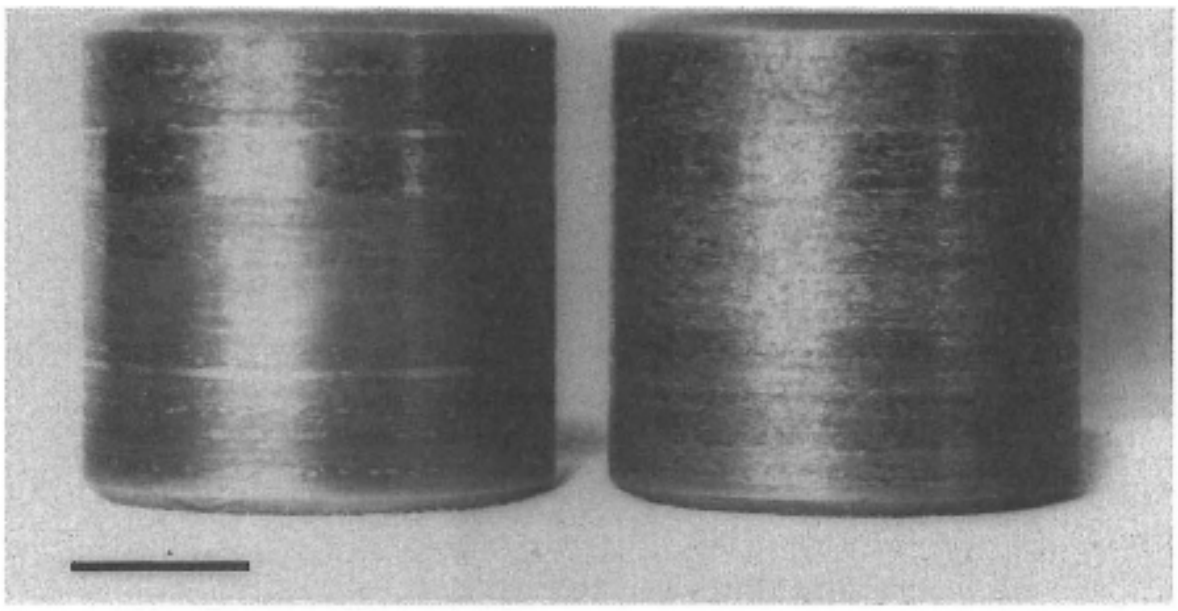


DESCRIPTIONS

Failure Description: Ball groove circled by galling streaks running in spin direction, probably from excessive speed for the applied load. The bearing is noisy and may seize, suffer heat imbalance failure or spall.
Image Description: The ball groove is the central arc on the thrust bearing ring ('washer'). Dark-appearing streaks of transferred material (*A*) run from groove centerline toward groove OD, in the direction of ball spin velocity (image SW to NE). The galled material is shiny, the dark appearance in the image is due to light reflection away from the camera.
Suspected Causes: Thrust ball bearings run with high spin to roll velocity ratio. When rotational speed is excessive and load relatively low, centrifugal forces agravate spin. Galling is a common failure mode, especially under marginal lubrication.

Data

Plate No: 8.7
Archive No: 093-027x
Image type: view
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 2: 00.13.02 Extensive galling
Failure Code 3: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
Failure Code 4: -



DESCRIPTIONS

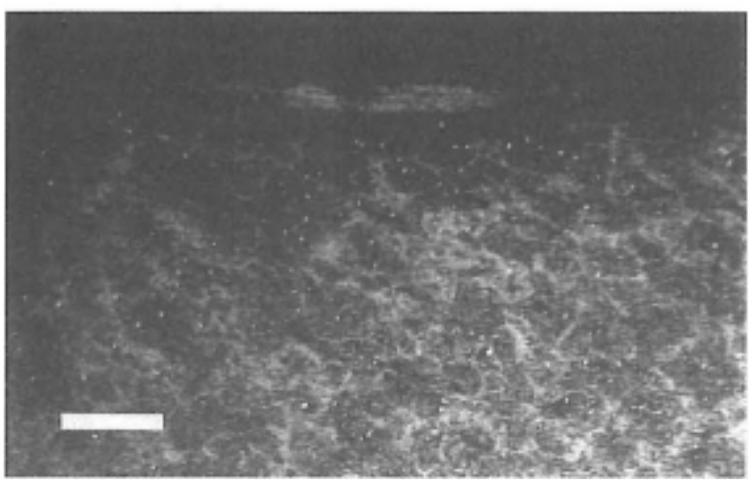
Failure Description: Extensive circumferential galling streaks on rolling surface, concentrated on 2/3 of roller path width on both rollers. The rollers are extensively worn on the rolling track. Bearing is noisy and may run hot. With continued galling, seizure is likely.
Image Description: Both rollers (from the same bearing) show wear across rolling path. Many intermittent circumferential galling marks appear matte and light colored.
Suspected Causes: The wear and galling appears to have arisen from solid contaminant. Contamination, nicks, skidding of rollers jammed in the separator and bearing misalignment are suspected as galling causes.

Data

Plate No: 8.8
Archive No: 074-11&12
Image type: a: light micrograph, b: metallogram, etched
Scalebar = a: 100, b: 20 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: 00.19.5 Local structure damage from frictional heating
Failure Code 4: -



a



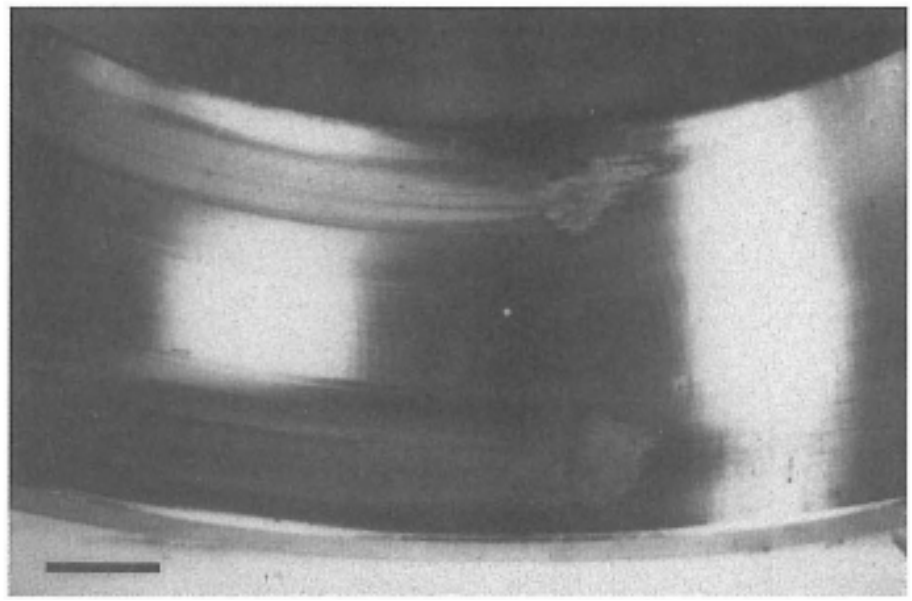
b

DESCRIPTIONS

Failure Description: (a): Material transferred onto surface by galling; subsequently overrolled and fatigued; surface distress microcracking and microspalling. The transferred material is expected to initiate a spall. (b): Material underlying the galled surface suffered structure damage (overtempering). The transfer particle is rehardened or heavily cold worked.
Image Description: (a): Largely featureless gray background is material transferred in galling. Thin N-S lines are wear marks subsequent to galling. Branching irregular lines are microcracks of surface distress in the transferred material. Black spots are surface distress microspalls. (b): S 2/3 of image is cross section, etching darker from overtempering near surface. Transfer particle near image N etches light (worked or rehardened).
Suspected Causes: Excessive sliding under high load may initiate galling. Deposited material is heavily cold worked, with high residual stress, leading to early microcracking upon overrolling. This creates surface distress microcracks and microspalls. Sliding events sufficient to cause severe galling may overheat and retemper subsurface material. Transfer particles undergo severe heating and plastic working.

DATA

Plate No: 8.9
Archive No: 093-030
Image type: light macro
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.1.1.1 Ring galling at load zone entry
Failure Code 2: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 3: -
Failure Code 4: -

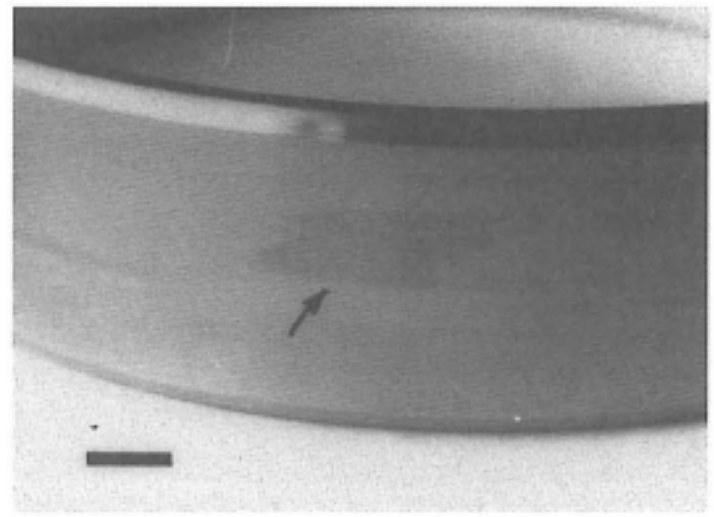


DESCRIPTIONS

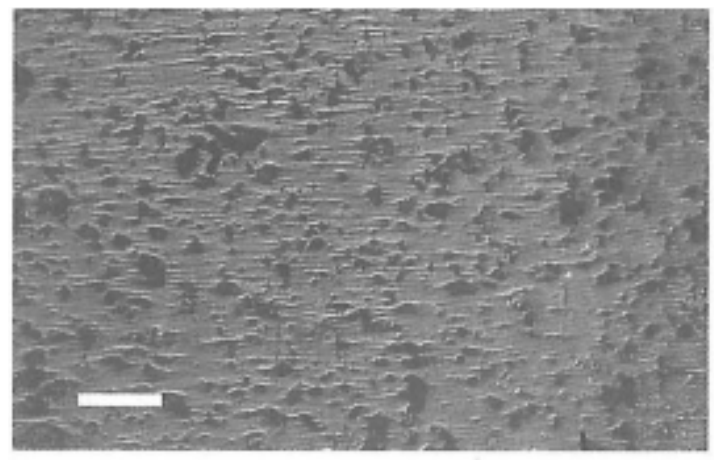
Failure Description: Both rolling paths in the SRB OR show wear tracks in the load zone. At the load zone entry point, a patch of galling precedes each wear track. The rollers in this large bearing slowed autorotation in the unloaded zone (separator braking) and accelerated rapdily at load zone entry, causing galling. In the load zone, wear tracks, from contaminant or galled roller. Galling may cause seizure, heat imbalance, or spalling.
Image Description: Two matte gray E–W wear tracks, bordered by dark-appearing shiny bands, extend over 3/4 image width, from image W. Over most of their length, the tracks are constant width, but narrow near E end. Just to the E of each track is a light-colored irregular patch of galling outlined in a dark-appearing shiny halo. The tracks mark the load zone in this OR, the galling is at its entrance.
Suspected Causes: Rollers in the unloaded zone of a large horizontal-shaft bearing may lose epicyclic autorotation speed due to separator friction. The high accelerating moment needed to restore speed at load zone entry may exceed contact traction and lead to slip, with galling. The wear band may be due to contaminant or ring marking by the galled roller.

DATA

Plate No: 8.10
Archive No: 074-8&9
Image type: a: light macro, b: SEM
Scalebar = a,b: 50 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.1.1.2 Contact galling from high acceleration
Failure Code 2: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 3: -
Failure Code 4: -



a



b

DESCRIPTIONS

Failure Description: Patch of thin discontinuous lamina of transferred material on otherwise sound rolling path. Transferred material has been worn by subsequent running. Such galling occurs when sudden acceleration is imposed on roller with insufficient friction, so that momentary high sliding results. If acceleration is not repeated, galling may heal (be worn smooth), which has already started. Further sliding tends to add gross galling at same area.
Image Description: (a): Part of IR roller path. Dark-appearing irregular patch at arrow is galled. Other surfaces show normal wear. (b): Discontinuous layer of transferred metal (shiny) interrupted by many roughly circular patches of original surface, indicating that material transfer occurred in many small increments. Transferred material is higher than surrounding surface and wears preferentially (E-W wear scratches from sliding).
Suspected Causes: In some high-speed CRB applications (as in gas turbine engines), load is low and variable (maneuvering loads). Roller autorotation and orbiting speed may slow down when unloaded and is rapidly accelerated when load returns. Under light load, friction does not suffice to prevent high-speed sliding, causing the galling. During continued operation the transferred material wears.

DATA

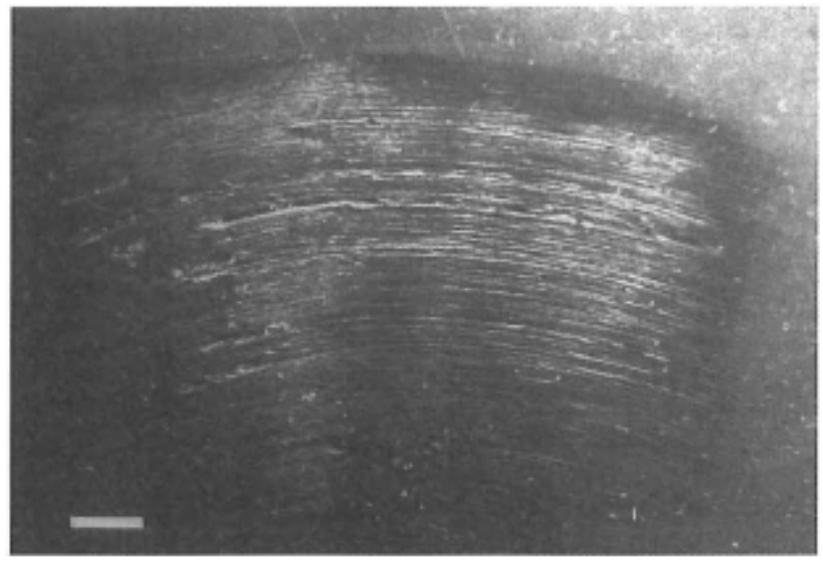
Plate No: 8.11
Archive No: 107-001a&b&c
Image type: SEM
Scalebar = a: 100, b: 100, c: 10 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.13.2.1.1.2 Contact galling from high acceleration
Failure Code 2: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 3: 00.12.0.1 Adhesive mild wear
Failure Code 4: -

DESCRIPTIONS

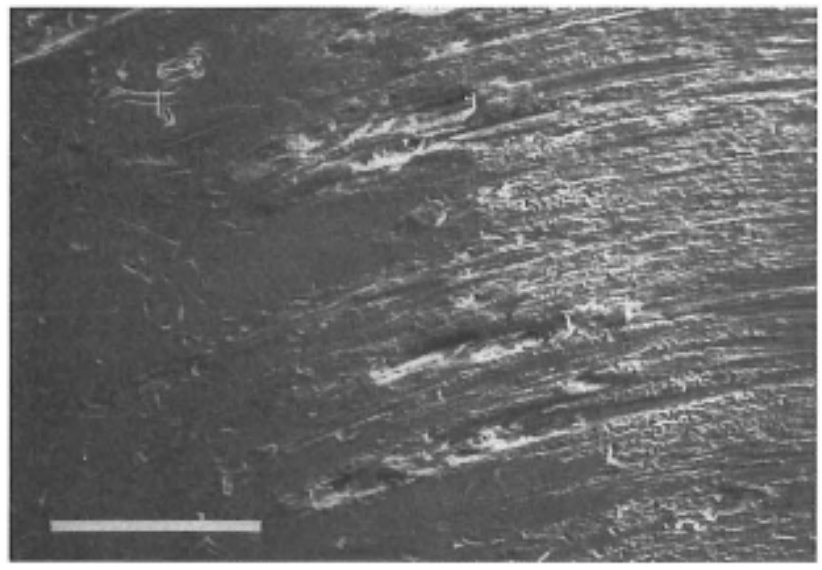
Failure Description: Confined sliding mark on ball surface. The ball spun and became worn by adhesive wear and, at points of most severe contact, galled. Such damage occurs in high-speed applications when kinematic anomalies precipitate sudden high sliding rates (for example, rapid ball acceleration). As the ball approaches epicyclic speed, sliding rate diminishes and galling occurrences fade out. Galled surfaces tend to gall again, spall or seize.

Image Description: (a): On gray matte background, circular sector of wear marks (dark background, scratch marks). At W sector edge, several deep tears, extending along arcs, are galling. Galling fades to the E. (b): Galling initiation area, already smoothed by rolling over. (c): Detail of galling, with plastically flown material moved and welded on surface. Small random background scratches are kinematic wear marks.

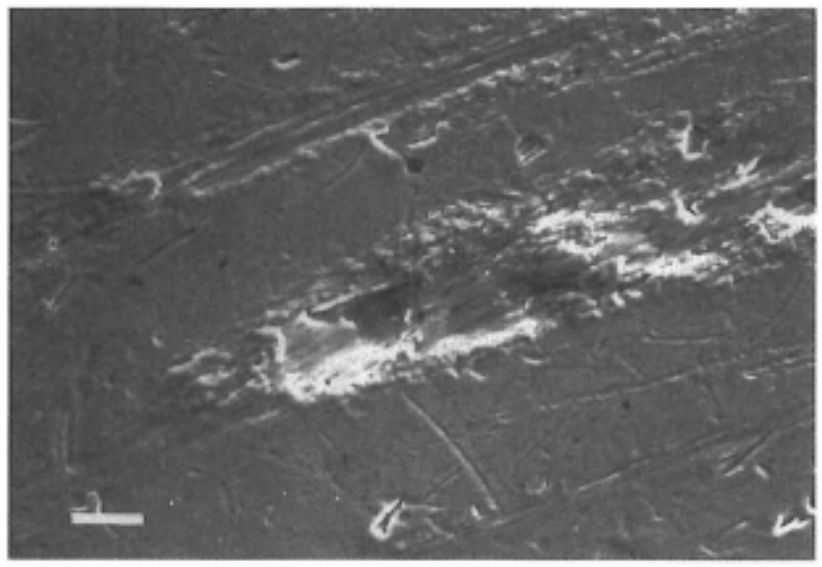
Suspected Causes: If in a high speed bearing, unloading of a ball and/or high separator friction causes drop in ball autorotation speed, and load suddenly returns, the angular acceleration becomes very high. Friction may not suffice to prevent gross sliding, local overheating, asperity welding, tearing and redeposition of material elsewhere on the surface. See also FC 00.14: Skid marking.



a



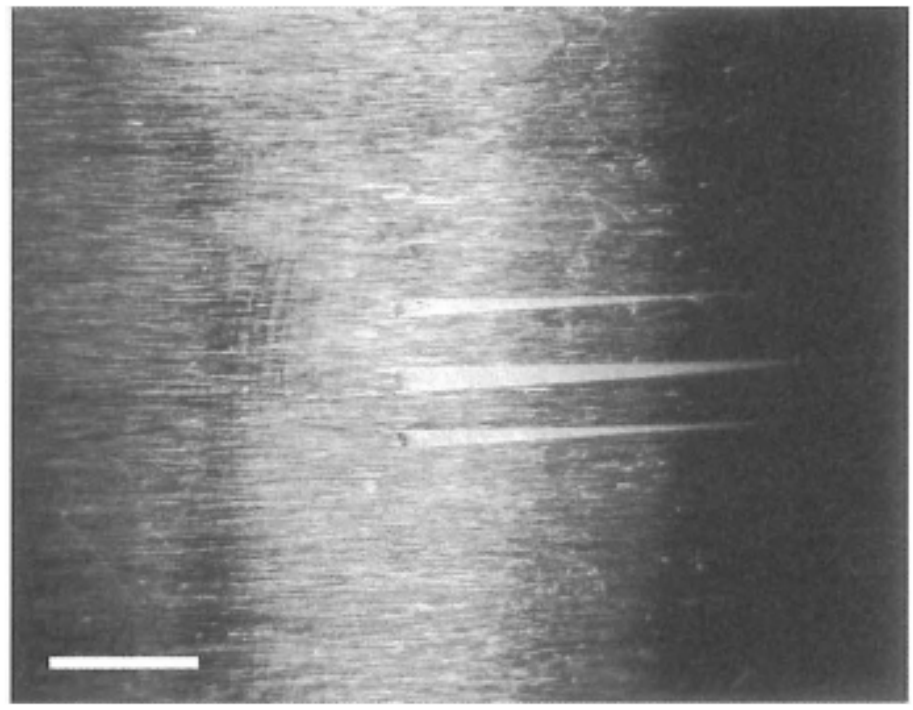
b



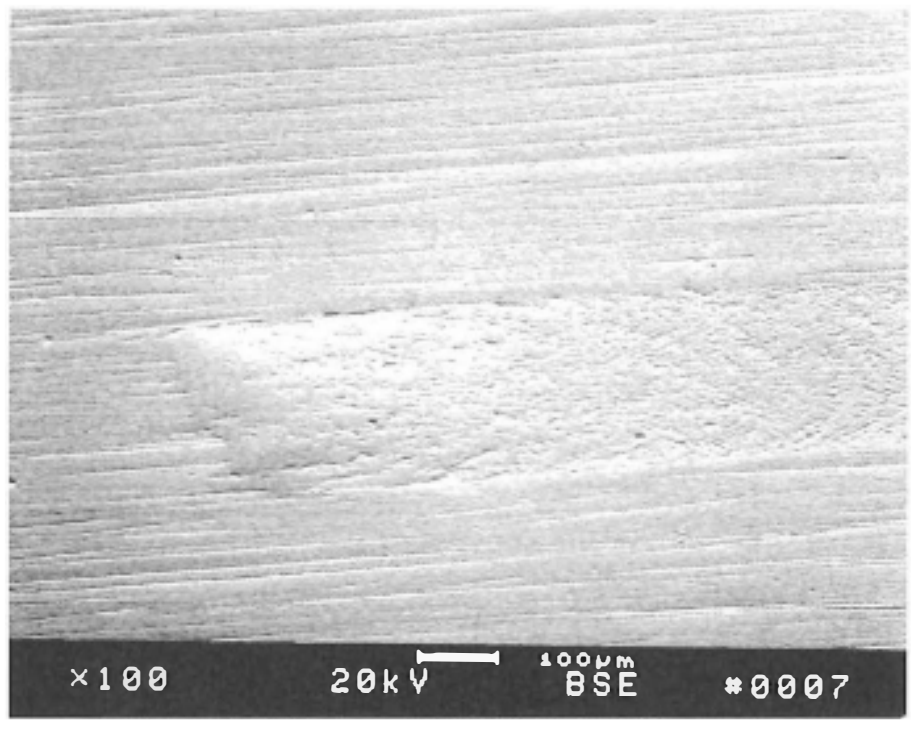
c

DATA

Plate No: 8.12
Archive No: 005-32&33
Scalebar = a: 1 mm, b: 100 μm (micros: ±20%, others: +100%, −50%)
Image type: a: light micrograph, b: SEM backscatter
Component: C; CM, run
Speed: 1.18 - 2.5 m/sec rolling
Load: 1.10 - 1.25 GPa
Lubrication: engine mineral oil; temp: varying
Failure Code 1: 00.13.2.1.1.2 Contact galling from high acceleration
Failure Code 2: 00.13.01 Incipient galling
Failure Code 3: 00.18.01.1.2 Denting of rolling surface, minor sliding
Failure Code 4: -
See also PLATE: 10.37



a



b

DESCRIPTIONS

Failure Description: Fine galling marks on the valve-opening ramp of an engine cam contacted by a roller follower traveling over the cam surface from tip to blunt end of the mark, in the presence of substantial sliding. Galling streak progressively widens by transferred material pileup and abruptly ends when roller achieves pure rolling velocity. Close alignment of galling marks, especially at endpoint, suggests they were formed in the same roller pass over the cam surface. Isolated short dents (scoremarks) elsewhere may develop into incipient galling. Overrolling direction is image E to W, sliding velocity of roller over cam is E to W, that is, the roller is being accelerated to cam speed and the roller is the lagging surface.
Image Description: (a): Light micrograph of part of cam surface on valve-opening ramp. Finishing marks are circumferential. Three strongly elongated triangular (arrowhead shaped) light gray, finely mottled galling streaks are seen with sharp inception points at slightly staggered vertical position 1/4 from E image edge. Galling mark abruptly ends in piled-up transferred material at the same E–W position near image center. Four much shorter, thinner bright dents (scoremarks) N of the ending line of the galling marks. (b): SEM of endpoint of S-most galling streak shown in (a). Finishing marks obliterated in galling streak. Arcuate rows of fine stippled indentations on plastically displaced metal, with tips of arcs pointing E. Bulging pileup of transferred metal at W end of streak. Surface rolled over repeatedly after galling event, resulting in smoothed appearance.
Suspected Causes: Roller followers in internal-combustion engine cam systems can follow the angularly varying cam surface velocity without sliding only by undergoing high accelerations. The normal contact pressure varies from zero to high values during each cam cycle. The roller follower is supported on a sliding pin-bearing in which sharp friction torque excursions were found to occur. The traction force available in the cam/roller contact may at some points in the cam cycle be insufficient to provide the required acceleration and overcome pin friction, resulting in sliding in the contact. If the sliding velocity and prevailing contact pressure exceed the galling limit of the contact, galling occurs. It consists typically of fine streaks widening as they progress and ending sharply when the combination of acceleration requirements and pin torque drops sufficiently to permit pure rolling. On subsequent rollovers, the combination of roller acceleration requirement and pin friction may remain below the galling threshold.

DATA

Plate No: 8.13
Archive No: 002-016c&g
Image type: a: light macro,
b: metallogram, etched
Scalebar = a: 5 mm, b: 400 μm
(micros: ±20%, others: +100%, −50%)
Component: CRB; OR, 52100 steel, run
Speed: 0.09 MdN
Load: 0.8 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.13.2.1.2 Rolling surface galling, dent or nick visible
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.04.1 Forming lap
Failure Code 4: -

DESCRIPTIONS

Failure Description: Foreign steel chip rolled into contact surface; welded in; galling of the chip surface extended laps over original rolling surface. This unusual damage sequence creates high stress concentration and was observed to have caused bulk cracking.
Image Description: (a): In ball groove (S of 'rear land'), round-ended E–W streak of lighter-color material surrounded by dark area, runs E for *A–A*. It is a rolled-in foreign steel chip. Thin laminae of transferred metal at black arrows. (b): Metallographic section, Nital + Zephiran etch. Heavily plastically worked chip (swirl flow-lines) in NW image quadrant. Dark weld line to base metal from SW corner to arrow *A*. Lap at *A*.
Suspected Causes: A steel chip was entrapped on the OR roller path when operation was initiated. It was rolled into the original surface, welded in and laminae were transferred along the edges. Incorporation of such a large chip into a rolling surface during operation is extremely rare.



a

b

DATA
Plate No: 8.14
Archive No: 093-026
Image type: view
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.2 Galling of sliding contact surface
Failure Code 2: 00.13.01 Incipient galling
Failure Code 3: -
Failure Code 4: -

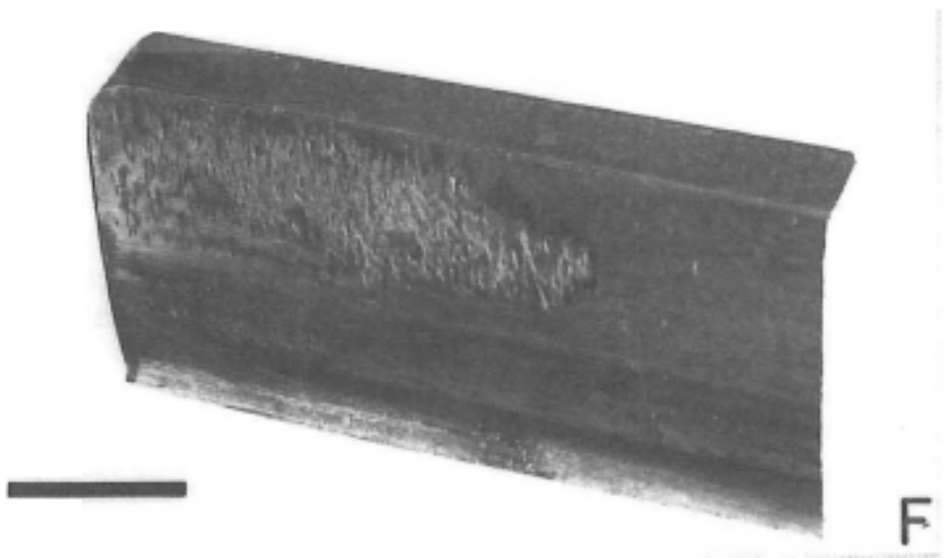
DESCRIPTIONS
Failure Description: Epicycloidal galling marks on roller thrust face, extending from the roller corner radius to flange height. The marks trace the path of a locally overloaded flange point over the roller thrust face, as it transfers material to that thrust face. In this image, no sign of sharp edge contact is visible, indicating that the geometry is correct. Galling is self-aggravating, may cause seizure, heat imbalance or separator failure.
Image Description: On gray background of roller thrust face, dark-appearing cycloid streaks end radially near the corner and curve to tangential direction at the flange height. The streak material is shiny; dark image is due to light reflection. If magnified, transferred material would be discernible. In the image, an entire half-cycloid is visible since flange and roller face conform. Otherwise, marks appear only near corner radius or at flange edge level.
Suspected Causes: Excessive thrust load, inadequate lubrication, skewed rollers, contamination, rough surfaces. Galling near edge indicates a sharp edge at the flange.

DATA
Plate No: 8.15
Archive No: 018-128
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR & R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.2.2 Galling of sliding contact surface
Failure Code 2: 00.13.02 Extensive galling
Failure Code 3: 00.12.3.3.1 Wear at edge of sliding contact
Failure Code 4: -

DESCRIPTIONS
Failure Description: Short epicycloidal galling marks on roller thrust faces, and IR thrust flange face, centered in thrust contact band. Step worn into roller thrust faces, to flange height, as galled work-hardened materal slides over mating part. The step worn into the roller end suggests excessive contact with IR flange edge. Damage destroys geometry, causes roller skewing and debris that may lead to spalling. Heat imbalance failure is likely.
Image Description: Short angled galling streaks of light color on visible face of IR thrust flange, near both E and W image edges. Depressed annulus worn on roller thrust faces, with angled galling streaks near center of annulus. Streaks may appear light or dark colored depending on lighting.
Suspected Causes: Contamination, rough contact surfaces or inadequate lubrication of thrust surfaces, probably acting in combination, produce the galling. Roller skewing shifts contact toward flange edge.

DATA

Plate No: 8.16
Archive No: 099-125a
Image type: light macro
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, med. hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.3 Tooth contact galling
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 8.18

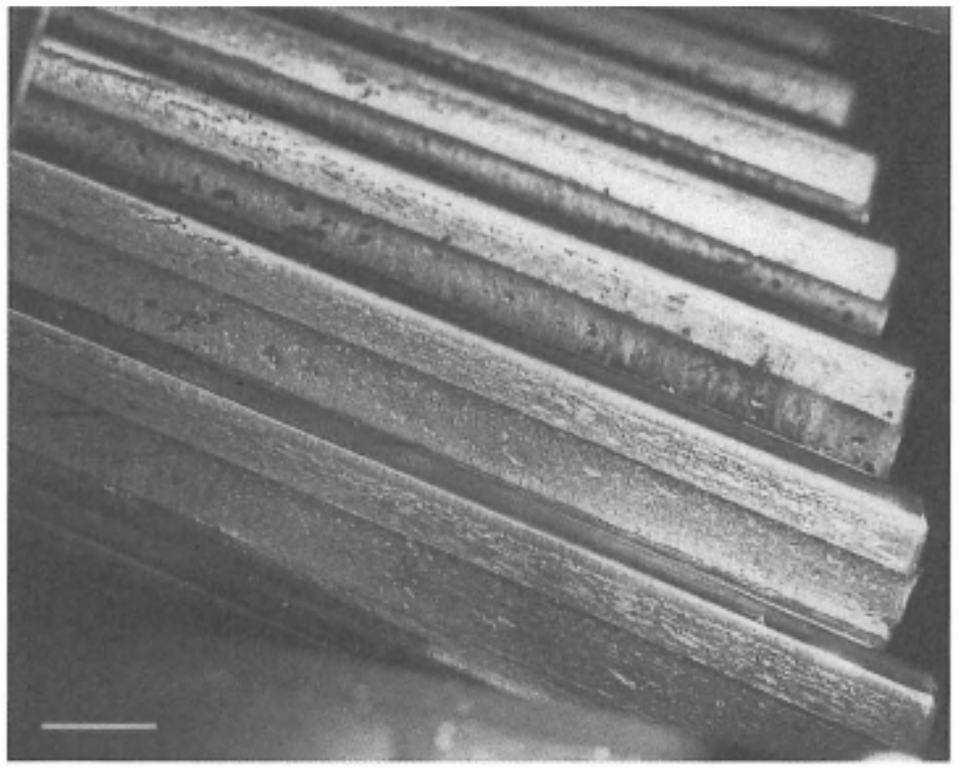


DESCRIPTIONS

Failure Description: Major galling of tooth addendum surface, also designated as scoring. Welding of asperities between pinion and wheel, with immediate tearing as teeth separate. Leaves transferred material on one tooth and a matching pit on the mating tooth. High load, high sliding velocity and insufficient lubrication produce galling on teeth with unsuitable finish and/or hardness. This is a destructive failure.
Image Description: From W edge of gear through 2/3 of image width, multiple radial galling streaks in addendum, appear light colored on gray background. Dark halo around galling is shiny, polished (worn) surface. It appears dark due to lighting. Minimal galling in dedendum.
Suspected Causes: Geometrical inaccuracy or misalignment (overload near one sideface), rough surface, insufficient hardness, overload, high speed and inadequate lubrication all may contribute to galling. See also Plate 8.17 showing material transferred by galling between mating locations on pinion and wheel.

DATA

Plate No: 8.17
Archive No: 064-404
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others; +100%, −50%)
Component: HG; W, surface hardened, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.3 Tooth contact galling
Failure Code 2: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 3: 00.12.5.3.1 Abrasive (destructive) tooth wear
Failure Code 4: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities



DESCRIPTIONS

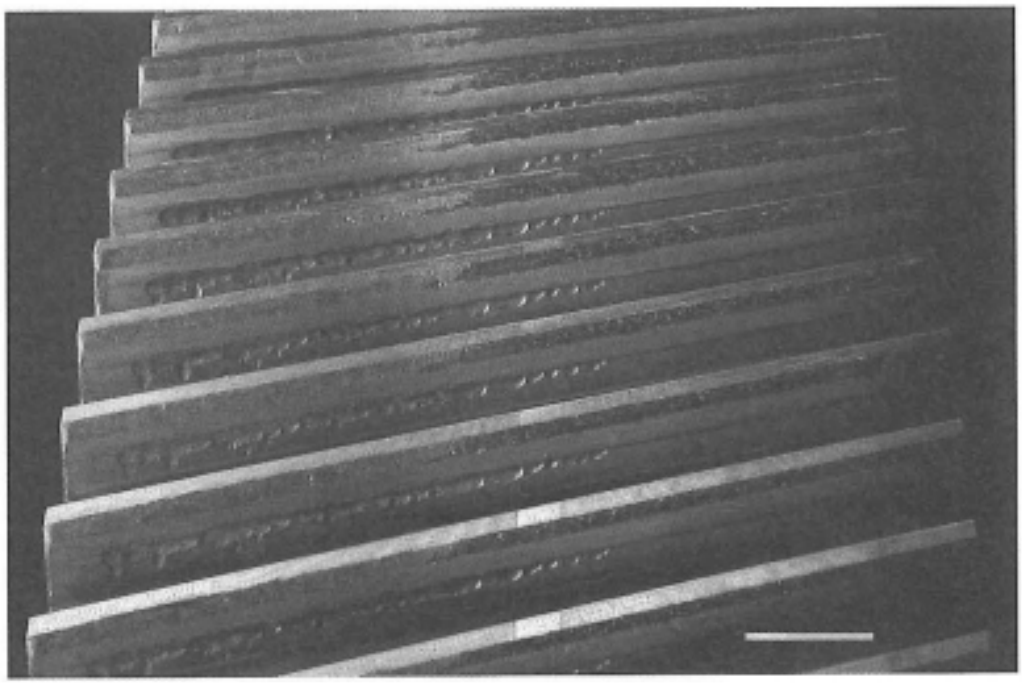
Failure Description: Advanced tooth surface damage comprising galling, destructive mild wear (probably abrasive), denting and spalling. The galling is concentrated in the addendum, dents and abrasive wear in the dedendum, with spalls in both areas, more toward one side of the gear. The gear may still run, but would be noisy, with increased backlash. It may eventually fracture.
Image Description: Across tooth flanks (especially well shown on tooth starting in SE corner), four distinct contact bands are visible. At the tip, a narrow band with radial wear marks, followed by a band of many axial galling streaks (light) and some black spall craters. After a sharp demarcation at the pitchline, a band of severe debris denting with some radial wear bands and many spall craters (in W), followed by the apparently unworn root.
Suspected Causes: Contaminated operation with heavy wear over long period, at speed sufficient to promote galling (at roughened spots?) and eventual spalling.

DATA

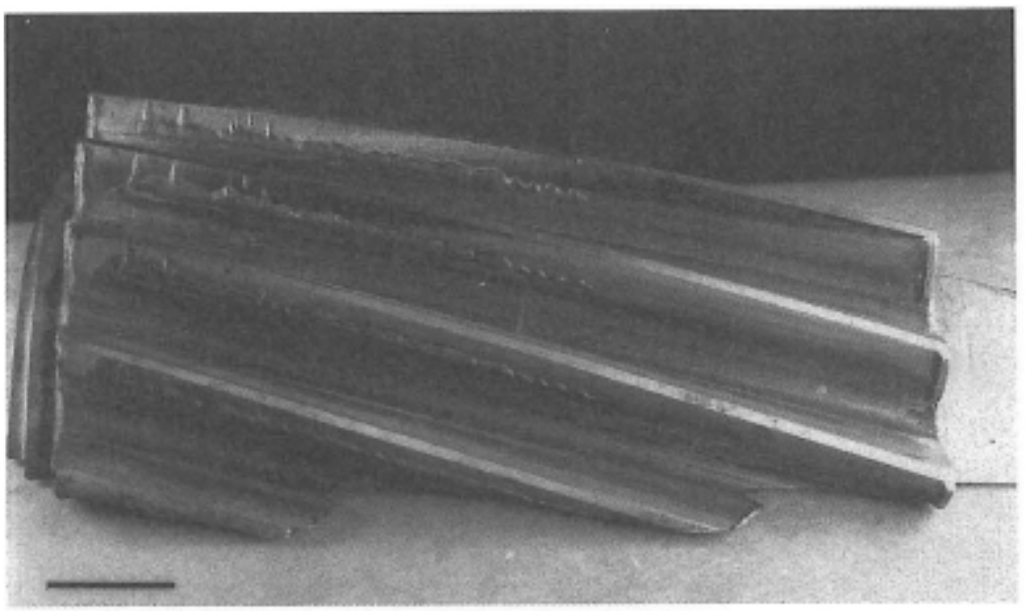
Plate No: 8.18
Archive No: 099-126a&b
Image type: a,b: light macro
Scalebar = a,b: 30 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W&P, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.13.3 Tooth contact galling
Failure Code 2: 00.16.1.2 Surface origin spall
Failure Code 3: 00.12.5.3.2 Adhesive (destructive, non-galling) tooth wear
Failure Code 4: -

DESCRIPTIONS

Failure Description: In a mating gear set, asperity origin cracks form in dedendum of gear (wheel) (a). The weakened material is welded to the opposing pinion surface. Transferred metal on pinion (b) forms protrusions, mating with craters left on the wheel. Wear, denting of wheel tooth tips. Gear set is prone to early failure from overstressing of damaged flanks.
Image Description: On wheel (a): cratering (dark pits) on dedendum. On pinion (b): transferred metal streaks on the addendum are generally light colored on the addendum and mate with dedendum spall craters. Tooth tips on (a) are worn and dented.
Suspected Causes: High-load, low-speed gear sets, of medium hardness, with poor lubrication, may develop this combined condition of spalling and galling, whereas at high speed, galling, if present, generally occurs before spalls can form, and tends to lead to gross failure.



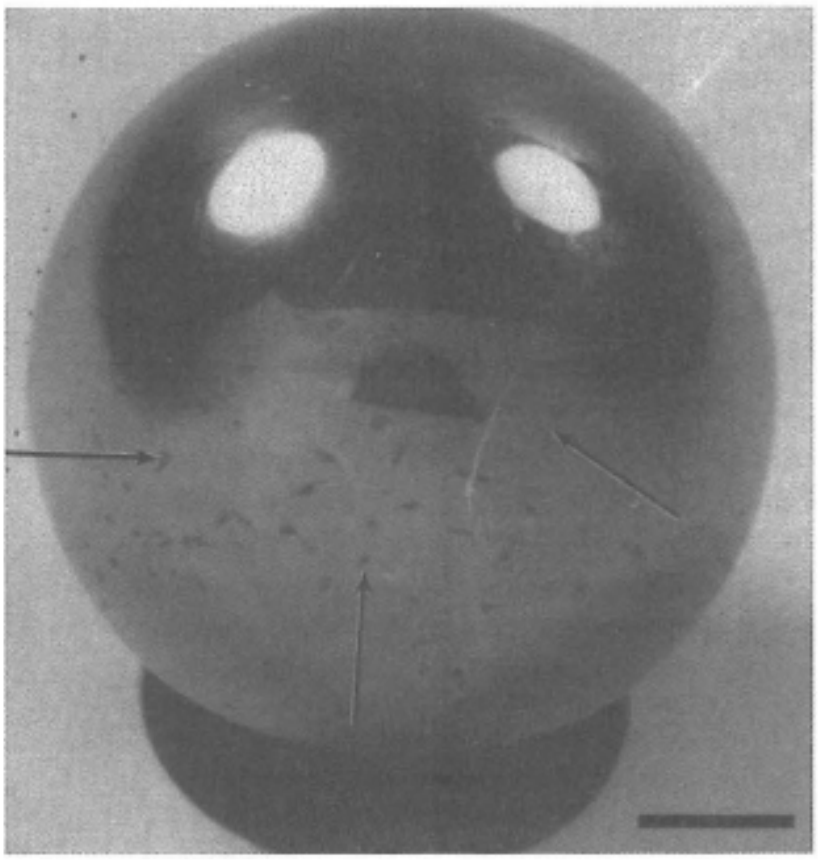
a



b

DATA

Plate No: 8.19
Archive No: 027-178
Image type: view
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed: 270 KdN
Load: 1.8 GPa
Lubrication: grease, 60°C
Failure Code 1: 00.14 Skid marking (microscopic severe wear)
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Multiple short skid marks in random directions on entire ball surface, from many short acceleration events under insufficient load. Skid marking causes noisy operation in quiet running bearings and may eventually lead to spalling.
Image Description: The mirror-finished ball surface is illuminated by two spotlights (white circle reflections). The light stand and camera reflect as black shapes, covering most of N hemisphere. Elsewhere, the ball surface is gray. Multiple black brush marks in random directions are skid marks. Three are identified by arrows.
Suspected Causes: This angular contact ball bearing must operate under preload. In the present case, preload was insufficient and at each startup of the machine, skidding occurred, making a skid mark. The ball repeatedly changed orientation.

DATA

Plate No: 8.20
Archive No: 007-109
Image type: light metallogram, unetched surface
Scalebar = 400 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.14 Skid marking (microscopic severe wear)
Failure Code 2: 00.02.1 Grinding, honing, lapping furrow
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Repeated skid marking of a lapped ball surface. Ball assumed three orientations. Skid marking results from momentary high sliding speed in the contact, arising from insufficient traction to transmit required acceleration. In high-speed bearings, skid marking may lead to spalling.
Image Description: In this view of the ball surface through a metallograph, light incidence is normal and collimated. Any surface reflecting specularly away from normal appears dark. Unaffected ball surface is gray background. Lapping marks are thin, dark random straight lines. Long skid mark (interrupted parallel black streaks) runs NW to S; another crosses it W-E near center; one each in SE and NE corners, running SW to NE.
Suspected Causes: Excessive radial looseness, sudden loss of load or excessive friction in separator contact may reduce ball autorotation speed, requiring high acceleration when load returns, which leads to skid marks.

DATA
Plate No: 8.21
Archive No: 027-153
Image type: light macro
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed: 270 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.14 Skid marking (microscopic severe wear)
Failure Code 2: 00.12.3.2.0.6 (Wear track for combined radial/ axial load)
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: In the wear track of this OR are numerous short streaks of skid marking resulting from momentary sliding between ball and ring, due to insufficient axial preload, or rapid starts, or inadequate lubrication for given operating conditions. The local heating during a sliding event causes EHD film thinning and asperity-scale galling. Skid marks produce noisy running in quiet bearing applications and may lead to spalling.
Image Description: Except for streaks of reflected illuminating light running N-S, the unworn rolling path surface appears dark. A gray arced band running E-W about 1/4 from N image edge is the wear track. The many whitish circumferential streaks (as at arrows) are the skid marks. The overall appearance of a skid marked surface is 'frosted', when seen under no or low magnification.
Suspected Causes: This application must operate under axial preload in order to forestall sliding during rapid starts and at moments when the load drops. When preload is below specification, then insufficient traction is available to accelerate the balls for starts and when the intermittent external load returns, resulting in momentary sliding, EHD film overheating and breakdown and asperity-scale galling.

DATA
Plate No: 8.22
Archive No: 018-616
Image type: light macro
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed: >1 MdN
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.14 Skid marking (microscopic severe wear)
Failure Code 2: 00.13.2.1 Rolling surface galling
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: 00.16.1.2.1 Shallow entry spall from surface point-defect

DESCRIPTIONS
Failure Description: Failure was initiated as a streak of skid marks, followed by macroscale galling, and initial spalling. Spall debris caused multiple dents, decorated by surface distress halos.
Image Description: NW–SE running streaks of darker gray on uniform gray ball surface are skid marks which in the vicinity of the large spall appear to progress to macroscale galling (darker irregular areas) within the light gray 'halo' of surface distress bordering the large, dark, NW-SE running spall crater. Fracture ridges show spall progression. In the E hemisphere, irregular small dents with light-gray surface-distress halo.
Suspected Causes: The skid marking is due to rapid changes in bearing speed and temporary unloading of this turbine engine bearing (as in aircraft maneuvers), during which insufficient tractive forces exist to maintain epicyclic ball autorotation speed. Sliding results. Macro-galling initiates from skid marks and eventually leads to spalls. Spall debris causes dents. Depressions (dents, craters) deplete the EHD film causing surface distress halos.

DATA

Plate No: 8.23
Archive No: 093-14.1.3&5&8
Image type: a: light microgram,
b: SEM, c: metallog., etched
Scalebar = a: 850, b: 70, c: 12 μm
(micros: ±20%, others: +100%, −50%)
Component: a,c: ACBB; IR, b: CRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.14 Skid marking
(microscopic severe wear)
Failure Code 2: 00.19.5 Local structure
damage from frictional heating
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Skid marking represents multiple asperity-scale galling events that do *not* individually grow into micro-galling. This occurs if tractive forces momentarily required to overcome rolling body/ring surface speed differences are excessive so that skidding occurs. Skid marking may cause structure damage by local overheating. In high-speed applications skid marking may lead to spalling.
Image Description: (a): Gray, unmarked surface in NE quadrant. White E-W lines in area *A* are skid marks. At *C*, the skid mark area feathers out. Isolated marks at *B*. (b): Two skid mark streaks (white patches) run S from N image edge (*A* and within dashed oval). Skid marking stops at honing line *B*. Other honing lines at *C*. (c): Section through rolling surface (area *B*). White, rehardened skid mark deposits on dark tempered matrix at *A*.
Suspected Causes: Excessive radial looseness in bearing, or unexpected loss of load or excess friction in separator to rolling body contact may slow down autorotation of rolling body outside the load zone. When load returns, rolling body must accelerate rapidly. Tractive contact force may be insufficient and skidding (gross sliding) occurs momentarily, causing skid marking. Once rolling speed is reached, sliding stops, so no macroscopic galling occurs.

a

b

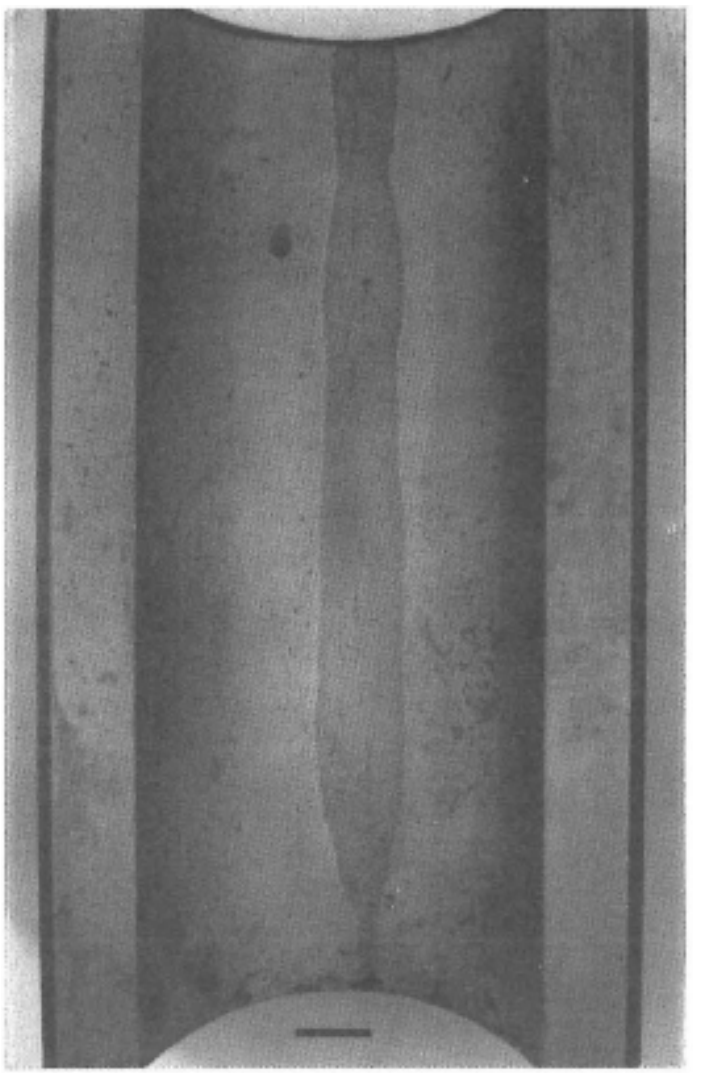
c

DATA

Plate No: 8.24
Archive No: 007-111&107&108
Image type: a: view, b, c: SEM
Scalebar = a: 25 mm, b: 200, c: 40 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: varying
Load: 3.5 GPa
Lubrication: grease, temp.: varying
Failure Code 1: 00.14 Skid marking (microscopic severe wear)
Failure Code 2: 00.20.01.1 Generalized corrosion
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

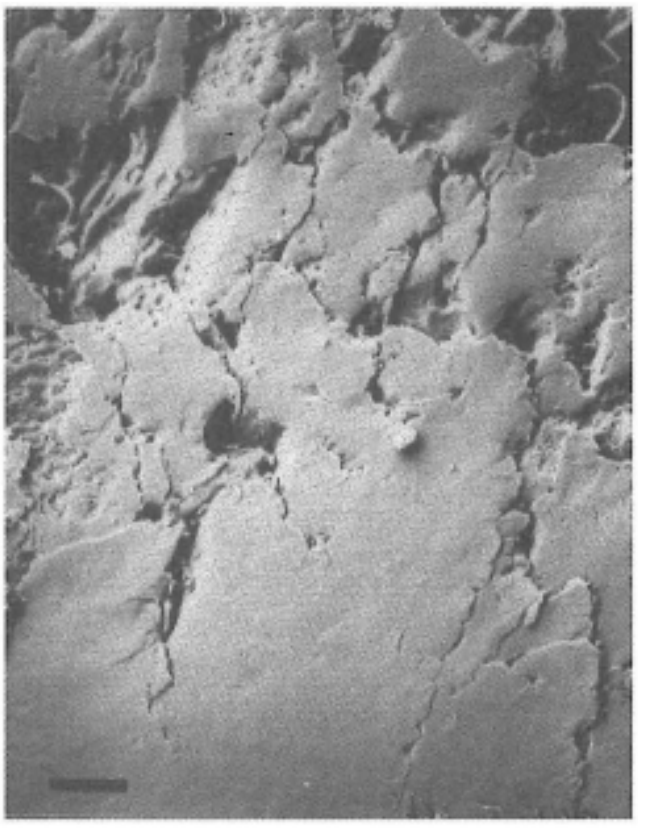
Failure Description: (a): Massive skid marking (microscopic severe wear) of IR ball path as a result of numerous brief high-acceleration events under high load. Incidental generalized corrosion. (b), (c): Details of skid marking: asperity scale material transfer with subsequent microspalling, in burnished surface. The cratering will eventually destroy the ring by seizure or fracture. As now seen, ring is still serviceable (separator may not be).
Image Description: (a): Varying width streak of mottled (frosted) surface down center of ball path, probably darkened by preferential corrosion after dismounting. Corrosion spotting elsewhere. (b): On featureless burnished surface, angular craters with N–S orientation. (c): Featureless transferred metal laminae in S image half, which overlap at edges (jagged black lines). In N 1/3, microscopic craters and cracks at exfoliated laminae.
Suspected Causes: This bearing is used in a naval aircraft arresting gear which operates by absorbing landing aircraft kinetic energy via an arresting cable unwinding from this gear. Bearings undergo high acceleration under high load during each arresting cycle. Skid marking arises from inability of ball complement to accelerate to epicyclic velocity.



a



b



c

FRETTING WEAR 9

Failure Code 00.15

9.1 Definition

Fretting wear is adhesive wear taking place in a nominally static contact under normal load and *microscopic* surface-parallel relative motion. The two types of fretting wear are *(common) fretting* and *false brinnelling*. Both are further defined below.

9.2 Nomenclature

In this Atlas, the term *fretting wear* is adopted to cover both (common) fretting and false brinnelling.

9.3 Failure Process

Fretting wear is an adhesive wear process with special features resulting from the confined geometry of the (macroscopically static) contact.

Fretting wear requires normal load on the contact, and microscopically small surface-parallel motion, which can be *vibratory* (in common fretting or false brinnellling) or *creeping* (in common fretting).

9.4 FRETTING — FAILURE CODE: 00.15.1

9.4.1 Definition

Fretting (common fretting) is defined as fretting wear in a conforming contact (typically a fit interface).

9.4.2 Nomenclature

Fretting wear in a conforming contact is designated as (common) fretting. (The word 'wear' is not used for this case.) A commonly used alternative designation is *fretting corrosion*. This latter designation is not used in the Atlas to avoid possible confusion with chemical attack (corrosion) unrelated to fretting and also because not all materials subject to fretting show discolored corrosion products.

9.4.3 Failure Process

Fretting (common fretting) occurs usually in fit interfaces that transmit radial (or combined radial and axial) load moving with respect to the fitted pair, as between bearing ring, gear or cam and fitted shaft, or bearing ring and housing. The fit must be tight enough so that rapid "spinning" of the fitted part is prevented but not so tight as to prevent entirely a slow creep (or reversing motion) in the fit interface. This creeping motion creates loose wear particles which, for common steels, oxidize in the (oxygen-starved) fit interface to form a blackish red, tightly adhering layer covering portions or all of the fit interface. This color justifies the name 'fretting corrosion', although the fretted oxide has been found to be chemically different from the brown stain of common corrosion formed on free surfaces in the presence of moisture.

9.4.4 Distinctive Appearance

A fretted (fit) surface of steel is a patchwork of three types of appearance:

- Oxidized patches varying in color from dark reddish to virtual black.

- Burnished areas of metallic color in which the original finishing marks are effaced; these areas may show wear marks in the sliding direction.
- Areas with original finishing marks.

There may be galled areas (FC 00.13) interspersed with the others, if the interface underwent rapid sliding.

Fretted surfaces of material other than the usual bearing steels may produce fretting debris that is not discolored.

Under the (scanning electron) microscope, fretted areas (after light etching to remove the adhering oxide) show micropits, where fretted particles have been worn off. They may also show clusters of short scratches, made by the wear particles during further motion.

9.4.5 Causes

General Causes of Fretting. The controlling *operating* parameters in (common) fretting are normal contact pressure and the specifics of the microscopic surface-parallel motion (total displacement or number of reversing cycles, amplitude).

The controlling *contact* parameters in fretting are not completely identified. Fit interference, which controls contact pressure and influences surface-parallel motion, is the dominant parameter. Surface material and microgeometry also exert influence, as follows.

Hard material appears to fret less than lower hardness material of the same composition:

- Hardened steel parts (bearing rings) fret less than soft steel shafts or housings.

Material composition appears to have an effect on fretting:

- Cast iron housings fret less than soft steel housings.
- Hard-chromium plated shafts or housings fitted to hardened bearing rings resist fretting better than soft steel shafts and housings. It is not clear whether the chromium material or its hardness is the principal factor.
- Two smooth surfaces in contact appear to fret less than rougher surfaces.
- Certain plastic coatings on a fit surface retard fretting.
- Suitable chemical coatings (example: phosphate coating) retard fretting.
- Certain compounded lubricants are believed to alleviate fretting.

Notes:

1. Most experience with fretting is related to corrodible steel and cast iron fit surfaces. "Stainless" steel and nonferrous metals also fret, but the oxidation to visible reddish oxide is not observed.
2. Little information is published regarding fretting of ceramic rings in (metal) housings. Fretting is believed to occur.

Fretting Causes in Rolling Bearings. Fretting in the radial fit surfaces between rolling bearing rings and shafts or housings is a widespread phenomenon not necessarily regarded as a (disabling) failure.

The fitting practice of rolling bearing rings is adapted to three classes of load orientation as follows.

1. Load of stationary direction with respect to the fit interface. In order to permit axial alignment of the bearing, such a fit is often made with positive looseness. The stationary load direction tends to hold ring and mounting part in a fixed relationship and fretting can be avoided. If the load substantially changes direction with some frequency and the fit is loose, rapid spinning in the fit surface is likely, producing polishing and galling, but not fretting. Bearing technology generally holds that this spinning is not effectively countered by end clamping; it may, at the

risk of cracks, be prevented by keying. Small changes in load direction that occur with some frequency may precipitate fretting.

2. Load of moving direction with respect to the fit interface. Due to the traveling deflection under the moving load, the ring tends to creep circumferentially with respect to the mounting part and fretting is probable. To limit fretting, a fit for moving load is almost always made with interference (negative looseness). In tight fitted moving-load interfaces, fretting decreases with increased fit interference. However, excessive tensile hoop stresses in relatively thin-walled rings, and mounting difficulties, limit the permissible fit interference so that fretting may not be totally avoidable.
3. A special case is where both rings in a bearing see loads moving with respect to the fit interface (example: in shaker screens). Interference fits for both rings may be impractical due to the resulting inability to accommodate differential thermal expansion of machine components. In these cases, surface coatings may be helpful in counteracting excessive fretting.

Fretting Causes in Gears and Cams. Gears or cams are generally not fitted into housings (with the possible exception of an internal gear), but often are mounted on shafts. The load direction in the fit interface of a gear or cam on a shaft is very rarely stationary.

Gears transmit torque so that they are often keyed to shafts. Even so, fretting is occasionally observed, from causes identical to those listed for bearings.

Cams undergo torque whenever the normal contact force on the cam lobe fails to intersect the shaft axis, such as along all ramps. If the cam is fitted on a shaft, fretting may occur.

9.4.6 Effects of (Common) Fretting

Fretting in a load carrying fit interface may have the following effects:

- Fretting may prevent smooth disassembly by greatly increasing friction against axial removal of bearing ring or gear from shaft or housing. The obstruction may be severe enough to cause fractures or require cutting of rings or gears.
- Fretting roughens the surface and damages the fit geometry causing increased rate of fretting, or spinning with wear or galling. The geometric distortion may suffice to weaken load support and lead to ring or gear cross section cracking.
- A severely fretted surface may contain microcracks. If the component is subject to cyclic bending stresses (examples: bearing rings, gears or shafts), then bulk fatigue cracking may initiate from these microcracks. This is a common failure progression sequence.

9.5 FALSE BRINNELLING FAILURE CODE: 00.15.2

9.5.1 Definition

False brinnelling is defined as fretting wear in a Hertzian contact.

9.5.2 Nomenclature

There is no common alternative designation for false brinnelling.

9.5.3 Failure Process

False brinnelling describes the creation of a surface depression in a loaded, macroscopically static Hertzian contact, by the fretting wear produced between the contacting elements when subject to repeated microscopic vibratory motion. The motion may be a small angular oscillation and/or repeated widening and narrowing of the Hertz area as a result of time-variable normal contact load.

The surface in a *false* brinnell mark is worn, as distinct from that of a *true* brinnell mark (FC 00.18), which is a plastic indentation created by the one-time application of a high normal load to a static contact or of a shock load of brief duration to a slowly moving contact.

9.5.4 Distinctive Appearance

The false brinnell mark on a Hertz contact surface is a depression in the shape of the static Hertz contact area. This mark is identical in shape to a true brinnell mark created by plastic indentation of the contacting body (see FC 00.18). The surface in the false brinnell mark is a wear surface—original finishing marks are effaced and a matte, non-directional surface appears. By contrast, the surface of a true brinnell mark retains the original finishing marks.

9.5.5 Causes

Rolling Bearings. Two distinct causes of false brinnelling in bearings are known.

1. Bearings under load while not rotating, but subject to ambient vibration or shock as during the transport of a packaged bearing or a machine by rail (to a lesser degree by truck), undergo microscopic relative motion in the Hertzian contacts and develop false brinnelling. The effect on bearings transported in machinery may be controlled by making changes in shipping arrangements, such as unloading the bearing or cushioning the vibration. The effect on bearings shipped in packages appears to be limited to certain classes of large bearings and is controlled by packaging that applies known elastic loads across the contacts.
2. Bearings in a service entailing load carried under *low-angle* oscillatory motion may suffer false brinnelling which may be mitigated by design, load adjustment and selection of lubricant. However, false brinnelling is not always avoidable in such service conditions.

It is believed that contact pressure reduction, harder contact material including some coatings and smoother contact surfaces reduce the severity of false brinnelling.

Certain compounded lubricants are reputed to alleviate false brinnelling, but their efficacy appears to be limited to marginal cases.

Gears and Cams. Gears in loaded contact under microscopic motion (example: spline couplings) may suffer false brinnelling.

False brinnelling in cam systems is not believed to be a common failure.

9.5.6 Effects of False Brinnelling

Rolling Bearings

- A false-brinnelled bearing will be noisy (vibratory) in operation.
- Severe false brinnelling may produce sufficient load increases upon operation to bring on premature spalling.
- The false-brinnelled surface, being different in topography than the manufactured surface finish, is likely to impair EHD lubrication and be more prone to surface distress and consequent spalling than undamaged surface areas.

Gears and Cams. False brinnelling is not generally considered a failure in gear technology, unless it makes the system vulnerable to secondary wear, fatigue or galling failure resulting from further contact on the false-brinnelled, and therefore geometrically impaired, surfaces. Causes and control are similar to rolling bearings.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.15.1	9.15 10.44
00.15.1.1	14.13
00.15.1.2	6.37 7.16 7.26 10.12 19.1
00.15.1.2.0.2	18.11
00.15.1.2.0.3	15.1
00.15.1.2.0.6	15.33
00.15.1.2.0.7	15.33
00.15.2	11.4

PLATES

DATA

Plate No: 9.1
Archive No: 093-15.1.3
Image type: SEM, HCl etch
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: synthetic polyester oil, 80°C
Failure Code 1: 00.15.1 Fretting (fretting corrosion)
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Surface covered with short parallel scratch marks caused by the asperity scale sliding motion of IR moving on shaft under rotating load. Length of marks suggests 20–40 μm sliding amplitude. Numerous small (<10 μm) pits indicate fretting. A few fretting corrosion flakes. Fretting destroys shaft geometry for mounting a replacement bearing. Excessive fretting may initiate cracking or lead to ring spinning on shaft and seizure.
Image Description: Background surface, where visible, is a featureless gray indicating removal of grinding lines. Many circumscribed patches filled with W–E (or slightly S of E) running wear marks. Numerous pits due to fretting, with light-colored 'halos' (indicating sharp edges?). Fretting corrosion product removed by etching, except for a few isolated dark flakes.
Suspected Causes: IR operating under rotating load (stationary against OR), and fitted with moderate interference, may deform under load to create a gap opposite the load and then it describe epicyclic motion on the shaft. If motion is *slow*, then moderate fretting occurs. If it is *fast,* heavy fretting, polishing or galling may occur.

DATA

Plate No: 9.2
Archive No: 093-22.1.4
Image type: light macro
Scalebar = 12 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; IR&OR, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral oil, 100°C
Failure Code 1: 00.15.1.1 Generalized fretting, radial fit surface
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: 00.16.1.1.2 Spall from subsurface defect
Failure Code 4: 00.22.1 Overstress crack

DESCRIPTIONS

Failure Description: OR of heavily loaded DGBB moved microscopically in housing, possibly aided by housing wear or inaccuracy causing heavy fretting corrosion. An inward-going cross-section crack was initiated in bending fatigue at the OD where the surface was damaged by the fretting. When the crack reached the Hertzian shear stresses, a subsurface-origin spall was precipitated. Eventually, an overload crack split the ring. The bearing has failed.
Image Description: Sectioned outerring viewed from OD (part 'a'), with heavy black fretting patches and a gray round spot where housing was interrupted by a sensor bore. Crack surface is E face (not seen). Other ring half viewed from ID (part 'b'), with mating crack surface at *A*. Fatigue crack starts at OD (half-moon shape); spall extends from it. Remaining section suffered overload cracking.
Suspected Causes: Very heavy radial load of (fatigue test) bearing often causes OD fretting, requiring special fitting precautions. When fretting is excessive, fit surface becomes vulnerable to bending fatigue cracking, which may be followed by spalling at the contact surface and, finally, overload fracture.

DATA

Plate No: 9.3
Archive No: 027-119
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: DGBB, run
Speed: 250 KdN
Load: 2.7 GPa
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.2.0.3 Excessive fretting, loose or inaccurate radial fit
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.4 to 9.8

[See Image in Appendix]

DESCRIPTIONS

Failure Description: OR OD covered with fretting corrosion (in localized load zone) indicates radial load and loose or inaccurate fit. Excessive vibration of rotor has same effect. See Plates 9.4 through 9.8 for comparison. Fretting of this severity may lead to bulk cracking.
Image Description: Reddish-brown coating covering OR OD to full OD width, extending angularly through load zone. Fretting corrosion product may be more reddish than chemical corrosion (not distinguishable in this image). Location and pattern on bearing are diagnostic.
Suspected Causes: Significantly radially loaded ring may move in loose fit even if load is nominally stationary, if fit is excessively loose or inaccurate or if strong rotor vibrations exist. These causes promote heavy fretting.

DATA

Plate No: 9.4
Archive No: 027-120
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB (with plastic separator), run
Speed: 180 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.2.0.4 Displaced radial fit fretting from high thrust load
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.3, 9.5 to 9.8

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Excessive thrust load caused fretting bands on both OR OD and IR bore, offset in opposite axial directions (each above the ball contact plane). See Plates 9.3 and 9.5 through 9.8 for comparison. Excessive thrust may cause early failures.
Image Description: Reddish-brown band surrounding OR OD and IR bore (arrows), roughly over ball contact planes. Fretting band in IR bore is displaced from center plane to image N, band on OR OD is displaced to image S, indicating thrust load. Fretting corrosion product may be more reddish than chemical corrosion. Location and pattern on bearing are diagnostic.
Suspected Causes: Very heavily thrust loaded bearing will move in both housing and shaft fits, even if fit is properly selected. Fretting concentrates over plane of ball contact.

Failure Code: 00.15.1.2.0.5
Failure Code: 00.15.1.2.0.6

DATA

Plate No: 9.5
Archive No: 027-124
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB, run
Speed: 160 KdN
Load: 2.8 GPa
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.2.0.5 Skewed radial fit fretting from misalignment
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.3, 9.4, 9.6 to 9.8

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Fretting corrosion on OR OD shows two patches diametrically and diagonally opposite, indicative of misaligned OR in housing. See Plates 9.3, 9.4 and 9.6 through 9.8 for comparison. Misaligned OR is likely to produce parasitic contact loads and early spalling, also noisy running and possibly bulk ring fracture.
Image Description: Reddish-brown patches on OR OD placed diametrically and diagonally opposite. Fretting corrosion product may be more reddish than chemical corrosion. Location and pattern on bearing are diagnostic.
Suspected Causes: Misaligned mounting of OR in housing may place moment load on fit; this concentrates fit pressures at two diametrically and diagonally opposite areas. These areas are likely to fret.

DATA

Plate No: 9.6
Archive No: 027-125
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB, run
Speed: 230 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.2.0.6 One-sided radial fit fretting from taper
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.3 to 9.5 and 9.7, 9.8

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Fretting on OR OD, from center plane to one corner radius, indicating concentration of fit pressure on one side (tapered housing bore). See Plates 9.3 through 9.5, 9.7 and 9.8 for comparison. Fitting OR in tapered housing bore may cause noisy running and circumferential bulk ring cracking or internal radial preload with early spalling.
Image Description: Reddish-brown streak circling OR OD, far to one side of center plane. Fretting corrosion product may be more reddish than chemical corrosion. Location and pattern on bearing are diagnostic.
Suspected Causes: Fitting an OR into a housing bore with excessive taper concentrates fit pressure near one sideface, causing fretting and possibly internal radial preload.

DATA

Plate No: 9.7
Archive No: 027-121
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB, run
Speed: 160 KdN
Load: 2.4 GPa
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.2.0.7 Irregular fretting in distorted radial fit
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.3 to 9.6 and 9.8

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Patchy fretting on OR OD, highlighting areas of heavier contact with distorted housing. See Plates 9.3 through 9.6 and 9.8 for comparison. Distorted housing may produce ring bulk fracture or early spalling. Local heavy fretting may in itself lead to bulk cracking.
Image Description: Reddish-brown circumferential patches on OR OD interrupted radially where fit contact is insufficient. Fretting corrosion product may be more reddish than chemical corrosion. Location and pattern on bearing are diagnostic. Pattern of fretting varies with distorted geometry of fit.
Suspected Causes: Distorted housing, weak housing (or, for IR, distorted or hollow shaft) concentrates fretting at points of heavier contact.

DATA

Plate No: 9.8
Archive No: 027-126
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB (double row), run
Speed: 250 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.2.0.8 Fretting in chatter-marked radial fit
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.3 to 9.7

[See Image in Appendix]

DESCRIPTIONS

Failure Description: OR OD fitted in housing with high-order waviness ('chatter') shows axial fretting marks spaced periodically. Fretting of this severity is not a failure. If excessive, chatter in a housing may cause ring distortion, and local contact overload with spalling. See also Plates 9.3 through 9.7 for comparison.
Image Description: Reddish-brown, periodic axial markings circling OR OD, to one side of center plane. Streaks are more pronounced and more diffuse in two bands near the center plane. This pattern shows little ring rotation in the housing and indicates chatter in housing. Fretting corrosion product may be more reddish than chemical corrosion. Location and pattern on bearing are diagnostic.
Suspected Causes: Vibrations in the process of machining the housing bore may cause chatter marks (waviness of high order). The ring fits more heavily at the high points and frets more. Little ring rotation has taken place if marks remain distinct. (Chatter of this severity on ring OD is unlikely.)

Failure Code: 00.15.1.3
Failure Code: 00.15.2

DATA

Plate No: 9.9
Archive No: 027-282
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed: 160 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.15.1.3 Fit sideface fretting
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Thrust sideface of ACBB IR shows an itermittent circumferential streak of fretting corrosion due to movement under axial load against shaft thrust shoulder. Serves as indication of axial load. Not a failure.
Image Description: On thrust face of IR, a streak of reddish-brown fretting corrosion forms a dashed circumferential line. Minor fretting elsewhere. Dark band next to bore is (unground) corner radius.
Suspected Causes: IR moving slightly in interference fit against shaft is pressed against thrust shoulder under combined load with significant thrust component. Fretting may result.

DATA

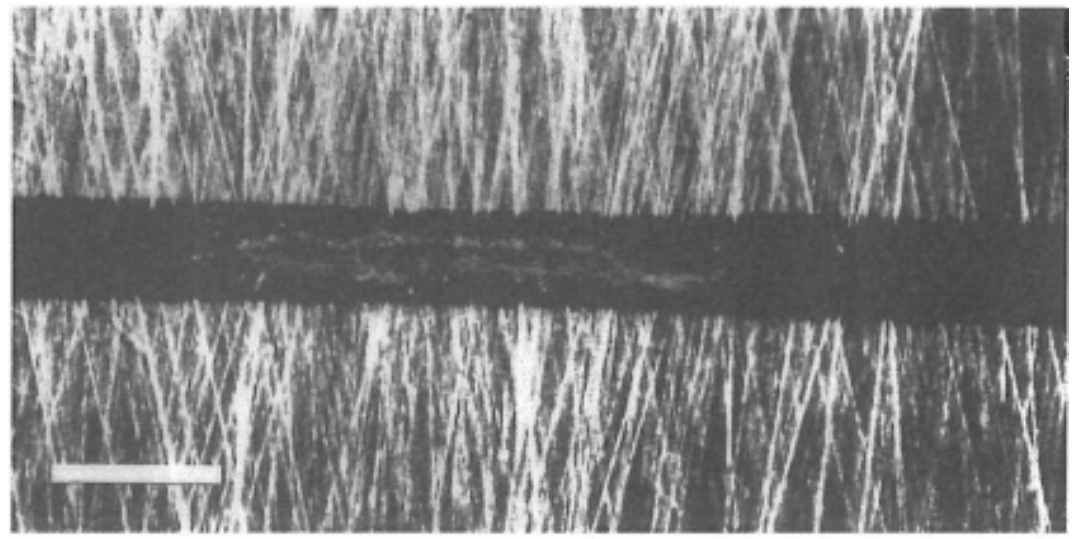
Plate No: 9.10
Archive No: 014-61
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, transported
Speed: 0 dN
Load:
Lubrication:
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Incipient false brinnelling marks at roller spacing, on the rolling path of a TRB IR (cone). Marks as mild as these may cause no noisy running or failure.
Image Description: Diffuse axial streaks on roller path, at roller spacing. Marks become visible by changing the luster of the surface as original finishing lines are obliterated. Profile tracing may show little depth. Microscopy would indicate change in, or removal of, some finishing lines.
Suspected Causes: Transportation of a machine (such as a road vehicle) with the bearing mounted and weight-loaded (as in a wheel bearing) imposes small oscillatory motions on stationary bearing.

DATA

Plate No: 9.11
Archive No: 014-131
Image type: light microgram
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; OR, transported
Speed: 0 dN
Load:
Lubrication:
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: False brinnell mark from roller line contact on OR. Cross-hatch finishing marks obliterated by fretting. False brinnelling may cause noisy running bearing and if severe, may lead to spalling.
Image Description: Background shows cross-hatch honing pattern of OR roller path. N–S band running along image center is false-brinnell mark. No cross-hatch marks in it. Dark and light areas in mark may be due to light reflection or possibly fretting corrosion.
Suspected Causes: False brinnelling occurs in stationary Hertzian contacts under load, subject to vibration which causes motions on the asperity scale. Transport of automobiles on carrier vehicles may cause false brinnelling in wheel bearings.

DATA

Plate No: 9.12
Archive No: 093-045
Image type: light microgram
Scalebar = 300 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, transported
Speed: 0 dN
Load:
Lubrication:
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: False brinnelling has removed finishing marks over a patch in the contact area, leaving irregular transverse markings. False brinnelling arises from vibratory load, mostly in the absence of bearing rotation, as a fretting wear process. It creates noisy running bearings and may lead to spalling.
Image Description: Finishing lines run E–W. Two deep, black scratch marks (in NE and SE image corners) are artifacts. In image center, finishing lines are missing due to fretting over oblong area extending E–W (the contact major axis is N–S). Irregular N–S markings in the false-brinnelled area were produced in the fretting process.
Suspected Causes: False brinnelling occurs in (nearly) stationary Hertzian contacts subject to vibration under load, causing motions on the asperity scale. The circumferential elongation of the false-brinnelled area suggests that the ball positions shifted during the fretting process.

DATA

Plate No: 9.13
Archive No: 107-003a&b&c
Image type: SEM
Scalebar = a: 1000, b: 200, c: 40 μm (micros: +20%, others: +100%, −50%)
Component: ACBB; IR, vibratory test
Speed: 0 dN
Load:
Lubrication: grease, 30°C
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.11, 9.12 and 9.16

DESCRIPTIONS

Failure Description: False-brinnelling along outline of Hertzian contact subjected to strictly normal vibratory load, no rotation. Fretting starts at contour, predominantly near contact endpoints, where sliding is greatest. False brinnelling begins with smoothing of finishing lines and progresses to cratering. Appearance of craters differs from surface distress: no steep crater walls. (Compare Plate 9.16.)
Image Description: (a): View of entire contact ellipse, major axis running NW–SE and outlined as a light-colored elliptical line on darker background of finishing lines running SW–NE. (b): Ellipse end expands and contracts with load. Smoothing of finishing lines (NE of craters). Craters outlining minimum and maximum position and dotting the area between. (c): Smoothed finishing lines and craters at extreme of ellipse tip.
Suspected Causes: Contact subjected to stationary vibratory loading in normal direction. Size of contact ellipse changes with load, with sliding due to toroidal geometry of contact area. Sliding is most pronounced at contact endpoints. This microscopic sliding produces the fretting phenomenon. Overview of false brinnell mark in Plates 9.11 and 9.12.

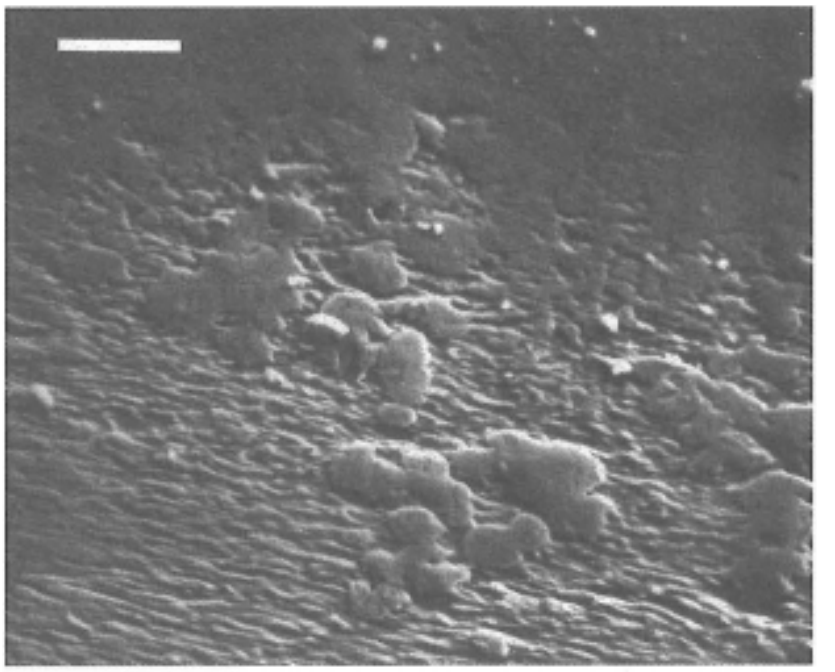
a

b

c

DATA

Plate No: 9.14
Archive No: 007-103
Image type: SEM
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; OR, martensitic stainless, run
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: 00.06.1.3 Primary carbide
Failure Code 3: -
Failure Code 4: -

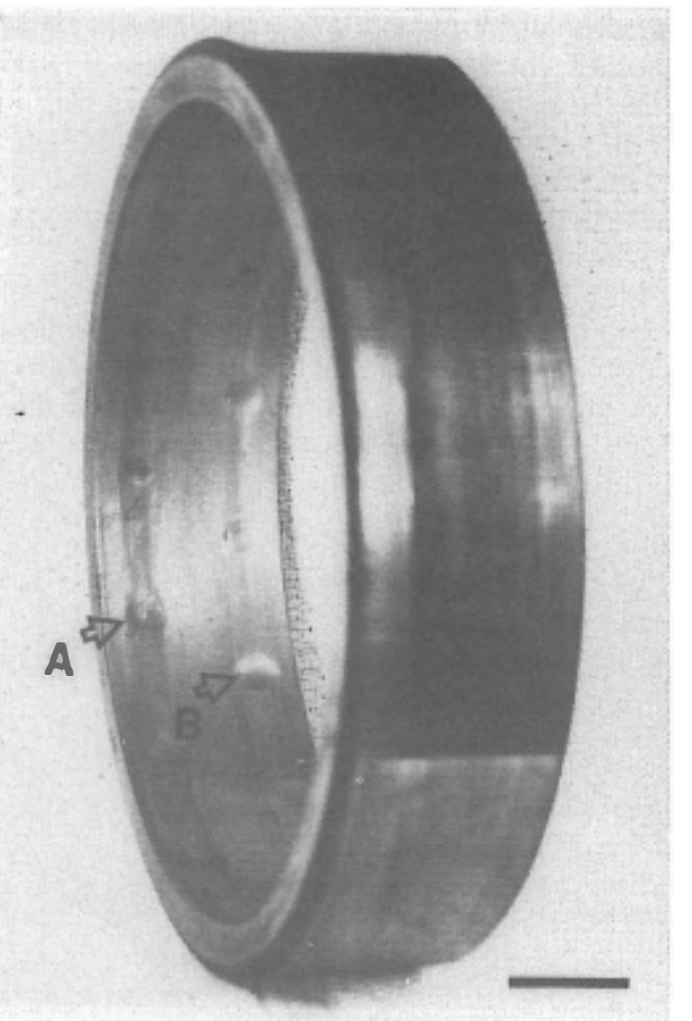


DESCRIPTIONS

Failure Description: Removal of matrix material by false brinnelling type of fretting. Primary carbides in martensitic stainless steel are large and very hard, thus fret less and protrude. This gyroscope gimbal bearing undergoes slow intermittent motion, overlaid by small amplitude oscillation (hunting). EHD film cannot form, fretting occurs over entire overrolled surface. The bearing loses precision and friction control is impaired.
Image Description: Image shows fretted contact surface. S 2/3 of image shows E–W ridging from false-brinnelling type of fretting. Large protruding smooth lumps are primary carbides. N image edge appears less fretted, but finishing lines have been obliterated.
Suspected Causes: Gyroscope gimbal bearings have extremely fine finish and require high precision. They are often made of martensitic stainless steel. Due to small amplitude oscillation (hunting), superimposed on intermittent slow motions, fretting (false brinnelling) conditions exist. Fretted matrix material is interspersed with primary carbides.

DATA

Plate No: 9.15
Archive No: 093-15.2.1
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: SABB; OR, transported, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 3: 00.15.1 Fretting (fretting corrosion)
Failure Code 4: -



DESCRIPTIONS

Failure Description: Circular false brinnell marks at ball spacing in the spherical ball path of the OR. Wear tracks from subsequent running connect the false brinnell marks. Fretting corrosion on OD. False brinnell marks, when severe, as here, cause noisy running and early spalling. May also damage separator through high ball contact loads. Visible wear track and OD fretting are not failures.
Image Description: OD surface of OR shows circumferential black streaks of fretting corrosion over at least ½ circumference. Ring may have shifted in housing. ID surface is spherical ball path, with regularly spaced dark and light circular marks in both ball rows, as at *A* and *B*, from false brinnelling. Change in luster of ball path between false brinnell marks is wear track, presumably from running before or after stationary damage.
Suspected Causes: Bearing was probably radially preloaded since false brinnell marks extend over at least ½ circumference. Bearing was exposed to vibratory motion in stationary condition, probably during transport of the machine containing the bearing. Later, bearing was run, causing the wear path (aggravated by false brinnell marks) and fretting bands on OD.

DATA

Plate No: 9.16
Archive No: 107-002a&b&c
Image type: SEM
Scalebar = a: 300, b: 100, c: 10 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, mounted, transported, run
Speed:
Load:
Lubrication: grease, 30°C
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: -
Failure Code 4: -
See also PLATES: 9.11, 9.12 and 11.16

DESCRIPTIONS

Failure Description: False brinnelling, that is, fretting of stationary ball/race contact under vibration. Finishing marks completely obliterated, extremely fine microspalling of asperity contacts, constituting surface distress. This wheel bearing, transported on a vehicle, was subject to angular oscillation. False brinnell marks cause noisy running and may lead to early macro-spalling. See Plate 9.11 and 9.12 for overview of false brinnelling.

Image Description: (a): Overview of false-brinnelled patch, appearing shot blasted. A few N–S finishing lines outside patches. (b): Medium magnification view of false brinnell. Dense cluster of black 'pits' in featureless plastically worked, worn surface. (c): High magnification of the 'pits' shows them to be microspall craters. These individual craters cannot be distinguished from surface distress microspalls (see Plate 11.16). Macro-configuration is diagnostic.

Suspected Causes: False brinnelling occurs in stationary Hertzian contacts under load, subject to vibration which causes motions on the asperity scale. Subsequent running may have superimposed surface distress (FC 00.17).

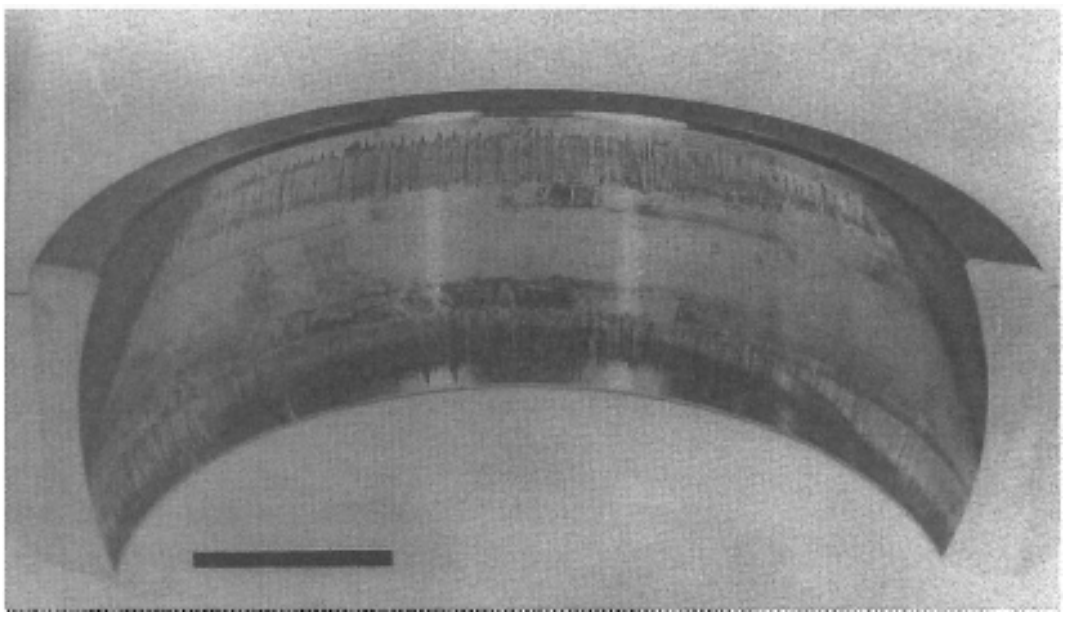
a

b

c

DATA

Plate No: 9.17
Archive No: 018-120
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: 00.20.1 Corrosion stain
Failure Code 3: -
Failure Code 4: -

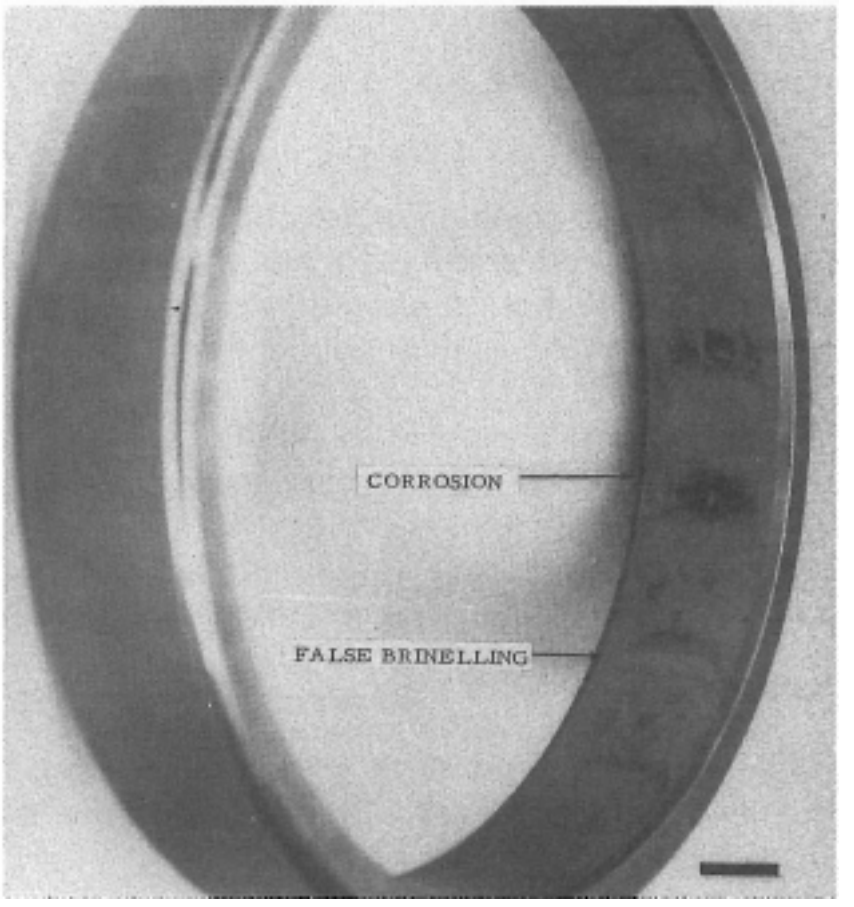


DESCRIPTIONS

Failure Description: Dense parallel axial marks of false brinnelling in both roller paths, concentrated in a load zone. Scattered corrosion stains in bands on spherical ID of OR, mostly in two bands accompanying fretted strips. Dense rows of false brinnell marks indicate vibration superimposed on rotation, as in a vibratory application. Water ingress into the lubricant may explain the corrosion. Early spalling expected.
Image Description: In the spherical ID of the cut OR, two circumferential bands of light- and dark-colored sharp axial marks are from false brinnelling. Black patches in the ID, concentrating in two bands inboard from false brinnell marks, are corrosion stains. At image S, center, these overlap false brinnell marks, suggesting corrosion at a later time. Contrast with electric erosion fluting (FC 00.21) showing molten surface craters.
Suspected Causes: Vibratory machinery (for example, shaker screens) subject shaft support bearings to heavy vibratory forces which are not synchronous with roller passage. False brinnell marks can initiate at random locations. A self-reinforcing process is postulated to explain serrated, rather than smooth fretting. Shaker screens often operate wet, and water ingress into the lubricant can cause corrosion.

DATA

Plate No: 9.18
Archive No: 087-031
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: CRB: OR, transported
Speed: 0 dN
Load:
Lubrication:
Failure Code 1: 00.15.2 False brinnelling on contact surface
Failure Code 2: 00.20.1.3 Contact corrosion
Failure Code 3: 00.12.3.2 Wear in rolling surface
Failure Code 4: -



DESCRIPTIONS

Failure Description: Bearing stored (in mounted condition) with insufficient rust protection suffered patchy corrosion staining on roller path, indicating corrosive lubricant or preservative. Rollers oscillated through several degrees, removing stain under them. In some positions, oscillation sufficed to cause false brinnelling. The bearing is expected to fail from wear, or spalling, if operated.
Image Description: Black patches in the roller path are corrosion (label). Wide rectangles at roller spacing are worn clear of corrosion. False brinnelling (label) consists of narrow rectangles with a luster different from the intact surface. Bearing, mounted when transported, shifted position to wear away corrosion over the wide rectangles. In some position(s), false brinnelling occurred.
Suspected Causes: Mounted bearing transported with insufficient rust protection and exposed to substantial oscillation, some of which persisted long enough to create false brinnelling.

SPALLING 10

Failure Code 00.16

10.1 Definition

Spalling is defined as macroscale Hertzian contact fatigue. It is failure by the formation of macroscopic craters in the contact surface as a result of fatigue crack propagation in the Hertzian stress field. When fully developed, the craters are of depth comparable to that of the maximum Hertz shear stress. Spalling is distinguished from:

- *Surface distress,* which is Hertzian contact fatigue in asperity dimensions.
- *Pit formation,* from porosity arising from material casting or processing, as a result of corrosion, electric erosion, or pitting wear.

10.2 Nomenclature

Spalling, pitting, or *flaking* are designations used indiscriminately in the tribological literature to designate contact fatigue. This Atlas adopts *spalling* as the only designation for macroscale contact fatigue, reserving *pitting* for the formation of craters or pores by processes other than fatigue cracking. *Flaking* is used in this Atlas only to designate the generation of fissures in the material from the release of hydrogen that may occur during cooling from forging or rolling operations on heavy cross-section parts.

In some of the gear literature [8, 9], *pitting, micropitting* and *spalling* are used to designate contact fatigue of differing severity. This distinction is not used in the Atlas. Macroscale contact fatigue is always designated as *spalling,* and asperity scale contact fatigue as *surface distress.*

The American Gear Manufacturers' Association gear tooth failure nomenclature [8] designates all contact fatigue as *surface fatigue.* Within this class, it uses the distinctions cited in the preceding paragraph.

10.3 Failure Process

Contact fatigue models have proliferated in rolling bearing and gear technology. Fatigue spalling is commonly attributed to the repeated traverse of a Hertzian stress field over the same material volume, primarily under *rolling* contact conditions (with relatively little sliding and correspondingly low tractive interface stresses) in which other competing failure modes, such as denting, mild wear or galling, are less likely to lead to earlier failure.

The sequence of changes in a component preceding the emergence of a spall is designated as fatigue damage accumulation. Although this process is still incompletely understood, the following main events appear confirmed [15, 16, 23].

The fatigue process can be divided into three pre-cracking phases [16]: 1) a brief initial phase of bulk changes in the material; 2) a long, stable phase where only microscale changes take place, and 3) the final phase involving rapid accumulation of structural changes. When Phase 3 reaches a critical severity, then crack and spall formation occurs in a *fourth phase.* In detail:

1. During the relatively brief initial phase, bulk changes in material structure occur in the highly stressed volume under the contact path. Changes in hardness, residual stress, retained austenite and structure may occur. Plastic deformation may cause changes in contact geometry.
2. Alternating microplastic flow occurs in the highly stressed volume under the contact path during the stable second phase which occupies most of the fatigue life of the part. No visible structural changes occur.
3. At some point in stress cycling, the stable Phase 2 condition ends. The triggering conditions of the change to Phase 3 are not understood, but it is observed that several types of structural

and microstress alterations begin to occur rapidly. These changes in material structure brought about by the microplastic flow have been described variously as deformation bands, light-etching or white-etching areas, when disseminated in the highly stressed volume. They are designated as butterflies when formed around a point defect such as an inclusion. The light-etching structure appears in the form of thin lenticular volumes oriented at fixed angles to the contact surface. When viewed in a section parallel to the rolling direction, the deformation bands appear as two series of narrow bands rising at angles around 30° and 80° with reference to the direction of contact travel.

4. Microcracks are initiated at some time during Phase 3 at "defect" locations within the plastically altered material volume. The microcracking usually occurs at the contact surface or between that and the depth of maximum Hertzian shear stress. (See subcase fatigue, below, for cracks initiated at deeper levels.)
5. A macroscopic crack, driven by high Hertz shear stresses, is initiated from one of the microcracks. This constitutes Phase 4: crack formation and crack growth. From a normal initiation point above the maximum Hertz shear stress, the crack travels downward into the material, at an acute angle with respect to the direction of contact travel, until it reaches the depth corresponding to the maximum (unidirectional) Hertzian shear stress.
6. The material volume undermined by the crack *spalls out* forming a crater (exfoliates) along a crack running upward at an angle of about 30° to the surface and parallel to the 30° deformation bands, hereby forming a crater bounded by fracture surfaces [17].
7. This process may repeat itself to expand the same spall or to initiate others.

Spalling fatigue life is inherently statistical. This is the case presumably because defect severity and location, two determining variables of life, are statistically distributed among macroscopically identical contact components. Other spalling life models postulate an inherent dispersion of crack growth rates in the matrix, without invoking defects of statistically distributed severity.

Two major classes of spalling failure are distinguished according to the location of the initiating defect:

1. *Subsurface origin spalling* from defects in the bulk material subject to the Hertzian cyclic stress field. The defects most likely to produce this type of spall are located near (but generally above) the depth of maximum alternating Hertz shear stress. In this type of spalling, Hertz shear stress level, material matrix fatigue resistance, defect severity, and defect location are the governing variables determining life to spalling.
2. *Surface origin spalling* from defects in the immediate subsurface material subject to asperity-scale cyclic stress fields. These defects fall into two main classes: pre-existing defects and surface distress. It can be argued that all defects in the former class initiate spalling by first causing localized surface distress. In this type of spalling, factors promoting spalling in addition to severe levels of the variables enumerated under subsurface origin spalling are: surface distress and high values of tractive stresses in the contact interface. Residual stress in the subsurface layers may promote or retard spalling, depending on whether it is tensile or compressive.

Numerous different mathematical models have been proposed as tools for the selection and design of rolling bearings based on the prediction of spalling fatigue life. A review of many such models is in Tallian [23]. That paper also includes a review of proposed failure mechanisms.

10.4 Distinctive Appearance

Spalls, as a class, show a highly distinctive appearance. A fully developed spall (with its diameter much larger than its depth) shows a distinct bottom and walls. The walls may intersect the surface at a steep or shallow angle, as further specified below.

The spall bottom consists of a series of crack surfaces. As a whole, it parallels the contact surface at roughly the depth of the maximum unidirectional shear stress in Hertzian contact. Spalls substantially larger in area than their depth often show serrations in the spall bottom, which run transverse to the rolling direction. They are formed one at a time as a crack penetrates downward in the direction of contact travel at an angle of about 30° away from the surface until it reaches the spall bottom level, and then the undermined piece breaks away along a plane rising in the direction of contact travel at an angle of about 30° toward the surface. A subsequent crack forms further along the rolling direction, proceeds down into the material and forms the next step when the undermined material breaks away. As this description implies, spalls tend to propagate in the direction of contact travel.

The sidewalls of a spall and a band on the exit wall closest to the surface are often near-radial fracture surfaces.

The spall entry (the end first reached by the rolling body) varies in appearance depending on spall origin and is useful in differentiating between origination processes (see below).

Notes on Atypical Spalls:

1. Spalls on balls. The balls change rolling axis, causing spalls to appear more circular. Overlapping circular spalls, starting from different points, may form a cluster.
2. Spalls near sharp edges or line defects (scratches). These tend to be shallow, form a narrow band or become less numerous as one recedes from the edge. Spalls arising near edges or from line defects may show atypical outlines reflecting the defect or edge geometry. A spall forming at a sharp contact edge often leaves a narrow unspalled lip of material at the edge as a result of the distribution of shear stresses which reach their peak value a small distance away from the "cliff" formed by the edge.
3. Spalls in (silicon nitride) ceramics are not extensively documented. Good silicon nitride is quite spall resistant and the Plates showing silicon nitride spalling represent unusual test conditions. Nonetheless it appears that spalls in silicon nitride tend to propagate slowly, and may restart several times rather than propagate from a single origin.

One or more of the following distinguishing features of surface and subsurface origin spalls may be present in a spall. However, spalls showing no clear distinguishing features are common and are classified as spalls of indeterminate origin.

Subsurface Origin Spall. Any of the following distinguishing features indicates a subsurface origin spall:

- A *steep entrance wall* (inclined by more than a 45° angle to the contact surface).
- An *originating subsurface defect* may remain visible after the spall has formed or may be lost with the spalled material.

Surface Origin Spall. The distinguishing features of a surface origin spall are in the entrance zone of the spall, which may show any of the following features:

- A *shallow-angle entry wall* (inclined at less than a 30° angle to the contact surface).
- An *arrowhead* configuration formed by two shallow cracks emanating from a common point defect.
- The presence of a *visible surface defect* (nick, dent, furrow, pit) just upstream of the spall initiation, often with a narrow ledge of unspalled surface between defect and spall.

Subcase Spalling. In subcase spalling (see explanation of causation below), spall depth is greater than the maximum Hertz shear stress depth. The spall bottom follows the case/core interface. This type of spalling is often called case crushing. (See also core cracking under FC 00.22.)

10.5 Causes

Spalling fatigue was long considered the "default" failure mode of Hertzian rolling contacts. It was believed that the fatigue limit stress for Hertz contact fatigue is zero, so that any load, if applied long enough, will cause spalling even when no assignable failure cause can be found. Therefore, a contact surviving all other failure modes was expected eventually to fail in contact fatigue.

Recent evidence obtained with very carefully made rolling bearings operating under highly favorable conditions suggests that a non-zero fatigue limit stress exists so that at quite low loads, and in the absence of all significant surface and subsurface defects, spalling fatigue may not occur. More common is the case that spalling fatigue is preempted by one of the many competing failure modes, or is brought on by some practically unavoidable damage including contamination.

Common Spalling Causes

Material (Matrix) Deficiencies

- *Low hardness.* No low-hardness material is known which possesses good spalling fatigue resistance. In steels, spalling resistance increases with hardness up to quite high values. In bearings, only high hardness parts have exhibited satisfactory fatigue life under significant contact loads. In gears, where contact stresses are typically lower but sliding is substantial, both high and medium hardness components show fatigue resistance that competes successfully with the other failure modes.
- *Subcase Spalling.* In case-hardened components, a gradient of decreasing hardness exists from the case to the core. If the hardness gradient is steeper than the gradient of Hertz shear stress, then the stress to strength ratio is least favorable at some depth beneath the normal maximum Hertz shear stress region. Fatigue failure may initiate in the core or at the case/core interface.

Matrix Inhomogeneity

- In steels, soft structural constituents reduce spalling resistance.
- Materials consisting of hard particles in binders (cermets and many ceramics) fail at binders. Silicon nitride components (most often used are balls or rollers) may spall from porosity, binder deficiencies or as a consequence of surface damage such as a nick or dent, either on the ceramic component or on the mating component (usually a steel ring).

Contact Load. Any operating condition bringing about higher than designed Hertz pressures on any part of the contact drastically reduces spalling life, unless the load is so low as to be below the fatigue limit. (Life generally decreases as the inverse 9th to 12th power of Hertz pressure.) Examples:

- Total machine element load in excess of design.
- Load maldistribution among rolling elements in a bearing or among gear-teeth in gearing.
- Maldistribution of pressure in a contact (through edge-loading or profile errors).

Contact Temperature. Excessively high operating temperature, at which the material's working hardness is substantially less than its room-temperature hardness, reduces spalling resistance. (Other failures, such as lubrication failure are also likely, unless special precautions have been taken.)

Number of Stress Cycles. Spalling is a damage accumulation failure mode so that its cumulative probability increases with the number of stress cycles. This does not imply that the hazard of spalling within a fixed incremental number of cycles necessarily increases with total accumulated life.

Causes of Subsurface Origin Spalling

Subsurface Defect Severity

- *Inclusions.* Non-metallic inclusions in steel and foreign metallic inclusions in powder metals or ceramics can be spall-originating defects.
- In steel, *hard, brittle* non-metallics are more severe defects than *sulfide* inclusions of comparable size.
- *Large* carbides may act as defects, although some steels with quite large carbides (example: hardenable stainless steels) show acceptable spalling resistance. Carbide *segregation* or *networks* are detrimental.
- *Porosity* (voids) in the matrix, are spall initiating defects just as inclusions are. Porosity is a particular hazard for ceramics.

Causes of Surface-Origin Spalling

Surface Defect Severity

Pre-existing Defects

- *Nicks and dents* (FC 00.01 and FC 00.18) are direct asperity-scale stress raisers capable of initiating cracks. Depending on the size of the defect, these may be asperity-scale microcracks (then the fatigue initiated is surface distress) or macrocracks (then spalling is directly initiated).
- *Finishing marks* (grinding furrows, unfinished areas, etc., see FC 00.02) may be direct stress raisers or may cause surface-origin spalling by precipitating surface distress (see FC 00.17) through interference with EHD film formation.
- *Grinding damage* (FC 00.08) may comprise tempered material, rehardened material or grinding cracks. Upon cyclic stressing, cracks form readily in material damaged by grinding, even if no cracks existed at the start of service. Grinding-damaged matrix has low fatigue resistance, so either surface distress or direct spalling may originate there.
- *Near-surface structural damage* to the matrix, such as surface decarburization in steel (FC 00.07) produces reduced fatigue resistance specifically for asperity-scale cracking.
- *Pitting* from manufacturing operations (FC 00.03), corrosion (FC 00.22) or electric erosion (FC 00.21).

Surface Distress

- The phenomenon described under FC 00.17 as surface distress or asperity-scale fatigue produces a large population of asperity-scale microcracks and microspalls, which act as precursors to macroscopic spalling.

Galling or skidmarking can be precursors of spalling.

Tractive Stress in the Contact Interface. High traction may result from high sliding speed, low ratio of EHD film thickness to surface roughness height, or ineffective boundary lubrication. High traction is believed to exert a direct effect on surface-origin spalling. It is observed that the copious microcracking characterizing advanced surface distress does not automatically lead to massive spalling as it would if all microcracks propagated to produce macroscopic cracks and spalls. It is conjectured that the microcracks fail to propagate in depth when there is a *quiescent layer* of material between the

microcracks and the high Hertz shear stress zone, in which no substantial shear stresses prevail to drive the cracks. This is the case when interface traction is low. For higher interface traction, this quiescent layer is increasingly invaded by shear stresses capable of driving cracks and initiating spalling.

Hydraulic Effect on Crack Propagation. It is observed when collinear sliding accompanies rolling that the *trailing* surface, in which the sliding direction is *forward* (the same as the direction of contact travel), spalls first. Cracks angle downward *in the direction of contact travel* in this surface. The *leading* surface, on which sliding occurs in the opposite direction spalls later, to a lesser degree, or not at all. When cracks form in this surface, they angle downward away from the direction of contact travel. In gearing, the *dedendum,* which is a trailing surface, is observed to spall more than the *addendum,* a leading surface.

Notes:

1. In spherical roller bearings (barrel-shaped rollers), which normally spall near the midpoint of the roller length due to high normal pressure, no clear evidence exists that rollers, which are the leading surface at that point, would be significantly less prone to spalling than innerrings, which are the trailing surface.
2. Ball bearing balls, the leading surface in innerring contacts, do spall less than innerrings. However, balls are harder than innerrings, have smoother surfaces and index their axis of rotation, all of which operate to reduce ball spalling.

A persistent hypothesis to explain selectivity in the direction and frequency of cracking is that the presence of a liquid lubricant is required for crack propagation in contact fatigue. The most common form of this hypothesis, attributed to S. Way [18], postulates that in a crack extending downward in the direction of contact travel and filled with oil, the approaching contact reaches the surface opening, pinches the crack closed, traps the lubricant and puts it under hydraulic pressure which extends the crack tip. A crack extending downward opposite the direction of contact travel is squeezed empty of oil by the contact and does not propagate.

Arguments can be advanced to challenge the extensively quoted Way hypothesis. One objection is that it cannot apply to subsurface-origin cracks. Yet their frequency and direction depends upon sliding direction in the same way as for surface-origin cracks. More detailed arguments are based on recent fracture-mechanical analyses of crack propagation in the presence of oil, some of which [19] do not appear to support the Way model. Nonetheless the issue of hydraulic effects on spall propagation is still unresolved.

Alternatively, one may attribute the effect of sliding direction on spalling to the asymmetry in the elastic-plastic stress condition existing under any traveling Hertzian contact. The asymmetry of deformation bands with respect to the direction of contact travel is direct evidence of this stress / strain asymmetry. Elastic-plastic analyses of the stress condition during crack propagation are underway for sliding either with or against the direction of contact travel [20, 23], but have not yet produced consensus.

10.6 Effects of Spalling

Spalling failure is of differing severity depending on design, material and application of the contact component. Generally, spalling directly leads to non-functionality, because it is progressive (at times propagating very rapidly after initiation) and often leads to fractures or seizure.

In small or high-speed, through hardened steel *rolling bearings,* and in bearings with poor lubrication, spalling is a disabling failure unless arrested by a relaxation of operating conditions. It propagates rapidly and can lead to bulk fracture and loss of functionality. Accuracy of shaft support is often

compromised. Vibration and noise from a spalled component is often unacceptable. Separators of spalled small bearings may fracture and cause seizure.

In large, slow-speed *roller bearings* with good lubrication, especially if parts are case hardened, spalling may propagate slowly and considerable service life may be obtained after spall initiation. However, catastrophic spall progression and failure is also observed in such components.

In rolling bearings, spalls do not heal. They are arrested spontaneously only if they have occurred in an area that subsequently becomes unloaded (a protruding "lip" near an edge, which wears off; a portion of the rolling contact which, due to realignment of the machine element, is no longer under load).

In *gears,* progression of spalls to functional failure is common. However, spalling ("pitting") conditions have been identified which do not lead to failure, specifically:

- Fine spalling ("pitting") on a new gear, due to rough as-finished surfaces, which, after running-in, become smoother and sustain further cycling without more severe spalling.
- Spalling in worm gears, which remain functional even after considerable spalling.

Gears are made of materials of widely varying hardness and fatigue resistance. Surface finishes also vary greatly. Therefore the relative prevalence of spalling compared to wear or galling failures cannot be generally established as a function of a single variable such as hardness, because hardness influences resistance to all these failure modes.

Cam systems, especially those under heavy Hertz pressure and high speed such as in Diesel engines, may fail in spalling, often preceded by microgalling. These failures may disable the cam system.

Cross-Index of Secondary Failure Codes

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	15.34
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	10.61
00.16.01.1.2	13.6
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00.16.01.2.2	19.2
00.16.01.2.3	16.4
00.16.01.3	7.31
	14.2
	15.17
	15.22
	15.25
00.16.01.3.1	7.38
	11.11
	15.23
00.16.02.1.1	5.24
	6.4
	10.34
00.16.02.1.2	10.35
00.16.02.2	5.5
	6.4
	6.18
	7.35
	10.8
	10.26
	10.36
	10.41
	10.46
	10.54
	10.55
	10.56
	10.58
	10.64
	10.68
	11.12
	11.22
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00.16.02.3	5.9
	7.4
	7.17
	7.37
	10.5
	10.41
	10.47
	10.48
	15.7

Failure Code	Plate No.
00.16.02.4	5.24
	6.7
	7.34
	8.17
	10.9
	10.19
	10.23
	11.11
	12.21
	14.18
	16.21
00.16.02.5	6.10
	10.1
	10.2
	10.3
	10.6
	10.10
	10.15
	10.16
	10.17
	10.20
	10.24
	10.31
	10.49
	10.63
	10.70
	15.31
	16.4
00.16.03.1	10.25
	10.42
	10.43
	10.45
	10.59
00.16.03.2	10.11
	10.21
	10.50
	10.57
	10.60
	10.61
	10.62
	14.9
00.16.1.1	4.2
	10.6
	10.12
00.16.1.1.1	10.13

Failure Code	Plate No.
00.16.1.1.2	6.18
	9.2
	10.33
	10.34
	10.42
	10.44
	15.1
	15.12
	15.28
	15.31
00.16.1.1.3	10.39
	15.25
00.16.1.2	6.25
	8.18
	11.22
00.16.1.2.1	8.22
	10.21
	10.26
	10.35
	10.40
	11.13
	11.14
	11.23
	12.19
	14.5
	14.8
	14.9
	14.10
	14.17
	14.18
	14.20
00.16.1.2.2	4.9
	5.22
	6.35
	10.62
	11.24
	12.11
00.16.1.2.3	10.5
	10.36

PLATES

DATA

Plate No: 10.1
Archive No: 031-602
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.1.1 Centered spalling, normal track width
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 00.12.0.2 Abrasive mild wear
Failure Code 4: 00.20.1 Corrosion stain

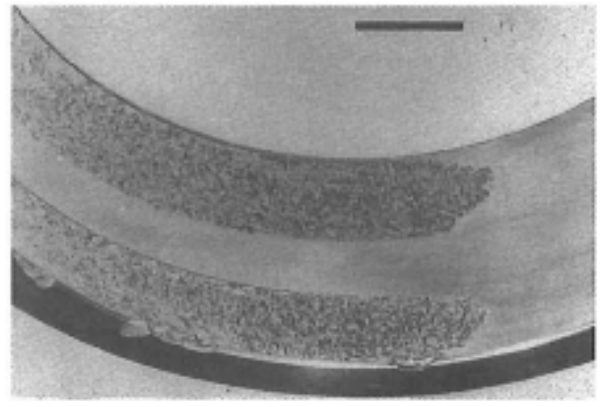


DESCRIPTIONS

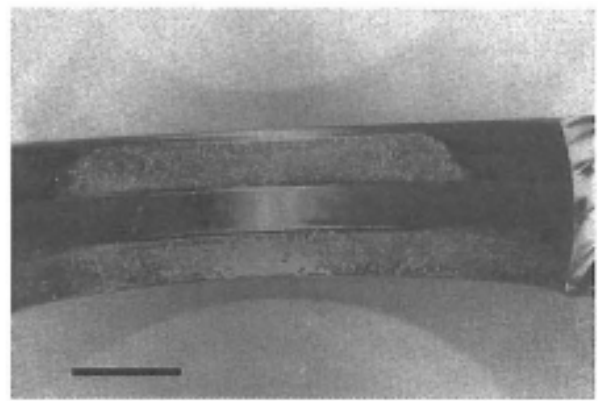
Failure Description: Advanced compound failure of several modes. Extensive spalling of both roller paths, initating from many points, originally may have been caused by corrosion. Corrosion stains formed in unspalled tracks. There is extensive abrasive wear and debris denting in tracks. Bearings in heavy industrial machinery often run to severe compound failure before diagnosis and removal.
Image Description: Numerous spall craters, with unspalled surfaces interposed, indicate multiple origin spalling on both roller paths. Near the outboard edge of both paths, the many small dark spots are probably corrosion stains. Debris dents appear between spalls, near track centers.
Suspected Causes: Multiple origin spalling of this paper machine bearing may have initiated from corrosion due to water ingress into bearing. Spalls later proliferate from debris dents.

DATA

Plate No: 10.2
Archive No: 018-134&135
Image type: a, b: light macro
Scalebar = a, b: 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.1.2 Centered spalling, wide track
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 00.22.2 Bulk fatigue crack
Failure Code 4: 00.12.4 Wear of guiding-component support surface



a



b

DESCRIPTIONS

Failure Description: Extensively spalled SRB OR, in load zone of both roller paths, extending nearly full width of contact. (a): Load is radial; spalls extend into edge chipping. (b): Load is combined, with thrust component; unspalled band is visible at outboard edge of less-loaded row. Some wear marks are visible in separator support surface. In slow speed, heavy machinery, these bearings may have run extensively since spall initiation, but are not fit for further service.
Image Description: (a): In smooth spherical OR rolling surface, two wide, long load zones totally spall cratered, from load zone start at ¼ image width from E edge to W edge. The load zone start point in both tracks is aligned (radial load). Spalling gradually widens as roller load increases into the zone. Several edge chips broke out at S edge. (b): Similar spalling, load zone starts further E in S track. Unspalled band at N edge (combined load).
Suspected Causes: Very heavy load (possibly acceptable in slow speed machinery) caused spalling. Once spalling is extensive, load carrying ability of surface is lost so spalling becomes progressively wider and eventually covers full contact width. (a): Roller rows are equally loaded (radial load). Spalling fatigue cracks can separate chips at ring edges. (b): S roller row is more heavily loaded (thrust load).

Failure Code: 00.16.01.1.2
Failure Code: 00.16.01.2

DATA

Plate No: 10.3
Archive No: 027-133
Image type: light macro
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed: 130 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.16.01.1.2 Centered spalling, wide track
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 12.3 Friction polymer, grease lubrication
Failure Code 4: -
See also PLATES: 10.11 and 10.47

DESCRIPTIONS

Failure Description: Large circular spall extending across ball path to near a land edge. Friction polymer in loaded half of groove. Width of spall, normal depth and regular outline suggests absence of major local defect and existence of overload (wide contact path). Friction polymer also suggests wide track from heavy load. Plates 10.3, 10.12 and 10.47 show different spalling modes on similar bearings.
Image Description: Ball groove visible between symmetric land surfaces. N half of groove is dark (with a separate thin dark line in center); S half is clear. Round spall crater spans virtually all N half of groove. Dark stain is brown friction polymer. The separate line, also brown, is from a similar cause. Separate friction polymer lines are often observed. The detailed balance between deposition and wear causing them is not clearly understood.
Suspected Causes: Heavily loaded bearing develops wide contact, with significant Heathcote slip, increasing temperature and favoring friction polymer formation from grease. Overload may cause spalling which, due to wide contact, will also be wider than usual (approaches land edge).

DATA

Plate No: 10.4
Archive No: 093-16.2.11
Image type: SEM
Scalebar = 350 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; R, run
Speed: 500 ? KdN
Load:
Lubrication: synthetic polyester oil, 100°C?
Failure Code 1: 00.16.01.2 Spalling at contact edge
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Multiple spalling emanates from near roller corner and extends toward midlength. Spall depth is greatest near edge, indicating edge loading. The extreme edge, adjacent to radius, is unspalled. Progressive spalling will cause bearing failure.
Image Description: Oblique SEM view of OD and endface of (small) cylindrical roller. Corner radius is *A–A*. Spall craters begin close to corner (at *B*) where they are deeper than further inboard, as at *C*, indicating edge loading. Spalls do not extend into the corner. This unspalled lip effect is seen between nicks or furrows and spalls as well as in edge loading.
Suspected Causes: Edge loading is likely to have precipitated the spalling. It may arise, in a CRB, from: (a) skewing of roller in OR; (b) bearing misalignment; (c) taper in rings or mounting surfaces; (d) thrust loading of rollers; or (e) insufficient crowning (edge relief) of roller profile.

DATA
Plate No: 10.5
Archive No: 014-B003
Image type: SEM
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: O, RC test rig rod; silicon nitride, hot isostatic pressed; run
Speed: 1.9 m/sec
Load: 5.93 GPa
Lubrication: mineral oil w. additives; approx. 40°C
Failure Code 1: 00.16.01.2 Spalling at contact edge
Failure Code 2: 00.16.02.3 Incipient spalling, single spall
Failure Code 3: 00.16.1.2.3 Shallow entry spall from tensile cracking (ceramic)
Failure Code 4: -
See also PLATES: 6.1 and 11.29

DESCRIPTIONS
Failure Description: Cluster of small spalls forming individual craters with flat bottoms about 250 μm across, found to originate near track edge, where tensile Hertzian stress is present. The rectangular spall shape and flat bottom suggest linear cracking as spall initiator. This failure mode is characteristic of fully dense silicon nitride ceramic.
Image Description: At image center N, three small spalls, each about 250 μm diameter, with flat, rectangular bottoms and shallow crater walls. Undamaged surface is featureless gray. Overrolling direction is image S to N. Note individual spall bottoms are large (~250 μm) compared to ceramic grain size (<10 μm).
Suspected Causes: Extremely heavy Hertz pressure (well above plastic limit of steel, possibly also of ceramic binder) cycled for very long period creates high repetitive stresses. Linear tensile cracks are thought to coalesce into shallow spalls.

DATA
Plate No: 10.6
Archive No: 001-7
Image type: view
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed: 1 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.16.01.2 Spalling at contact edge
Failure Code 2: 00.18.2.1 Rolled-in line at contact edge
Failure Code 3: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 4: 00.16.02.5 Advanced spalling
See also PLATES: 10.13 and 10.14

DESCRIPTIONS
Failure Description: Band of severe spalling along great circle of ball. This ball was found to have contacted the sharp edge of the IR ball groove, under load. One or more close-spaced lines were rolled in (FC 00.18.2.1) and spalling originating from the edge overload occurred. The ball has failed. See Plates 10.13 and 10.14 for details of edge spalling.
Image Description: The E–W great circle of the ball shows two parallel grooves (clearer at image E) following rolled-in lines which have begun to spall. At image center and W, steep-entry spalls have progressed. A rolled-in, dark line followed by a spall is also faintly visible on N–S great circle, and a spall N of the E end of the E–W great circle.
Suspected Causes: A geometry error in the bearing caused heavy contact between balls and the sharp edge of the IR groove. This edge loading produced the rolled-in line and spalling.

DATA

Plate No: 10.7
Archive No: 031-103
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: TRB (double row); IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.01.1 Spalling centered in contact
Failure Code 3: 00.13.2.1.2 Rolling surface galling, dent or nick visible
Failure Code 4: 00.13.1 Fit surface galling

DESCRIPTIONS

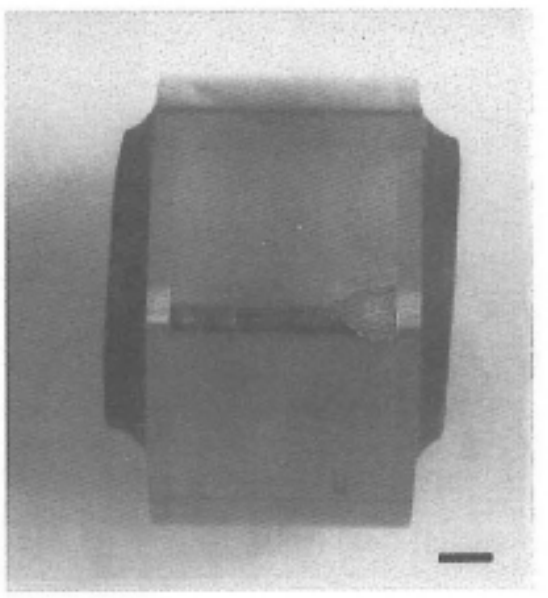
Failure Description: Advanced compound failure of several modes. Spalling occurred at the track edge, and separately in track center (perhaps from spall debris). Galling resulted from track center spalls. There is severe IR bore damage, probably galling. Bearings in heavy industrial machinery often run to severe compound failure before diagnosis and removal.

Image Description: W image half shows one of two roller paths of a multirow TRB. The E half of image is the wide non-contacting center flange on which black deposits may be carbonized lubricant. Row of spall craters at E roller path edge, near thrust flange. Two groups of spalls are in the track center (at N and center), surrounded by dark-appearing (but shiny) galling streaks. At W image edge, the bore surface is severely battered (possibly by galling).

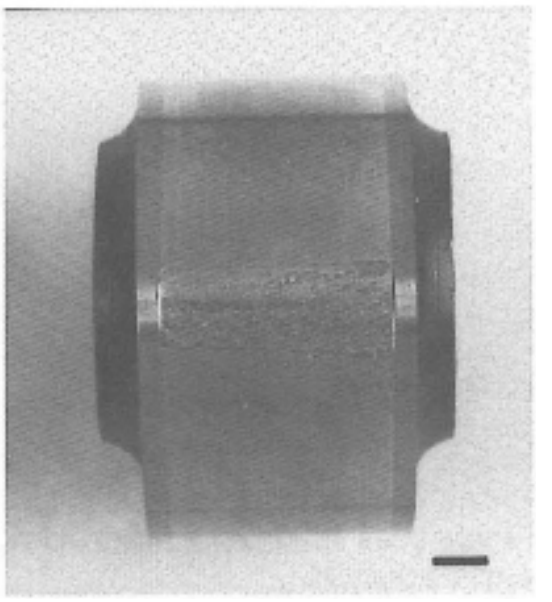
Suspected Causes: The row of spall craters near the thrust flange suggests edge loading (geometry error). Debris from these spalls may have triggered spalling at track center, which in turn led to galling, probably as rollers jammed in separator from debris interference. Bore damage is not clearly imaged, but if it is galling, it would require fast rotation of ring on shaft, due to loose fit, overheating or seizure in the bearing.

DATA

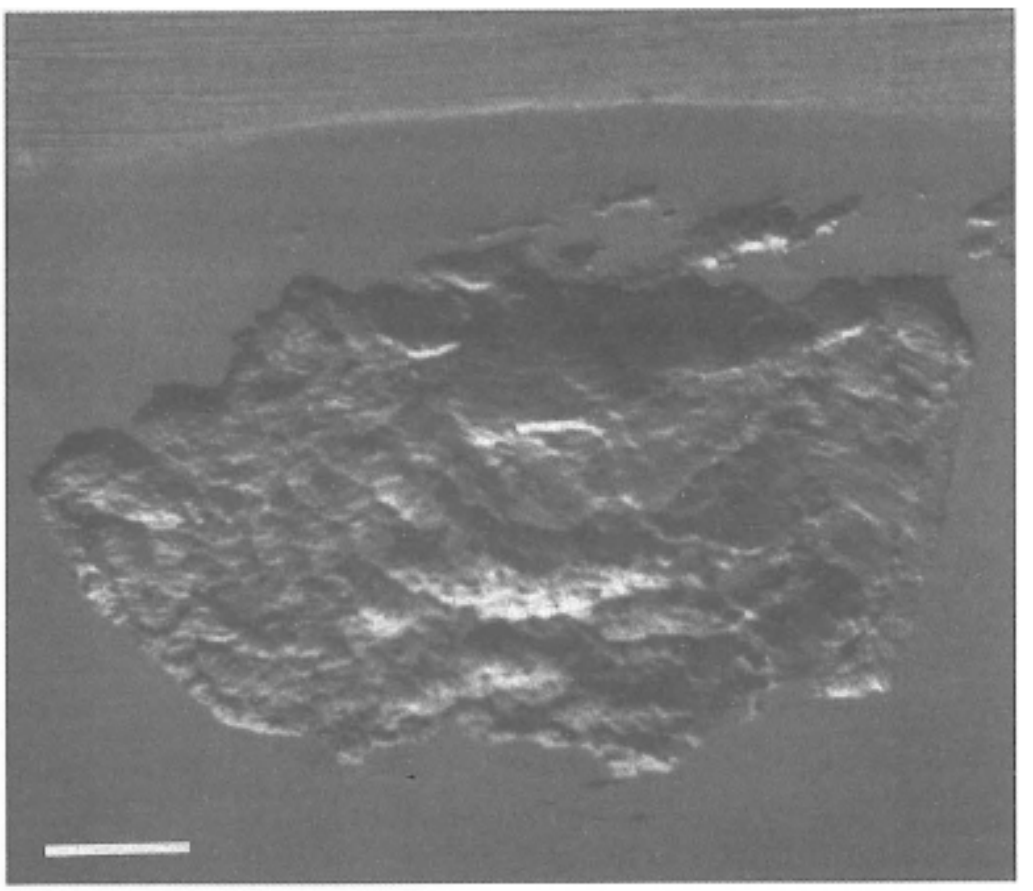
Plate No: 10.8
Archive No: 005-7&8&20
Image type: a, b: light macro, c: SEM backscatter
Scalebar = a, b: 5 mm, c: 400 μm
(micros: ±20%, others: +100%, −50%)
Component: C; CM, run
Speed: 4.5 m/sec
Load: 1.4 GPa
Lubrication: mineral oil, 115°C
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.01.2.1 Spalling at contact edge, from misalignment
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: -



a



b



c

DESCRIPTIONS

Failure Description: Sharp-edged spall at one contact edge in (a) and at both edges, but wider at one edge in (b). Sharp-edged spalls, widest at edge, indicate edge contact under load. One edge is more strongly marked and spalled, suggesting misalignment or taper. Straight axial entry edge of spall in (b), where cam/follower contact under load begins. Sharp-edged spall in detail in (c) with cracks beyond spall exit.
Image Description: (a), (b): cam lobe (gray) on (black) camshaft. Sharp demarcation of contact edges. Spall with straight wall at contact edge to the E in (a): spall across contact width in (b), wider in E. Dark axial band in (a) due to lighting. (c): Spall crater, with sharp, steep, straight N sideface, near contact edge and shallower sidefaces elsewhere. The spall bottom deepens toward contact edge where stresses are highest.
Suspected Causes: Cam contact loading varies around circumference, starting at well-defined angle, where spall in (b) starts abruptly. Cam follower is not crowned (the profile is a true cylinder up to the corner radius). Lack of crowning caused sharp edge contact, producing high stresses. Edge stress initiated subsurface origin spalls. In both (a) and (b) one edge spalled more than other due to taper or misalignment.

DATA

Plate No: 10.9
Archive No: 007-112
Image type: light macro
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, run
Speed: 50 KdN
Load: 2.1 GPa
Lubrication: mineral oil based grease, 0-40°C
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 3: 00.18.1.3 Multi-fragment dent (brittle contaminant)
Failure Code 4: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
See also PLATE: 12.3

DESCRIPTIONS

Failure Description: Several independently initiated spalls are widest at the small-end undercut of IR (cone) roller path and taper to a point. Extensive debris denting of roller path, with larger dents from spall debris and many point-size dents probably from external contaminant (dust). Denting does not appear to be the failure cause; edge loading is. Bearing will soon fail by progressive spalling. See Plate 12.3 for denting detail.
Image Description: Roller path TRB IR (cone) is seen as a shiny surface between undercuts and flanges. N side is 'small end.' Innumerable fine indentations, as from dust, are visibile on the roller path; numerous larger (1 mm) dents appear to be from spall debris. From small-end undercut extend several spall craters, widest at edge and tapering, indicating origination from edge load.
Suspected Causes: Taper error, from manufacturing or from mounting on tapered shaft, can concentrate load at one roller path edge. Insufficient roller crowning (edge relief) of roller and/or too wide undercut accentuate edge contact. Contaminant denting from dust ingress occurred in this truck wheel bearing and was aggravated by larger debris as from spalls.

DATA

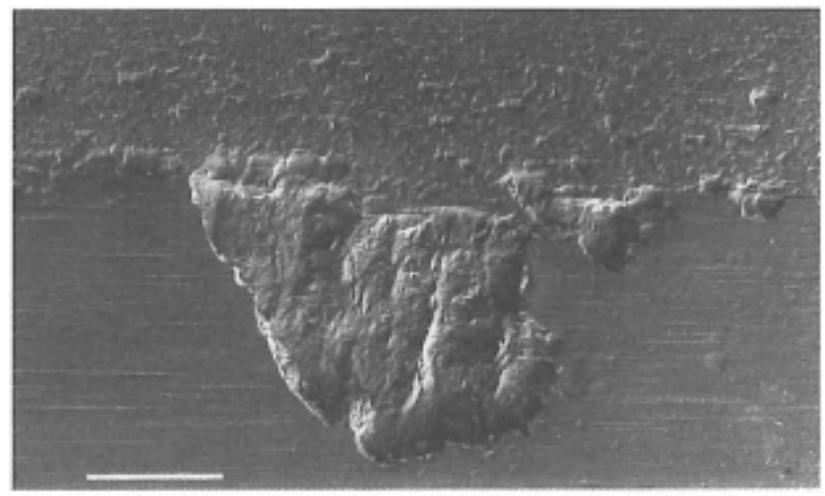
Plate No: 10.10
Archive No: 003-010
Image type: view
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; R&IR&S, run
Speed: 60 KdN
Load: 1.5 GPa
Lubrication: synthetic polyester oil, 110°C?
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

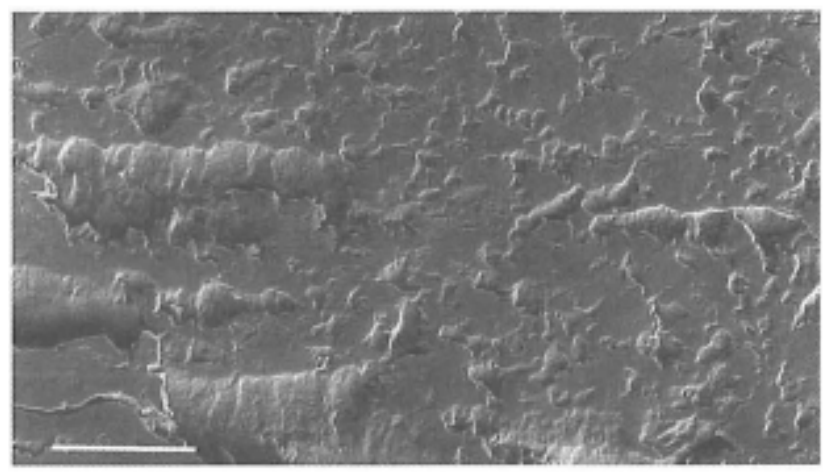
Failure Description: Two rollers with extensive spalls extending from a line near the roller corner radius to the roller midplane. Rolled-in lines appear on other rollers. The relatively sharp edge of the spalls near the roller corner indicates (and IR examination confirms) edge loading from IR undercuts of excess width. Lines on rollers at IR undercut edge also may indicate undercut edge contact or separator prong wear marks. A progression of spalls to gross failure is likely.
Image Description: In the machined separator, rollers are held by staked prongs. S half of second roller from W shows large spall with relatively straight S edge. Third roller from W shows spall with straight N edge. First and fourth roller from W both show circumferential light and dark lines located approximately under the separator prongs. Location of the IR undercut (not shown) was observed to match spall edge.
Suspected Causes: Excessively wide undercuts on IR roller path of CRB create edge loading because crowning (edge relief) of roller is not dimensioned to confine contact this far from roller corners. Edge loading initiates spalls that spread toward roller center plane. Either IR edge contact or separator prong contact can mark roller with circumferential lines. Study of separator wear and of roller wear marks is needed to differentiate the cause.

DATA

Plate No: 10.11
Archive No: 122-6&7
Image type: a,b: SEM
Scalebar = a: 500 b: 100 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed: 46 KdN
Load: 1.8 GPa
Lubrication: mineral oil, ? °C
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.03.2 Spall propagating by reinitiation at surface
Failure Code 3: -
Failure Code 4: -



a



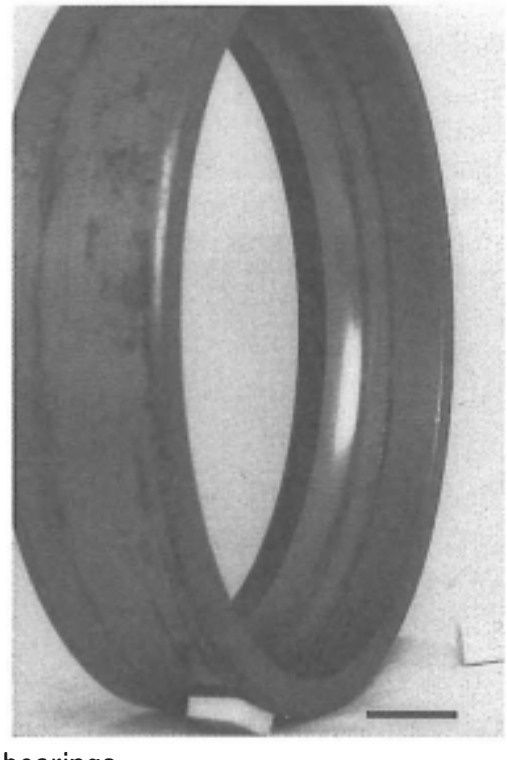
b

DESCRIPTIONS

Failure Description: Contact extending to edge of undercut on IR, with heavy stress concentration at edge (probably from edge geometry error), forms dense band of shallow spalls near edge, with deeper, larger craters extending into the contact area. The bearing has failed.
Image Description: (a): E–W band with dark and light lines at image N is undercut. S thereof is a densely microspalled and rolled down surface. Next adjacent to S are larger spalls of normal depth, which originated from the microspalled band. (b): Microspalled band with featureless surface between craters, at higher magnification. Appearance is similar to advanced surface distress but some craters, 250 μm long, would be untypical of surface distress.
Suspected Causes: Improperly dressed grinding wheel may leave prominent lip adjacent to undercut. When rolled over, the lip is heavily overloaded, plastically rolled down and spalls at the (shallow) depth of high Hertz shear stress in this edge contact. Small depth of stress field makes such spalls virtually indistinguishable from surface distress. Spalled lip initiates normal depth spalls in adjacent normal contact area.

DATA

Plate No: 10.12
Archive No: 027-247
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; OR, run
Speed: 160 KdN
Load:
Lubrication: grease 60°C
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 3: 00.15.1.1 Generalized fretting, radial fit surface
Failure Code 4: -
See also PLATES: 10.3 and 10.47



DESCRIPTIONS

Failure Description: Narrow elongated line of spalls on edge between low land (dam) of the OR and ball groove. The dam must remain unloaded for proper function but becomes loaded if bearing is installed in reverse, so the dam faces the thrust direction. Prompt spalling and damage to balls occurs. Plates 10.3, 10.12 and 10.47 show different spalling modes in similar bearings.
Image Description: On the inner surface of this OR, the low land (dam) area is to image E from the groove. A sharp edge separates it from the (glossy) ball path which extends W to the dark gray land at the thrust side. Slightly S of image center is a row of dark spall craters at the edge. They lie in a circumferential wear track suggesting that the ball rolled over onto the land. Normal fretting visible on OD.
Suspected Causes: If an unsymmetrical ACBB (one land high for thrust, the other low for assembly) is installed in reverse and thrust loaded, the load overrides the groove edge and spalling failure at or just over the edge occurs.

DATA
Plate No: 10.13
Archive No: 001-8
Image type: light microgram
Scalebar = 500 μm (micros: +20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed: 1 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.16.1.1.1 Steep entry spall (subsurface origin)
Failure Code 3: 00.18.2.1 Rolled-in line at contact edge
Failure Code 4: -
See also PLATE: 10.6

DESCRIPTIONS
Failure Description: Rolled-up groove edge from edge contact under heavy load. The edge has spalled from subsurface origin fatigue due to the high edge-stresses. The spalls may inflict further damage on balls (see Plate 10.5). The bearing has failed.
Image Description: A bright E-W band S of image center divides the ball track lying to the S from the land lying to the N. The sharp edge of the land is the N boundary of the bright area. Four spall craters with steep walls are visible at the edge. The shadow cast to the N of the edge indicates that the edge is elevated (plastically "rolled up") above the land surface.
Suspected Causes: A geometry error in the bearing caused heavy contact between balls and the sharp edge of the IR groove. This edge loading produced a rolling up of the edge above the land surface and subsequent spalling of the IR (see Plate 10.5) by subsurface-origin fatigue due to the high edge stresses.

DATA
Plate No: 10.14
Archive No: 005-17
Image type: SEM, backscatter
Scalebar = 400 μm (micros: +20%, others: +100%, −50%)
Component: C; CM, run
Speed: 7 m/sec
Load:
Lubrication: mineral oil, 115°C
Failure Code 1: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 2: 00.18.2.1 Rolled-in line at contact edge
Failure Code 3: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 4: 00.17.1.1 Glazing (incipient surface distress)

DESCRIPTIONS
Failure Description: Narrow band of small, shallow spalls at contact edge, in and near a rolled-in line at the edge. Incipient glazing surface distress appears within the contact; advanced glazing and microspalling becomes visible as edge is approached. The band of small shallow spalls resulting from sharp edge contact is indistinguishable from surface distress microspalling in the edge area. Large-scale spalling and failure are likely.
Image Description: Finishing marks run E–W. The N image half is outside the contact. A sharp edge delineates N side of dark rolled-in line at contact edge, in which multiple, small (50 μm wide), shallow spall craters are visible. To the S, adjacent to the rolled-in edge, finishing lines are obliterated by surface distress glazing and a few spalls are seen. S 1/3 of image shows incipient glazing.
Suspected Causes: Cam follower was not crowned (it was a true cylinder up to the corner radius). This, possibly combined with misalignment, causes sharp edge contact with high stresses, resulting in rolled-in line, followed by spalling. General surface distress due to low EHD film is typical of edge contact.

DATA
Plate No: 10.15
Archive No: 087-021
Image type: light view
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: BB (maximum complement); IR & OR, run
Speed:
Load: axial
Lubrication:
Failure Code 1: 00.16.01.2.3 Spalling at contact edge from thrust load
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Extensive spalling around circumference of IR ball groove, offset axially, as under thrust load and running over loading slot edge. Failure from edge contact at that point has spread over most of the ball groove during extended additional running. This is a gross failure.
Image Description: OR surrounds IR in image. On IR ball path, a band of spall craters covers much of the groove bottom, but is offset to the W side, where the loading slot, ground into the land, is seen. The edge of the slot (labeled "loading notch") extends into the ball groove and was over-rolled. Direction of thrust load on innerring, as deduced from offset of contact path to the W, is labeled.
Suspected Causes: Maximum-complement ball bearings contain more balls than can be assembled without a loading slot for the insertion of the last balls. Such bearings can take thrust load only on the IR face away from the loading slot, so that the contact does not overroll the slot edge. This bearing was mismounted, resulting in load application toward the loading slot, causing edge spalling.

DATA
Plate No: 10.16
Archive No: 031-005&012
Image type: a, b: view
Scalebar = a, b: 25 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.2.3 Spalling at contact edge from thrust load
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 4: 00.22.1 Overstress crack

DESCRIPTIONS
Failure Description: Advanced compound failure of more than one mode. Thrust loaded groove is half spalled; land edge is overrolled. Large chip has broken out of the land and another adjacent chip out of the groove (bulk fracture). There are spalled and fractured balls. Probable bearing seizure. Bearings in heavy industrial machinery often run to severe compound failure before diagnosis and removal.
Image Description: (a): IR, covered with heavy grease (on lands and in chipped area). S half of ball grove spalled and spalls rolled down. In SE half of S land, a large chip is broken off. Near ring center, chip broken out of track; the cavities of the two fractures merge. (b): Spalls on several balls. Two balls at NW, shattered. Second ball from N has a row of spalls along a great circle suggesting edge loading.
Suspected Causes: Groove spalling appears due to axial overload (spalls extend past groove edge). After continued running, some balls spalled; one or two shattered and jammed. They chipped the ball path and a land.

a

b

Failure Code: 00.16.01.2.3
Failure Code: 00.16.01.3

DATA
Plate No: 10.17
Archive No: 001-25&26
Image type: light macro
Scalebar = a, b: 4 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; IR&OR, run
Speed: 700 KdN
Load: 1 GPa
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.16.01.2.3 Spalling at contact edge from thrust load
Failure Code 2: 00.23.1.1 Contact path rolldown in bearing
Failure Code 3: 00.16.02.5 Advanced spalling
Failure Code 4: 00.12.4 Wear of guiding-component support surface

DESCRIPTIONS
Failure Description: Rings of a DGBB under heavy thrust load show extensive spalling on opposite edges of ball grooves. On both rings, the spalling extends to one (sharp) groove edge and has serrated that edge. A thrust load sufficient to produce severe edge contact caused plastic rolldown at the edges and early spalling from the stress concentration at the edge. Some circumferential wear marks are on separator (cage) guide surfaces of IR.
Image Description: (a) IR ball groove extensively spalled S of label: "Center of raceway." (b) Similar spalling on OR ball groove, N of "Center of raceway." These are the two diagonally opposite groove halves under thrust load. Edges of spalled groove halves are serrated by rollout and spalls extending to the edges. Faint circumferential wear marks on separator guide surfaces labeled "Cage Pilot Diameter."
Suspected Causes: Excessive thrust load for the design and looseness selected cause contact ellipse to override groove edges significantly. Stress concentration at edge initiates early spalling. Wear at separator guide surfaces may be due to debris from spalls.

a

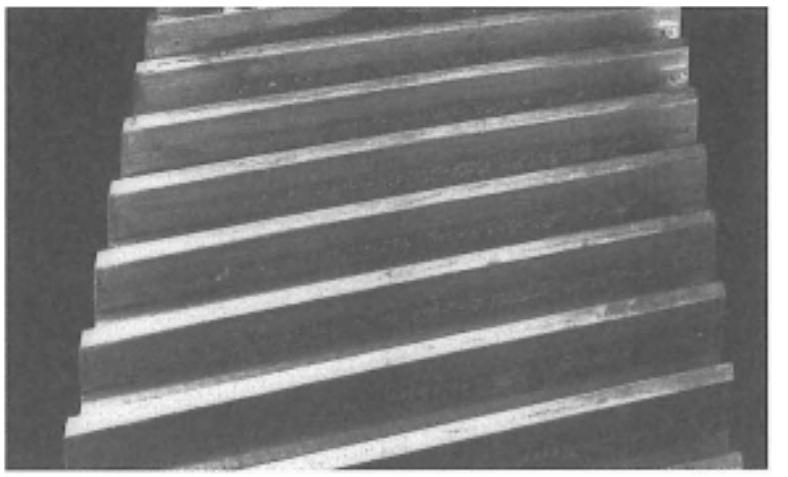
b

DATA
Plate No: 10.18
Archive No: 080-123
Image type: light macro
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: SG; W, case hardened, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3 Tooth spalling
Failure Code 2: 00.13.3 Tooth contact galling
Failure Code 3: -
Failure Code 4: -

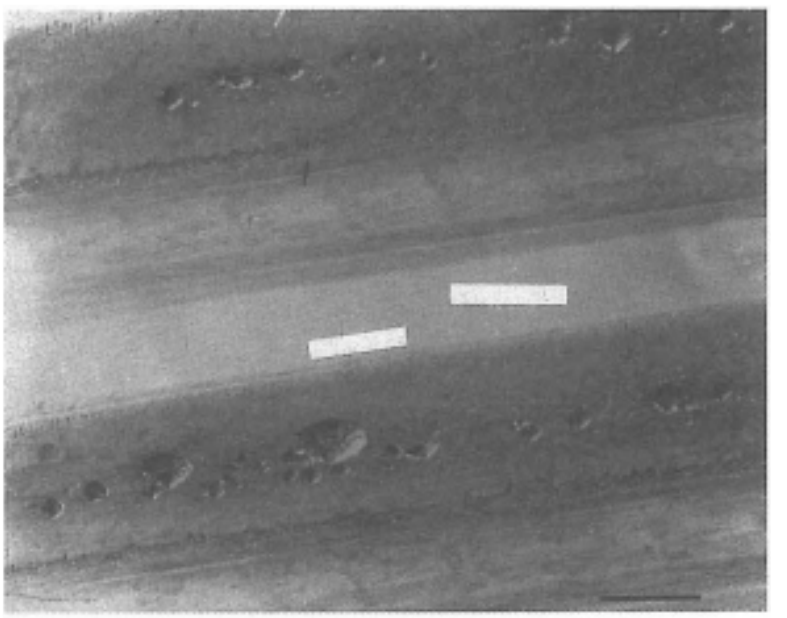
DESCRIPTIONS
Failure Description: Multiple galling marks (scoring) running radially over addendum act as sources for fatigue spalls. In its present condition, the gear is still operable, but continued spalling may lead to tooth fracture (FC 00.22.01.4).
Image Description: Light-colored radial galling streaks in many locations on the addendum, on first and second fully visible tooth from N. On all tooth flanks, dark spall craters are interspersed with the galling marks. Microscopy would indicate that spalls originate from galling marks as defects.
Suspected Causes: Galling (scoring) of gear teeth may occur due to overload, insufficient EHD film, excessive operating speed, surface defects or excessive roughness. Galling streaks are significant sources of spalling fatigue. Occasionally gear galling may "heal" when operating conditions become subsequently less severe. However, spall initiation may have taken place while the galling was fresh and spall formation may proceed afterward.

DATA

Plate No: 10.19
Archive No: 099-107&102
Image type: a: light macro, b: light microgram
Scalebar = a: 30 mm, b: 3 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3 Tooth spalling
Failure Code 2: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 3: 00.12.5.2 Smooth tooth wear
Failure Code 4: -
See also PLATES: 10.22 and 10.27



a



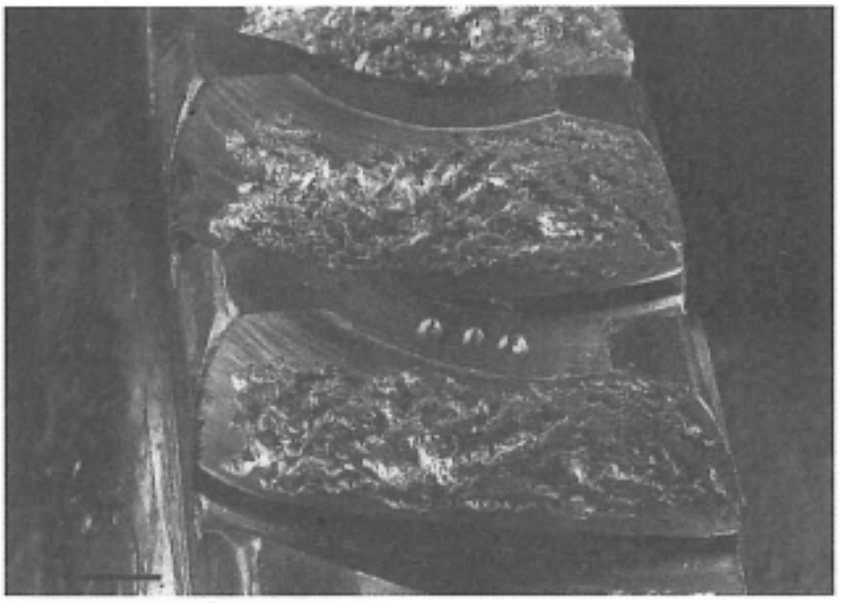
b

DESCRIPTIONS

Failure Description: In medium-hard gears, small spalls may appear on much of the dedendum area during early running. Spalling is believed to be more sliding-direction sensitive in medium-hard steel (enhanced when sliding is co-directional to rolling, as in dedendum). Such spalls may wear away and stop to proliferate, allowing the gear to continue running. See also Plate 10.22. In other cases, failure progresses. See Plate 10.27.
Image Description: (a): All visible tooth contact surfaces show many small spall craters aligned from pitchline down into dedendum. Cratering is more pronounced in E half of tooth image (possible misalignment). (b): Dedendum surfaces of two consecutive teeth are mottled dark gray areas at N and S of image. Intervening tooth root, tip and addendum are light gray. Craters are rounded by wear in dedendum; no new craters. White rectangles are artifacts.
Suspected Causes: Highly loaded medium-hard gears, often with as-machined and relatively rough surfaces, tend to wear during run-in. Near pitchline, toward dedendum, where sliding is low, but co-directional to rolling, small spalls tend to appear, rather than wear. Spalling may be arrested in this class of material as surfaces become smoother in run-in.

DATA

Plate No: 10.20
Archive No: 099-116
Image type: light macro
Scalebar = 25 mm (micros: ±20%, others: +100%, −50%)
Component: WG; W, bronze, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3 Tooth spalling
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 00.12.3.3.2 Wear, centered in sliding contact
Failure Code 4: -



DESCRIPTIONS

Failure Description: Spall cratering covering most of tooth contact surface in worm gear wheel. Wear marks are on all unspalled areas. Worm gear wheels, generally of bronze, remain functional with extremely heavy spalling wear. Data on spall progression in bronze are scarce but it appears slow under these conditions.
Image Description: Worm gear wheel is viewed on flank with axis E–W. Two full teeth and part of a third (N image edge) show generally spalled contact surface, except at W and NW edges, which show kinematic wear marks. High areas between spall craters are also worn smooth.
Suspected Causes: Severe surface destruction, including wear, spalling and possibly galling is encountered in worm gear contacts which undergo high sliding. Large contact area keeps stresses sufficiently low that functioning can be maintained (at slow worm gear speeds) even in the presence of significant surface destruction.

DATA

Plate No: 10.21
Archive No: 099-205
Image type: light macro
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, carburized, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3 Tooth spalling
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.16.03.2 Spall propagating by re-initiation at surface
Failure Code 4: 00.17.1.2 Microspalling (advanced surface distress)

DESCRIPTIONS

Failure Description: Large spalls originating from line of surface distress and spalling at pitchline and extending across entire tooth flank. The spalls were propagated by progression along the spall bottom and are of surface origin. One spall has chipped the tooth tip. The gear is failed.
Image Description: Three tooth flanks are visible, proceeding N to S. The N tooth shows a line of small spalls in dedendum and signs of frosting (microspalling from surface distress) surrounding these spalls. The second tooth from N shows similar damage plus a large, leaf-shaped spall crater originating at a dedendum spall and covering the addendum. The third tooth, at S edge, shows similar spall, with tip chipping. Reflection of inch scale on S tooth.
Suspected Causes: Surface distress and microspalling in dedendum arise from high load, possibly rough surface, and insufficient EHD film. Extensive spalling across addendum is unusual; dedendum spalling is more common. (Spall crater is too shallow for subcase failure.)

DATA

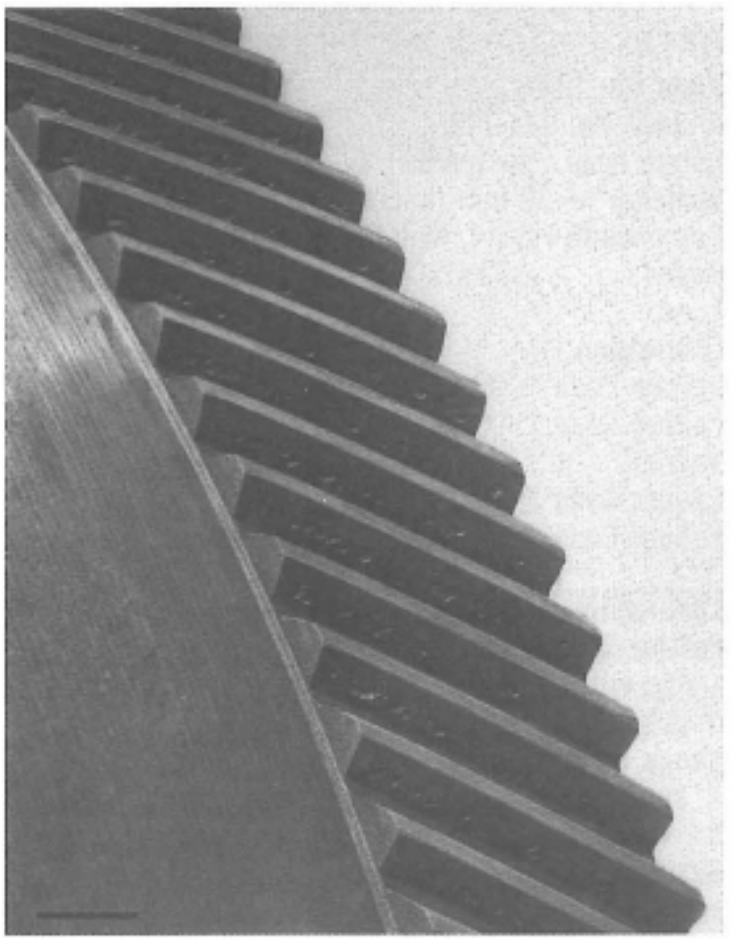
Plate No: 10.22
Archive No: 099-108
Image type: light macro
Scalebar = 25 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 2: 00.12.5.2 Smooth tooth wear
Failure Code 3: -
Failure Code 4: -
See also PLATES: 10.19 and 10.27

DESCRIPTIONS

Failure Description: Dedendum spalling, similar to that in Plate 10.19, with subsequent wear, removing smaller craters and rounding edges of remaining spalls. This may be a stable condition for medium-hard gears. See Plate 10.19 for more description detail. See also Plate 10.27 for destructive spalling that is not arrested.
Image Description: One tooth cut from a gear shows wear in dedendum, with sharp dark line as N edge of wear. In the worn area, several small spall craters remain from earlier spalling. Addendum appears intact.
Suspected Causes: Highly loaded medium-hard gears, often with as-machined and relatively rough surfaces, tend to wear during run-in. In the dedendum, near pitchline, where sliding is low, and co-directional to rolling, small spalls may appear before wear. Spalling may be arrested in this material by smoothing of surfaces in wear during run-in. If the degree of wear is tolerable, the gear remains serviceable. (In gear shown, geometry is lost.)

DATA

Plate No: 10.23
Archive No: 099-111
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 2: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 3: -
Failure Code 4: -
See also PLATES: 10.19 and 10.24

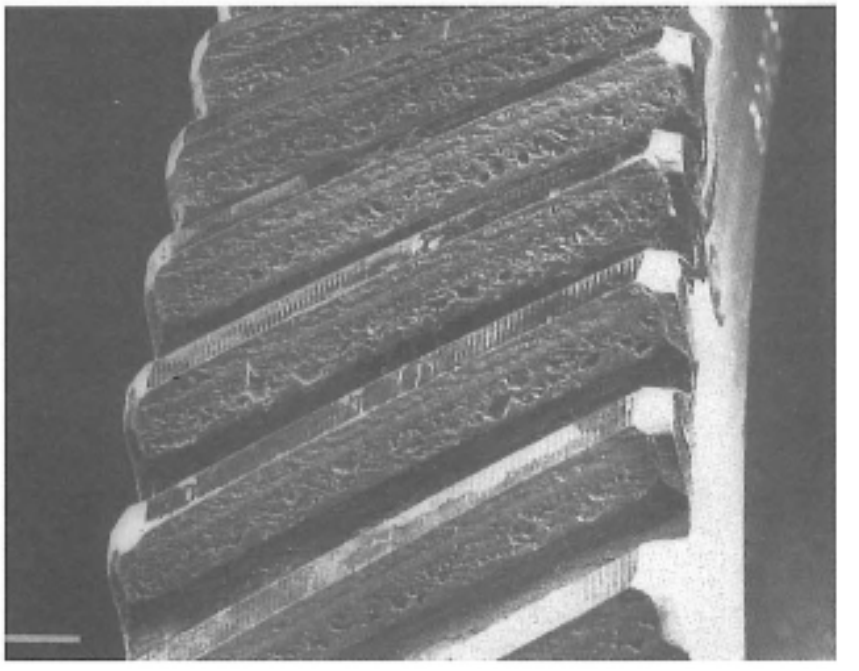


DESCRIPTIONS

Failure Description: Incipient pitchline spalling in medium-hard gear, extending into dedendum. Spall craters are too deep and large to expect continued safe operation of gear. Compare to slow-progressing spalling in Plate 10.19. See also Plate 10.24 for more advanced spalling in similar gear.
Image Description: Gear is viewed from above its side. SW image corner is sideface. Visible tooth flanks all show rows of spall craters of varying size and depth arranged along pitchline and extending into dedendum.
Suspected Causes: Highly loaded medium-hard gears, often with as-machined and relatively rough surfaces, may develop spalls near pitchline where sliding is low and contact pressures high. They tend to extend into dedendum where sliding is codirectional with rolling. In medium-hard material, spalling is promoted by this sliding direction. Rate of progression depends on severity of operating conditions and on material.

DATA

Plate No: 10.24
Archive No: 099-112
Image type: light macro
Scalebar = 25 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: -
Failure Code 4: -
See also PLATES: 10.19 and 10.23



DESCRIPTIONS

Failure Description: Advanced spalling in medium hard gear covers entire contact area and is heaviest in dedendum. Craters are too deep and numerous to permit safe operation of gear. Compare to lesser spalling in Plate 10.23 and to slow-progressing spalling in Plate 10.19.
Image Description: Helical gear teeth are viewed on flanks. The gear is heavily spall cratered on all visible tooth contact surfaces, with density of cratering greater in dedendum than in addendum. Original machined gear OD surfaces.
Suspected Causes: Highly loaded medium-hard gears, often with as-machined and relatively rough surfaces, may develop spalls near pitchline where sliding is low and contact pressures high. They tend to be most pronounced in dedendum where sliding is co-directional to rolling. Spalling in medium-hard material appears more sensitive to sliding direction. Rate of progression of spalling depends on severity of operating condition and on material.

DATA
Plate No: 10.25
Archive No: 064-409
Image type: view (partial)
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: HG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 2: 00.16.03.1 Spall propagating by cracking at spall bottom
Failure Code 3: 00.22.01.4 Gear tooth crack or fracture
Failure Code 4: 00.12.5.1 Tooth polishing

DESCRIPTIONS
Failure Description: Along pitchline, several small spalls on many teeth. On one tooth, large spall extending into addendum and forming a chip out of the tooth tip. Radial wear marks and polishing of contact surface are visible near one end of the mesh, indicating possible misalignment. The tooth has failed.
Image Description: W end of mesh shows polishing of all tooth surfaces on gear filling S ¾ of image. N ¼ of image is mating gear. At *A*, spall crater on dedendum. Crosses pitchline into addendum, where a deep chip has broken out, extending into tooth tip. On the tooth marked *A*, and on teeth to both sides of it are multiple, fine spall craters below pitchline.
Suspected Causes: Pitchline or dedendum spalling of gear teeth occurs under heavy load and low EHD film condition (relatively low speed). In high hardness gears, spalls can grow explosively and occasionally result in bulk fracture, as in this image.

DATA
Plate No: 10.26
Archive No: 080-204&205
Image type: SEM of toothface and section
Scalebar = a: 1 mm, b: 50 μm (micros: ±20%, others: +100%, −50%)
Component: SG; W, carburized, hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: 00.12.5.2 Smooth tooth wear

DESCRIPTIONS
Failure Description: Incipient spalling near tooth pitchline showing shallow-entry spalls and cracks entering at angle 25° from surface. The unspalled surface is very smooth, from surface distress and/or smooth wear. Pitchline spalling may not immediately fail gear when it is as small (1 mm dia.) as shown here, but is expected to lead to eventual spalling failure.
Image Description: (a): Sectioned tooth. Far W: dark mounting material, next to E, light gray tooth flank, then, to E, dark gray (labeled) polished section. Spalls are dark spots just W of section edge (in box). (b): Field within box, at 200×. W image half shows craters. Shallow entry from S to N and breakout at N end. Crack runs 25° NE into polished section. Unspalled tooth face is featureless (surface distress, wear).
Suspected Causes: Spalling (often designated 'pitting' in gear technology) occurs in highly loaded gears in dedendum near pitchline where sliding is moderate. This gear was found to have low surface hardness. Wear occurred in the high sliding areas, surface distress and incipient spalling in the lower sliding areas.

a

b

DATA

Plate No: 10.27
Archive No: 080-118
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, med. high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 2: 00.19.1.2 Temper colors in contact surfaces
Failure Code 3: 00.12.5.3 Destructive tooth wear
Failure Code 4: -

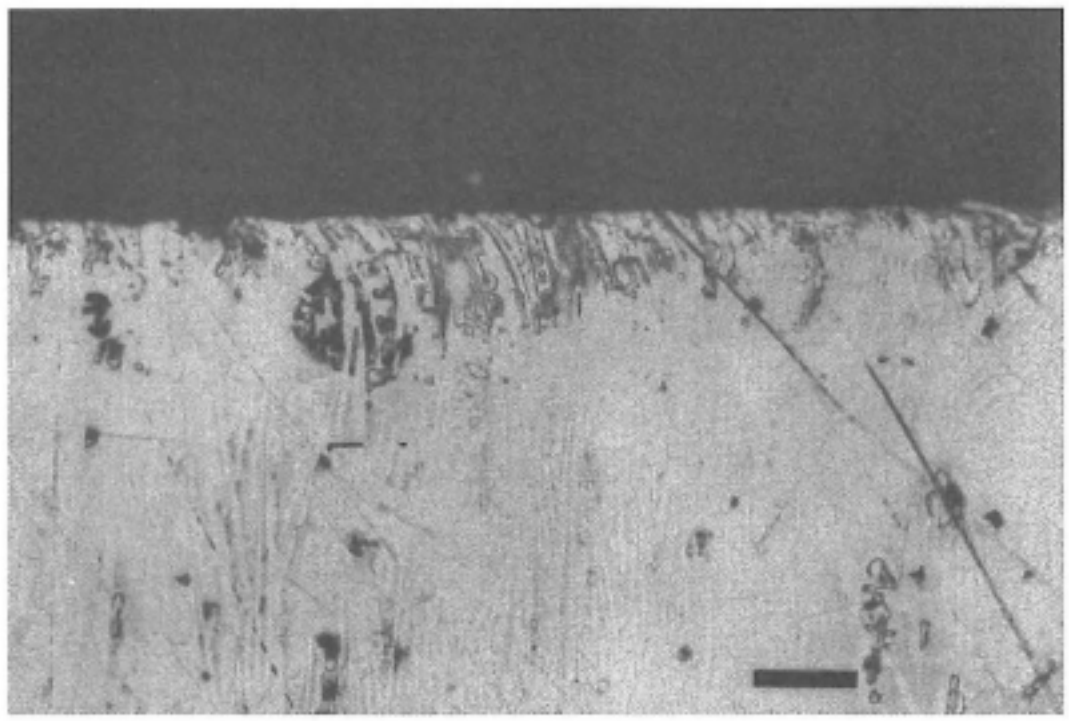
[See Image in Appendix]

DESCRIPTIONS

Failure Description: spalled ('pitted') pitchline area and deeply worn addendum and dedendum on high-hardness gear. Temper coloring from heat imbalance. Wear of surfaces with high sliding leaves pitchline elevated. This later spalls, generating debris and aggravating wear elsewhere. High wear rate may explain why spalling has not progressed to larger craters: surface wears away almost as fast as craters form. Gear is failed.
Image Description: View from gear face indicates severe tooth shape distortion due to wear, both in addendum and dedendum. Pitchline shows axial band of multiple, moderate-size spall craters ('pitting'). The hue of the entire gear is bluish from temper-coloring upon operation at excessive temperature. The red background is not significant.
Suspected Causes: If addendum and dedendum of gear wear from contamination, inadequate lubrication or excessive surface roughness, then the pitchline zone becomes elevated and carries excessive load. This possibly combined with overheating and material softening, may precipitate pitchline spalling.

DATA

Plate No: 10.28
Archive No: 006-27
Image type: light metallogram, etched
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: C; CF, run
Speed:
Load:
Lubrication: mineral oil based diesel engine oil, ? °C
Failure Code 1: 00.16.02.1 Microplastic deformation indication
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.61

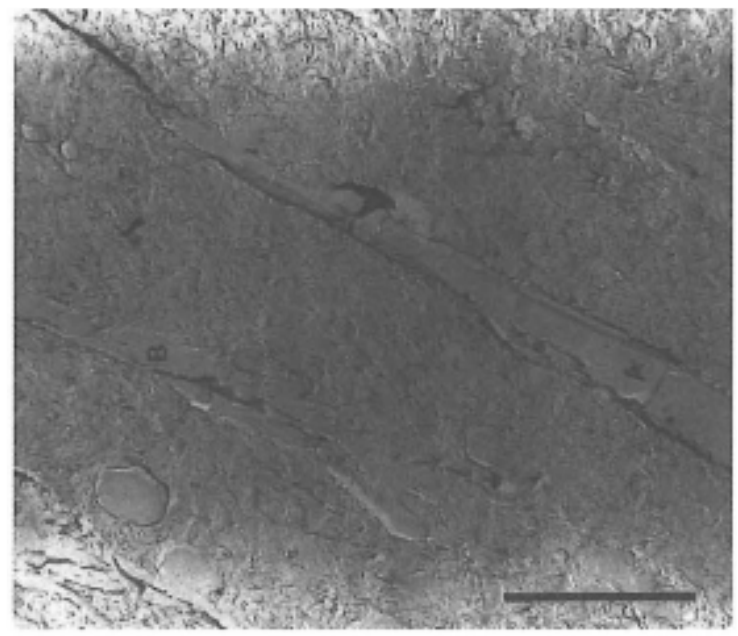


DESCRIPTIONS

Failure Description: Sliding combined with rolling produced sufficient traction in this *sliding type* cam follower to cause shear of near-surface material, with forward bending of visible vertical structures in the sliding direction. See also Plate 10.60 for spalling from surface distress.
Image Description: Contact surface runs in E–W direction one-quarter from N image edge. Etched structure elements (finer flow) are perpendicular to surface except in the 40 μm closest to the surface where they bend to the W due to plastic deformation caused by high tractive forces produced by E to W sliding.
Suspected Causes: Cam to follower contact is predominantly sliding, with a rolling component resulting from rotation of the (sphere ended) follower around its axis. In the present case, sliding/rolling caused surface distress and spalling, and also plastically deformed the subsurface material.

DATA

Plate No: 10.29
Archive No: 093-16.3.7
Image type: replica TEM of etched section
Scalebar = 2.5 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 420 KdN
Load: 3.4 GPa
Lubrication: mineral oil, 100°C
Failure Code 1: 00.16.02.1.1 Microplastic deformation bands or 'butterflies'
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.31

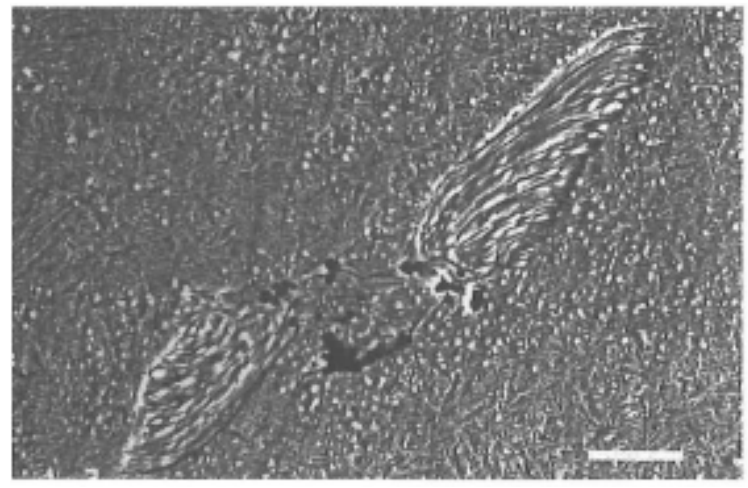


DESCRIPTIONS

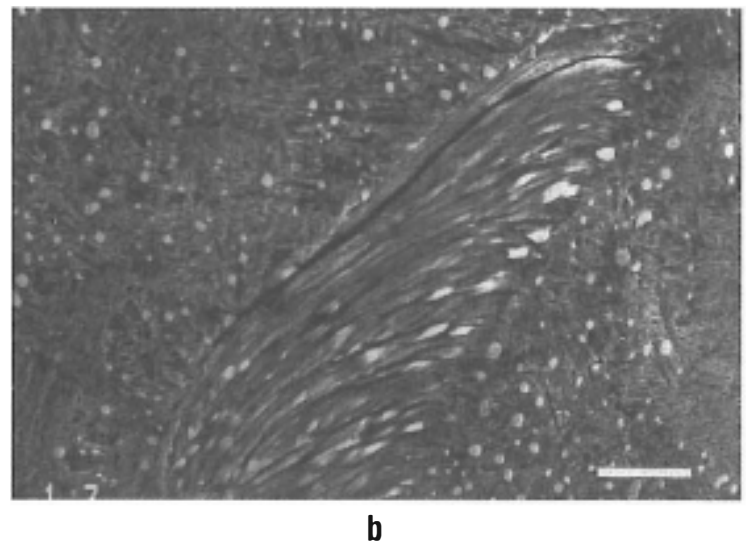
Failure Description: Shown is the structure within a deformation band. The cold-worked martensitic structure with dislocation cells is interspersed with newly formed lenticular carbides and some untransformed globular carbides. The lenticular carbide interfaces are believed weak and prone to channeling existing cracks in their direction. See also Plate 10.31.
Image Description: Gray background with multiple short dark swirls and lines is cold worked martensite in the deformation band. Smooth, lighter gray oblong structures running SE–NW as at *A* and *B* are lenticular carbides. Round structure in SW image corner is an original globular carbide. Black, crack-like lines and spots near lenticular carbides may be microcracks formed in cycling, but more likely arise from etching.
Suspected Causes: Deformation bands are sheets of martensite with many dislocation cells from cyclic cold working in the observably defect-free matrix. Carbon migrates to the boundaries of these sheets and forms lenticular carbides. Weak interfaces between deformation bands, lenticular carbides and matrix may channel cracks in spall bottoms.

DATA

Plate No: 10.30
Archive No: 107-027a&b
Image type: SEM of Nital etched section
Scalebar = a: 10, b: 5 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.16.02.1.1 Microplastic deformation bands or 'butterflies'
Failure Code 2: 00.06.1.1 Hard micro-inclusion
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.31



a



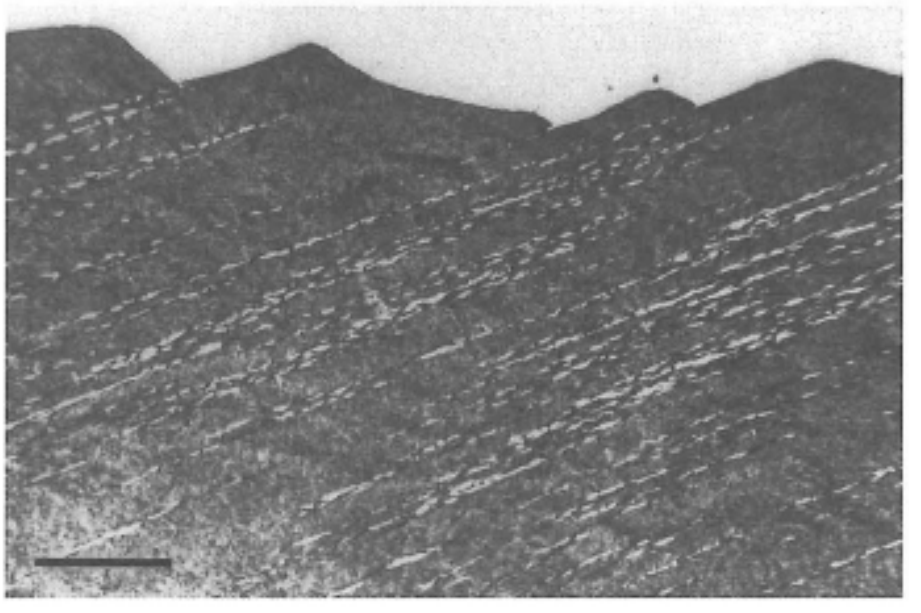
b

DESCRIPTIONS

Failure Description: Microplastic deformation band (*butterfly*) from fatigue cycling has formed around a cluster of small (about 5μm), hard non-metallics between two "wings" of the band. Possible microcrack at one wing edge. Deformation bands contain heavily cold-worked martensite bands separated by lamellar carbides formed during deformation.
Image Description: (a): Mottled background is a martensitic structure with carbides as white points. In image center, several black jagged spots are non-metallics. Two wing-shaped patches of curved lines, extending SW–NE are 60 μm long deformation bands (butterflies). Black lines within the wings are lenticular carbides and/or dislocation tangles. (b) Wing, higher magnification. Heavy black line at N wing border is probably a crack, enhanced by etching.
Suspected Causes: Repeated high-stress contact cycling of steel causes cumulative local plastic deformation which may produce deformation bands, either in the defect-free matrix or at defects. Deformation banding increases with stress and total cycle count but is not necessarily a crack originator. Cracks, if formed, may follow deformation band direction. (See Plate 10.31.)

DATA

Plate No: 10.31
Archive No: 093-16.3.6
Image type: light metallogram, Picral etched section
Scalebar = 10 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.02.1.1 Microplastic deformation bands or 'butterflies'
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.29



DESCRIPTIONS

Failure Description: In circumferential section of spalled ring, many parallel straight traces of matrix deformation bands (not at observed defects). The spall bottom follows deformation bands intermittently, with breaks from band to band. Deformation bands are microplastic events from contact stress cycling. They increase with stress and cycle count. They are not known to *initiate* cracks, but will channel existing cracks. See also Plate 10.29.
Image Description: Dark gray mottled background is Picral etched martensitic matrix. Multiple SW–NE running straight white-and-black lines are sections of laminar deformation bands. Jagged line near N image edge is the section through the spall bottom. Segments of bottom rising to NE follow deformation bands (at about 25° 'Martin angle').
Suspected Causes: Repeated high-stress contact cycling of steel causes cumulative local plastic deformation which may produce deformation bands in the observably defect-free matrix. Deformation banding increases with stress and total cycle count but is not known to be a crack originator. Cracks, once formed, may follow deformation band direction jumping from band to band to create serrated spall bottom.

DATA

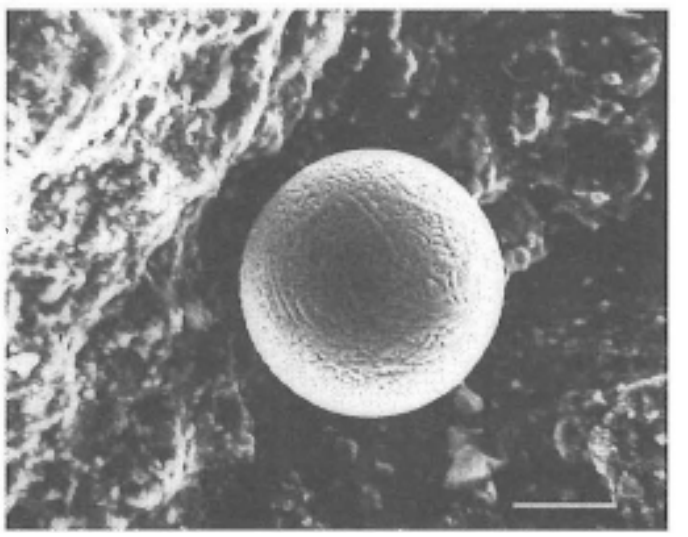
Plate No: 10.32
Archive No: 075-103&111
Image type: a, b: SEM
Scalebar = a: 60, b: 30 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; R, carburized steel, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.02.1.3 Microsphere spalling debris
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: This Plate shows the SEM appearance of spherical debris formed in spalling cracks. The generation of such debris is believed characteristic of spalling fatigue. The material is the same as the matrix steel, but is possibly oxidized at the surface. Alternating micro-motions between crack faces are suspected causes. The spheres range 10–200 μm in size: (a): 200 μm, (b): 50 μm.
Image Description: (a): The large dark hemisphere at image center, with adhering laminae, is a partly formed spherical debris particle. Other laminae surround it in the crack face. Gray-scale reflects thinness of the lamina (thinner is lighter). The background area is a crack face. (b): Large white sphere at image center is fully formed spherical debris particle. Texture and hue indicate the presence of oxides (confirmed by X-ray analysis).
Suspected Causes: Most debris formed by micro-motion of surfaces under load is laminar (example: fretting debris). Spherical (not merely cylindrical) debris have been observed only under rolling contact fatigue spalling conditions. The specific mechanism of their generation is not understood.



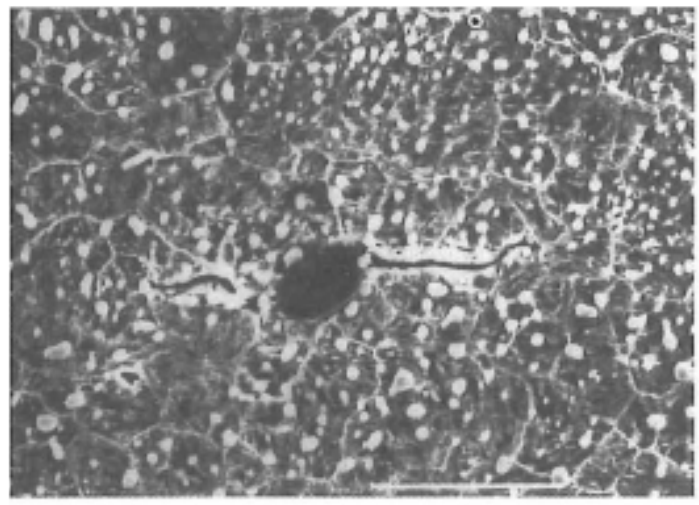
a



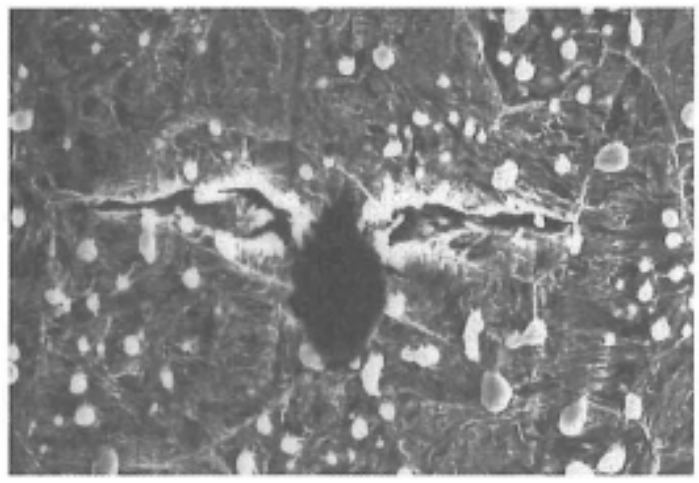
b

DATA

Plate No: 10.33
Archive No: 107-026a&b
Image type: SEM of Nital etched section
Scalebar = a: 5, b: 3 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.16.02.2 Contact fatigue cracking
Failure Code 2: 00.16.1.1.2 Spall from subsurface defect
Failure Code 3: 00.06.1.2 Sulfide inclusion
Failure Code 4: -
See also PLATE: 10.30



a



b

DESCRIPTIONS

Failure Description: Initiation of microscopic fatigue cracks from subsurface manganese sulfide inclusions of (a) 5 μm and (b) 3 μm diameter, under high load and prolonged cycling. Sulfide inclusions are believed to be less severe spall-originating defects than are hard inclusions, and 3 or 5 μm inclusions are minimum size to cause spalling. The possibility exists that these microcracks (12–15 μm long) will not propagate.
Image Description: (a): Nital etched metallographic section at high magnification in SEM. White dots are carbides in dark matrix, with martensite needles as faint outlines. The black oval in the center is a manganese sulfide inclusion. Black horizontal lines in white bands are microcracks (SEM shows sharp edges as white). (b): Similar image of another inclusion. Cracks are horizontal dark openings extending from N end of inclusion.
Suspected Causes: The microcracks originate from the small subsurface manganese sulfide inclusion acting as a stress raiser (low strength soft material in void). Load and cycling time must be extreme to cause the fatigue cracking (see Plate 10.30).

DATA

Plate No: 10.34
Archive No: 002-005a&c
Image type: a: view, b: light metallogram, etched
Scalebar = a: 6 mm, b: 300 μm (micros: +20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 0.8 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.16.02.2 Contact fatigue cracking
Failure Code 2: 00.16.1.1.2 Spall from subsurface defect
Failure Code 3: 00.16.02.1.1 Microplastic deformation bands or 'butterflies'
Failure Code 4: 00.04.3.1.1 Incipient melting from forging at excessive temperature
See also PLATE: 10.53



DESCRIPTIONS

Failure Description: (a): Several radial cracks from contact loading of crack-prone tool steel forged at excessive temperature. Secondary spalls exist at three of the cracks. Great-circle wear marks (FC 00.12.4) (probably separator contact). (b): Spall. Deformation bands (butterflies) at micro-porosity and elsewhere. Cracks growing into material from spall bottom are due to crack-prone material. See also Plate 10.53.
Image Description: (a): Three radial cracks (light-colored straight lines at arrow pairs). Spall craters exist on each crack. Light-colored halos decorate spall edges from reduced EHD film. Several circular wear marks run E–W, one NW–SE (possibly from separator contact). (b): Cross-section. Rolling direction E to W. Spall bottom at N, crack at W edge (arrows). Dark hairline cracks and white deformation bands (butterflies) SE–NW. Micro-voids visible at *A*.
Suspected Causes: Tool steel is sensitive to excessive forging temperature, which causes local melting and porosity. Structure is damaged. Such material is spall and crack-prone. This explains the radial cracking under contact load with subsequent spalling in an element (ball) not subject to tensile hoop stress.

DATA

Plate No: 10.35
Archive No: 018-604&606&607
Image type: a: light macro; b: SEM; c: light micro, Nital etch
Scalebar = a, b, c: 100 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR hard turned, honed, run
Speed: 100 KdN
Load: 3.7 GPa
Lubrication: mineral oil, 66°C
Failure Code 1: 00.16.02.2 Contact fatigue cracking
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 4: 00.16.02.1.2 Dark-etching microplastic deformation zone

DESCRIPTIONS

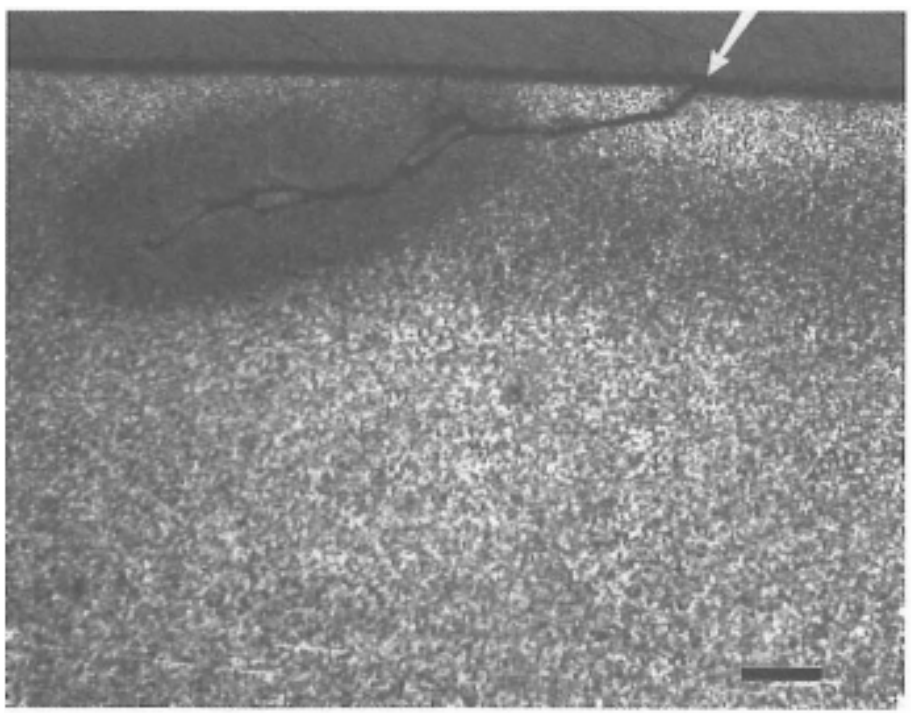
Failure Description: (a,b): Debris dent on surface is followed by shallow-entry spall initiation through surface-origin fatigue crack entering at approximately 10° to surface. (c): Etched section shows altered (dark-etching), microplastically worked structure surrounding crack, indicating concentrated stress acting over a substantial cycle count. Note the intact ridge between dent and spall. The ring has failed.
Image Description: (a): Rolling surface with E–W finishing lines. Dent (NE of arrowhead) is the angular structure, dark at W, and lighter than surroundings at E. V-shaped crack extends NW and SW from a point W of dent. N–S crack further W. (b): Rolling surface is to the N of sharp edge; section is to the S. Crack seen on both. Black vertical rectangle is artifact. (c): Etched section. Rolling surface with crack (arrow) is at N. Dark-etching structure is visible around crack tip.
Suspected Causes: Dent is common cause of early spalling by creating stress concentration, loss of EHD film and possibly material damage. Typically, a spalling crack starts a small distance away from dent edge, leaving an intact ridge, since maximum shear stress concentration is not at the very edge.



a



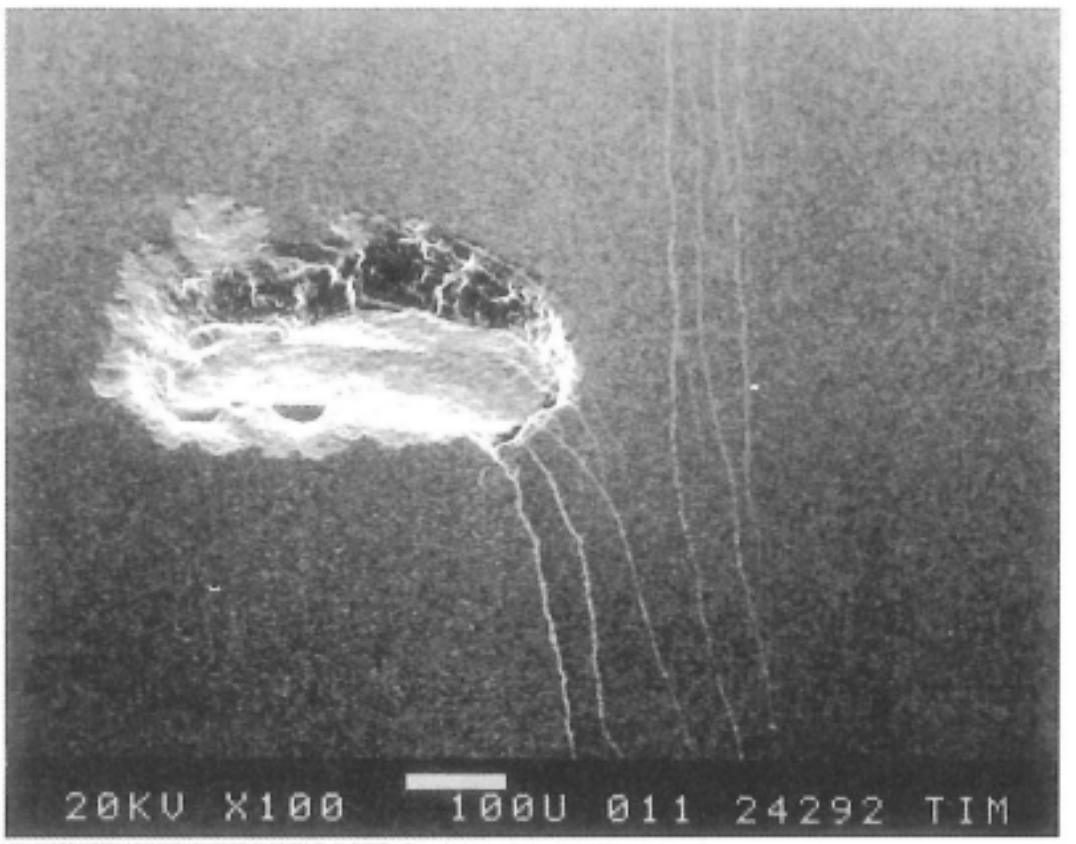
b



c

DATA

Plate No: 10.36
Archive No: 014-B004
Image type: SEM
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Component: 0, RC test rig rod; silicon nitride, hot isostatic pressed; run
Speed: 1.9 m/sec
Load: 5.93 GPa
Lubrication: mineral oil, with additives; approx. 40°C
Failure Code 1: 00.16.02.3 Incipient spalling, single spall
Failure Code 2: 00.16.1.2.3 Shallow entry spall from tensile cracking (ceramic)
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: -
See also PLATE: 6.1



DESCRIPTIONS

Failure Description: One small oblong spall about 500 μm long, formed on a cluster of four curved parallel tensile cracks. Additional, linear tensile cracks not yet spalled. This failure was found to originate near the track edge, where tensile Hertzian stresses are present.
Image Description: At image center W, one horizontally elongated spall crater of brittle ("sandy") appearance. N wall steep, others shallow. Four light gray crack lines on dark gray undamaged surface lead S–N into the spall, curving W as they enter the spall. Four additional light gray crack lines run N–S at 1/3 from E image edge. Overrolling direction is image N to S.
Suspected Causes: Extremely heavy Hertz pressure (well above plastic limit of steel, possibly also of ceramic binder) cycled for very long periods creates high repetitive stresses. Tensile cracks form and some coalesce into a spall. Some of the cracks curve while others are straight. It is conjectured that the curving cracks were attracted by a material defect which then spalled out.

DATA

Plate No: 10.37
Archive No: 005-36
Image type: SEM backscatter
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Component: C; CM, run
Speed: 1.18–2.5 m/sec rolling
Load: 1.10–1.25 GPa
Lubrication: engine mineral oil; temp: varying
Failure Code 1: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 2: 00.13.2.1.1.2 Contact galling from high acceleration
Failure Code 3: 00.12.3.2.4 Scoring wear (macroscopic gouging without galling)
Failure Code 4: 00.18.01.1.2 Denting of rolling surface, minor sliding
See also PLATE: 8.12

DESCRIPTIONS

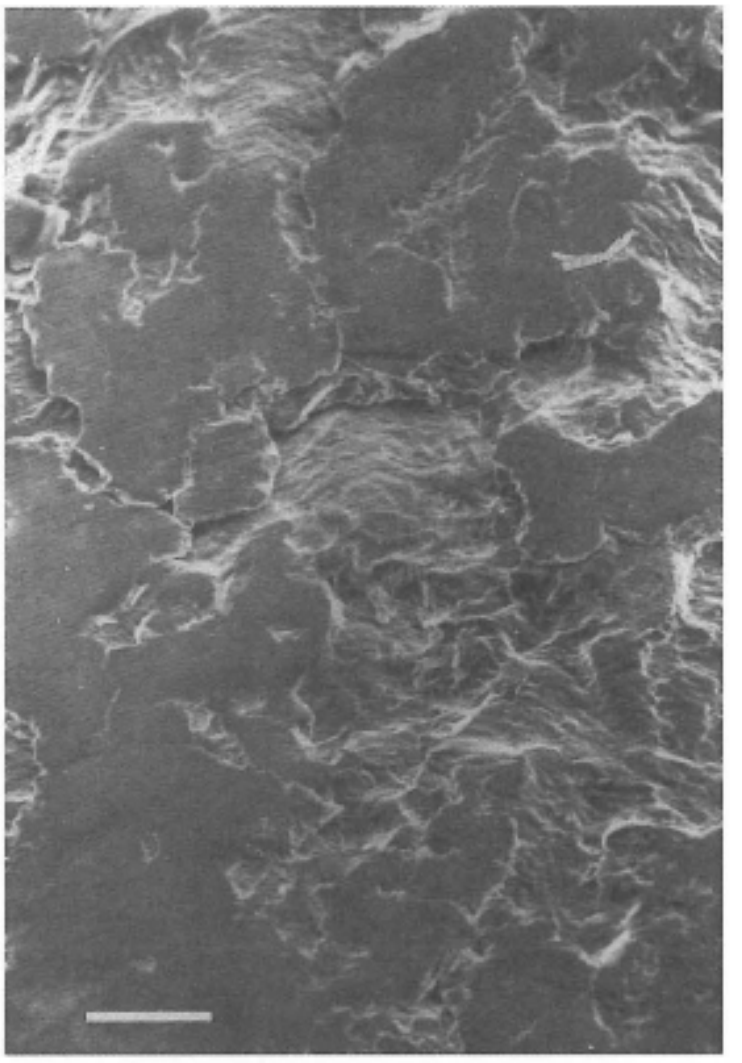
Failure Description: Multiple small, shallow spalls formed in galled, transferred material on the valve-opening ramp of an internal-combustion engine cam contacted by a roller follower. Many debris dents. Scoremarks. Primary failure is galling in the presence of substantial sliding under high normal pressure, with conditions exceeding the galling limit of the system. On the image, overrolling direction is E to W. Arrow-shaped pileup of galled metal displaced E to W indicates sliding velocity of the roller over the cam is also E to W, that is, the cam is the leading surface.

Image Description: Area of cam surface on valve-opening ramp. A few long E–W scoremarks traverse image. Between two E–W scores is galled, rolled-over streak with several blunt arrow-shaped tears pointing E. Three tears show shallow spalls at tips. Near N and S edges of image, many debris dents, some microspalled. Circumferential finishing marks largely obliterated, transferred metal smoothed by repeated rollovers subsequent to galling.

Suspected Causes: Roller followers in internal-combustion engine cam systems can follow the angularly varying cam surface velocity without sliding only by undergoing high accelerations. The normal contact pressure varies from zero to high values during each cam cycle. The follower is supported on a sliding pin bearing in which sharp friction torque excursions were found to occur. The traction force available in the cam/roller contact may at some points in the cam cycle be insufficient to provide the required acceleration and overcome pin friction, resulting in sliding in the contact. If the sliding velocity and prevailing contact pressure exceed the galling limit of the contact, galling occurs. As soon as the torque demand drops, galling stops. Repeated rollover of galled material produces spalling, concentrated where transferred metal stands proud of surface and/or is crack-sensitive after plastic working.

DATA

Plate No: 10.38
Archive No: 093-16.1.10
Image type: SEM
Scalebar = 25 μm (micros: ±20%, others: +100%, −50%)
Component: NRB; R, run
Speed: 40 KdN
Load: 1.3 GPa
Lubrication: mineral oil, 60°C
Failure Code 1: 00.16.02.5 Advanced spalling
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

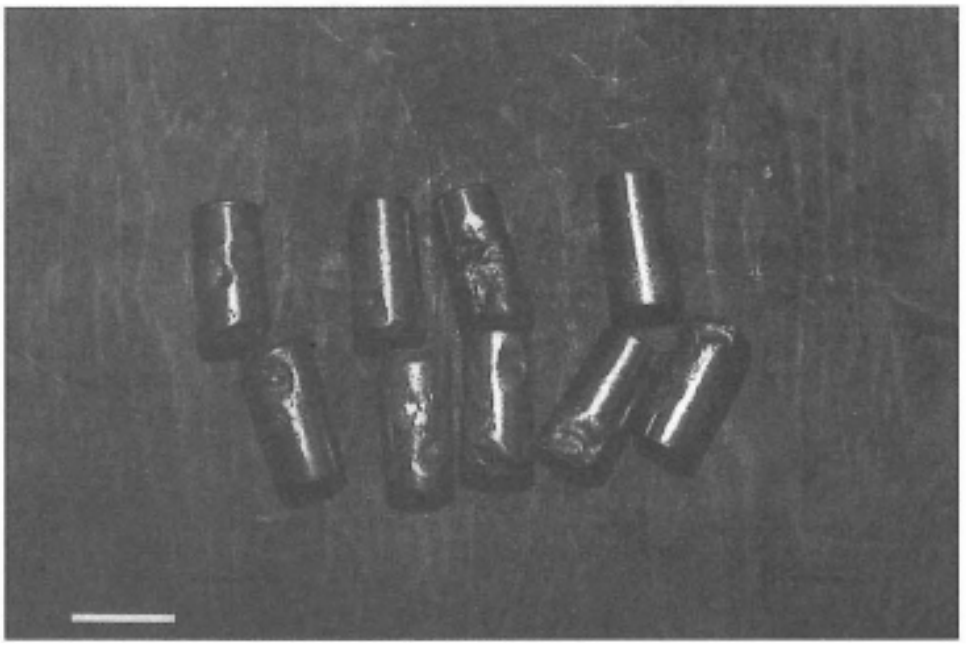


DESCRIPTIONS

Failure Description: Spall cratering on needle roller. Craters are shallow, show multiple origins and propagation directions (striations). Some unspalled areas appear undermined by cracks. Spalling of small (3 mm) diameter needle rollers is shallow due to small depth of Hertz shear stresses and is not generally a gross failure, but bearing is noisy and inaccurate. Roller fracture may eventually result.
Image Description: Spall craters are irregularly shaped areas with a striated fracture surface as bottom. Unspalled, featureless rolling surface of roller finished by tumbling is undermined by fatigue cracks at its edges (see dark shadows along curved E–W edge just N of image center).
Suspected Causes: Spalling is due to high-stress cycling, with low EHD film, contamination and rough mating surface (shaft as innerring) as likely contributors.

DATA

Plate No: 10.39
Archive No: 031-701
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.02.5 Advanced spalling
Failure Code 2: 00.16.1.1.3 Subcase-fatigue spall
Failure Code 3: 00.22.1 Overstress crack
Failure Code 4: 00.23.2 Plastic distortion of bulk shape



DESCRIPTIONS

Failure Description: Advanced compound failure of several modes. Several deep spalls formed on each roller, probably due to overload and subcase fatigue (contact stressing of core below case/core boundary). Edges of craters were then chipped off due to overrolling of debris. General roller shape was lost due to plastic working. Bearings in heavy industrial machinery often run to severe compound failure before diagnosis and removal.
Image Description: Several rollers of a TRB show deep cavities, which are spall craters battered and rolled over after formation. Edges of all rollers except those in the NE and SW end positions are chipped. Overall roller shapes are destroyed by overrolling of debris, and/or sliding after seizure of the roller in the separator.
Suspected Causes: The origin of the roller spalls is unclear in the absence of the other components. Severe debris denting (perhaps from ring spall debris) or material defects may have initiated them. Further destruction of rollers is due to long running after failure inception.

DATA

Plate No: 10.40
Archive No: 026-6
Image type: view (partial)
Scalebar = 60 mm (micros: ±20%, others: +100%, −50%)
Component: CRB (multirow); IR, run
Speed:
Load:
Lubrication: mineral oil mist, ? °C
Failure Code 1: 00.16.02.5 Advanced spalling
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.20.1.3 Contact corrosion
Failure Code 4: 00.12.0.2 Abrasive mild wear
See also PLATE: 10.51

DESCRIPTIONS

Failure Description: The roller path on this CRB IR is spalled over the entire area. The bearing suffered roller failure (see Plate 10.51), producing sharply irregular contact surfaces and copious debris which indented the IR roller path everywhere. Application is known to suffer from ingress of aggressive steel-rolling oil into bearing, which damages rolling surfaces and thus promotes spalling.

Image Description: Roller path extends from S image edge to N and NE and is flanked by undercuts and guide flanges. Entire roller path is covered by spall craters of somewhat uniform depth, except near N end where a SW–NE running curved deep spall is followed by a relatively unspalled ridge. This feature may be due to an accident of overrolling or possibly a local material hardness difference.

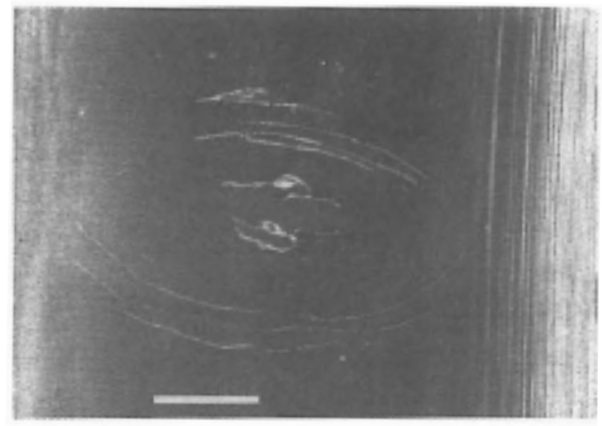
Suspected Causes: The initial failure of this large multirow steel mill roll neck bearing is the roller fatigue shown in Plate 10.51. This IR failure may be secondary. Loads, speed, inertia and noise in a mill stand are great. Mills are not instrumented to detect early bearing failure. Mills cannot be stopped abruptly without serious consequences. Accordingly, the bearing was run long after initial failure, causing this severe secondary damage.

DATA

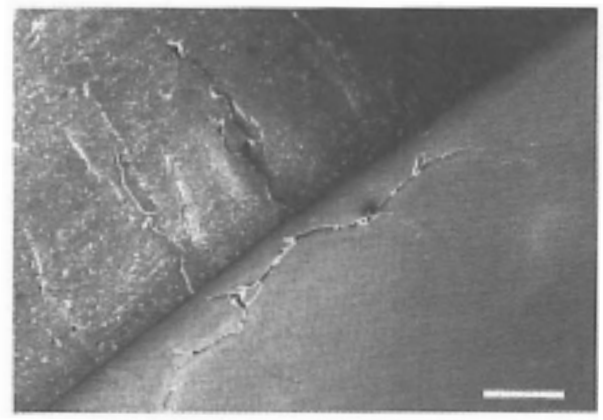
Plate No: 10.41
Archive No: 107-025a&b&c
Image type: SEM
Scalebar = a: 1 mm, b, c: 400 μm (micros: ±, others: + 100%, −50%)
Component: ACBB; OR, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: 00.16.02.3 Incipient spalling, single spall
Failure Code 4: -

DESCRIPTIONS

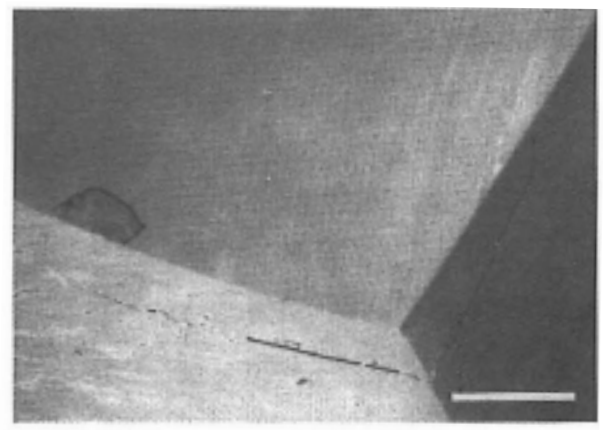
Failure Description: Spalling originated in subsurface (surface-parallel) crack which exfoliated via a number of concentric surface cracks. The subsurface defect that originates the failure is not shown. This mechanism of spalling results from high load and subsurface defects in the absence of surface distress or other severe surface spall originators.
Image Description: (a): Concentric (light color) elliptical cracks surround two incipient spalls. (b): NW image half is rolling surface; SE: circumferential section. Subsurface crack (in section) undermines surface and penetrates to it in four cracks. (c): Other location. N image quadrant is the rolling surface; E quadrant: circumferential cut; SW quadrant: axial cut. Subsurface crack in SW and E quadrants. Dark spot at W is artifact.
Suspected Causes: Spall-initiating subsurface defect caused surface-parallel crack, at the approximate maximum Hertz shear stress level, which broke through to the surface in several cracks. Exfoliation of the spall crater has begun.



a



b



c

DATA

Plate No: 10.42
Archive No: 074-22&23
Image type: a,b: light macro
Scalebar = a,b: 80 mm (micros: ±20%, others: + 100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 2: 00.16.03.1 Spall propagating by cracking at spall bottom
Failure Code 3: 00.16.1.1.2 Spall from subsurface defect
Failure Code 4: 00.06.2 Inclusion stringer
See also PLATE: 10.59

a **b**

DESCRIPTIONS

Failure Description: Subsurface origin spalls on a ball, propagating by symmetrical extension of the spall bottom, as the ball changes orientation and the spall is overrolled from different directions. (a) Originates from point defect (circular symmetry), (b) from a linear inclusion (bilateral symmetry). The ball has failed. See Plate 10.59 for surface origin ball spalling.
Image Description: (a): Bull's-eye-shaped spall crater, initiating at the center of concentric circular striations, just W of image center. Two further arcs of crack propagation extend NE and SE beyond the original spall. (b): N–S black line at image center is inclusion stringer. Bilateral (orange slice) spall propagation to circular shape and beyond. Due to small depth of focus, outermost areas of spall are ill resolved in (a) and (b).
Suspected Causes: Balls in radially loaded bearings change axis of rotation frequently. After a spall has initiated, it may be overrolled in any direction and thus grow circularly. Once the spall becomes sizeable it may exert an orienting effect on the ball so that axis changes become more rare and further spall extension proceeds only in two directions.

DATA

Plate No: 10.43
Archive No: 018-701
Image type: SEM
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, silicon nitride, hot isostatic pressed, run
Speed: 105 KdN
Load: 3.65 GPa
Lubrication: mineral oil
Failure Code 1: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 2: 00.16.03.1 Spall propagating by cracking at spall bottom
Failure Code 3: 00.05.4.2 Binder defect in ceramic
Failure Code 4: -
See also PLATES: 10.57 and 11.29

DESCRIPTIONS

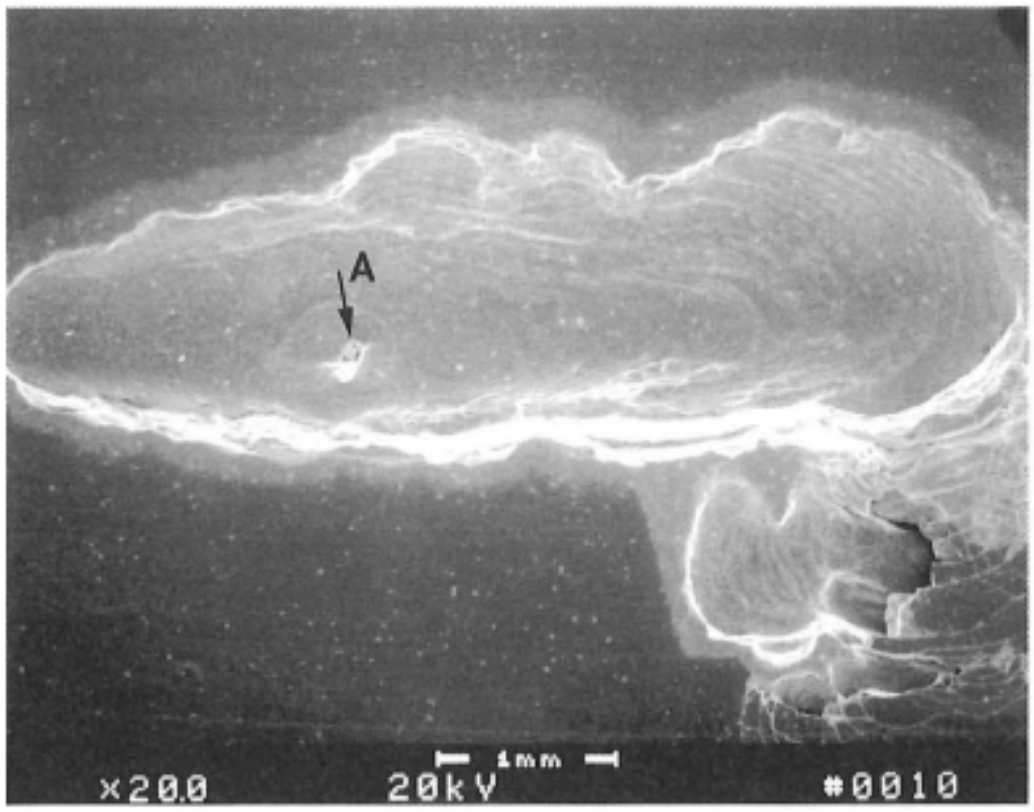
Failure Description: Macrospall on silicon-nitride ball, showing three major and several minor reinitiation points, circular propagation from each, relatively steep walls and very smooth flat bottom.
Image Description: Spall origin near image center, one circular propagation phase at image center, another W, the third SE of first, all partly overlapping. Three minor propagation spurts extend spall boundary toward NE. No visible defect on unspalled surface.
Suspected Causes: This ball reported to be one of a few early failures in a bearing test group with nitrided low-carbon tool steel rings. No artificial defect was introduced. Most other balls in group survived manyfold longer, suggesting unidentified material defect (perhaps binder defect) in failed balls.

DATA

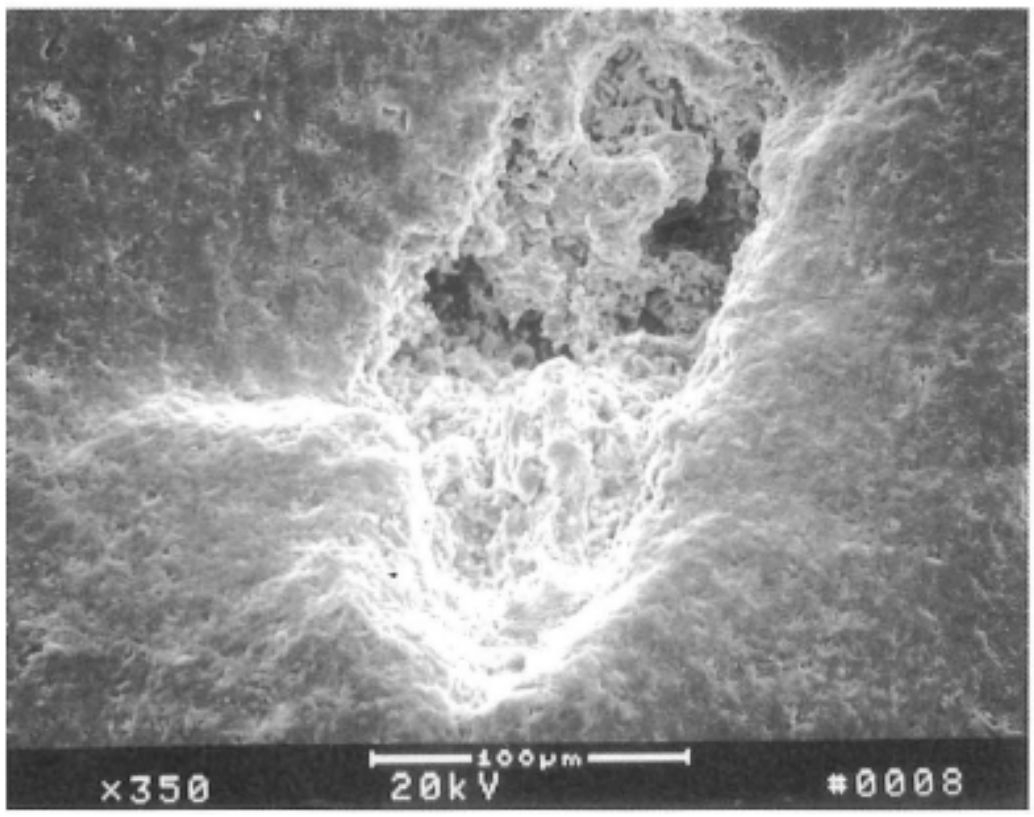
Plate No: 10.44
Archive No: 005-34&35
Image type: a, b: SEM
Scalebar = a: 1 mm, b: 100 μm (micros: ±20%, others: +100%, −50%)
Component: C; R, silicon nitride (gas over-pressure sintered), run
Speed: 0.94 m/sec
Load: 2.8 GPa max. pressure
Lubrication: mineral oil w. boundary lubr. additive
Failure Code 1: 00.16.1.1 Subsurface origin spall (high Hertz shear stress)
Failure Code 2: 00.16.1.1.2 Spall from subsurface defect
Failure Code 3: 00.15.1 Micro-porosity
Failure Code 4: -

DESCRIPTIONS

Failure Description: (a): Multiple spalls, originating from distributed porosity in the bulk material. Large number of spall origins at depth of high shear stress, spreading rapidly and removing the entire overlaying material. Pore at *A*. (b): Extended pore cluster shown in image (a) at *A*, remaining visible in spall bottom. Profuse pits in spall bottom surface surrounding pore cluster, where silicon nitride grains have separated at the binder.
Image Description: (a): In N half of image: elongated, flat-bottomed spall originating at pore cluster 1/3 E from W image edge and 2/5 S from N image edge. Roller axis runs E–W on image. Another spall with large undermined lamina in SE image corner. Fine light-gray spots both in spall bottom and on unspalled surface may be the pits described in image (b). (b): Magnified view of pore cluster shown in (a). Silicon nitride grains poorly bonded or unbonded in large pore. Profuse small pits and pit clusters, of a few μm size on pebbly appearing spall bottom surface outside large pore. Pits are likely to stem from pulled-out silicon nitride grains which separated at binder during spall formation.
Suspected Causes: Sintered silicon nitride frequently has some porosity due to incomplete compaction and bonding during manufacture. Porosity in ceramic is a potent spall-initiating defect, both for first spalling and for spall re-initiation during spall propagation.



a



b

DATA
Plate No: 10.45
Archive No: 122.3
Image type: SEM
Scalebar = 400 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed: 140 KdN
Load: 2.8 GPa
Lubrication: mineral oil, ? °C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.04.2 Forming seam
Failure Code 3: 00.16.03.1 Spall propagating by cracking at spall bottom
Failure Code 4: -

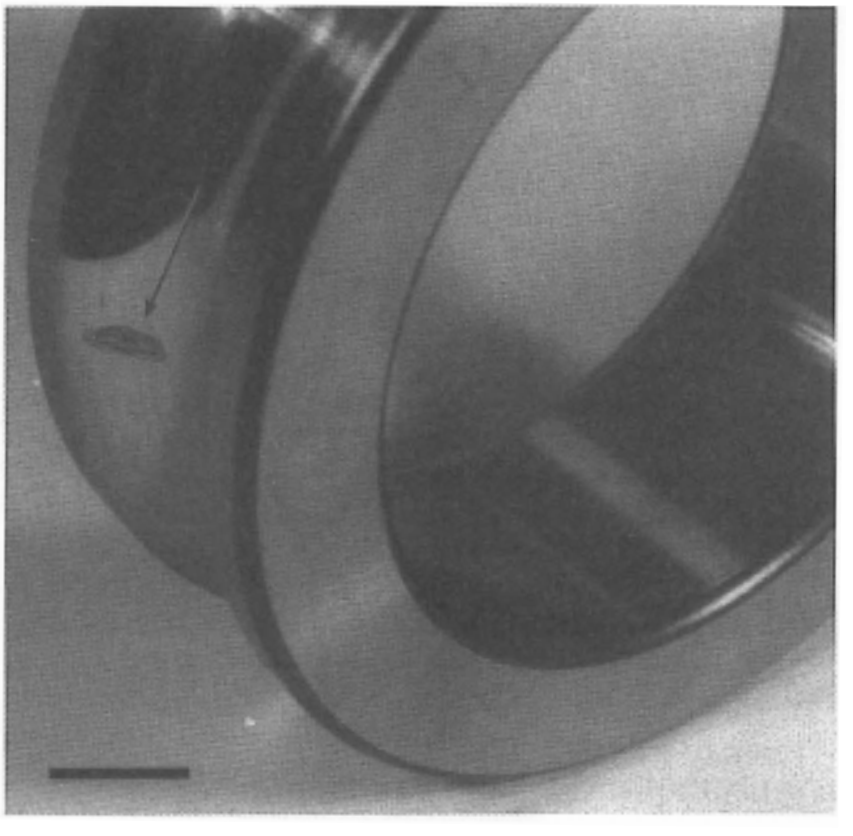
DESCRIPTIONS
Failure Description: Spall originating from a forming seam has propagated in concentric striations, primarily downstream in direction of contact travel. Some spall formation has occurred upstream from the seam. Continued spalling from this subsurface defect is likely to cause functional failure of the ball. In its present condition, the ball is noisy.
Image Description: Seam runs E–W across image at one-third image height from S edge, forming dark straight line, with ledge at several locations. To N of seam (downstream in overrolling direction), the spall extends in several concentric striations into the NW image quadrant propagating by continued spall bottom cracking. Spall edge has collapsed just S of seam, continuing crater about 500 μm in that direction.
Suspected Causes: Seams are discontinuous interfaces arising during rolling (or drawing) of ball wire, and are often oxidized. They are weak interfaces, causing severe stress concentration that is likely to lead to early spalling.

DATA
Plate No: 10.46
Archive No: 122-5
Image type: SEM
Scalebar = 100 μm (micros: +20%, others: +100%, −50%)
Component: TBB; IR, run
Speed: 40 ? KdN
Load: 5 GPa
Lubrication: grease, ? °C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.06.1.1 Hard micro-inclusion
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: 00.18.02.1 Light or incipient denting

DESCRIPTIONS
Failure Description: Incipient spall originating at a (cluster of) hard subsurface micro-inclusions.
Circular crack edges emerging on contact surface, with small exfoliation. Small (10 μm) hard inclusion at spall bottom, with others probable. Unspalled surface has many fine debris dents. Spall is likely to propagate, causing functional failure.
Image Description: Image center is occupied by cracks extending three-fourths of a circle from E through S and W to N. S half circle has spalled out. A lamina of material is undermined by crack at the E–W diameter. White globular body with black outline and white halo at *A* is believed to be a hard nonmetallic inclusion. An inclusion probably spalled out near N spall edge (*B*). Debris dents are visible on contact surface.
Suspected Causes: Clusters of hard nonmetallics may remain in steel from steelmaking and are a classical source of early spalling failure. The inclusions shown are relatively small (3 μm) but may still be significant stress concentrators under very heavy load.

DATA

Plate No: 10.47
Archive No: 027-167
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 130 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.16.02.3 Incipient spalling, single spall
Failure Code 3: 00.16.01.1.1 Centered spalling, normal track width
Failure Code 4: 00.12.3.2.0.5 Wear track for centered axial load
See also PLATES: 10.3 and 10.12



DESCRIPTIONS

Failure Description: Elliptical, steep-edged spall near center of ball path (under thrust load), with a line-depression in the spall bottom, suggesting an inclusion stringer as origin. Plates 10.3, 10.12 and 10.47 show various spalling modes in similar bearings for comparison. The wear track offset to one side indicates axial load. This bearing is noisy and has failed in the quiet running application.

Image Description: Oblong spall crater with major axis in axial direction, at arrow. Short black axial line centered in spall bottom may indicate inclusion stringer (requires metallographic examination). Two faint dark circumferential lines run near spall tips indicating the rolling track. Note the clean, undented surface away from the spall.

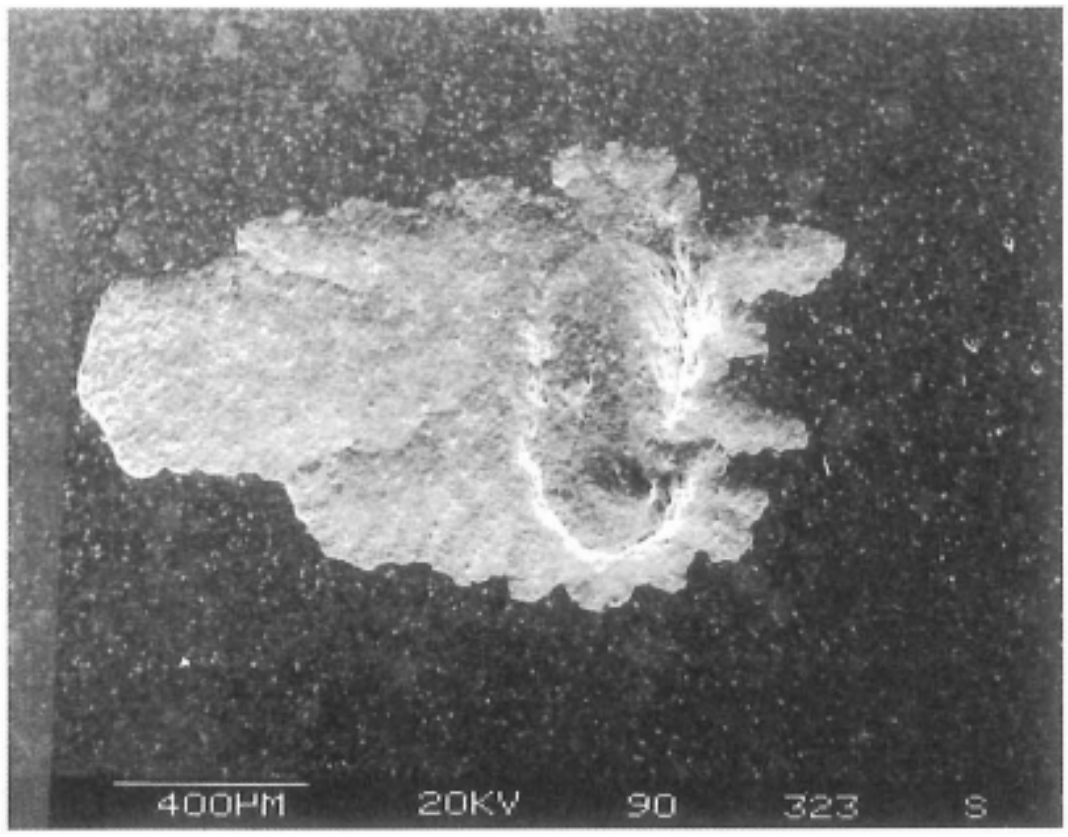
Suspected Causes: An inclusion stringer under the surface is a likely cause of this single spall in a normally loaded bearing operated in clean environment.

DATA

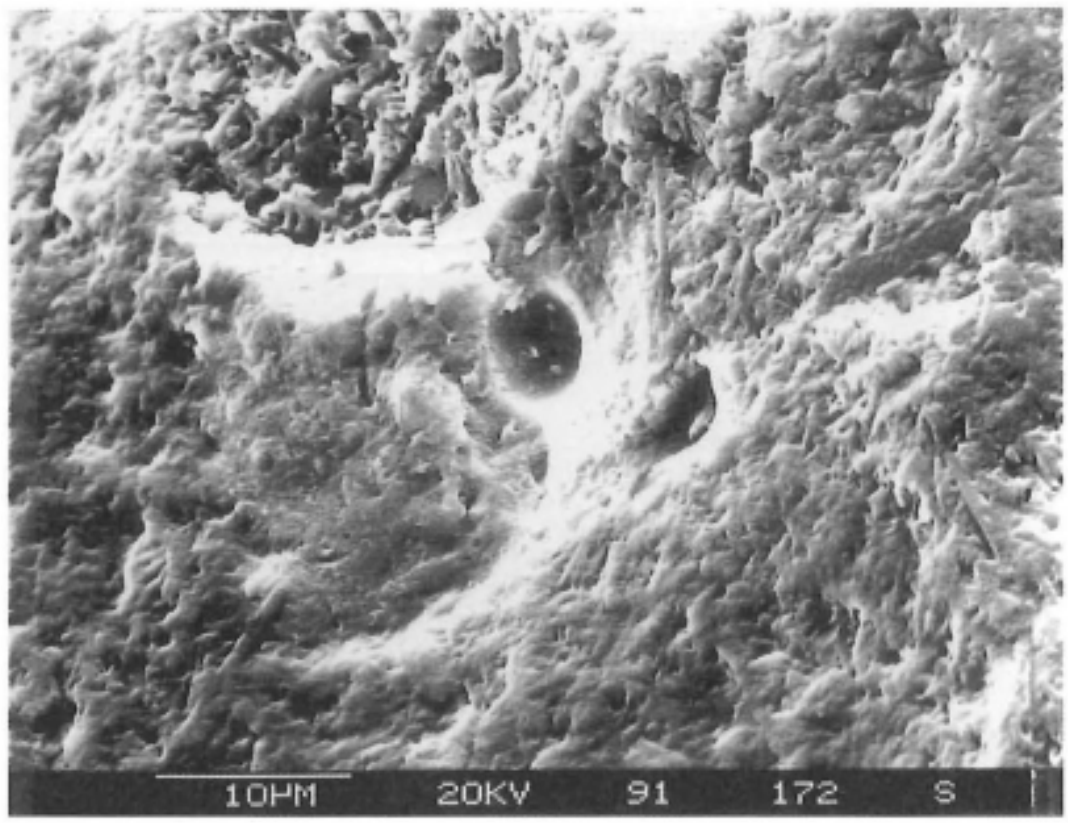
Plate No: 10.48
Archive No: 014-B005&B006
Image type: a, b: SEM
Scalebar = a: 400 μm; b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: O, RC test rig rod; silicon nitride; run
Speed: 1.9 m/sec
Load: 5.93 GPa
Lubrication: mineral oil w. additives; approx. 40°C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.16.02.3 Incipient spalling, single spall
Failure Code 3: 00.05.4.1 Micro-porosity in ceramic
Failure Code 4: 00.05.4.2 Binder defect in ceramic
See also PLATE: 6.1

DESCRIPTIONS

Failure Description: Spall originating at a subsurface structure defect of the ceramic (porosity and/or binder defect) spreads at shallower depth outside defective structure.
Image Description: (a): On dark gray contact surface, an irregular spall at image center. In the spall bottom, a darker gray vertical oval outlined in light gray is remnant of subsurface defect area. Outside the oval, the spall is shallower and has no steep walls. Overrolling direction is image E to W. (b): Fracture surface of the same material (not the same location) shows, at image center, and 1/5 to E, two black bubblelike voids of porosity, approximately 5 μm diameter. The center void is surrounded by white-appearing excess binder material extending W in a streak to within 1/6 of W edge and present in patches near the void.
Suspected Causes: Porosity in ceramics is the most deleterious material defect and degrades silicon nitride spalling fatigue life drastically. Poorly distributed and poorly adhering binder material produces spalls by intergranular cracking.



a



b

DATA
Plate No: 10.49
Archive No: 002-022b
Image type: light microgram
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: 00.08.2 Rehardened grinding burn
Failure Code 4: -
See also PLATE: 6.25

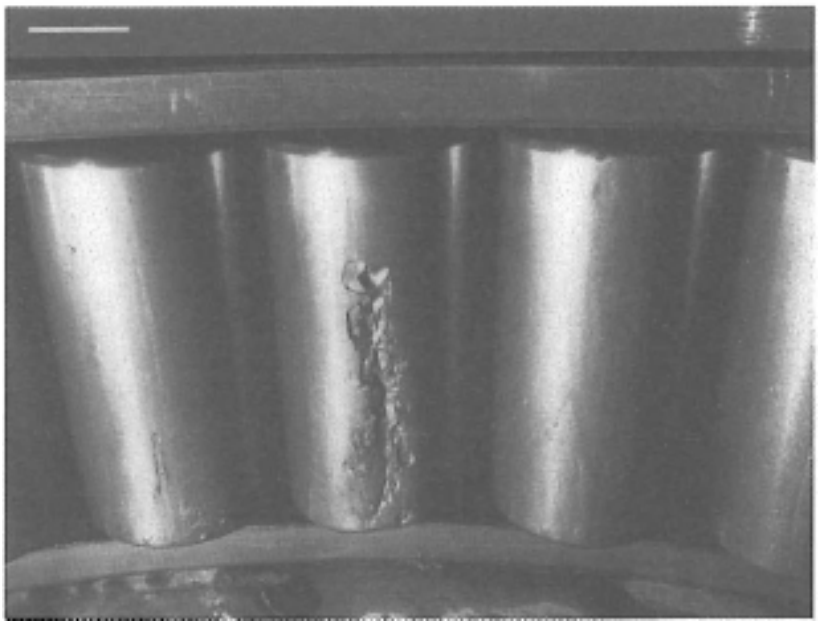
DESCRIPTIONS
Failure Description: A deep grinding burn (see Plate 6.25) has created a 200 μm deep weak zone, which spalled out prematurely, with an unusual smooth flat crater bottom. Subsequent spalling of normal material has progressed both with and against the rolling direction, creating a normal sawtooth-bottomed spall. An extensive network of angled cracks is the precursor of further spalling.
Image Description: Oblong complex spall crater occupies image center. Central to the spall, a horseshoe shaped flat-bottomed area between three arrows is the spalled-out grinding burn. Just W of spall crater, an extensive network of cracks emerging to surface as white lines on dark background, as at arrows *A*, will form additional cratering if running continues.
Suspected Causes: A deep, rehardened grinding burn is a very severe spall initiating defect. Once spalled out, the spall rims are stress concentrators, driving further spalling.

DATA
Plate No: 10.50
Archive No: 014-109
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, carburized, run
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.16.03.2 Spall propagating by reinitiation at surface
Failure Code 3: 00.17.2 Localized surface distress (halo at defect)
Failure Code 4: -
See also PLATES: 10.46 and 10.62

DESCRIPTIONS
Failure Description: Spall initiated at subsurface defect first formed elliptical crater as in Plate 10.46. Due to marginal EHD condition, propagation from surface-origin cracking then took over, adding irregularly shaped, shallow-entry craters in rolling direction. This propagation mode is typically more rapid than subsurface crack propagation. Contrast with Plate 10.62, which shows a surface-origin spall.
Image Description: TRB IR ('cone') roller path with E–W finishing lines. Undercut near S image edge. Overrolling direction E to W. Small elliptical spall at E end of cratering, followed in overrolling direction by several irregular shallow-entry craters. Light-color edging ('halo') is visible on the craters from surface distress glazing.
Suspected Causes: After initiation of spalling from subsurface inclusion, the primary crater creates a surface defect (possibly augmented by debris denting). Low EHD film collapses at crater edges, causing repeated initiation of surface-origin spalling.

DATA

Plate No: 10.51
Archive No: 026-16
Image type: view (partial)
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRB (multirow); R & G, run
Speed:
Load:
Lubrication: mineral oil mist, ? °C
Failure Code 1: 00.16.1.1.2 spall from subsurface defect
Failure Code 2: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.40

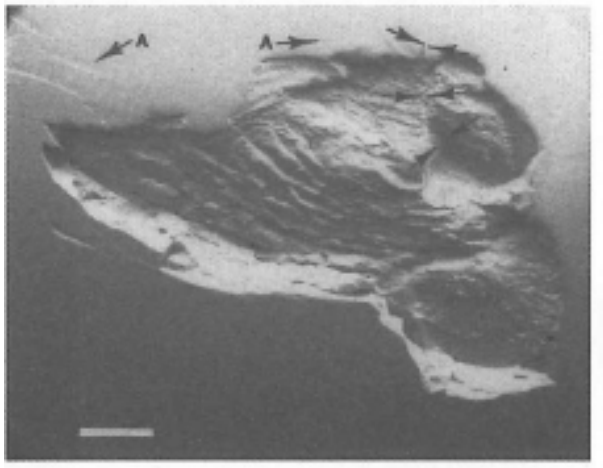


DESCRIPTIONS

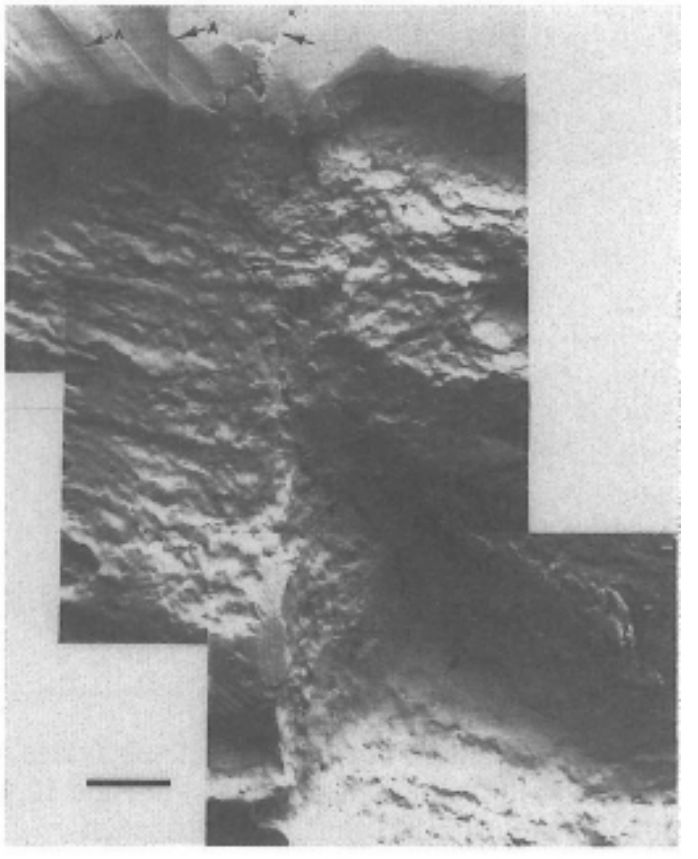
Failure Description: The case-hardened rollers in this CRB are drilled to accommodate pins welded into the separator rings which serve as guiding elements. The roller failure initiated as a fatigue crack at the roller bore (probably from a machining mark), propagated through the section and caused the axially elongated steep and deep spall. Overrolling caused plastic peening near roller end. The roller is likely to fracture.
Image Description: Rollers, held between the two rings of a pin-type separator are removed from bearing. Welded pins are not visible. The second roller from the W shows irregular axial cratering on S two-thirds of length. Near center of cratering, the black axial opening is a cross-section crack. Near S end of spalls, crack curves to W and is partly peened shut by roll-over.
Suspected Causes: Roller bores are drilled before heat treatment and may show machining marks. In carburizing, bores are usually masked to keep carbon out, but some carburized spots may occur, creating local residual stress. Bending stresses from contact loading peak at the bore and may initiate fatigue cracks at these surface defects or residual stress areas. The cracks eventually propagate to the roller OD. Plate 10.40 shows spalling of IR.

DATA

Plate No: 10.52
Archive No: 002-023c&e
Image type: a: SEM, b: SEM composite
Scalebar = a: 1 mm, b: 200 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 3: 00.01.1 Local nick
Failure Code 4: 00.12.0.2 Abrasive mild wear



a



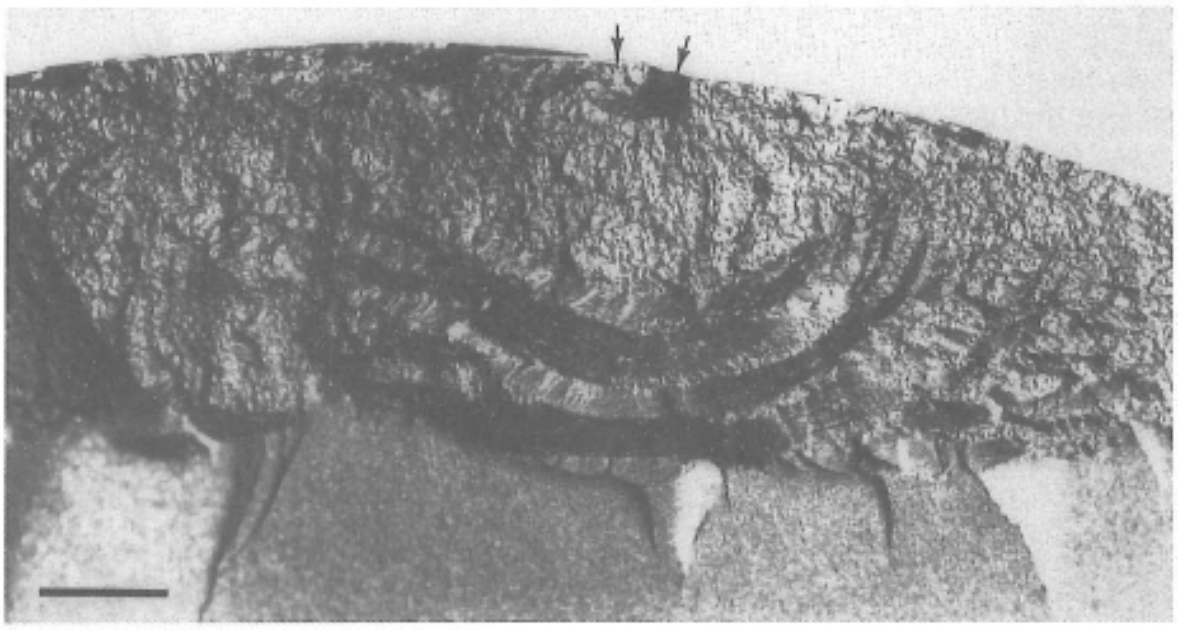
b

DESCRIPTIONS

Failure Description: (a): Apparent failure progression is: (1) indentation marks as from rolling over a sharp edge (possibly in assembly), (2) in-depth cracking, (3) spalling. Tool steel balls are thought to be more crack-prone. In bearing steel balls, a bulk crack from nicking and before spalling would be rare. The ball is failed. (b): Nicks from edge contact originate an in-depth crack and subsequent spall. Spall surface is slightly worn by debris. The ball is failed.
Image Description: (a): Shallow rolled-in lines on ball surface, as at *A*. Three arrow pairs in NE quadrant mark in-depth going hairline crack. Spall origin is at this crack, spread in both directions. 'Beach marks' (curved ridges) from spall origin to SW.
(b): Smooth contact marks at *A*, from rolling edge over ball surface. In-depth crack travels from N to S to SE (arrows). Crack starts outside spall (N image edge). Wear marks are visible in the SW corner.
Suspected Causes: In assembly of balls into separator (or in bearing assembly), indentations may be made on the ball surface by an edge. In crack-prone material these may initiate a bulk crack upon running. Spalling follows.

DATA

Plate No: 10.53
Archive No: 002-002d
Image type: light macro of fracture
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 0.8 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.16.1.1.2 Spall from subsurface defect
Failure Code 2: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 3: 00.07.3.2 Lamellar carbide
Failure Code 4: 00.04.3.1.1 Incipient melting from forging at excessive temperature

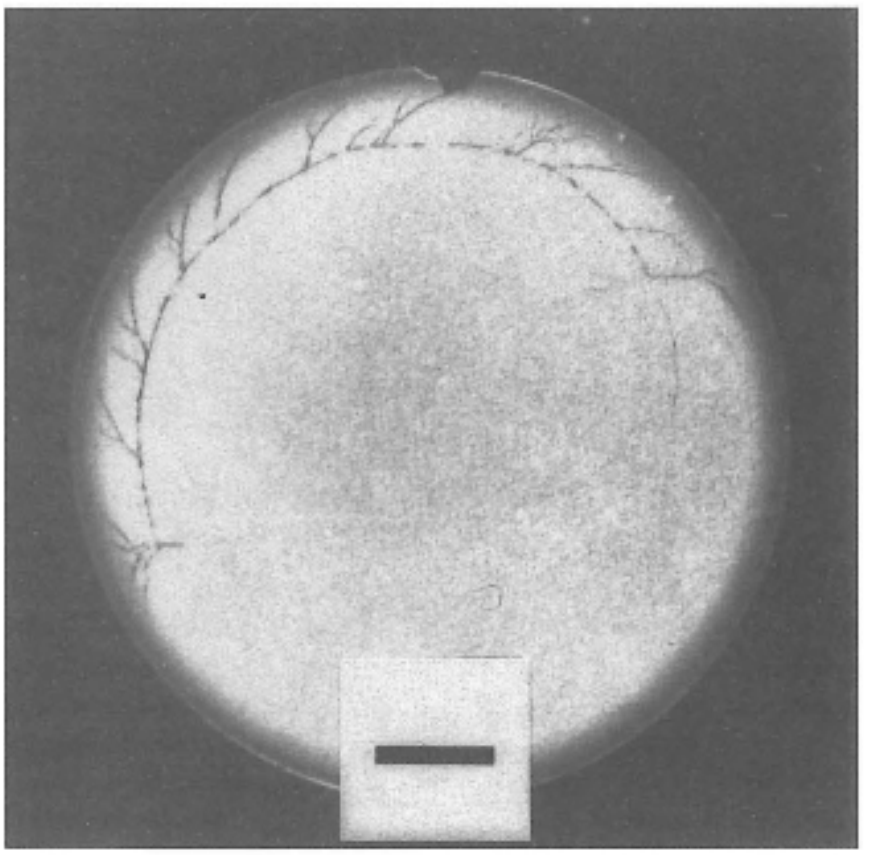


DESCRIPTIONS

Failure Description: Spall originating in defective material structure has progressed to bulk fatigue crack. The ball was broken in half following the crack, for examination. The structure defects (verified by metallography) are: lamellar carbides, pores due to remelting, and defective martensite structure—all attributed to overheating in manufacture. They make the part fracture-prone. The bearing has failed.
Image Description: At arrows, cross-section through spall crater. The rough-faceted fracture surface extending from there along the ball surface and into the material is the bulk fatigue crack, showing (further away) elliptical steps concentric to the spall. The smooth surface near S image edge is the artifical fracture made to expose the crack.
Suspected Causes: Tool steel is sensitive to excessive forging temperature, which causes local melting and porosity. Improper anneal after forging causes off-specification martensite needles. Such material is spall- and crack-prone. This explains the radial cracking under contact load, with subsequent spalling, in an element (ball) not subject to tensile hoop stress.

DATA

Plate No: 10.54
Archive No: 014-523
Image type: light macro of section, etched
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: CRB (roller/roller test); R, run
Speed: 50 KdN (eqv.)
Load: 3.9 GPa
Lubrication: mineral oil, 65°C
Failure Code 1: 00.16.1.1.3 Subcase-fatigue spall
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Very heavily loaded (3.9 GPa Hertz pressure) roller to roller test on carburized specimen. Case depth exceeded by depth of high Hertz shear stresses causes surface-parallel cracks which repeatedly rise to the surface. One has penetrated the case and caused a spall; others are trapped beneath the case. Subcase contact fatigue is a design or application error (case too shallow for load condition).
Image Description: Metallographic cross section through cylindrical roller. Core etches light gray, case: dark gray. Circular crack at great depth (2 mm) with case about 0.3 mm deep. Numerous branching cracks rise to the surface in the over-rolling direction (clockwise). One crack penetrates the case (at N edge) creating a spall.
Suspected Causes: In case-hardened parts, the fatigue strength of the material diminishes as the inner boundary of the case is reached, due to diminishing hardness. The alternating Hertzian shear stress amplitude peaks at depth equal to one-quarter contact width, and then gradually diminishes. If the strength drops faster with depth than the shear stress, then the most critical depth for cracking is in the core, causing deep cracking.

Failure Code: 00.16.1.1.3
Failure Code: 00.16.1.2

DATA
Plate No: 10.55
Archive No: 080-113&115
Image type: a: light macro, b: view (etched section)
Scalebar = a: 20, b: 15 mm (micros: +20%, others: +100%, −50%)
Component: SG; P, case hardened, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.1.1.3 Subcase-fatigue spall
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 4: -

DESCRIPTIONS
Failure Description: Contact fatigue failure in the low-hardness core of a case-hardened gear. The load was so high that high shear stress was created beneath the case/core interface. After cracks formed in the core, they penetrated to the surface as axial cracks and created straight-edged spalls. Gears with subcase fatigue will suffer gross failure upon additional running. Elsewhere on the tooth are radial wear marks.
Image Description: (a): At center of W-most tooth flank, deep spall crater with straight S edge. Case appears undermined. Metallography shows that spall depth exceeds case depth. Elsewhere on the tooth are light-colored radial wear marks. (b): Gear cross section. On second and third tooth from W, arrowhead-shaped black lines are subcase cracks following case/core interface, with branch cracks to surface. On W-most tooth the spall extends to case/core interface.



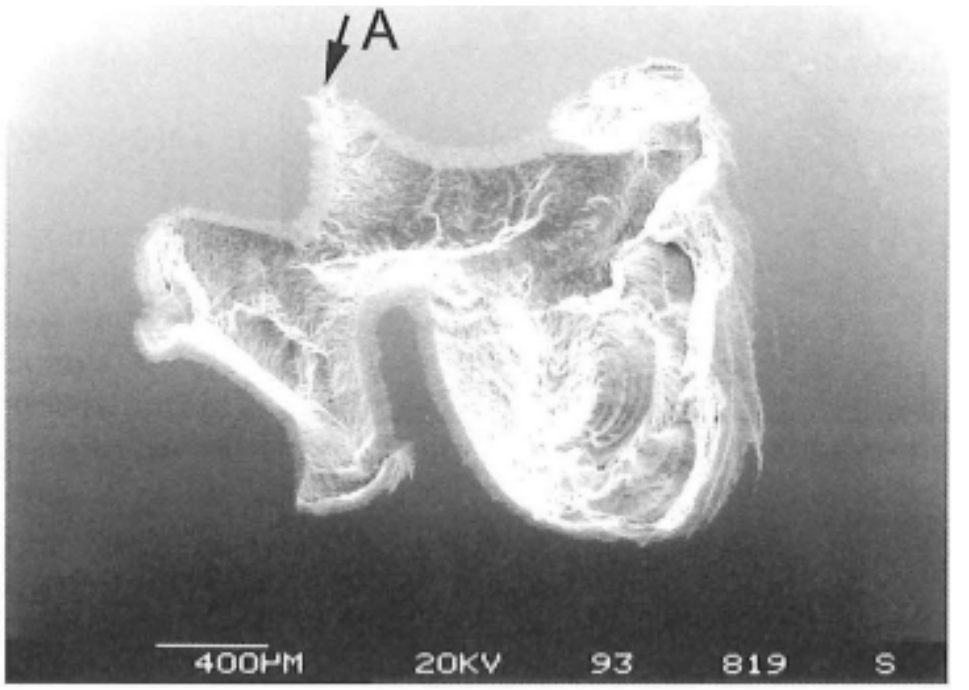
Suspected Causes: Case depth may be below specification or the gear may be severely overloaded. In either case, the magnitude of Hertz shear stress diminishes slower with depth than the material fatigue resistance (hardness). Fatigue cracks form at the case/core interface, undermine the case and eventually exfoliate to the surface.

DATA
Plate No: 10.56
Archive No: 093-16.2.4
Image type: SEM
Scalebar = 120 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral oil, 100°C
Failure Code 1: 00.16.1.2 Surface origin spall
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: -
Failure Code 4: -

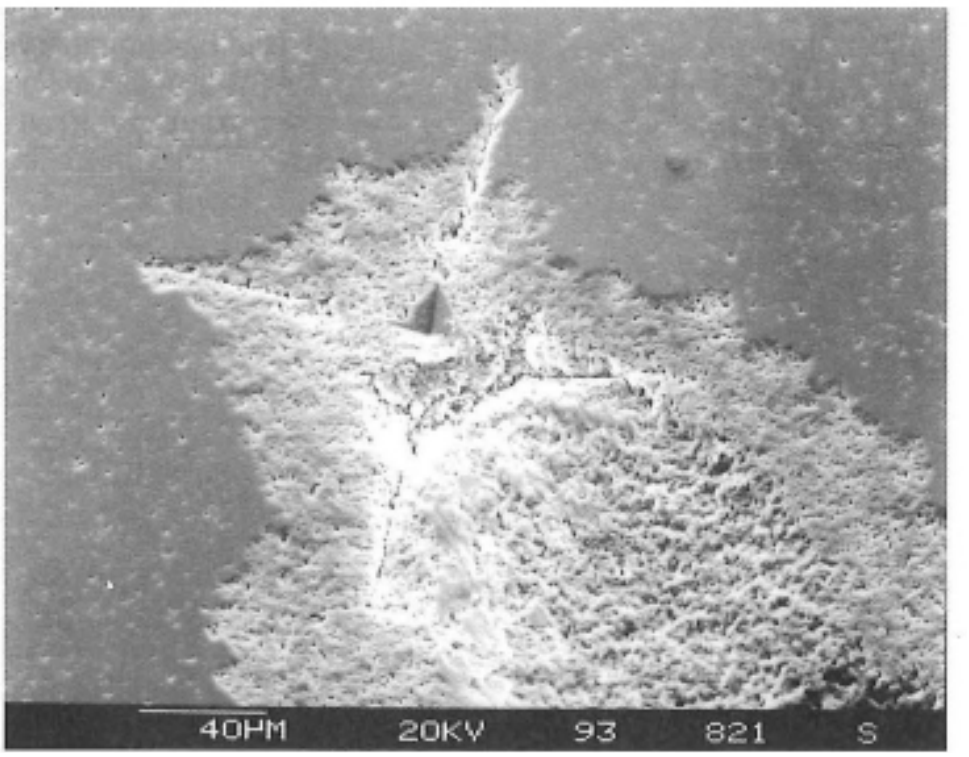
DESCRIPTIONS
Failure Description: Surface origin spall entry area (at upstream spall end, in overrolling direction). Unspalled rolling surface is followed by a shadow-entry spall edge. The entry step is about 40 μm deep (about one-eighth the maximum Hertz shear stress depth), indicating surface origin. Further crack formation is in progress. The ring has failed.
Image Description: Area *A* in the NE image quadrant is the unspalled rolling surface. *B*, in the NW quadrant, is the spall bottom. The shallow-entry edge is a complex curve between them. *C* is the section cut through the spall. *D* is a shallow crack similar to the one that initiated the spall.
Suspected Causes: Shallow-entry spalls originate from surface defects including surface distress, occurring under low EHD film conditions.

DATA

Plate No: 10.57
Archive No: 014-601&602
Image type: a, b: SEM
Scalebar = a: 400 μm, b: 40 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B; silicon nitride; run; DP indent on ball
Speed: 2700 r/min
Load: 1.9 GPa
Lubrication: polyester synthetic oil; 66°C
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.01.4 Chipped nick in ceramic
Failure Code 3: 00.17.2 Localized surface distress (halo at defect)
Failure Code 4: 00.16.03.2 Spall propagating by re-initiation at surface
See also PLATES: 10.43 and 11.29



a



b

DESCRIPTIONS

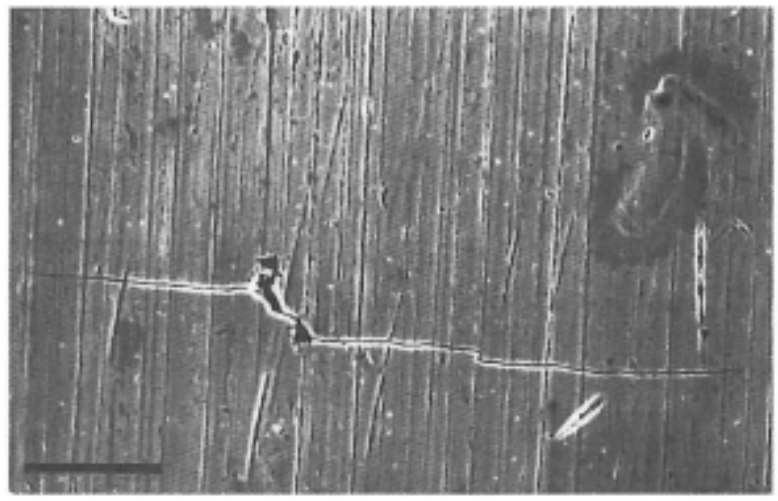
Failure Description: Spall initiated by a 0.5 mm wide, diamond-pyramid indentation causing a chipped nick (FC 00.01.4) on the silicon nitride ball surface. (a): Spall showing first initiation as localized shallow surface distress microspalling at the indentation, subsequent progression to macrospall depth, with multiple reinitiation and erratic, one-sided propagation. (b): All but the tip and crossed edges of the indentation have spalled out. The surrounding spall is so shallow that the indentation tip is left intact though the indentation is only several μm deep. This is analogous to the "halo" seen around defects in steel surfaces, but in ceramic it is not a "glazed," burnished surface.

Image Description: (a): Spall with multiple lobes at image center. Initiating indentation is at A, at the pointed NW protrusion of spall. Linear ridges running E–W near N spall edge, NW–SE at SW boundary, N–S at E boundary and E–W near S constriction of spall indicate restarting zones of spall. (b): NW protrusion of spall, magnified, shows tip of DP indent N of image center, and straight edges of pyramid indenter running roughly N–S and E–W from tip. Spall near indenter is a shallow surface distress microspall. Macrospall depth is reached further away from initiation.

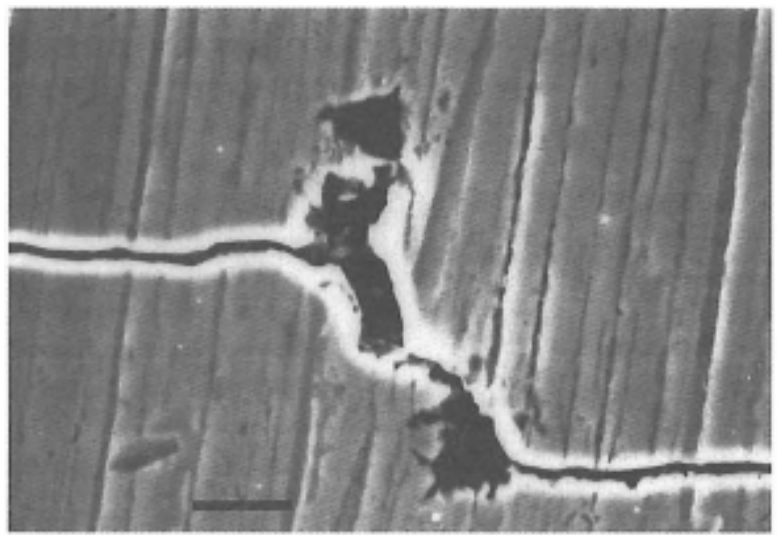
Suspected Causes: (Hot isostatic pressed) silicon nitride balls are highly spall resistant. To produce spalling, DP indentations were made on several test balls, prior to endurance testing in bearings. On this ball, the indenter load was 5 Kg. It was observed that the indentation produced raised shoulders and that a critical shoulder height was needed to initiate a spall. It is reported that spalls initiate in these silicon nitride balls from the raised edges of the indentation and not the cracks formed within the indentation under the indenter edges. If the indentation is small enough, failure is arrested at surface distress stage.

DATA

Plate No: 10.58
Archive No: 107-024a&b
Image type: SEM
Scalebar = a: 30, b: 5 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: 00.18.1.1 Rounded dent (from soft contaminant)
Failure Code 4: 00.17.2 Localized surface distress (halo at defect)



a



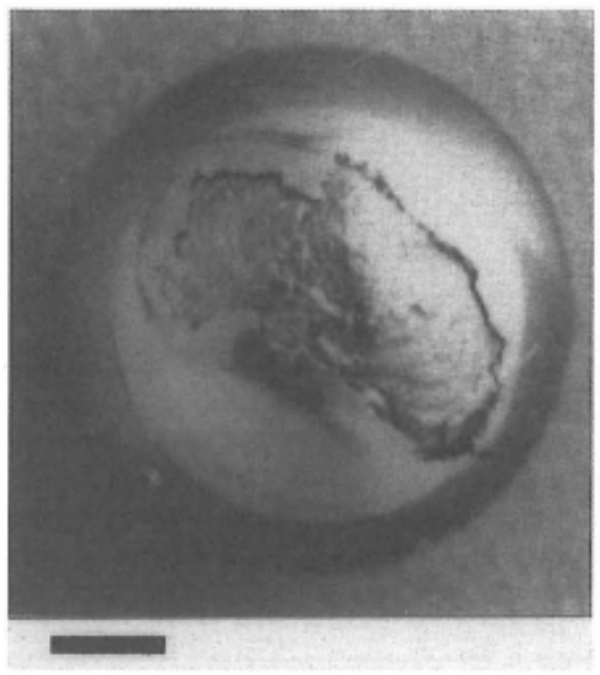
b

DESCRIPTIONS

Failure Description: Small (120 μm long) crack running normal to rolling direction and incipient spall formed from alumina microinclusion at the surface. (Calcium and aluminum were verified by microprobe analysis.) This is the earliest phase of spall crater formation. A rounded dent (15 μm) is unrelated to spalling, but shows a halo of surface distress. The bearing is likely to fail from progressive spalling.
Image Description: (a): N–S finishing lines; in NE corner, rounded dent from soft contaminant particle, decorated by (darker) surface distress halo in which finishing lines are partly obliterated. At mid-image, two E–W cracks are black E–W lines with white rim (sharp edge). They meet in three dark patches which are the alumina inclusions. (Spalling may have begun at the inclusions.) (b): Inclusions and cracks originating from them, at higher magnification.
Suspected Causes: Hard (for example, alumina) inclusions are sources of spalling. A surface inclusion is a severe spall initiator, especially when surface distress is present due to low EHD film thickness. This inclusion is close to the minimum size that has been reported to cause spalling.

DATA

Plate No: 10.59
Archive No: 074-27
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.16.03.1 Spall propagating by cracking at spall bottom
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.42



DESCRIPTIONS

Failure Description: Extensive spalling of ball surface, by removal of a uniform-depth layer. The spall is believed to originate from a surface defect (dent, nick, etc.) and then propagates in all directions as the ball changes axis of rotation. The ball has failed. Compare with Plate 10.42, showing subsurface origin spalls.
Image Description: Large oval spall extends from NW to SE. The spall is comparatively shallow and the spall bottom is relatively smooth, indicating extensive overrolling. From striations in spall bottom, origin is probably near N center of spall. Smooth, even bottom and relative shallowness suggest surface origin.
Suspected Causes: Damage to the ball surface by surface distress, denting or other causes may precipitate spalling. Balls in radially loaded bearings change axis of rotation frequently. After a spall has initiated, it may be over-rolled in different directions and thus grow in more than one direction.

DATA

Plate No: 10.60
Archive No: 087-120
Image type: view
Scalebar = 30 mm (micros ±20%, others: +100%, −50%)
Component: ACBB; OR, run
Speed: 1 ? MdN
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.16.03.2 Spall propagation by reinitiation at surface
Failure Code 3: 00.12.3.2.0.2 Wear track when load rotates over outerring
Failure Code 4: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities

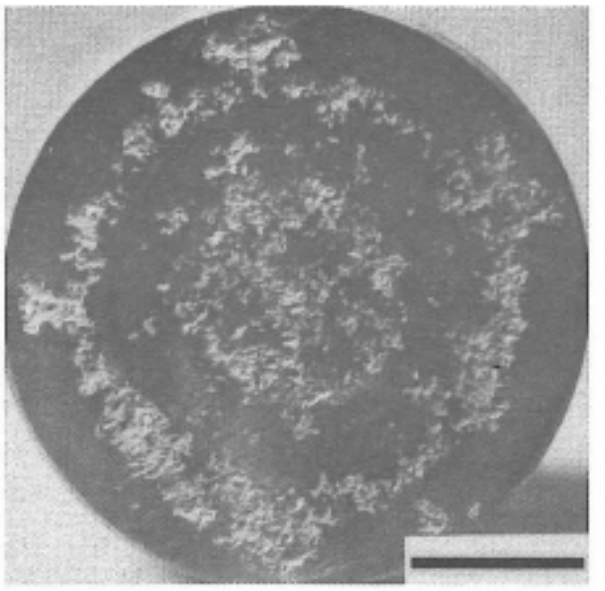


DESCRIPTIONS

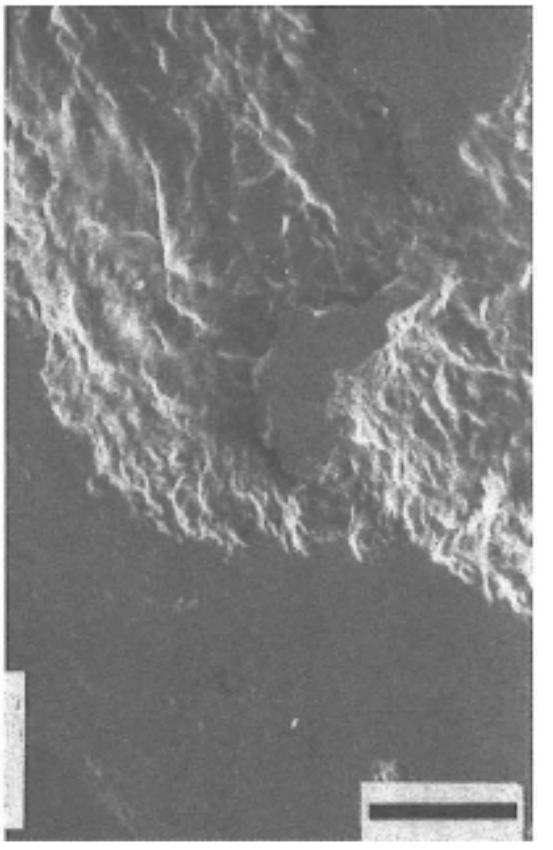
Failure Description: Two 'Heathcote bands' or circumferential wear marks indicate zero-slip zones in ball/groove contact. A large spall, consisting of many shallow spalls, confined essentially between the Heathcote bands, indicates surface origin promoted by sliding. The bearing has failed.
Image Description: Glossy surface of ball groove is divided by two sets of circumferential gray lines: the Heathcote bands. Large spall in SW quadrant is confined essentially between Heathcote bands. Jagged side edges and shallow depth of spall indicate reinitiation at surface. Significant debris denting (dark points) are visible elsewhere in the groove.
Suspected Causes: This OR of a high-speed bearing has high centrifugal loading, producing 360° load zone (see Heathcote bands). Surface-initiated spalling may have been aided by debris denting and concentrated in the high-stress, high-sliding zone between Heathcote bands.

DATA

Plate No: 10.61
Archive No: 006-18&19
Image type: a: light macro, b: SEM
Scalebar = a: 10 mm, b: 200 μm
(micros: ±20%, others: +100%, −50%)
Component: C; CF (sliding), run
Speed:
Load:
Lubrication: mineral oil based diesel engine oil, ? °C
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.16.03.2 Spall propagating by reinitiation at surface
Failure Code 3: 00.16.01.1 Spalling centered in contact
Failure Code 4: 00.12.3.3.2 Wear, centered in sliding contact



a



b

DESCRIPTIONS

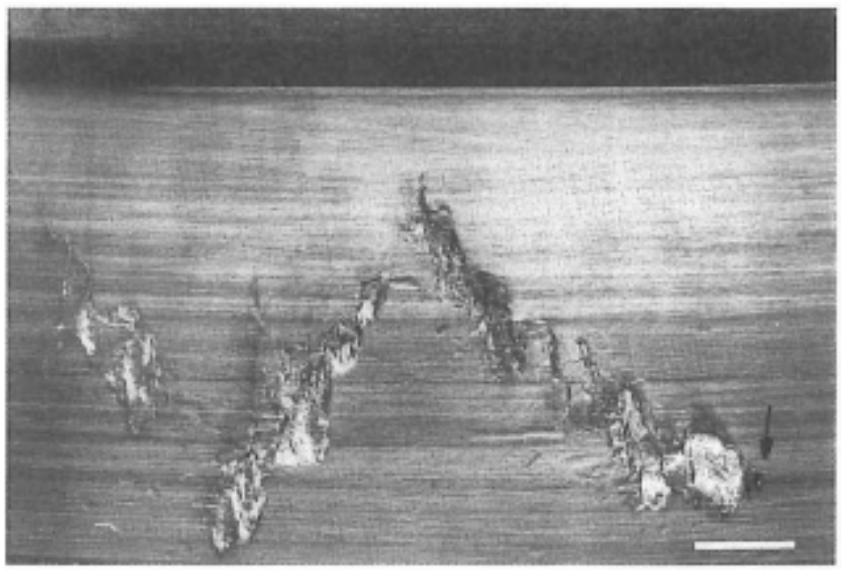
Failure Description: (a): Extensive surface-initiated spalling of cam follower rod end in sliding-rolling Hertzian contact with cam. (b): Fatigue spalls from (a). Spalling fatigue in Hertzian contact with predominant sliding is less common than wear (FC 00.12) or galling (FC 00.13), but does occur as shown here. Unspalled areas are featureless from wear.
Image Description: (a): Circular endface of non-roller cam follower. Roughly circular dark worn areas are near OD and at mid-radius. Circle of light-colored spalls at center and 1/4 in from edge. (b): S quarter of image is an unspalled area with a few faint NW–SE wear marks. N three-fourths of the image comprises two spall crater areas with interposed lamina preparing to spall out.
Suspected Causes: Non-roller cam followers are sphere capped rod-ends in contact with a slightly tapered cam surface which is placed so as to induce rotation of the follower rod around its own axis, while the rod-end slides over the follower. During the lift phase, high pressures and (due to the sliding) high tractive forces exist which may cause spalling.

DATA

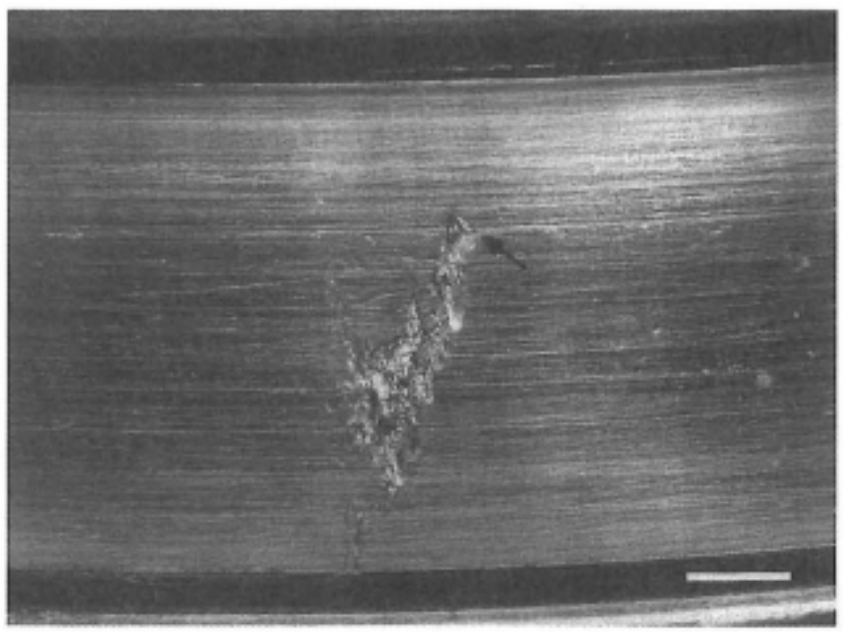
Plate No: 10.62
Archive No: 014-520a&b&c
Image type: a, b, c: light macro
Scalebar = a, b, c: 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, carburized, run
Speed:
Load:
Lubrication: mineral oil (low viscosity), 135°C
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 3: 00.16.03.2 Spall propagating by reinitiation at surface
Failure Code 4: -
See also PLATE: 10.50

DESCRIPTIONS

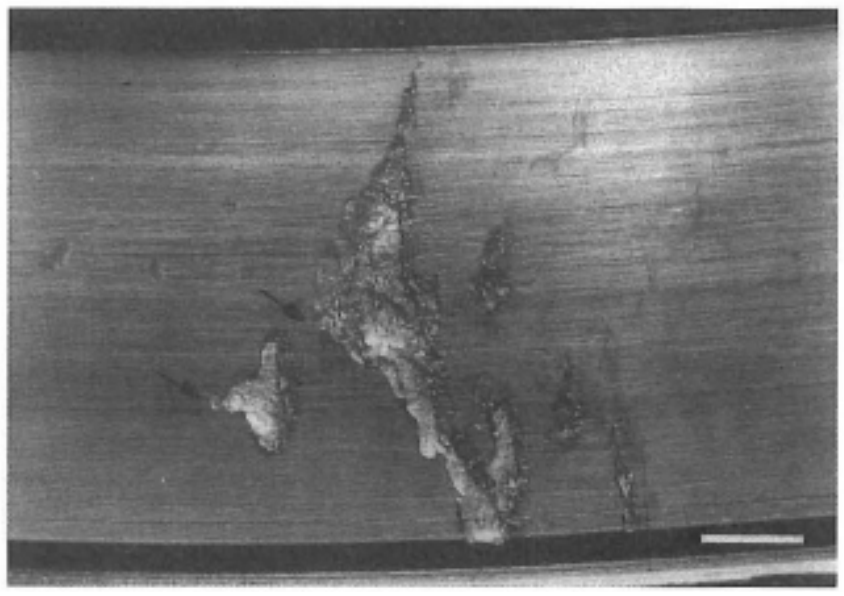
Failure Description: Three examples of spalling originating from surface interaction (low EHD film, rough or dented surfaces). In (a), the initiator is a dent; in (b) a furrow; and in (c) two dents. Spalls propagate in the shape of an arrowhead opening in the rolling direction. The entry area is a shallow-angle crack. Contrast with Plate 10.50: subsurface origin spall.
Image Description: (a), (b), and (c): TRB IR (cone) roller track with E–W finishing lines and undercuts at image N and S. (a): Rolling is E to W; spall initiates at dent (arrow), progresses to NW, then to SW and again to NW. (b): Rolling is E to W; spall initiates at furrow (deep finishing line at arrow) and progresses to SW. (c): Rolling is W to E; two initiations at dents (arrows), progress in an arrowhead shape. All initiating angles are shallow.
Suspected Causes: Low viscosity oil (high temperature) causes low EHD film thickness; any surface defect (dent, furrow) depletes EHD film and may initiate spalling. Spall edge acts as a secondary initiating defect.



a



b



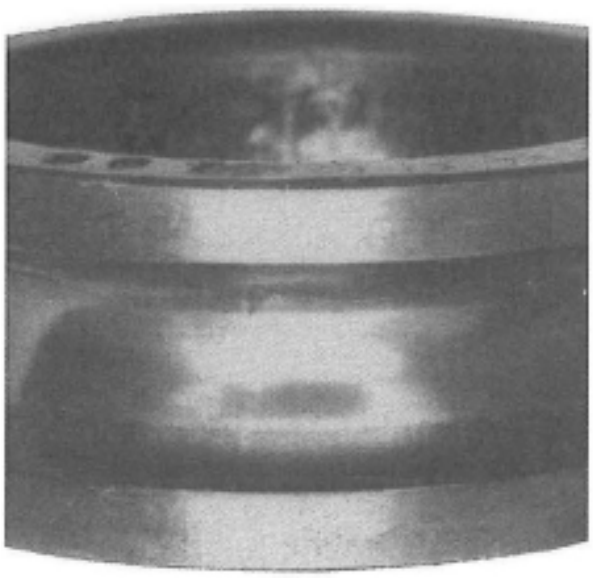
c

DATA

Plate No: 10.63
Archive No: 093-022
Image type: a, b, c, d: view
Scalebar = a:12, b:20, c:16, d:20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 3: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 4: 00.16.02.5 Advanced spalling

DESCRIPTIONS

Failure Description: Progression of surface-distress (FC 00.17.1) origin spalling on four IR-s from the same test group of bearings. (a): glazing only; (b): surface distress microspalling; (c): incipient spalling; (d): advanced spalling. (a) and (b) serviceable; (c) noisy but may run, (d) failed. If operating conditions causing surface distress (insufficient EHD film, aggressive lubricant, rough surface) persist, progression from (a) to (d) may be rapid.
Image Description: Four views of different rings from the same bearing test group (note the slightly different magnifications), after progressively longer running. (a): Centered band of changed luster in ball groove is early surface distress. (b): Frosted appearing areas (one-fourth W of ring center) are microspalls. (c): Series of spall craters, independently initiated. (d): Generalized spall cratering.
Suspected Causes: Surface distress occurs when asperity interactions in contact are excessive, such as from insufficient EHD film, rough surfaces, or possibly from aggressive lubricant. Microspalls develop that serve as severe initiating defects for macroscopic spalling fatigue. Progression rate varies sharply with conditions. Carburized parts may be more resistant than through-hardened parts.



a



b



c



d

DATA

Plate No: 10.64
Archive No: 122-8&9
Image type: SEM
Scalebar = a: 1 mm, b: 100 μm
(micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 170 KdN
Load: 2.8 GPa
Lubrication: mineral oil, ? °C
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: -

DESCRIPTIONS

Failure Description: Several sharp-edged shallow dents, as from rolled-in flakes (possibly from plating); some formed before, (some possibly after) spall initiation. A fan-shaped spall originated from one dent. Concentric cracks are visible downstream of the spall crater (in the rolling direction). Spalling is likely to propagate causing functional failure.
Image Description: (a): Fan-shaped spall crater covers image center. At tip of fan, at image S, the angular, shallow depression in the surface is a dent from a thin, ductile, hard contaminant. At N edge of crater, concentric cracks are ready to exfoliate additional material. Several dents, possibly from spall debris, cross crack lines N of the crater. (b): A detail view of spall origin shows edge of initiating dent S of spall tip, followed by cracks.
Suspected Causes: Debris dents cause (1) loss of EHD film, (2) local stress concentrations near dent edges, (3) damage to material underlying dent. These factors contribute to make dents spall initiators. Spall typically originates some small distance downstream (in the direction of contact travel) from the dent, leaving an unspalled lip between dent and crater.

a

b

DATA

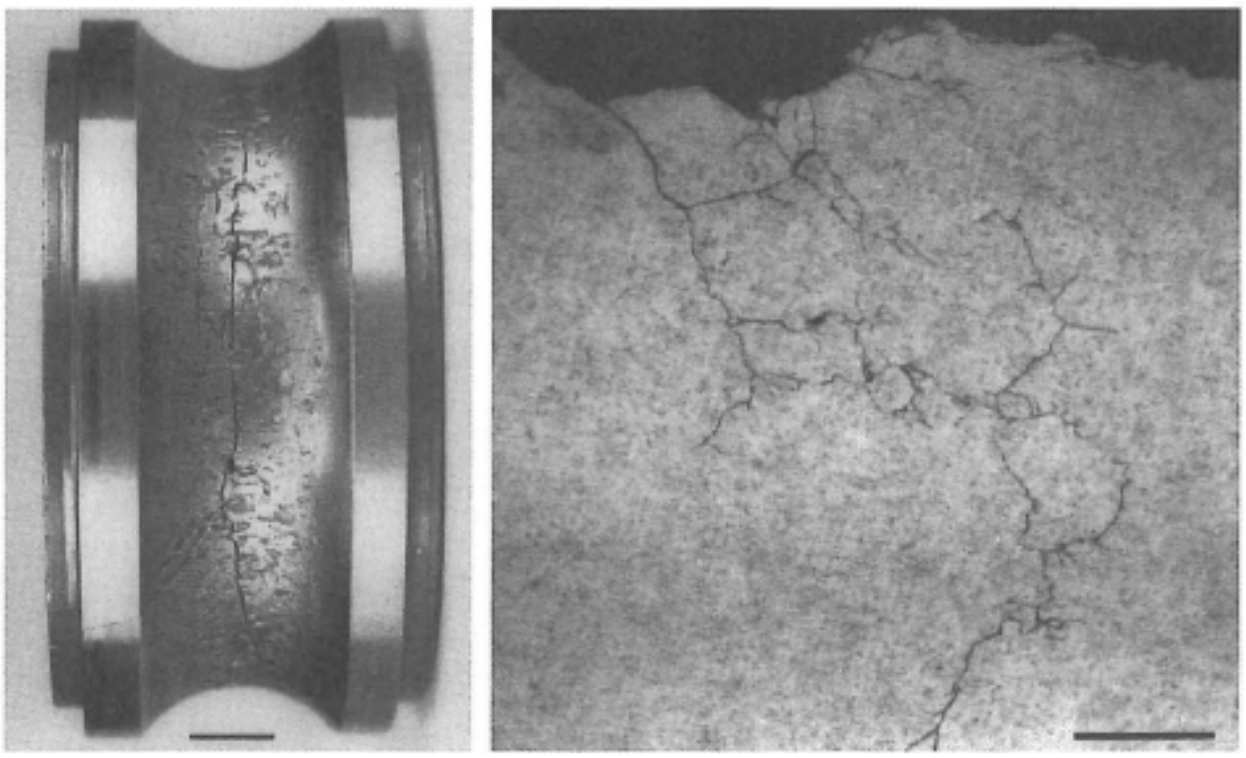
Plate No: 10.65
Archive No: 018-104
Image type: view
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.20.1.3 Contact corrosion
Failure Code 3: 00.12.3.2.1.1 Wear track centered in contact
Failure Code 4: 00.12.4 Wear of guiding-component support surface

DESCRIPTIONS

Failure Description: (1) Contact corrosion streaks spaced at roller spacing, on one roller path, which caused (2) extensive spalling in that roller path with cratering most severe at corrosion streaks. (3) Debris denting and wear on other roller path, caused at least one spall. (4) Center guide flange wear from debris trapped between separator and flange. The bearing was used in heavy, slow speed machinery and may have run a long period to reach this failure.
Image Description: Roller path to image N shows five dark axial corrosion streaks at roller spacing, underneath generalized spall cratering. The cratering band is widest around the streaks. Roller path to image S is finely dented and matte from debris denting and abrasive wear. One spall is near the center flange at W. Central guide-flange shows a step worn in the center plane, where two separator halves meet.
Suspected Causes: Contact corrosion arises from water in the lubricant (probably grease) of the mounted bearing, or possibly from water in the package during shipment prior to mounting. Severe contact corrosion (with pitting) is a serious spall-initiating defect. Spall debris from the extensive cratering act as abrasives and denting particles.

DATA

Plate No: 10.66
Archive No: 116-003&002
Image type: a: view, b: light metallogram, Nital etch
Scalebar = a: 4 mm, b: 60 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: oscillating
Load: 2 GPa
Lubrication: grease w. silica thickener, H_2O + CO_2 atmosphere
Failure Code 1: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 2: 00.22.4 Chemical origin (stress corrosion, embrittlement) crack
Failure Code 3: 00.12.0.2 Abrasive mild wear
Failure Code 4: 00.18.02.2 Severe or advanced denting



a b

DESCRIPTIONS

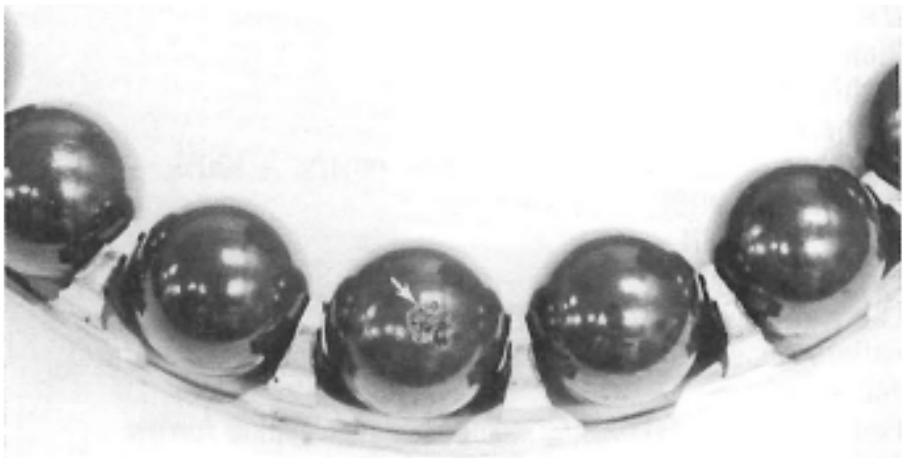
Failure Description: (a): Bearing operated in high-pressure atmosphere of CO_2 and water vapor, with oscillating motion. Failure occurred at one-tenth of the catalog calculated life from massive spalling and circumferential bulk cracking. Chemical effect of grease on failure mechanism is assumed but not explained. The surface between spalls is worn and dented by spall debris. (b): Cracks at the spall bottom are unusual, radial-going, and branched (may be intergranular).
Image Description: (a): IR viewed on ball groove. The contact area is covered with independent origin spalls in a worn and dented surface. A jagged circumferential bulk crack runs through mid-groove. (b): Etched metallographic section through a spall. Radially inward-going heavily branched cracks suggest intergranular cracking of chemically weakened material.
Suspected Causes: Unusual chemical environmental of this bearing application produced (in repeated runs) the catastrophic spalling and cracking failure shown. If water condenses in grease under these conditions, failure may be explained thereby. Chemical effect is also suggested by unusual spall-bottom cracks and bulk fatigue failure. Corrosive effect of CO_2 on bearings is not reported by other sources.

DATA

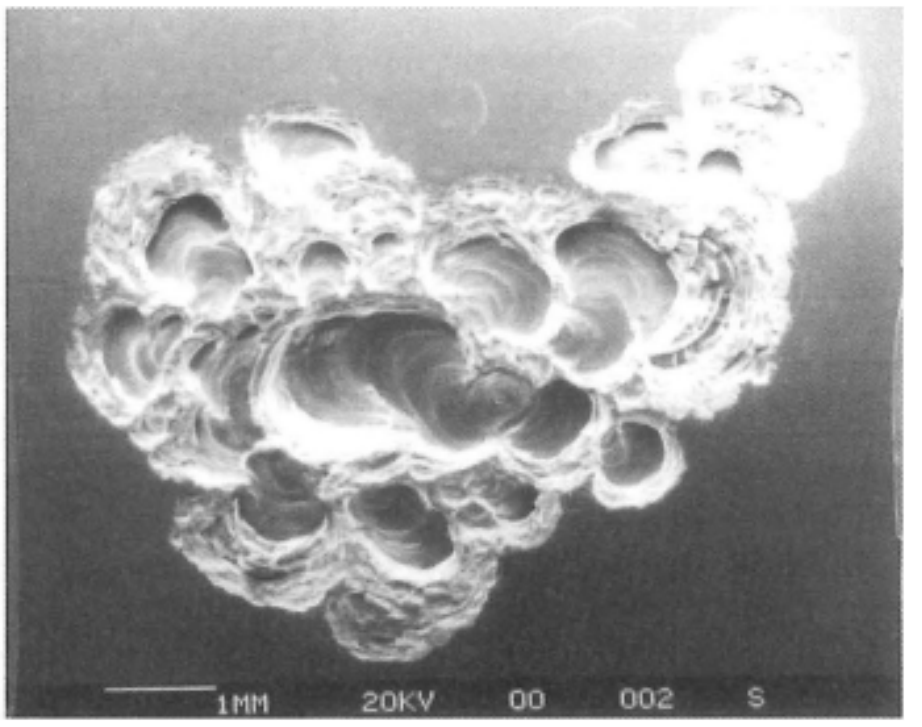
Plate No: 10.67
Archive No: 124-001 & 002
Image type: a: light macro, b: SEM
Scalebar = a: 20 mm, b: 1 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB (split IR), B & C; silicon-nitride B, M50NiL rings
Speed: 1.2 - 2.0 MdN
Load: variable
Lubrication: polyester synthetic oil; 121 - 149°C
Failure Code 1: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 2: 00.01.1 Local nick
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Multiple-initiation surface origin spall on silicon-nitride ball resulting from electro-discharge machined axial notch (artificial defect) across outerring ball track. Rings and cage were severely damaged.
Image Description: (a): Segment of separator with balls in pockets. Silicon nitride ball at image center shows spall (at arrow). Separator damage not visible. (b): Low-magnification SEM image of the ball spall shown in (a). The spalling forms a cluster of many initiation points which overlap, indicating that spalls propagate slowly from an initiation point under the test conditions.
Suspected Causes: The test was intended to study spall initiation and propagation in silicon nitride balls. In order to produce a spall, a severe surface nick (notch) was made by EDM on the OR ball path. The first effect of running with the notch was found to be separator fracture, followed by spalling of rings and finally spalling of silicon nitride balls.



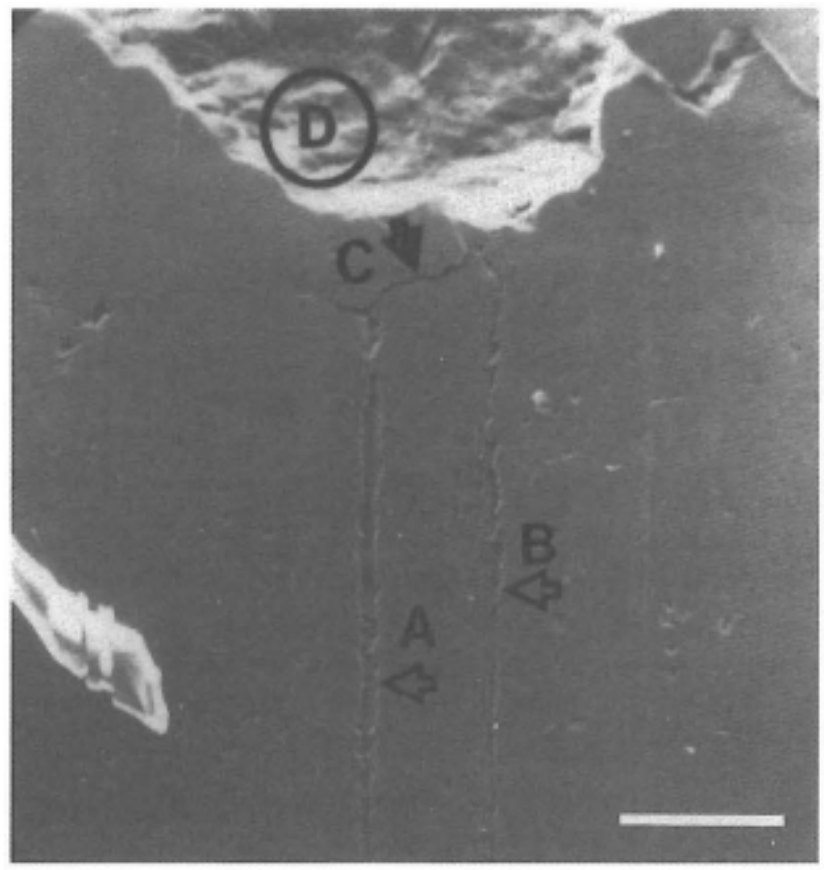
a



b

DATA

Plate No: 10.68
Archive No: 093-16.6.6
Image type: SEM
Scalebar = 50 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, honed, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral oil, 100°C
Failure Code 1: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 2: 00.02.1 Grinding, honing, lapping furrow
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: -

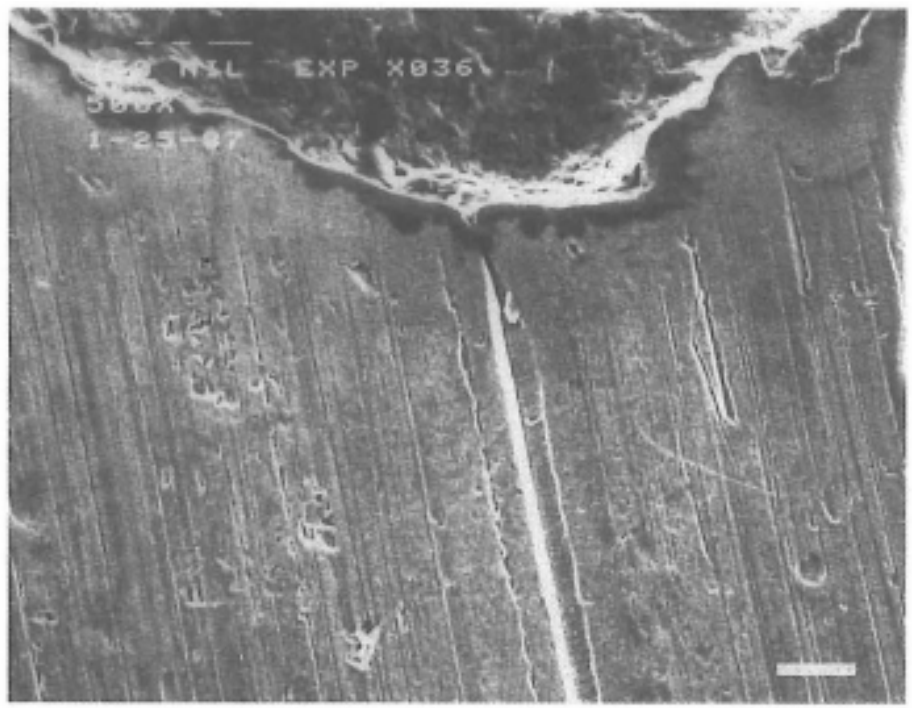


DESCRIPTIONS

Failure Description: Two honing furrows lead into a fatigue cracked and spalled region. Surface cracking has begun at one furrow end. The other furrow apparently initiated existing surface-origin spall. Furrows are serious fatigue-initiating defects, especially when high EHD film thickness otherwise offers long life. The film breaks down at a furrow and high stress concentrations arise.
Image Description: Gray background with faint N–S lines is the honed surface. At *A* and *B*, N–S running furrows with rolled-down feather edges at *B*, suggesting *honing* origin. At *C*, surface crack initiates from furrow *A* which ends at the bend in crack. *D* is the spall bottom area (only about 40 μm below the surface), a shallow spall entry. Very small (2–3 μm) contaminant dents on the surface. The large light-colored object at image SW is an artifact.
Suspected Causes: Grinding furrows may be left in honed surface if too deep to be removed in honing. Detached honing grit may also create furrows of its own. Since the area adjacent to the furrows shown is undisturbed and the furrow has feather edges suggesting no subsequent finishing, these seem to be honing furrows.

DATA

Plate No: 10.69
Archive No: 018-608
Image type: SEM
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; carburized tool steel, run
Speed: 100 KdN
Load: 3.7 GPa
Lubrication: mineral oil, 54°C
Failure Code 1: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 2: 00.02.1 Grinding, honing, lapping furrow
Failure Code 3: 00.18.1.3 Multi-fragment dent (brittle contaminant)
Failure Code 4: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities



DESCRIPTIONS

Failure Description: Several finishing furrows, the deepest of which initiates spalling. Very small multi-fragment dents; some small debris dents. The ring has failed.
Image Description: S two-thirds of image of rolling surface, with finishing marks running SE to NW. About mid-image, a white heavy line marks furrow with sharp point leading to the edge of the (dark) spall crater in the N one-third of the image. The crater has a sharp edge extruded toward the furrow tip. Several lesser furrows are in NE quadrant. Dark clustered points with light haloes are multi-fragment dents. Wide depressions, with finishing lines at bottom, are debris dents.
Suspected Causes: Contact surface was ground and subsequently honed. The grinding left several deep furrows not removed by honing, one of which caused the spall. Multi-fragment dents arise from brittle contaminant. Debris dents could be caused by spall debris. The crater edge appears raised in this SEM but probably is not.

DATA

Plate No: 10.70
Archive No: 002-018b
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; OR, run
Speed: 1.9 MdN
Load: 0.9 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 2: 00.16.02.5 Advanced spalling
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Long circumferential spalled area on one side of OR roller path, but away from edge, formed by multiple spall craters. External evidence suggests a wire gasket element may have been rolled over (before being expelled) to create severe denting. Denting is no longer identifiable. Shallow spalls surround deep craters at several points, possibly due to overrolled spall debris creating secondary spalling.
Image Description: Long area of contiguous deep spall craters is lined up circumferentially (arrows). The area is surrounded in several places by shallowly spalled fringes, as from secondary spalls due to overrolling of spall debris.
Suspected Causes: From evidence of rolled-over wire gasket element, it is suspected that the wire became trapped in the roller path and created a long heavy dent before being expelled in running. Such a dent explains the long line of deep spalls. The shallow peripheral spalling may be due to debris.

SURFACE DISTRESS 11

Failure Code 00.17

11.1 Definition

Surface distress is defined as microscale spalling fatigue. It is failure of *rolling* contact surfaces resulting in asperity scale *microspall* craters. In ductile materials such as *steel*, the failure process proceeds by the formation of (a) glazed (burnished) surface areas; (b) asperity scale microcracks; and (c) asperity scale *microspall* craters, in that sequence. Surface distress in *ceramic* surfaces does not discernibly exhibit the glazing of step (a).

Surface distress is the result of predominantly *normal* contact stresses acting in asperity dimensions. Tractive forces may be present, but not dominant (no large-scale sliding is likely). Surface distress is distinguished from:

- *Spalling* (FC 00.16), which is Hertzian contact fatigue in macroscopic dimensions.
- *(Mild) wear* (FC 00.12), which is the ablation of surface material in the form of loose particles, under the influence of predominant tractive contact stresses acting in asperity dimensions (substantial sliding is likely).
- *Pit* formation, as porosity (FC 00.03) from material casting, sintering or processing; as pitting wear (FC 00.12); as a result of corrosion (FC 00.20) or of electric erosion (FC 00.21).

11.2 Nomenclature

Surface distress is widely used to designate this failure mode in rolling bearing technology. Another designation for the *early*, plastic flow stage of surface distress failure is *glazing*.

The later, microspalling stage is also designated: *peeling*, *fatigue wear*, *delamination wear*, *micropitting* or *microspalling*. The term "frosting" has been used for surface distress as well as for skid marking (see FC 00.15). Due to the possibility of confusion, the term frosting is not used to designate surface distress in this Atlas.

11.3 Failure Process

Surface distress has been reported predominantly on *steel* rolling contact surfaces. However, silicon nitride ceramic components also exhibit the microcracking and microspalling of surface distress.

Two theories describing surface distress in *metal* are by Tallian [4] and Suh [21]. Both define the failure process as fatigue in asperity dimensions but differ in details of the failure mechanism. Suh's *delamination* theory is described in detail in [21]. Tallian's [4] description of surface distress development, used in this Atlas, follows.

When two surfaces are in predominant rolling contact under load and with lubrication, their asperities approach each other in a direction close to the surface normal. Depending on the average thickness and rheology of the (liquid or solid) lubricant layer between the surfaces, stresses substantially exceeding the macroscopic local Hertzian stress may develop in asperity encounters.

If the lubricant is an EHD film and its thickness is three or more times the composite RMS surface roughness height, then the extra asperity stresses are statistically negligible. As the EHD film becomes thinner, or if only a boundary film is present, then the asperity stresses (which can be modeled as microscale Hertzian stress fields) become dominant in an increasing fraction of the asperity encounters.

The magnitude of asperity stresses increases with the composite "sharpness" of the asperities participating in the encounter. This sharpness can be measured by composite RMS slope or composite RMS tip curvature.

Note: The parameter determining the sharpness of an asperity encounter is the *composite* slope or curvature of the two surfaces at the encounter point. Combining a very smooth surface with a rough one (ball in rough groove) does not protect the smooth surface from surface distress.

For asperity encounters in which the alternating shear stresses exceed a limit that depends on material properties, the following failure sequence is visually observable in (ductile) materials such as steel:

1. *Asperity-scale plastic flow.* Both cumulative and alternating plastic flow occur in the asperities.
   - The *cumulative* plastic deformation occurs early in cycling and leads to flattening of asperity tips, especially the sharp "feather edges" that often decorate the crests of asperities in ground surfaces. The appearance of the surface will become progressively more burnished (*glazed)* as the topography left from surface finishing is gradually leveled and only smooth low-frequency waviness and scratches at the bottom of deeper finishing marks remain. The surface and immediate subsurface material are heavily cold worked.
   - The *alternating* plastic flow produces structural changes on the asperity scale which are qualitatively similar to those suffered by macroscopic Hertz contacts under fatigue stressing.

Note: In silicon nitride ceramic, the plastic flow phenomena leading up to microcracking have not been observed. However, the similarity of the spalling in steel and silicon nitride suggests similarities in the changes leading to microcracking.

2. *Microcracking.* With continued cyclic stressing, the plasticity of the material is exhausted and microcracks form. These tend to run surface-parallel, at depths comparable to that of the high asperity-scale shear stresses. They may or may not be open to the surface. A heavily distressed surface is densely populated with these microcracks.
3. *Microspalling.* As microcracks grow and proliferate, the surface becomes undermined in asperity dimensions, and multiple microscopic spalls form.

11.4 Distinctive Appearance

Steel Surfaces. Glazed and microspalled surfaces appear macroscopically quite different. A microcracked surface appears just glazed. All three may be present side-by-side on the same specimen.

A *glazed* surface differs from an as-finished surface in that finishing lines are crisp and evenly distributed on the latter, and partly or wholly obliterated on the former. When viewed under different angles of illumination from a small light source, an as-finished surface gives a "brushed" light reflection from the combined reflections of many parallel finishing marks. A glazed surface tends to show a mirror-like reflection.

Note: Extremely smooth original finishes (in rolling bearings, especially balls) may show a virtual mirror reflection even if not surface-distressed.

Under low magnification (scanning electron) microscopy, a glazed surface shows the smoothing of asperity ridges into almost featureless flat areas (with valleys still discernible), possibly with some incidental wear marks or dents. In contrast, mild wear produces a pebbled, profusely scratch-marked or micro-dented surface.

Glazed areas may be *generalized* on the contact surface (generalized surface distress); or *local*, in the form of "halos" around local depressions (dents, nicks) or glazed bands following furrows.

A microcracked surface is not usually distinguishable from a glazed one by the unaided eye. However, microcracking and microspalling most often appear together. See below for unaided eye identification of microspalling.

Under low magnification (scanning electron) microscopy, microcracks opening to the surface may be visible in glazed areas. Microcracks can be seen in carefully prepared metallographic sections if the intersecting edge at the original surface is preserved by surface overplating.

A microspalled surface appears frosted to the unaided eye, possibly with barely visible black spots representing the microspalls. No safe differentiation between a microspalled distressed surface and one with skid marking is possible by the unaided eye. However, it is suggestive of skid marking, if the frosted surface is a circumscribed patch on the rolling surface, and suggestive of surface-distress if it runs more or less circumferentially around the rolling track following finishing lines.

Under low magnification (scanning electron) microscopy, microspalls in a glazed surface show a typical *peeling* pattern reminiscent of smooth wet soil that underwent freezing and thawing. The "mesas" are burnished and flat (unless there was subsequent mild wear, when they are scratch-marked); the pits are fracture-surfaced spall craters. Pit rims are sharp and often feather-edged.

Microspalls tend to "decorate" finishing lines remaining within (generalized) glazed areas and to cluster within the halos of local surface distress.

Microspalls can be seen in carefully prepared metallographic sections if the intersecting edge at the original surface is preserved by surface overplating.

Ceramic Surfaces. Silicon nitride ceramic surfaces show no recognizable glazing. Under the scanning electron microscope, surfaces with microspalls resemble fracture surfaces of concrete: there are no burnished mesas; the microspalls run together in a rough, pebbly surface. Surface distress in ceramics differs from macrospalling primarily in the shallow depth and small scale of individual craters.

11.5 Causes

Two dominant variables control surface distress:

1. *EHD film thickness.* In the presence of a sufficiently high EHD film thickness to surface roughness height ratio, surface distress does not occur because the film prevents high microstresses in asperity interactions.

   - Film thickness may be sufficient to prevent generalized surface distress, but not local distress in the vicinity of surface features such as depressions which locally depressurize and thereby thin the film.

2. *Surface microgeometry.* Both the *height* and sharpness of asperities (RMS roughness height and slope) influence surface distress.

   - Composite *roughness height* (RMS) enters the EHD film thickness/roughness height ratio. Above a ratio of 3, *generalized* surface distress does not occur. The likelihood of surface distress increases as the ratio drops below this value. Local surface distress can occur where local surface features are high compared to the average, or where the film is depleted by a "sink," such as a sharp surface depression or edge.
   - Composite *sharpness* (RMS slope, tip curvature) of asperities influences asperity stress levels for a given film thickness/roughness ratio. Because slope and roughness height are correlated for a given finishing method, surface distress is unlikely between very smooth, unblemished surfaces.

Other factors influential in surface distress are the following:

- *Surface material fatigue resistance.* Matrix properties that enhance spalling fatigue resistance also improve resistance to surface distress.
- The *boundary lubricating* ability of the lubricant can retard surface distress, although this effect is *not* very strong. This means that boundary lubricating additives are a much less potent remedy to surface distress than a thicker EHD film or smoother surfaces. However, a lubricant with very poor boundary lubricating ability (some unformulated synthetics) may promote surface distress.
- *Some solid lubricant coatings* appear to retard surface distress. In high-speed rolling bearings, black-oxide coatings (and tin coatings) have been found to be of some help.

The use of strongly adherent, crack-free *globular chromium plating* or other hard plating (not the common hard chrome plating) may be helpful in preventing surface distress under operating conditions where effective EHD lubrication cannot be achieved.

Comments on the limitation of methods to retard surface distress:

- Lubricant chemistry does not offer as potent and flexible a remedy as EHD film and surface roughness control. In fact, surface distress differs from mild wear (FC 00.12) and galling (FC 00.13), in that lubricant chemistry is a prime controlling variable for wear and galling, but not for surface distress. Some benefit from solid lubricant coatings has been observed.
- Material fatigue strength is not generally a variable available for the control of surface distress in a given material class. In the interest of spalling prevention, design choices for bulk material fatigue strength have already been made and can rarely be improved upon to retard surface distress. However, silicon nitride ceramic is highly resistant to surface distress if free of porosity and binder defects.
- Due to application problems, the use of currently available hard coatings is reserved for experimentally proven cases.

11.6 EFFECTS OF SURFACE DISTRESS

The most hazardous consequence of surface distress is spalling fatigue. In the absence of pre-existing surface defects (nicks, grinding burns, etc.) or dents acquired in service, surface-origin spalling initiates from surface distress, that is, from asperity-scale fatigue.

The rapidity with which surface distress leads to surface-origin spalling varies greatly. The principal operating factor influencing the rate of spalling from surface distress is *tractive* interface stress. When traction is high, spalls form rapidly and profusely from surface distress. The spalls are likely to appear from many initiation sites and can destroy a component in short order. See [5] for details.

If early spalling does not terminate the operation of a component that has suffered surface distress, then surface material delamination may occur. The original surface is thereby lost over wide areas and the component becomes unserviceable through loss of dimensional accuracy, through noise, or through secondary failures.

It is possible for surface distress to be arrested, especially in the glazing stage, without further deterioration. This may occur if mild wear (FC 00.12) is present and surfaces are successfully run-in to a smoother finish or if lubrication is subsequently improved. In this case, the surface distress may not prevent functionality. However, it is unsafe to count on surface distress to be consistently benign, even in similar applications or in repeated runs of the same application.

Gears and cams appear less sensitive to the consequences of surface distress than rolling bearings. This may be due to the greater ductility of lower-hardness gear and cam steels. However, surface distress is observed on all these machine elements.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.17.01	11.4 11.15 11.16 11.17
00.17.02	11.18 11.19 11.20 11.21 11.22 11.23
00.17.1	11.28
00.17.1.1	10.14 10.63 12.8 12.15 14.19 14.23
00.17.1.2	7.12 7.13 8.8 9.16 10.14 10.21 11.5 11.6 11.26 11.27 12.8 12.21 18.2
00.17.2	6.6 10.50 10.57 10.58 15.28

PLATES

DATA

Plate No: 11.1
Archive No: 014-32
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1 Generalized surface distress
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: On the roller path of the OR (cup), an extensive area in the load zone shows "frosted" ("peeled") appearance of generalized surface distress. The macro image does not permit distinction between glazing (FC 00.17.1.1) and the more advanced damage of microspalling (FC 00.17.1.2), but microspalling is more likely to correlate with the frosted appearance. Surface distress may lead to early spalling failure.
Image Description: View is into the roller path of a TRB OR (cup). The dark circle on the S edge is the (large) endface. To the N is the light gray roller path with a sharply delineated darker gray area occupying most of the S part of the roller path. This is the surface distressed area which has a "frosted" ("peeled") appearance. Under (low magnification, microspalls are likely to be visible.
Suspected Causes: Insufficient EHD film thickness, combined with relatively rough surfaces, may cause surface distress (fatigue in asperity dimensions). Plastic deformation of asperities is followed by microspalling. The frosted surface appearance is typically the result of the many microspalls. (A 'glazed' surface is lustrous).

DATA

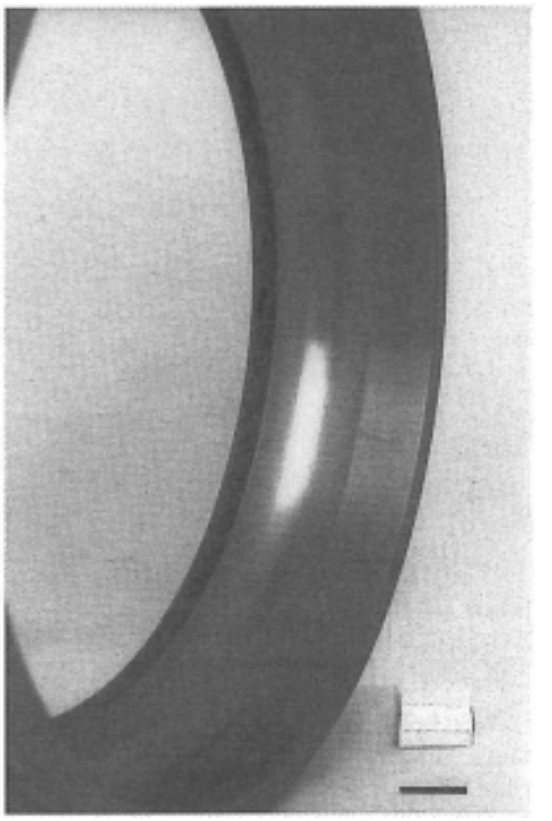
Plate No: 11.2
Archive No: 027-240
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 130 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.12.3.2.0.1 Wear track when load rotates over innerring
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: -

DESCRIPTIONS

Failure Description: Normal centered ball track in IR, overlaid in center plane, by narrow, surface-distressed and debris-dented band. Narrowness of band suggests profile geometry error. Bearing may have become noisy but has not failed.
Image Description: The center 1/3 of ball groove shows different luster from outside areas, marking a ball track, extending probably to the Heathcote bands. At the center of this ball track is a narrow, darker gray band, apparently surface distressed. Just S of the light-reflection band crossing the ring are several small debris dents in the surface-distressed band.
Suspected Causes: Insufficient EHD film thickness, possibly combined with relatively rough surface finish in ball path, can lead to surface distress in the contact zone. Distress in a narrow central band within the ball track may arise if surface finish or profile geometry in that area are defective. Debris denting, caused by contamination, can promote surface distress.

DATA

Plate No: 11.3
Archive No: 027-234
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; OR, run
Speed: 130 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.12.3.2.0.7 Wear track for misaligned outerring
Failure Code 3: -
Failure Code 4: -
See also PLATE: 7.3

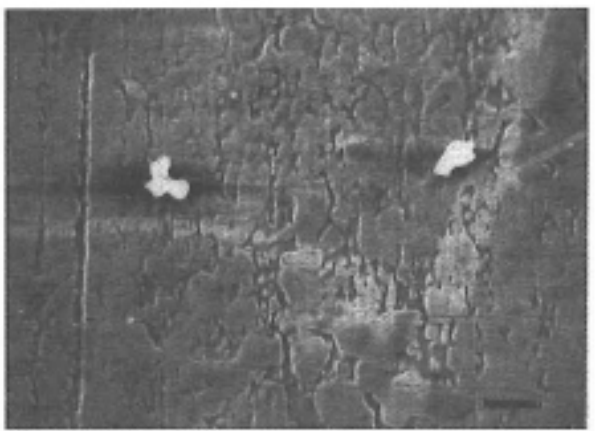


DESCRIPTIONS

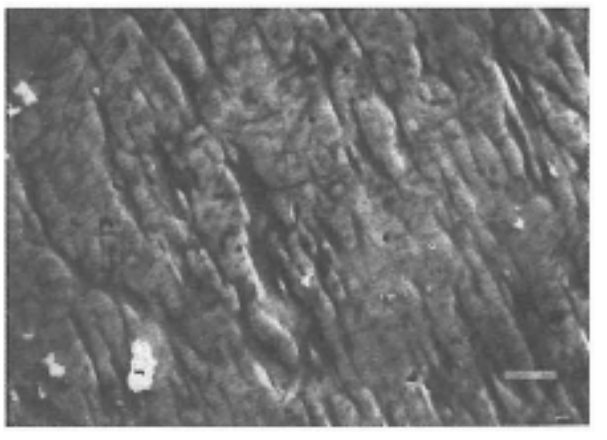
Failure Description: Early indication of surface distress in misaligned ball track of OR. The bearing may be noisy but has not failed. Continued surface distress may lead to spalling.
Image Description: Ball groove of OR, with high land at image W and low land at E. From S extremity, over approximately a 90° arc, the E half of the ball groove shows a gray, finely frosted appearance suggesting surface distress. The ball track shifts to E, toward the low-land edge, as it proceeds to the N, suggesting OR misalignment.
Suspected Causes: Insufficient EHD film thickness, possibly combined with relatively rough surface finish in ball path can lead to surface distress in the contact zone. OR misalignment can cause the contact zone to shift to one side of the groove. See drawings in Plate 7.3.

DATA

Plate No: 11.4
Archive No: 007-101&102
Image type: a, b: SEM
Scalebar = a: 10, b: 12 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; a: OR, b: B (stainless steel), run
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.17.01 Surface distress, no sliding
Failure Code 3: 00.15.2 False brinnelling on contact surface
Failure Code 4: 00.06.1.3 Primary carbide



a



b

DESCRIPTIONS

Failure Description: Extreme plastic flow of surface asperities from surface distress without microspalling. Removal of material (possibly along grain boundaries) by the false brinnelling type of fretting wear. This gyroscope gimbal bearing undergoes small amplitude oscillation (hunting). EHD film cannot form and fretting of weaker material elements occurs over the entire overrolled surface. The texture is characterized by blocky hard primary carbides of 440C steel.
Image Description: (a) & (b): Image covered with flattened, deformed areas with irregular contours (plastically deformed asperities with underlying blocky carbides). Darker gaps are believed to be fretted depressions along grain boundaries. (a): Finishing lines are visible as one continuous and one partially rolled-over furrow near W edge. (b): Random thin dark lines may be lapping marks. (a) & (b): Irregular white spots are imaging artifacts.
Suspected Causes: Gyroscope gimbal bearings have an extremely fine finish and require high precision. They are often made of martensitic stainless steel. Their motion is often oscillation (hunting). Surface distress and fretting conditions both exist. In the case shown, extreme plastic asperity deformation without microspalling is interspersed with fretted zones (perhaps grain boundaries). Blocky carbides distort surface topography.

DATA
Plate No: 11.5
Archive No: 107-019a&b
Image type: SEM
Scalebar = a: 500, b: 100 μm (micros: +20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Ball groove of ACBB extensively glazed by surface distress. One circumferential band, located in the contact center, shows microspalling. The bearing is not failed.
Image Description: (a): At E image edge, IR land is rough gray N–S band. Adjacent toward W is ball groove, starting with unrun area (dark), then glazed ball path (shaded gray), in which, about image center, a band of microcracks and microspalls decorates the contact center (maximum pressure, relatively high sliding). (b): Higher magnification. Featureless gray glazed background, E–W running microcracks and incipient microspall craters.
Suspected Causes: On relatively smooth surfaces, with insufficient EHD film, surface distress produces uniform plastic working yielding a high-luster 'glazed' surface. In a ball groove, the contact pressure and sliding are high in the contact center. This aggravates surface distress into microspalling. Traction from sliding favors cracking perpendicular to the sliding direction.

a

b

DATA
Plate No: 11.6
Archive No: 074-2
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: 00.01.2 Scratch, toolmark, scuffmark
Failure Code 4: -

DESCRIPTIONS
Failure Description: On both rollers shown, patches of surface distress near center plane. In one roller, the patch is angularly confined (not a band). Overall cause of distress is severe asperity contact through insufficient EHD film. Axial localization of distress suggests excessive profile crowning. Circumferential localization suggests uneven surface roughness. Scratches may contribute. Rollers may fail in spalling burt are not yet failed.
Image Description: Patch or band of "frosted" surface distress centrally on N roller. Confined frosted patch W of center on S roller. Both rollers show several minor scuffmarks: on N roller, near E end of centerline; on S roller, near E end, S of centerline.
Suspected Causes: Surface distress is generally due to insufficient EHD film. Heavy load contributes, hence suspicion of load concentration on roller center by "overcrowning," that is, excessive relief of the profile toward the edges. Sharp localization of surface distress suggests uneven roughness, possibly combined with scuffing or nicking to initiate the distress.

DATA

Plate No: 11.7
Archive No: 093-17.1.4&5
Image type: a, b: SEM
Scalebar = a: 35, b: 10 μm
(micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral oil, 100°C
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.18.1.1 Rounded dent (from soft contaminant)
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface

a b

DESCRIPTIONS

Failure Description: Multiple changes in an as-run surface under mild surface distress conditions. Glazing has obliterated many finishing lines. Kinematic wear marks from ball spin. Dents are from soft and hard contaminants, the latter decorated by surface distress halo and some microspalling. Condition diagnostic for ball bearing operating under marginal EHD film, with some contamination in the presence of some ball sliding (Heathcote slip).
Image Description: (a), (b): Finishing lines run N–S and are extensively glazed over by plastic flow (areas where lines are interrupted, missing, or dotted). Microspalled dents are kinematic wear marks [see (b)]. In (b): Kinematic wear mark at *C* and *D*, slightly microspalled debris dents at *A* and *B*.
Suspected Causes: Insufficient EHD film thickness compared to roughness leads to asperity contact under higher stress causing plastic flow of asperity ridges, initiating surface distress glazing, which gradually covers finishing lines by smoothing them or folding material over them. Denting on microscale is universal from contaminants below filtering level, which are larger than the film thickness.

DATA

Plate No: 11.8
Archive No: 005-18a&b
Image type: a, b: SEM (backscattered electron)
Scalebar = a, b: 40 μm (micros: ±20%, others: +100%, −50%)
Component: C; CM, run
Speed: 4.5 m/sec
Load: 1.4 GPa
Lubrication: mineral oil, 115°C
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: -
Failure Code 4: -

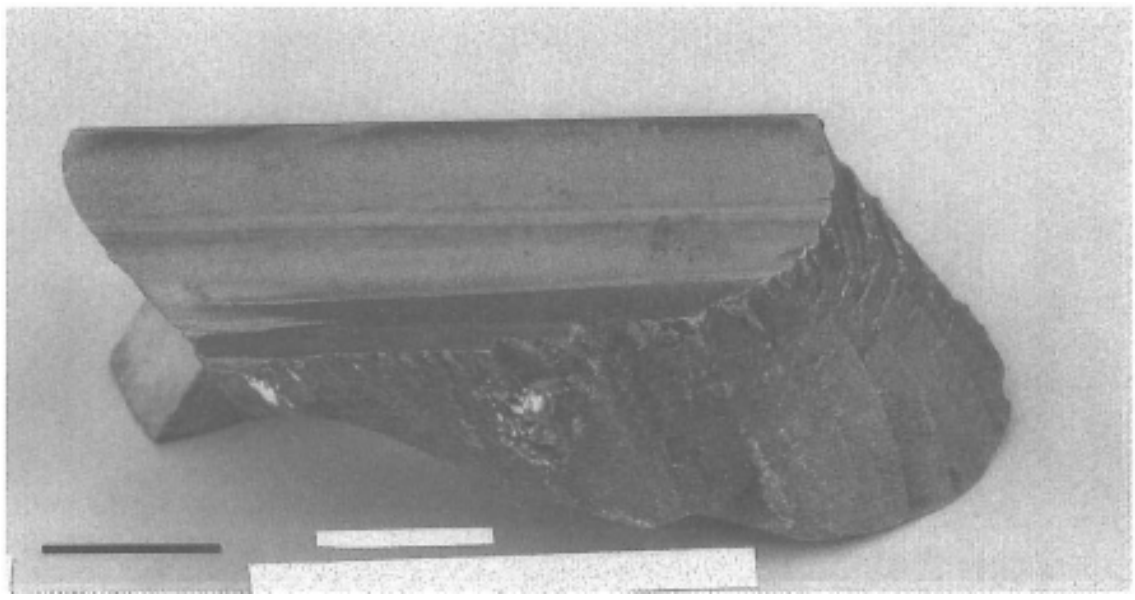
a b

DESCRIPTIONS

Failure Description: Comparison of finished unrun and run surface of cam. Unrun surface (a) has even grinding lines with an occasional line running at a low angle to the others. On run surface (b), many grinding lines are plastically obliterated by surface distress (glazing), leaving only the deeper lines. Fine dents are due to rolled-in contamination. Glazing and fine denting to the degree seen are not failures, but merely warning indications.
Image Description: (a): Normal grinding lines proceed E–W and are smooth and sharp-edged. A few lines are at shallow angles to the others. The backscattered electron SEM image exaggerates contrast and shows lines steeper than they are. (b): Several wide horizontal strips with little texture, where grinding lines are plastically obliterated. Deeper lines remain. Several round dents are caused by rolled-over debris.
Suspected Causes: Surface distress of the magnitude shown is common when rolling contacts operate without full EHD film. Debris dents of this magnitude (2–3 μm diameter) are inescapable in all but the most extreme cleanness conditions, from debris carried in even well-filtered lubricant.

DATA

Plate No: 11.9
Archive No: 099-202
Image type: light macro of fractured tooth
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, med., hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 2: 00.22.01.4 Gear tooth crack or fracture
Failure Code 3: -
Failure Code 4: -
See also PLATE: 11.11



DESCRIPTIONS

Failure Description: Tooth contact surface with surface distress glazing in a relatively rough finish on a medium-hard gear. Gross tooth fracture, unrelated to the glazing. The relatively rough surfaces of medium-hard gearing are subject to surface distress in insufficient EHD film conditions. This damage is not usually a cause for component failure.
Image Description: The rough fracture surface of the broken tooth is at image S and E. At image N, is a tooth flank with dark mottling in the addendum and dedendum and a clear band at the pitchline (and stains, probably from corrosion). The mottling represents glazed areas interspersed with unaffected areas or microspalls. Some sliding was required for surface distress, leaving pitchline band clear.
Suspected Causes: The tooth broke from causes unrelated to surface distress. Surface distress glazing, which in finer surfaces extends to asperity peaks and many valleys, may be limited to peaks (ridges) in the relatively soft, relatively rough surface of medium hardness gears. Compare with high hardness gear in Plate 11.11.

DATA

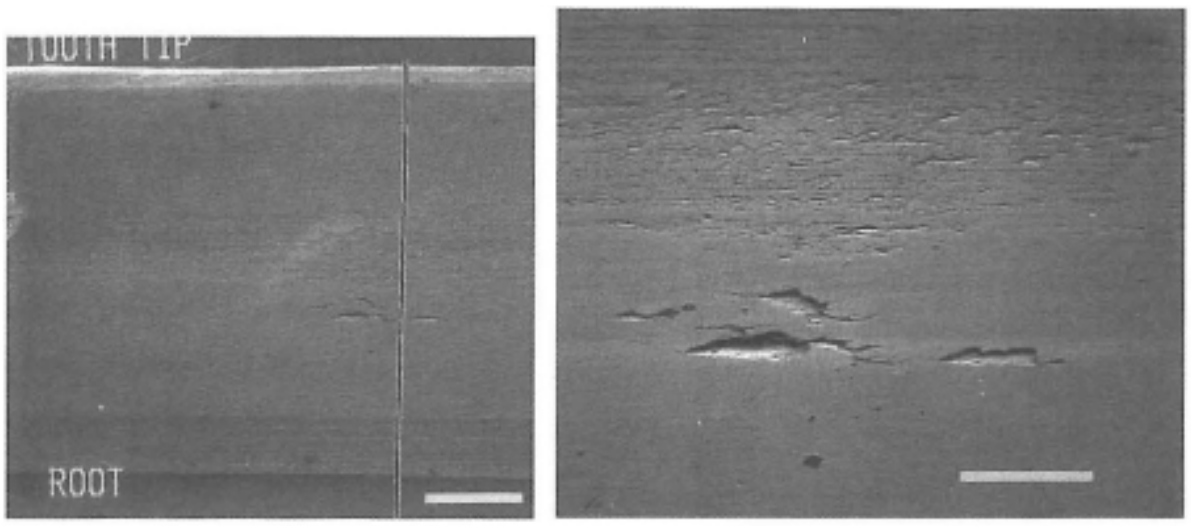
Plate No: 11.10
Archive No: 004-16
Image type: SEM
Scalebar = 100 μm (micros: +20%, others: +100%, −50%)
Component: DGBB; B, silicon nitride, run
Speed: <600 KdN
Load:
Lubrication: Sputtered molybdenum disulfide coating
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.05.1 Micro-porosity
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Ball from experimental bearing with steel rings and hot pressed silicon nitride ceramic balls, with molybdenum disulfide based lubricant coating and polymer separator. After running, the ceramic ball surface shows local microspalling as from surface distress, possibly at a pre-existing pore. Whole surface is pitted, as from damaged coating. (No plastic flow is visible.) X-ray analysis indicates incomplete solid lube coating remaining.
Image Description: Background is gray coated surface of ball, peppered with lighter-color micropits, as from incomplete coating. At image center is a cluster of microspalls as from surface distress. One small crater each to W and S of large cluster.
Suspected Causes: Dry lubricated ball bearings with ceramic balls are a unique component. Normal contact fatigue failures occur, as in the surface distress microspalling shown. Role of solid lubricant in preventing surface distress is not well understood. Hot pressed silicon nitride is prone to some porosity, serving to nucleate (micro or macro) spalling.

DATA

Plate No: 11.11
Archive No: 080-201&202
Image type: a, b: SEM (backscatter)
Scalebar = a: 1 mm, b: 400 μm
(micros: ±20%, others: +100%, −50%)
Component: SG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 3: 00.12.5.2 Smooth tooth wear
Failure Code 4: 00.16.02.4 Incipient spalling, multiple spalls
See also PLATE: 11.18



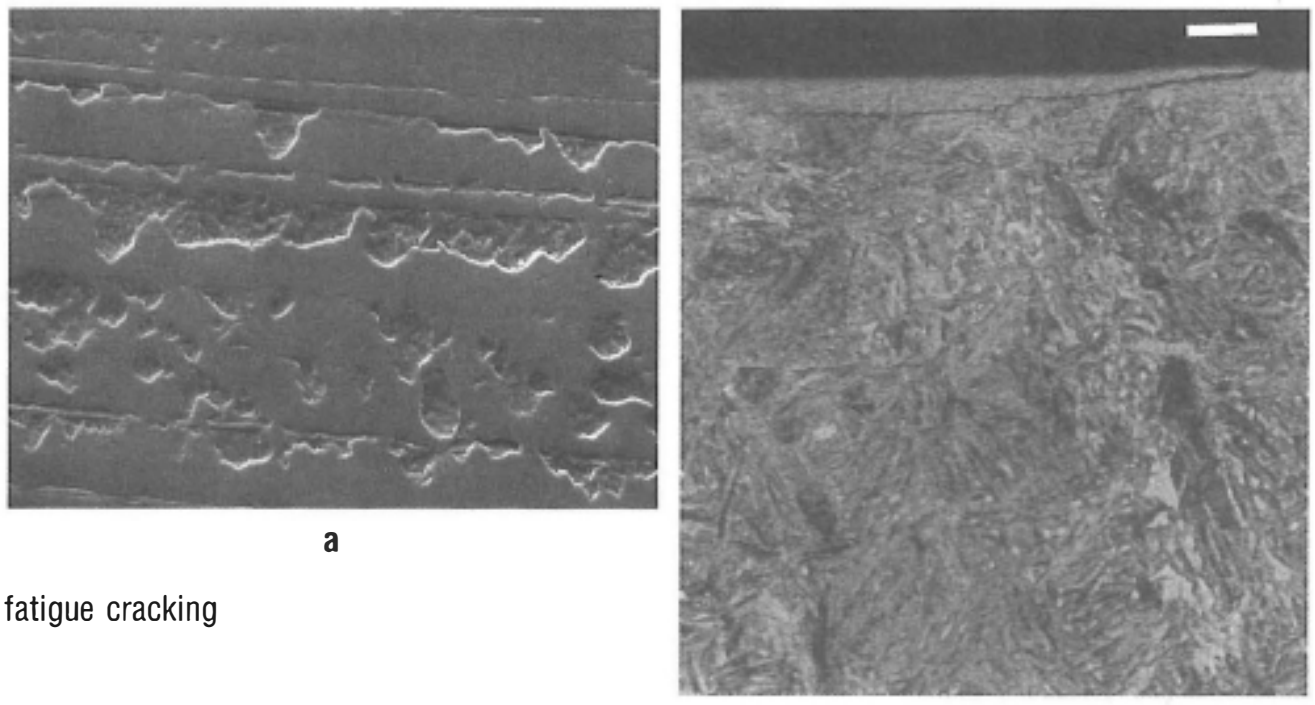
a b

DESCRIPTIONS

Failure Description: Surface distress microspalling (often designated "pitting") has occurred near the pitchline. A few macroscopic spalls are in the dedendum, at the edge of the surface distressed area. Addendum and dedendum are worn down in the high-sliding areas causing high pressure near the pitchline. The gear was found to be of insufficient hardness. It has not failed, but is expected to fail in spalling. See Plate 11.18 for detail.
Image Description: (a): View of tooth contact surface from tip to root (labeled). The black line crossing, from N to S, marks plane of subsequent sectioning (see Plate 11.18). Microspalls in E–W rows transverse to sliding direction cover addendum near pitchline. Smooth wear near tip and root. Four macroscopic spalls with straight E–W edge near image center (pitchline) appear originating from distress. (b): Details of micro- and macrospalls.
Suspected Causes: Gear was found to have insufficient surface hardness. Wear occurred in high-sliding zones away from pitchline, leaving the pitchline raised, and under excessive contact pressure. Surface distress occurred in the material, followed by spalling. (In normal gear, spalling is more common in dedendum, where sliding traction reduces fatigue life.)

DATA

Plate No: 11.12
Archive No: 005-22&26
Image type: a: SEM,
b: metallogram, Nital etch
Scalebar = a: 10, b: 8 μm
(micros: ±20%, others: +100%, −50%)
Component: C; CM, run
Speed: 8 m/sec
Load: 1.8 GPa
Lubrication: mineral oil, 115°C
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.16.02.2 Contact fatigue cracking
Failure Code 3: -
Failure Code 4: -



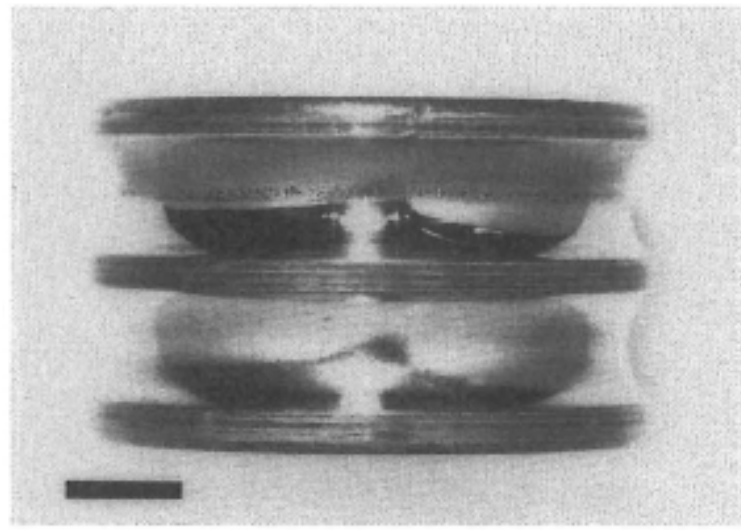
a b

DESCRIPTIONS

Failure Description: (a): Surface distress, with plastically worked material retaining some finishing lines. Microspalling follows finish lines. (b): Section through surface distressed area, showing microcrack (4 μm deep). Continued running under similar conditions leads to early spalling failure of cam.
Image Description: (a): Contact surface. Rolling direction is E-W along finishing lines, which appear as black furrows with intervening ridges. Surface distress glazing by plastic flow between finishing lines. Extensive microspalling of glazed ridges, confined between furrows. (b): Etched section through surface distressed material. Rolling direction E to W. Dark line of shallow-angle microcrack runs from surface to 3 μm depth.
Suspected Causes: Heavily loaded cam/follower contact in high speed engine undergoes high pressure and traction at entry point to lift lobe. With inadequate EHD film, surface distress arises.

DATA

Plate No: 11.13
Archive No: 074-1
Image type: view
Scalebar = 10 mm (micros ±20%, others: +100%, −50%)
Component: DRBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.12.3.2.0.5 Wear track for centered axial load
Failure Code 4: -

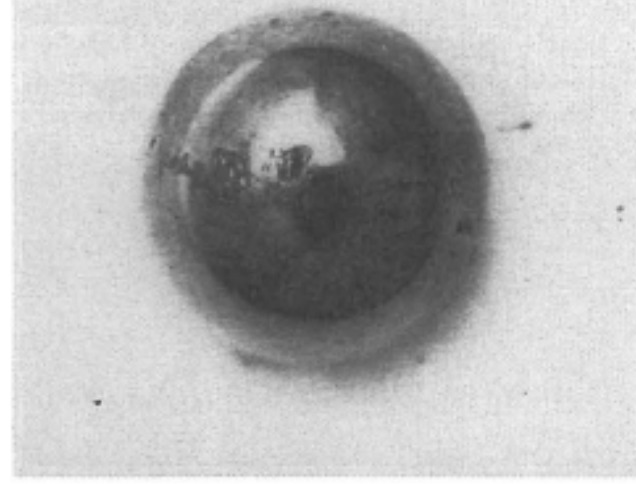


DESCRIPTIONS

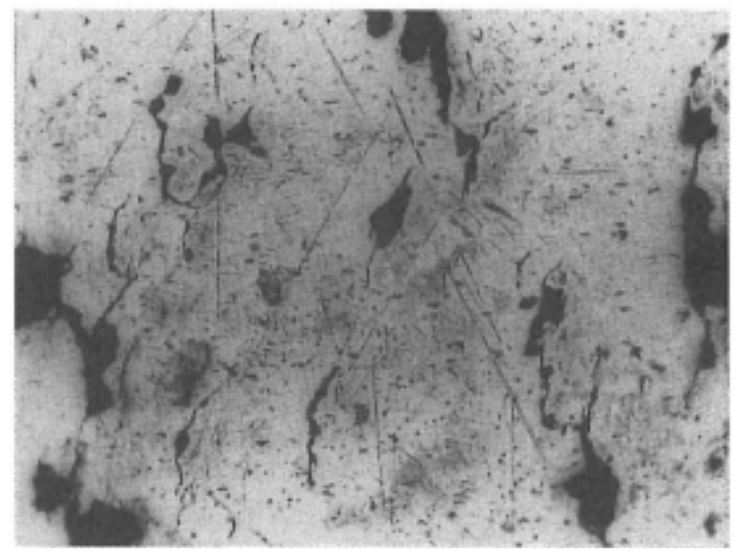
Failure Description: Double-row ball bearing IR operated under heavy axial load shows ball track on one side of both grooves. The ball track area is surface distressed ("frosted") by a profusion of asperity scale microspalls. In one groove, a row of macroscopic spalls has formed in the groove bottom. The bearing has failed.
Image Description: Double-row ball bearing IR, with two symmetrical ball grooves and three lands. Original finish of grooves is high luster as seen on S half of N groove. N half of both grooves appears frosted. A centered band of spall craters in N grove. Dark and light colored reflections in S half of both grooves are due to lighting.
Suspected Causes: Insufficient EHD film, possibly combined with rough surfaces or aggressive lubricant may produce surface distress, that is, plastic flow and microspalling on an asperity scale. Under continued running, surface distressed areas are prone to macroscopic spalling, where load is heaviest. In this case that location is the bottom of one groove.

DATA

Plate No: 11.14
Archive No: 074-28&29
Image type: a: view, b: light microgram
Scalebar = a: 10 mm, b: 100 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: -



a



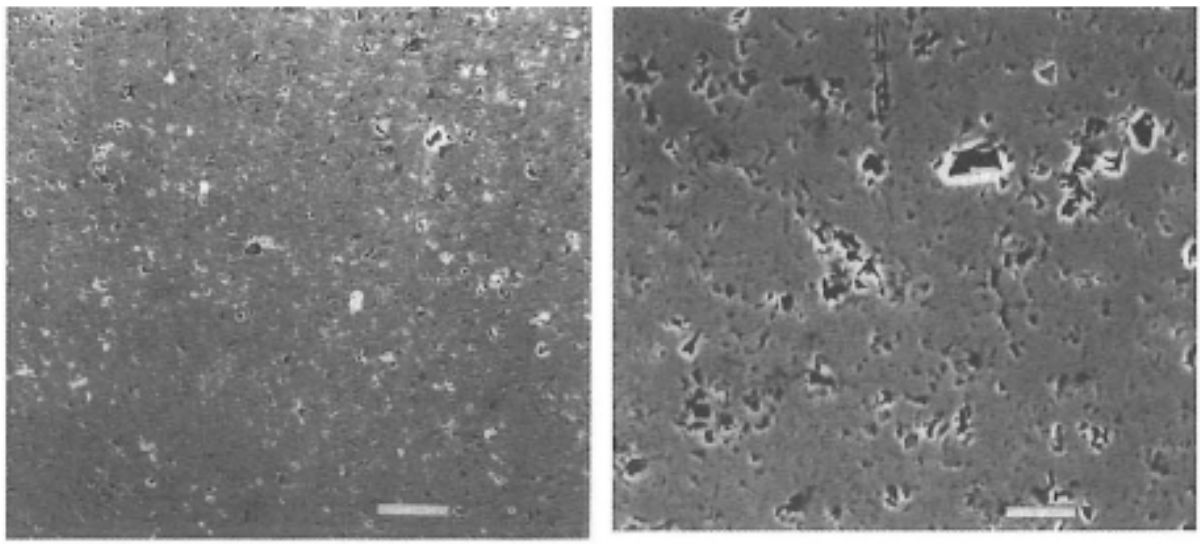
b

DESCRIPTIONS

Failure Description: Ball with band of spalls around a great circle, indicating operation without indexing of ball axis (a). Numerous surface distress microcracks and microspalls exist in the vicinity of the spalls, serving as initiating defects (b). Ball may have suffered surface distress when contacting a rough ring surface under low EHD film. Spalling was secondary. The ball has failed.
Image Description: (a): Numerous spall craters along E–W great circle of a ball. Elsewhere, the ball surface is debris dented, probably from spalling debris. (b): Background is light gray glazed ball surface from surface distress; finishing lines are still visible. There are many jagged N–S running microcracks and black-appearing microspalls.
Suspected Causes: In producing surface distress, the composite surface roughness in the contact governs. A smooth surface (ball) combined with a rough one (ring) can produce surface distress. Often the smooth surface suffers the distress, possibly because the work hardened asperities of the rough surface progressively overroll all areas on the smooth surface.

DATA

Plate No: 11.15
Archive No: 107-015a&c
Image type: SEM
Scalebar = a: 100, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.01 Surface distress, no sliding
Failure Code 3: -
Failure Code 4: -
See also PLATE: 11.21



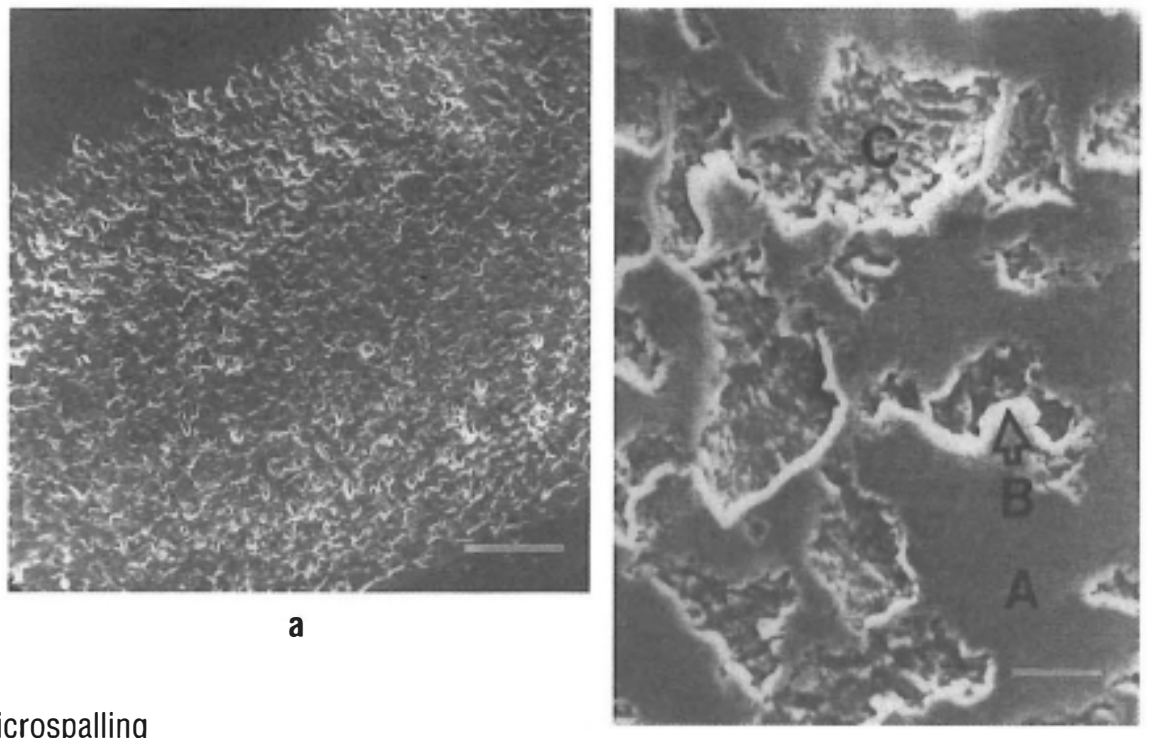
a b

DESCRIPTIONS

Failure Description: Advanced generalized surface distress. All finishing lines are obliterated by plastic working of the surface; a dense distribution of fine (1–5 μm dia.) microspalls has formed. No preferred orientation in microspalling. This characterizes absence of sliding. See Plate 11.21 for sliding. Rapid macrospalling is likely upon continued running, due to the profusion of microspalls acting as surface defects.
Image Description: (a), (b): Background is featureless gray surface of plastically smoothed asperities. Sharp-edged black shapes are microspalls. Some of them have a white halo indicating a "feather edge" of lamina undermined by cracks. The non-directionality of crater shapes is more clearly seen at higher magnification in (b).
Suspected Causes: Surface distress is contact fatigue in asperity dimensions, arising when asperity interaction stresses are excessive, as from insufficient EHD film and sharp asperity slopes (rough surface). Plastic 'glazing' of surface, with obliteration of finishing lines occurs first, microspalling of heavily worked asperities follows. The area shown is in or near a Heathcote band where sliding is minimal (Plate 11.21 shows contact edge).

DATA

Plate No: 11.16
Archive No: 093-17.1.11&13
Image type: a, b: SEM
Scalebar = a: 140, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 2.8 GPa
Lubrication: synthetic polyester oil, 130°C
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.01 Surface distress, no sliding
Failure Code 3: -
Failure Code 4: -



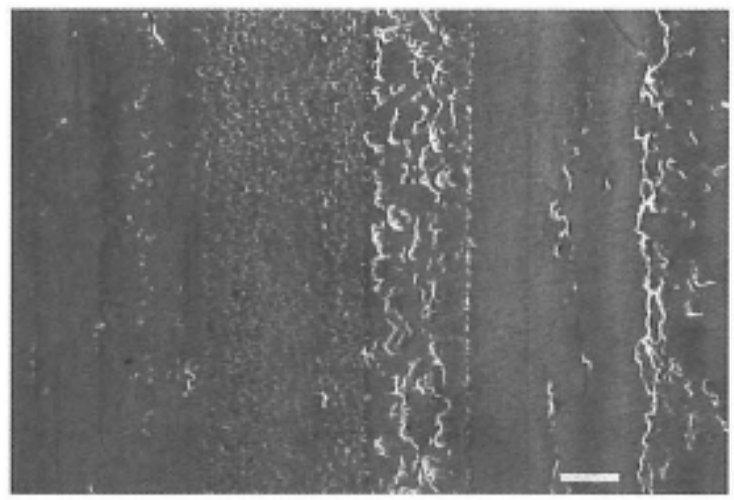
a b

DESCRIPTIONS

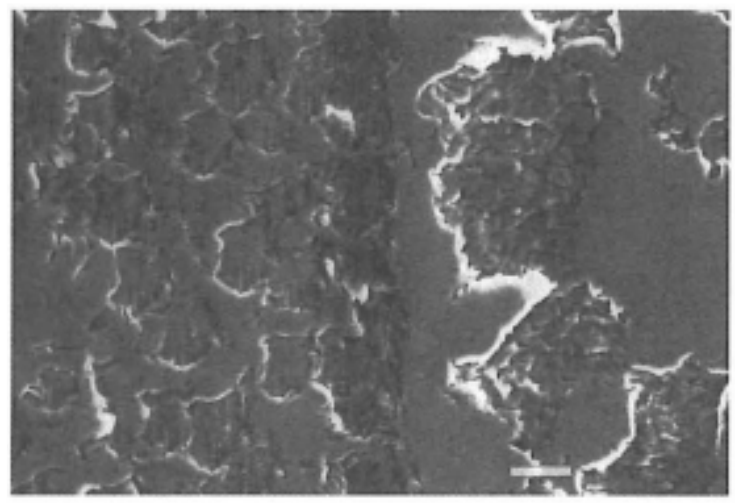
Failure Description: Band of surface distress microspalling with a dense population of spall craters on a background of glazed, plastically flown surface. "Feather edges" are rolled over crater rims. Spall bottoms show a typical fracture surface. Adjacent to the spalled bands is a surface area that is glazed only. The bearing will soon spall in continued running.
Image Description: (a): Wide, SW–NE band following rolling direction, covered with microspall craters in a featureless glazed surface. In NW and SE image corners are glazed but uncratered surfaces. (b): High magnification shows: a featureless glazed surface at *A*, the feather edge of plastically flowed material at *B* and a spall bottom fracture surface at *C*. Feather edges are not worn off.
Suspected Causes: Synthetic oils used in high speed (aerospace) applications at high temperature often have low working viscosity, forcing thin EHD films and promoting surface distress. Chemical aggressiveness of formulated lubricants, which may arise after long use, appears to accelerate surface distress microcracking and microspalling.

DATA

Plate No: 11.17
Archive No: 107-017a&b
Image type: a, b: SEM
Scalebar = a: 100, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.01 Surface distress, no sliding
Failure Code 3: 00.18.2.2.2 Stippled line(s) or band(s) from rolled-in debris
Failure Code 4: -



a



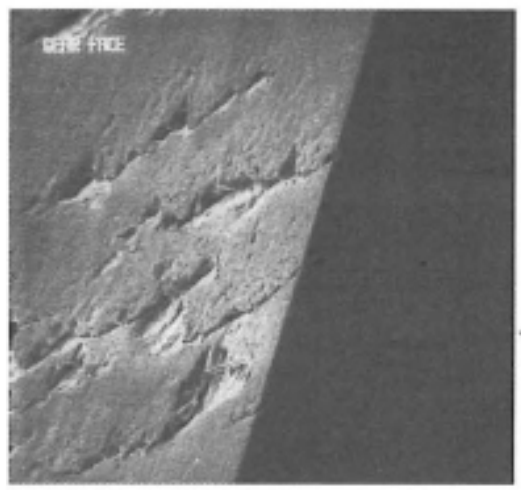
b

DESCRIPTIONS

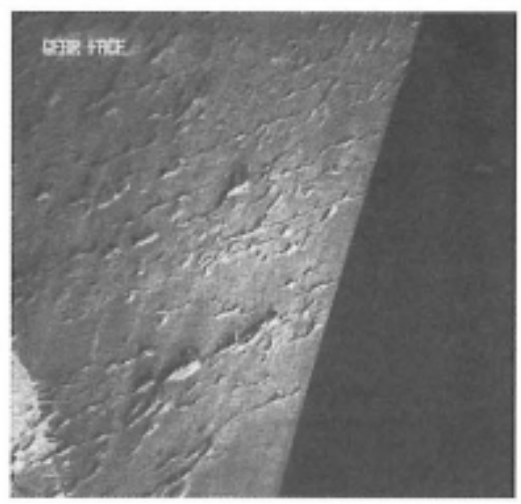
Failure Description: Rolling-in of solid contamination produced 'stippled' bands of indentations of varying density. Surface distress microspalling is initiated, chiefly at dents. Many smaller craters form in densely dented bands; fewer, larger crafters form in less densely dented bands. Some areas are virtually free of dents and microspalls. Severe surface distress is likely to lead to early macro-spalling failure.
Image Description: (a): Image divided by N–S lines into five main zones. 1st and 4th zones from W are relatively undamaged. 2d zone is densely dented, with small craters. 3d and 5th zones are less densely dented, with larger craters. (b): transition, zones 2 to 3. In W half, multiple dents with traces of N–S finishing marks change to sharp-edged microspalls interspersed with featureless surface. E half: fewer dents, larger craters.
Suspected Causes: Operation with solid contamination at low sliding creates rolled-in denting first. It may then undergo surface distress under insufficient EHD film, causing glazed surfaces and microspalls. (Surface distress can arise without denting.)

DATA

Plate No: 11.18
Archive No: 080-206&207
Image type: a, b: SEM (with section)
Scalebar = a: 100, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: SG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.02 Surface distress, with sliding
Failure Code 3: -
Failure Code 4: -
See also PLATE: 11.11



a



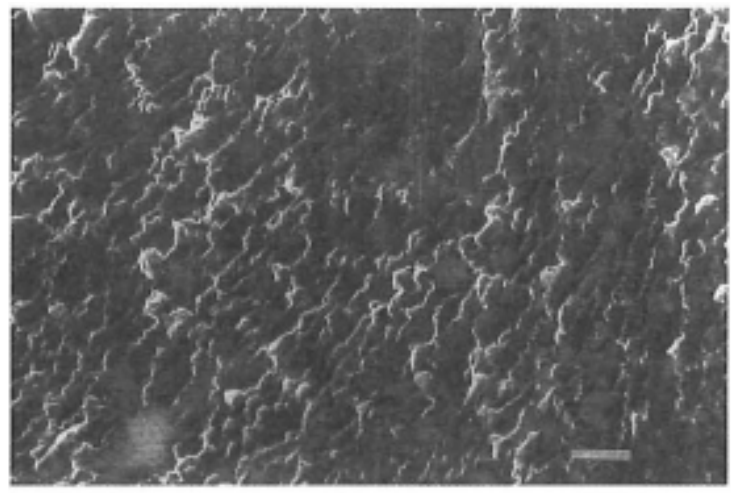
b

DESCRIPTIONS

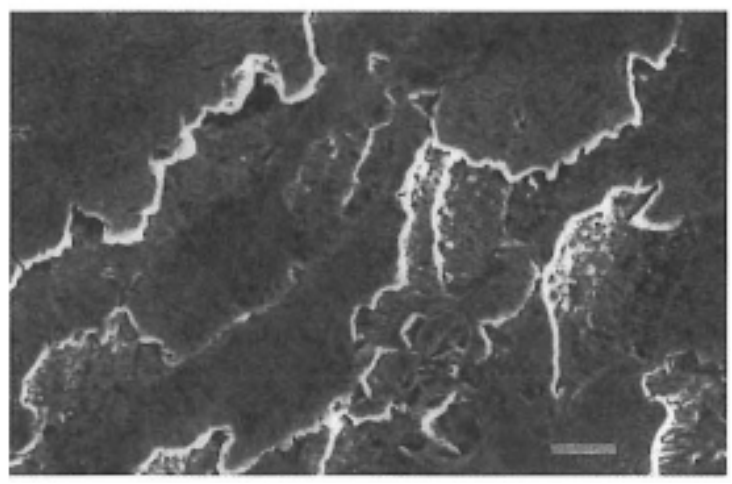
Failure Description: In a case-hardened gear, surface distress microspalling (often designated 'pitting'). (a) Shows multiple microspalls formed fish-scale fashion from microcracks transverse to rolling/sliding direction. In (b), a few microspalls with their initiating cracks extending about 10 μm deep into cross section, toward sliding direction. Macrospalls have not formed in this area. See Plate 11.11 for overview.
Image Description: (a), (b): W image half is tooth flank surface, E half polished cross-section. E–W running dark lines in tooth flank surface are microcracks transverse to rolling/sliding direction. Some exfoliation into microspalls. (b): Section through two microcracks shows their propagation at about 30° to contact surface, progressing toward the pitchline, located toward image N, that is, opposite to the sliding direction.
Suspected Causes: Gear was found to have insufficient surface hardness. Wear occurred in high-sliding zones away from pitchline, leaving the pitchline raised, under excessive contact pressure. Surface distress occurred in (soft) material, followed by spalling.

DATA

Plate No: 11.19
Archive No: 107-020a&c
Image type: a, b: SEM
Scalebar = a: 100, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.02 Surface distress, with sliding
Failure Code 3: -
Failure Code 4: -



a



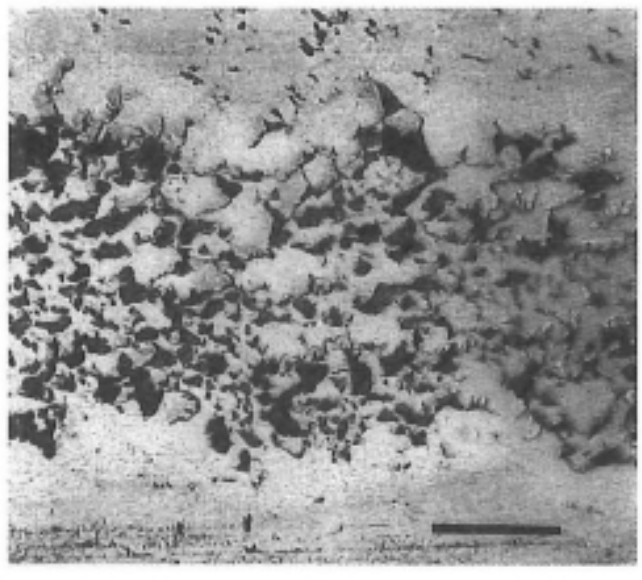
b

DESCRIPTIONS

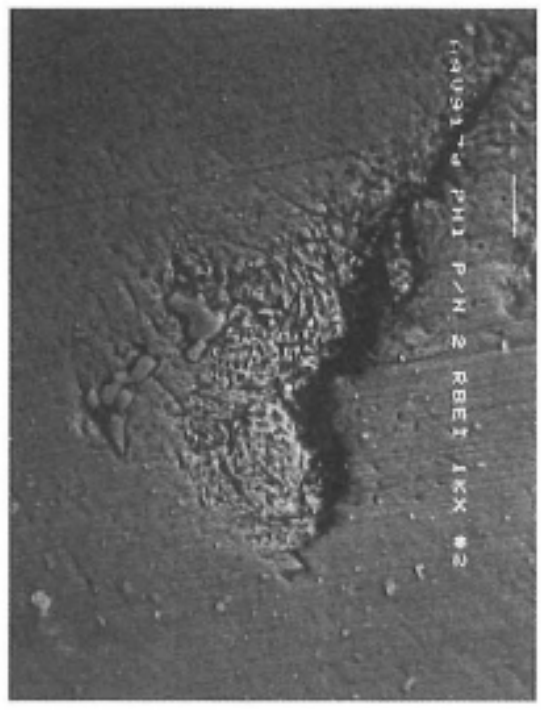
Failure Description: Surface destroyed by generalized microcracking and incipient microspalling due to surface distress in the presence of high tractive stresses from sliding under poor EHD lubrication. Imminent gross failure from macroscopic spalling or bulk cracking is likely.
Image Description: (a): Surface consists of dense SW–NE rows of microcracks and microspalls. Original surface is no longer discernible. Near center of image N edge, a few faint N–S lines may be remnants of circumferential finishing lines. (b): Higher magnification. Complex winding microcracks running in an overall SW–NE direction overlap and create a "fish-scale" surface pattern, which, without magnification, appears "frosted."
Suspected Causes: The as-manufactured surface was probably rather rough. Heathcote sliding, combined with axial slip, created a net SE to NW sliding direction. Microcracking from poor lubrication has a main direction perpendicular to sliding. This surface has much reduced long-term spalling resistance.

DATA

Plate No: 11.20
Archive No: 018-301&304
Image type: a: light microgram, b: SEM
Scalebar = a: 200, b: 20 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, tool steel, run
Speed: 400 KdN
Load: 3.1 GPa
Lubrication: synthetic polyester, 150°C
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.02 Surface distress, with sliding
Failure Code 3: 00.06.1.3 Primary carbide
Failure Code 4: -



a



b

DESCRIPTIONS

Failure Description: Generalized surface distress microspalling with directionality caused by sliding. Initiation of microspalls tends to be associated with hard carbides of the tool steel. Calculated EHD film thickness was 0.08 μm, resulting in film thickness/RMS roughness ratio below 1, which is conducive to surface distress. Early macrospalling failure is likely.
Image Description: (a): Area on IR ball path. Band of surface distress microcracking and angular microspall craters runs E–W at image center. Rolling and ball spin are E–W. (b): Shows apex of one angular microspall. Rolling, ball spin and finishing lines all run W–E. Microspalled area is an irregular fracture surface extending E from angular, smooth-surfaced carbides, to a sharp step shown as black due to shadowing.
Suspected Causes: Low EHD film thickness/roughness ratio, and kinematically required sliding of ball in groove (Heathcote slip), have produced surface distress. Hard, somewhat prominent carbides act as microspall initiators.

DATA

Plate No: 11.21
Archive No: 107-016a&c
Image type: SEM
Scalebar = a: 100, b: 10 μm (micros: +20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed:
Load:
Lubrication: grease, 50°C
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.02 Surface distress, with sliding
Failure Code 3: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 4: -
See also PLATE: 11.15

DESCRIPTIONS

Failure Description: Advanced generalized surface distress. All finishing lines are obliterated by plastic working of the surface; a dense distribution of fine (1–5 μm dia.) microspalls has formed. There is a strong preferred orientation in microspalls and many parallel kinematic wear marks. This characterizes the *presence* of sliding. See Plate 11.15 which shows the *absence* of sliding. Macroscopic spalling is likely in further running, due to microspalls as surface defects.

Image Description: (a): Background is featureless gray surface of plastically smoothed asperities. Sharp-edged black shapes are microspalls, some with a white halo indicating "feather edge." (b): Higher magnification shows dense population of straight N–S lines, which are kinematic wear marks in the *sliding* direction. Also, N–S elongated microspalls. Both with white haloes. Wear marks create asperities which initiate microspalling.

Suspected Causes: Surface distress is contact fatigue in asperity dimensions arising when asperity interaction stresses are excessive, as from insufficient EHD film and sharp asperity slopes (rough surface). Kinematic wearmarks, from sliding under asperity contact conditions, create additional microspall-initiating defects. The area shown is near the contact edge where sliding is substantial (Plate 11.15 is at or near Heathcote band).

a

b

DATA

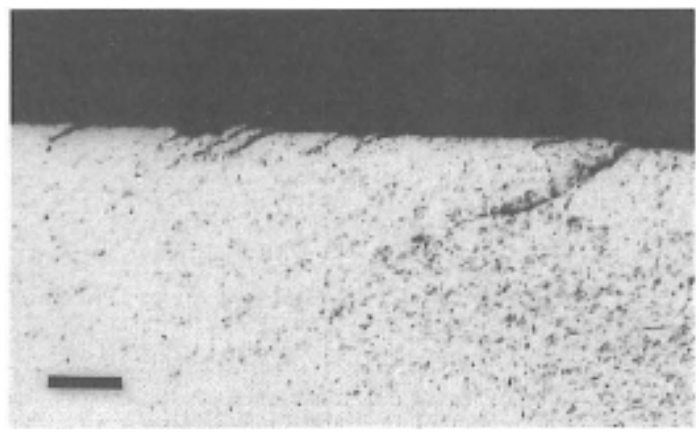
Plate No: 11.22
Archive No: 074-6&7
Image type: a: light microgram, b: metallogram (etched)
Scalebar = a: 100, b: 50 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.02 Surface distress, with sliding
Failure Code 3: 00.16.02.2 Contact fatigue cracking
Failure Code 4: 00.16.1.2 Surface origin spall

DESCRIPTIONS

Failure Description: (a): Extreme microcracking of surface transverse to rolling and sliding direction. (b): Microcracks progress down in rolling direction at about 30° angle from surface. At least one deep (over 100 μm) crack in same direction, suggesting unusually high tractive forces driving macrocrack deeper without preliminary microspalling.
Image Description: (a): Microgram shows a generally distressed surface with only a few E–W finishing lines remaining, and numerous jagged N–S microcracks. (b): metallogram (section) with several microcracks NE to SW, to about 20 μm depth. One crack progressed to about 100 μm depth, which is macroscopic in contact dimensions. Cracks proceed into material at approximately 30° angle with E to W rolling direction.
Suspected Causes: Surface distress microcracking is usually limited to asperity dimensions (a few μm depth). Under heavy tractive forces (sliding with poor lubrication), shear stresses are high at all depths, from the surface to the normal depth of the max. Hertz shear stress. This may drive cracks down to macroscopic depth, producing macrospalling.



a



b

DATA

Plate No: 11.23
Archive No: 018-124&125
Image type: view
Scalebar = a, b: 30 mm (micros: ±20%, others: + 100%, −50%)
Component: SRB; a: R&G&IR; b: R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 2: 00.17.02 Surface distress, with sliding
Failure Code 3: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 4: -

a

DESCRIPTIONS

Failure Description: Glazed and microspalled ("frosted," "peeled") bands with macrospalling near ends of all rollers, due to inadequate lubrication aggravated by the higher sliding velocity at roller ends. IR contact conformity may be too high, causing stress concentration near ends, resulting in spalling near the edges. The bearing has failed.
Image Description: (a): IR/R/separator assembly of separator-guided SRB. Frosted appearance on all roller OD-s, with micro and macrospall craters in two sharply defined bands at roller ends. Shallow craters as from surface origin. (b): Similar failure to (a) in rollers of another SRB. Frosted appearance extends in patches, from edges to contact center. Macrospalling from axial surface cracks due to traction in sliding. Edge spalling in both images.

b

Suspected Causes: Edge loading in SRB suggests excessive contact conformity. Thin EHD film, possibly with rougher surfaces, initiates surface distress, aggravated by higher sliding near roller ends and leading to surface-initiated spalls.

DATA

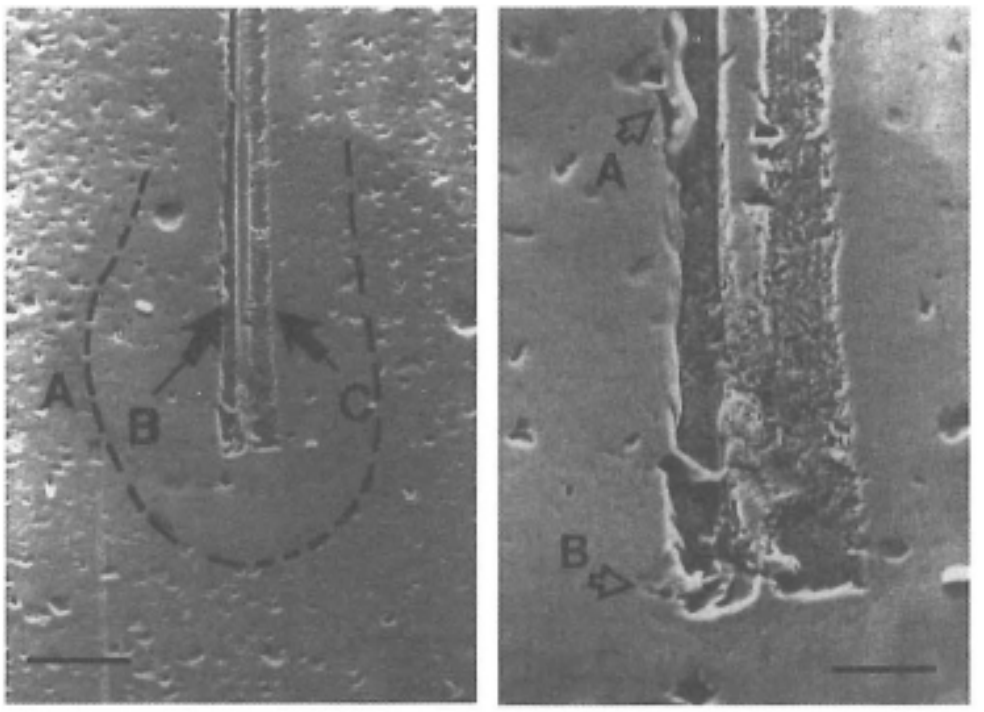
Plate No: 11.24
Archive No: 122-1&2
Image type: SEM composite
Scalebar = 100 μm (micros: +20%, others: +100%, −50%)
Component: SABB; IR, run
Speed: 120 KdN
Load: 3.7 GPa
Lubrication: mineral oil, ? °C
Failure Code 1: 00.17.2 Localized surface distress (halo at defect)
Failure Code 2: 00.02.1 Grinding, honing, lapping furrow
Failure Code 3: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 4: -
See also PLATE: 5.3

DESCRIPTIONS

Failure Description: Grinding furrow flanked by a glazed halo on both sides, shows several surface distress microspalls and leads into a line-defect origin spall. Grinding furrows are spall-initiating surface defects, both by causing collapse of EHD film (surface distress) and as direct stress raisers. The resulting spall is an incipient functional failure.
Image Description: Image is a composite of two SEM micrograms. At image W is the initiation of a spall crater which originated from the griding furrow running E–W across image center. The furrow starts deepening just W of E image edge and progresses to the crater. N and S of furrow, grinding lines are obliterated by glazing halo. Microspalls in N half of halo. Furrow ends just short of spall crater edge, leaving a lip of metal.
Suspected Causes: Grinding furrows are caused by detached grinding grit and are often "comet-tail" shaped (see Plate 5.3). This furrow deepened toward the spall, but its endpoint is obliterated by rolldown at spall edge. Surface distress arises at the furrow since the lubricant drains into the furrow out of the EHD film. Local stress concentration tends to initiate spalling.

DATA

Plate No: 11.25
Archive No: 093-17.2.2&3
Image type: a, b: SEM
Scalebar = a: 40, b: 12 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral oil, 65°C
Failure Code 1: 00.17.2 Localized surface distress (halo at defect)
Failure Code 2: 00.02.1 Grinding, honing, lapping furrow
Failure Code 3: 00.18.1.4 Multiple irregular denting from fine, loose hard debris
Failure Code 4: -
See also PLATE: 11.26



a b

DESCRIPTIONS

Failure Description: A pair of furrows (FC 00.02) with abrupt ending, probably produced by detached grains of grinding or honing grit. The surrounding surface shows minimal remnants of finishing lines, extensive glazing and denting. There is severe plastic working of surface material along furrows, with folding and cracking, due to a drained EHD film. The surface distress is due to insufficient EHD film, the denting to contaminants. Early spalling is likely.
Image Description: (a): Two furrows, apparently formed simultaneously in finishing by two grains of grinding or honing grit, extend from N image center to an abrupt end. There are many sharp-cornered debris dents on the surface. Faint N–S finishing lines are visible near S edge. Entire surface is glazed, most severely near dent edges, within contour *A*. Material is folded at *B* and *C*. (b): Same furrows, at higher magnification, show cracked, folded material at *A* and *B*. Some dents.
Suspected Causes: Grinding or honing furrows, when severe, drain the EHD film in their vicinity, causing severe asperity contact. In the debris-contaminated, low EHD film environment evidenced in this Plate, severe plastic working of material in furrow vicinity results. Sharp furrow edges fold and crack under plastic working. Surface distress also modifies dents by flowing the edges and possibly spalling the bottoms. See also Plate 11.26.

DATA

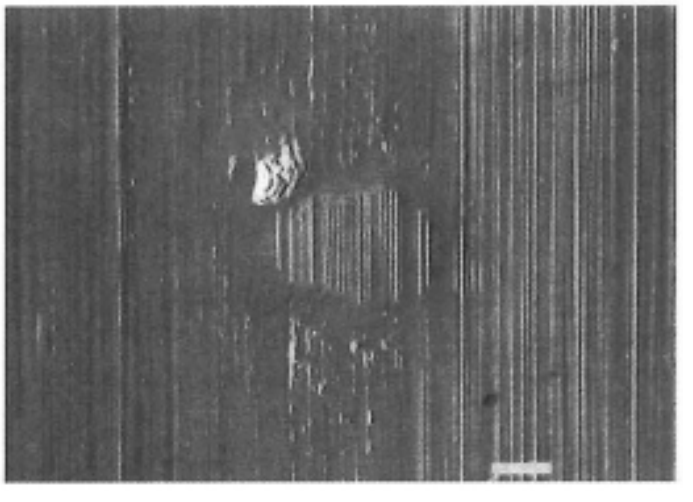
Plate No: 11.26
Archive No: 018-311
Image type: light microgram
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, tool steel, run
Speed: 400 KdN
Load: 2.3 GPa
Lubrication: synthetic polyester, 150°C
Failure Code 1: 00.17.2 Localized surface distress (halo at defect)
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: 00.02.1 Grinding, honing, lapping furrow
Failure Code 4: -
See also PLATE: 11.25



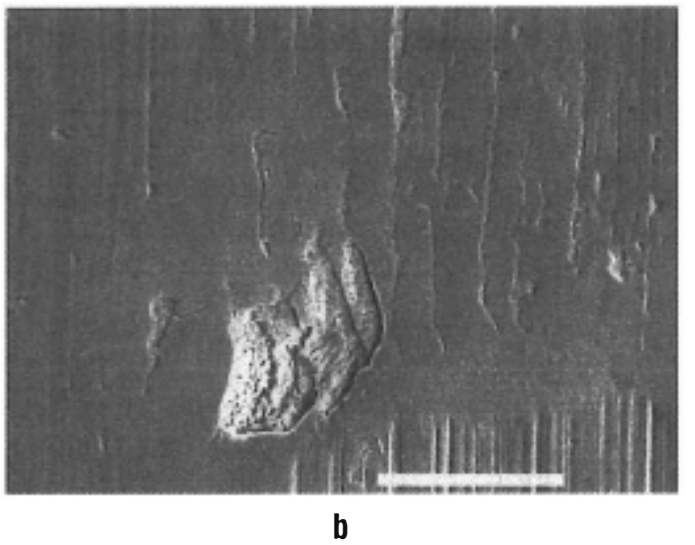
DESCRIPTIONS

Failure Description: Grinding furrow, possibly caused by detachment of a primary carbide in grinding. Halo of surface distress with microspalls along the furrow. Surface distressed furrows are serious surface defects likely to cause premature spalling failure.
Image Description: Background is contact surface with E–W finishing lines. In image center, heavy black E–W line with sharp ends is grinding furrow. N and S of furrow, oblong 'halo,' where finishing lines are partly obliterated. Irregular, sizeable black spots in halo are microspalls. Black spotting and staining elsewhere on image may be due to etching and is not diagnostic.
Suspected Causes: Finishing of tool steel components is more difficult than for 52100 type bearing steel, in part because of many larger carbides. Such carbides may become detached and gouge the surface in finishing to make a furrow. (See also Plate 11.25.) EHD film collapses near a furrow, causing asperity contact and surface distress glazing and microspalling.

DATA
Plate No: 11.27
Archive No: 107-023a&b
Image type: SEM
Scalebar = a, b: 100 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.17.2 Localized surface distress (halo at defect)
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: -



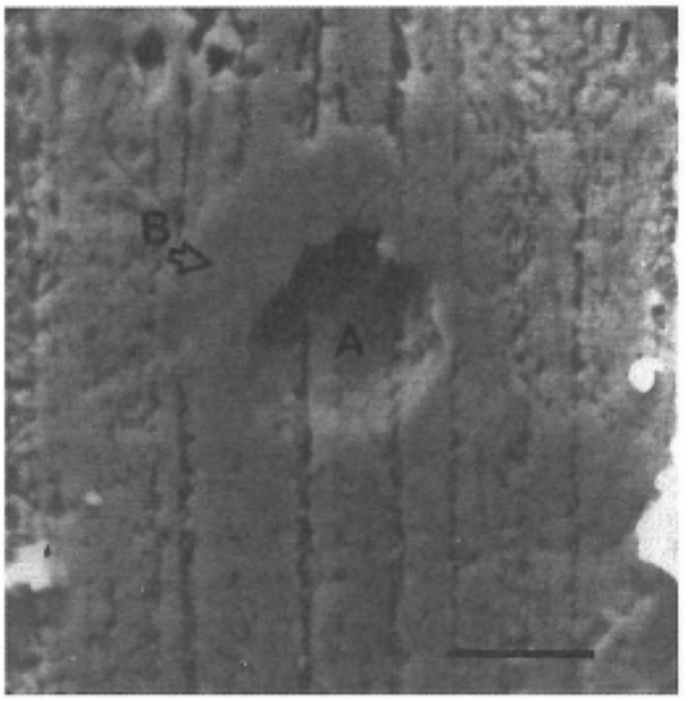
a



b

DESCRIPTIONS
Failure Description: Sharply delineated debris dent causes a glazing 'halo' of surface distress, within which surface distress microcracking and microspalling occurs. The bearing is not failed.
Image Description: (a): Background with N–S finishing lines is undamaged surface. In image center is a footprint-shaped debris dent, with finishing lines preserved in bottom. Rim of dent shows obliterated finishing lines (halo) gradually fading outward. Microspall NW of dent. (b): Microspall from (a) is S of image center, surrounded by 'glazed' surface, with folds along finishing lines. Glazed dent rim runs E from S spall edge.
Suspected Causes: Debris dent may have raised edges acting as stress concentrators. In EHD film, a local depression concentrates stress around edges even if these are not raised as a result of the collapse of the film. Surface distress halos result, which may initiate microspalling.

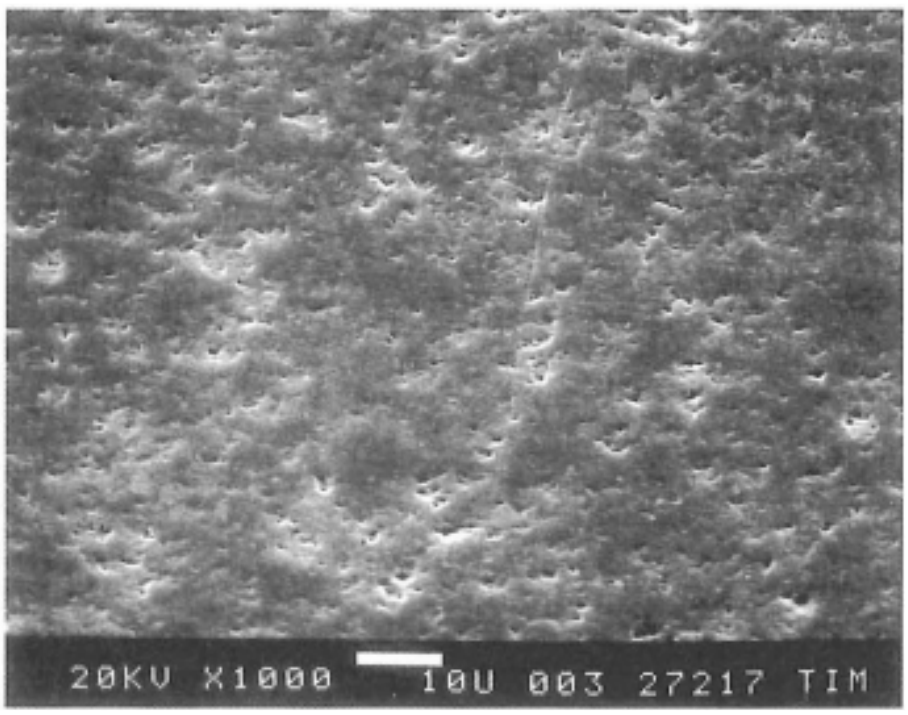
DATA
Plate No: 11.28
Archive No: 093-17.2.5
Image type: SEM
Scalebar = 55 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.5 GPa
Lubrication: mineral oil, 100°C
Failure Code 1: 00.17.2 Localized surface distress (halo at defect)
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.17.1 Generalized surface distress
Failure Code 4: -



DESCRIPTIONS
Failure Description: Circular debris dent of about 240 μm diameter with finishing lines in the dent bottom. Raised material rim around dent is plastically worked by surface distress, especially at trailing edge (in rolling direction) where EHD film tends to be thinner. There is some generalized glazing of the surface. Dents with distressed haloes are significant spall-originating defects.
Image Description: Finishing lines are dark, dotted N–S lines. At *A,* a circular dent is illuminated obliquely, causing light-colored wall in S and dark in N. Finishing lines continue in the dent. At *B*, circular elevated rim without finishing lines is surface distress halo. Rolling direction is S to N.
Suspected Causes: Insufficient EHD film thickness compared to roughness occurs preferentially at defects such as the dent at *A* where the film drains. Asperities contact under higher stress and flow plastically, initiating surface distress in the rim surrounding the dent, whether elevated in denting (as here) or not. Film thickness cannot build up promptly downstream from dent in rolling direction, hence more asperity contact occurs there.

DATA

Plate No: 11.29
Archive No: 014-B001
Image type: SEM
Scalebar = 10 μm (micros ±20%, others: +100% −50%)
Component: O, RC test rig rod; silicon nitride, hot isostatic pressed; run
Speed: 1.9 m/sec
Load: 5.93 GPa
Lubrication: mineral oil w. additives; approx. 40°C
Failure Code 1: 00.17.1.3 Grain pullout (surface distress of ceramic)
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 6.1, 10.5, 10.57



DESCRIPTIONS

Failure Description: Separation (at binder) of single surface grains or small grain clusters (surface distress), in the surface of silicon nitride ceramic finished to 0.09–0.1 μm Ra, run under very heavy Hertz pressure for 2.6 10^6 cycles. This failure mode is characteristic of fully dense ceramic. Imperfectly densified ceramic produces microporosity (FC 00.05.4.1) or binder defects (FC 00.05.4.2).
Image Description: Profuse micropits outlined by black and white edges on dark gray rolling surface.
Suspected Causes: Extremely heavy Hertz pressure (well above plastic limit of steel, possibly also of ceramic binder) cycled for long period creates high repetitive stresses, eventually destroys cohesion at binder and causes individual silicon nitride grains or grain clusters to separate (pull out) of surface. This failure is analogous to microplastic surface distress (glazing) seen in steel surfaces.

DENTING 12

Failure Code 00.18

12.1 Definition

A dent is a plastic depression (short gash, rounded-edged hollow, sharp-edged single or multifaceted impression, depressed solid or stippled line) caused in a *working* surface by a relatively incompressible object pressed into it by the passage of a contacting rolling element. Denting is the process by which dents form. It is often combined with wear-marks (FC 00.12). Denting, by the definition used in this Atlas, occurs *in service.*

Dents are distinguished from:

- *Nicks,* which are plastic indentations formed prior to service (FC 00.01);
- *Wear marks,* that is, scratch marks made by an opposing asperity or a third body in a sliding contact (FC 00.12);
- *Pits,* which are point depressions made by means other than plastic indentation (FC 00.03, FC 00.12, FC 00.20, FC 0.21);
- *Spalls,* which are craters caused by contact fatigue (FC 00.16).

12.2 Nomenclature

Denting is a commonly used designation for this failure mode. The most common alternative designation is *nicking* wherein the distinction between pre-service and in-service failure is lost. In this Atlas, the distinction will be maintained wherever it can be established. A designation found in some gear literature is *peening,* although the definition of peening does not clearly exclude wear.

12.3 Failure Process

Denting is the result of a plastic impression made on a surface when a sharp asperity or an entrapped foreign body is pressed into the contact surface under *normal* load. It is most distinct on rolling contact surfaces, where the relative motion in the contact is predominantly normal to the surface. (Sliding motion in the contact results in wear marks (FC 00.12).) The process of forming dents resembles an indentation hardness test: The indenter penetrates the surface in an approximate normal direction, carries surface material down with it and generally throws up significant raised edges. The rounded dents formed by soft debris, however, have no raised edges. An indented line can form by plastic flow beneath a rolling indenter (an edge on an opposing rolling element).

The detailed morphology of the failure depends on the nature of the indenter, as follows:

1. *Debris (hard particle) dent.* A single, sharply outlined dent, mostly with raised edges, is made by a hard (metal) particle passing *once* through the contact. In the process, the particle is generally flattened, but retains its distinctive outline, often with sharp corners and edges.
2. *(True) brinnell mark.* This is a plastic depression of simple outline (ellipse, truncated ellipse, rectangle, dumbbell) made by a mating rolling body under heavy static or impact load. (See FC 00.15 for *false* brinnelling.)
3. *Rounded (soft particle) dent* without sharp corners or raised edges is made by a soft, essentially incompressible particle entrapped in the contact. A Hertz contact (with EHD film) effectively confines any entrapped particle during the short contact passage so that particles of plastic or fiber fail to escape laterally and produce a dent. Some grease thickeners have been found to produce dents under shock loading of the contact.

4. *Multi-fragment dent* is produced by hard, brittle particles, such as sand or abrasive grit, if they shatter in the contact. These dents show many sharp-cornered facets and, at times, embedded grit.
5. *Rolled-in lines* are made by sharp circumferential edges on the mating rolling contact surface. They are plastically depressed lines formed by high edge-pressures. Deep circumferential scratch marks on the mating surface can also produce rolled-in lines.
6. *Stippled lines* in the rolling direction result from sharp asperities on the mating surface, including raised carbides and firmly embedded debris grains, which make a dent at every contact passage. A slight axial shift among the contacting bodies may produce bands of stippled lines.
7. *Contaminant denting*, giving a fine, matte surface with a pebbled appearance under magnification, is produced by copious loose fine hard debris, generally in the lubricant, passing through the contact.

12.4 Distinctive Appearance

A dent appears as a depression with a shiny surface. Original finishing marks generally remain visible. Raised edges often arise during denting but may be worn or rolled down in running. A line indentation has a shiny surface if formed plastically.

Classes of dents can be distinguished as follows (using a microscope, preferably scanning electron microscope, for details):

1. *Debris (hard particle) dents* are sharp-edged depressions corresponding to the shape of the indenting particle, originally with raised edges, which may be rolled or worn down in further running. The most common indenting particle is a metal chip, which forms a dent that looks roughly chip-shaped. Also common are dents secondary to spalling, with shapes reflecting spall debris that are blockier than chips.
2. *(True) brinnell marks* are regularly shaped elliptic, round, rectangular or dumbbell shaped indentations. The true brinnell mark on a Hertz contact surface is a plastic depression in the shape of the static Hertz contact area, and is identical in shape to a false brinnell mark created by fretting wear between Hertzian contacting bodies (FC 00.15). The surface of a true brinnell mark, which is formed by plastic deformation, retains the original finishing marks in the depressed surface. By contrast, the surface in the false brinnell mark is a wear surface on which original finishing marks are effaced and a matte, non-directional surface appears.
3. *Soft particle dents* show rounded or drop shapes and rounded edges. They result from the entrapment of soft materials (such as plastics, fibers, or wood chips) which deform under the contact pressure. Since such materials are essentially incompressible, they can form dents in the much harder contact material because the Hertz contact configuration allows them no escape. Roughly paddle-shaped rounded dents (with an extending narrow neck) have been observed in grease-lubricated contacts undergoing impact loading and are apparently the result of the delayed escape of grease (thickener) from the contact through a narrow channel.
4. *Multi-fragment dents* appear like the imprint of shattered glass into a soft surface. They consist of many sharp-faceted angular impressions clustered and overlapping in a small area. Their source is an entrapped brittle particle which shatters as the contact rolls over it. Sand (from external contamination or sand-cast parts), and also grains of abrasive, may provide the particles.
5. *Rolled-in lines* run in the rolling direction. They appear when a sharp edge on a rolling body contacts the opposing contact surface under a sufficient load to cause plastic deformation of the opposed body at the encounter with the edge. Rolled-in lines, when viewed under magnification, are distinguished from scratch marks by the absence of sharp (feather) edges on the mark and possibly by the preservation of finishing lines crossing the rolled-in mark.

A rolling element with a circumferential scratch-mark or finishing furrow of substantial depth can produce a rolled-in line in the opposing body. Commonly, cylindrical or tapered rollers of a bearing, scratched in the separator contact, produce rolled-in lines in a ring rolling-track.

6. *Stippled lines* in the rolling direction appear in contacts with very little sliding, in the presence of sharp, hard asperities or firmly embedded debris in the opposing contact surface. They consist of long series of dents of identical shape and are most common in cylindrical or tapered roller bearings in which an asperity contacts the opposing surface over and over along the same track, essentially without sliding. Stippled lines can occur as stippled bands, if the contact shifts axially or if there are many indenters.

   A special case of stippled bands formed of geometrically similar dents occurs in ball bearings, from an indenter imbedded in a ball slowly changing its axis of rotation (indexing).
7. *Contaminant denting* is profuse denting from fine loose hard debris. Macroscopically, a matte surface is generated which, under magnification, appears pebbled rather than scratch-marked as in wear (FC 00.12). In the presence of some sliding, contaminant denting and scratch-marking may be intermixed on the same surface.

Distinction between *nicks* (pre-service indentations) and *dents* (in-service indentations) is aided by considering the location and direction of the indentation. Nicks can appear on any surface and run in any direction since they are the result of random impacts. Dents, by contrast, are formed on the operating component so that they are limited to contact surfaces (including separator contact surfaces) and their direction must be compatible with the kinematics of relative motion.

It may be possible to determine whether substantial running time was accumulated by the surface since denting. A fresh dent is likely to have sharp, perhaps raised edges and any finishing marks in the depression appear similar to those outside it. A dent that accumulated much running time tends to have no raised edges and finishing marks inside it may be sharper than those on the more worn surface outside the indentation. Another indicator that the component was run since denting is surface distress decoration (FC 00.17) surrounding the dent.

12.5 Causes

Dents are caused by indigenous or exogenous particulate contaminants or sharp asperities. Common sources are listed below.

Sources Indigenous to the Machine-Element

1. *Hard particle dents:*

   - *Loose wear debris* from rolling components, metal separators (in rolling bearings) or seal riding surfaces;
   - *Spall fragments* from rolling components;
   - *Hard carbides* extending above the surface.

2. *Brinnell marks:* Static or impact overload of Hertzian contact.

3. *Soft particle dents*:

   - *Wear debris* from plastic separators (in rolling bearings) or elastomer seals;
   - *Grease* thickener (conjectural). Some soft dents (in rolling bearings) appear to be related to the behavior of the grease thickener under impact contact loading.

4. *Rolled-in lines:* Rolling body with edge or circumferential scratch. Rolling body with embedded particle (stippled lines).

Sources Internal to the Machine

1. *Wear debris* from other contact components in the chamber (bearings, gears, seals) or from unintended contact of mislocated components;
2. *Contaminant* in the lubricant;
3. *Contamination* left in the chamber from manufacturing or assembly.

Note: The named contaminants may produce (a) hard particle dents, (b) soft particle dents, (c) multi-fragment dents or (d) stippled lines, depending on whether they are (a) loose metallic or non-shattering ceramic particles, (b) organic particles, (c) shattering ceramic particles or (d) embedded hard particles.

External Sources

Solid contaminants from the environment that have entered through the seals. These contaminants usually produce hard-particle dents, multi-fragment dents or stippled lines.

12.6 EFFECTS OF DENTING

Dents have damaging effects on contact components through the following primary mechanisms:

- The plastic indentation process forming the dent imposes high local stresses on the surface. These can initiate cracks.
- Sharp edges may form at the dent which, when rolled over, cause cyclic edge stress leading to spalling failure near the dent.

Notes:

1. Spalls (FC 00.16) tend to initiate downstream of a dent in the rolling direction. A narrow unspalled ridge is often left between the dent and the spall edge.
2. There is some experience to show that a dent formed in a surface which has previously accumulated substantial Hertzian stress cycling is more likely to cause a spall than the same severity nick made prior to cycling. It has been conjectured that the ability of the material to accommodate plastic deformation without microcracking is exhausted in Hertzian cyclic stressing, so that a late dent is more prone to produce microcracks than an original nick.

- The dent represents a *sink* for the EHD film in the contact, which may locally depressurize the film, resulting in local film thinning around the dent edges. Asperity interactions may occur, producing local surface distress (a *halo* decorating the dent, FC 00.17). The surface distress, in turn, may initiate spalling fatigue.
- Raised edges around a dent in a contact with significant sliding may initiate galling (FC 00.13).
- When over-rolled, dents cause a clicking noise that may represent a failure in quiet running components.
- In an aggressive environment where corrosion is a risk any disruption of the smooth surface finish, such as by a dent, may be the initiation point for corrosion pitting (FC 00.20).

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.18.01.1.1	12.7 12.9
00.18.01.1.2	8.12 10.37 12.10
00.18.02.1	10.46
00.18.02.2	10.66 12.1 15.12 19.2
00.18.1.1	7.18 11.7 12.7
00.18.1.2	7.8 7.27 8.13 8.17 8.22 10.9 10.35 10.60 10.64 10.69 11.2 11.7 11.8 11.14 11.27 11.28 12.1 12.7 14.2 14.20
00.18.1.3	10.69 10.9
00.18.1.4	7.5 11.25
00.18.2.1	10.6 10.13 10.14
00.18.2.2	7.14
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00.18.2.2.2	6.7 11.17 12.4
00.18.3	4.8 8.2 18.4
00.18.4.2	15.23

PLATES

DATA

Plate No: 12.1
Archive No: 104-4&8
Image type: a, b: light macro
Scalebar = a: 40, b: 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.01.1.1 Denting of rolling surface, no sliding
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.18.02.1 Light or incipient denting
Failure Code 4: 00.18.02.2 Severe or advanced denting



(a)

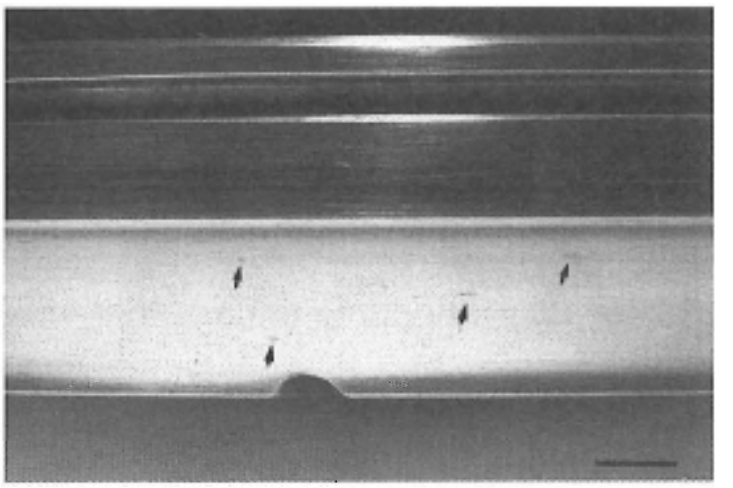
(b)

DESCRIPTIONS

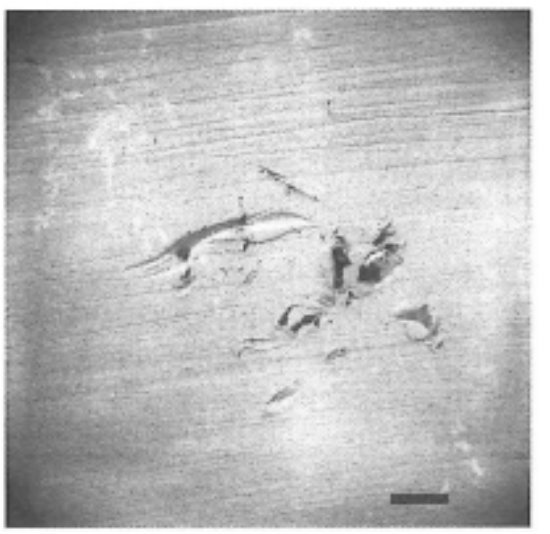
Failure Description: (a): Uniform light denting on IR roller track, from contaminant particles large enough to produce macroscopic dents, but smaller than contact width. No cracks or gouges were formed. Bearing can serve in heavy, slow applications. (b): Uniform severe denting on IR roller track, from contaminant particles as large as contact area width. There are raised dent edges. This IR may fail by spalling, separator fracture or heat imbalance failure.
Image Description: (a): Side view of TRB IR (cone), large end at N. Flanges dark, roller path gray, peppered with black dots representing dents. Magnification showed smooth-bottomed indentations. No cracks, gouges or raised edges are visible. (b): Side view of TRB IR, large end at N. Flanges appear dark, roller path gray, and peppered with black or light indentations of many sizes, which overlap in part. Magnification showed raised dent edges, and possibly small cracks.
Suspected Causes: In a contaminated environment, ingress of debris is at times unavoidable. Denting accumulates gradually. Fatigue life is reduced but may be acceptable if denting is limited as in (a). If seal failure or other causes admit numerous large contaminant particles, as in (b), many dents, large by contact dimensions, occur. They show raised edges (under low magnification), may produce cracks, and cause early failure.

DATA

Plate No: 12.2
Archive No: 002-006b&c
Image type: a: light macro, b: SEM
Scalebar = a: 5 mm, b: 50 μm
(micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, tool steel, run
Speed: 0.9 MdN
Load: 1.5 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



(a)



(b)

DESCRIPTIONS

Failure Description: Several debris dents are shown with raised edges in ball path, after a minimum of operation. Sliding is evident in the shape of the dents. Embedded brittle debris is visible in some dents. The bearing is unsuitable for high-speed service.
Image Description: (a): Light macro showing part of IR. Land with a "puller groove" is dark gray in N image half, the ball groove is whitish in S image half, ending in the "split surface" of split innerring design. An oil groove is cut in the edge. Four gray dents are in the ball path near the oil groove (arrows). (b): A cluster of dents. Gouging in NW dent from sliding. Dark spots are embedded debris. Raised edges on SE dent appear rolled down.
Suspected Causes: Irregular sliding directions suggest that contaminant was entrapped in the bearing at mounting and dented surface during mounting operation. Some rolldown of raised edges occurred in running.

DATA

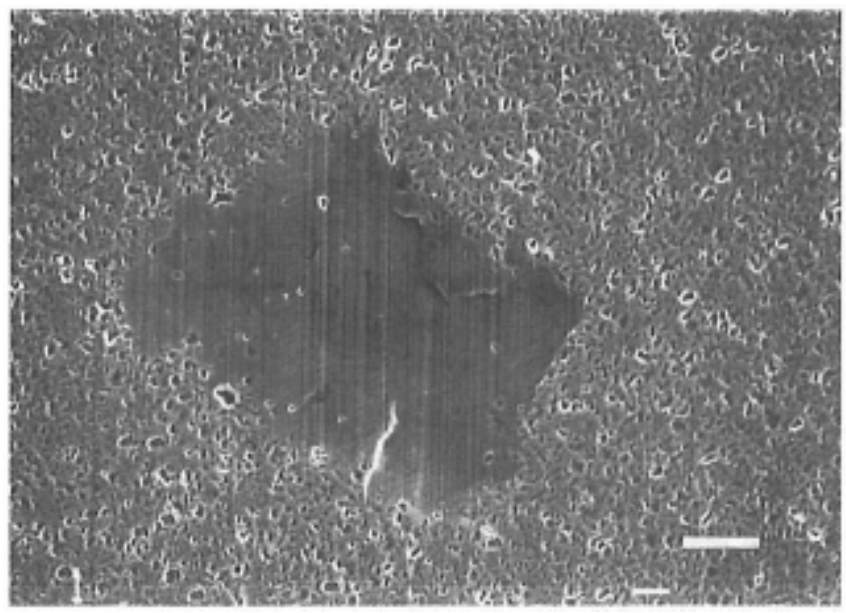
Plate No: 12.3
Archive No: 007-113
Image type: light micrograph
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, run
Speed: 50 KdN
Load:
Lubrication: mineral oil based grease, 0–40°C
Failure Code 1: 00.18.1.2 Sharp individual dent(s) rom metal debris, asperities
Failure Code 2: 00.12.0.2 Abrasive mild wear
Failure Code 3: 00.12.3.2.4 Scoring wear (macroscopic grouping without galling)
Failure Code 4: 00.16.02.2 Contact fatigue cracking

DESCRIPTIONS

Failure Description: Severe denting was caused by debris from fine to 1 mm diameter. The entire contact surface is severely worn. Scoring (gouge marks) occurred in the circumferential direction. Axial fatigue cracks connect the dents. Bearing has lost precision, is noisy and may suffer bulk cracking and/or spalling.
Image Description: TRB IR (cone) contact surface covers most of image. In W, the light band is the un-contacted edge of rolling surface. Beyond it, the part is cut. Contact surface is covered with multiple scratch- and scoremarks in N–S (rolling) direction. Original finish lines are worn off. Nicks of many sizes are sharp-edged irregular depressions, with smooth bottoms, and are also abrasively worn. E–W fatigue cracks are at *A* and *B*.
Suspected Causes: The bearing was used as wheel bearing in a truck working in dusty environment. Seal was observed to have failed. The ingress of dust and debris caused wear and denting.

DATA

Plate No: 12.4
Archive No: 107-008
Image type: SEM
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 2: 00.18.2.2.2 Stippled line(s) or band(s) from rolled-in debris
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Two-phase denting damage on rolling surface. An 80 μm long rectangular dent from ductile debris is visible, with finishing lines at bottom. The surface outside the dent is densely covered by fine sharp indentations caused by the rolling-in of hard contaminant particles embedded in the mating surface. These particles were too small to reach the bottom of the 80 μm wide dent.
Image Description: The background is a surface densely covered by fine sharp indentations less than 5 μm in diameter (black centers, light rims indicating sharp edges). In the image center, a nearly rectangular large flat dent is visible, as from a rolled-out metal chip. N–S finishing lines in this dent indicate that it occurred before general denting by rolled-in grit.
Suspected Causes: Deformable debris (metal) flatten but retain general shape when rolled over, forming a corresponding-shaped dent. The original surface remains undisturbed at the dent bottom. When a fine hard contaminant enters the bearing, it may embed in the rolling surfaces and mark the mating surface every time it is rolled over. In the presence of heavy contamination, the whole surface may become dented, except the pre-existing large dent bottom.

DATA

Plate No: 12.5
Archive No: 064-401
Image type: view
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P&W, high hardness, ground, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 2: 00.22.01.4 Gear tooth crack or fracture
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Extensive random denting of contact surfaces on both mating gears, from coarse hard debris. A chipping fracture on one tooth may have contributed to the debris. The chipping itself may have originated from overrolling of a large hard piece of debris. The gear has failed.
Image Description: Pinion is at image center. Near W and E edges, are mating gears. All contact surfaces of both gears in W-side mesh show irregular (light gray) dent marks. Pinion teeth near E-side mesh appear intact with finishing lines still visible. A large chip is broken out of the tooth tip at *A*.
Suspected Causes: A mass of debris was injected into the gear mesh, causing extensive denting of contact surfaces. The chip missing from the tooth, if fragmented, would contribute to the debris. It is not evident whether the chipping occurred from unrelated causes or was itself due to overrolling of a large piece of debris.

DATA

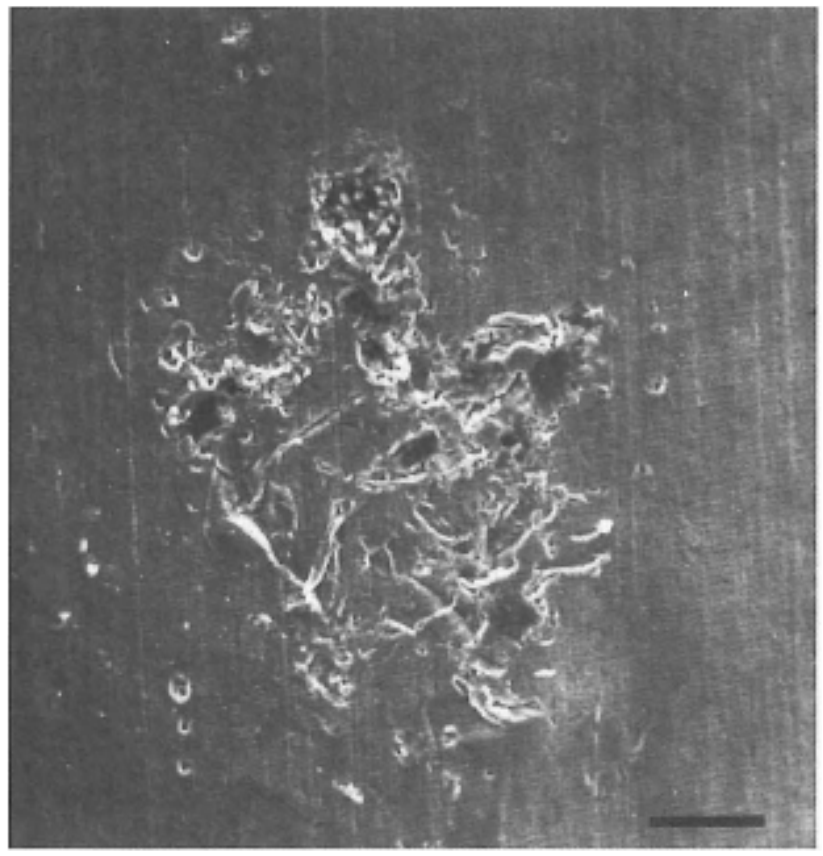
Plate No: 12.6
Archive No: 093-18.1.28&29&30
Image type: a, b, c: SEM
Scalebar = a: 20, b: 2.5, c: 3 μm
(micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.4 GPa
Lubrication: mineral oil, 60°C
Failure Code 1: 00.18.1.3 Multifragment dent (brittle contaminant)
Failure Code 2: 00.12.0.1 Adhesive mild wear
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

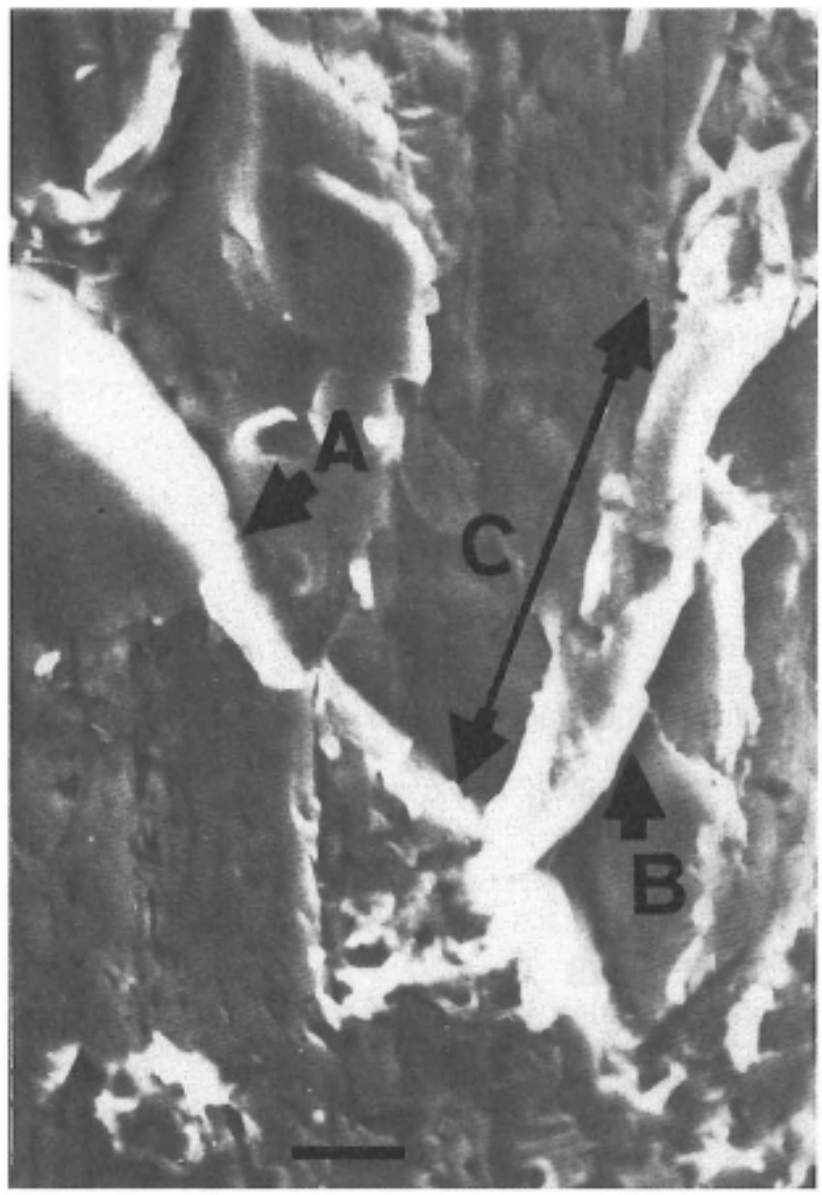
Failure Description: Multi-fragment dent in honed surface caused by the shattering and subsequent indentation of a hard, brittle contaminant particle. Sharply cut edges are intact in some areas; elsewhere, adhesive wear has removed edges, leaving tensile fracture surfaces. Such denting can lead to abrasive wear (from embedded debris), surface distress (through interruption of EHD film) and spalling.

Image Description: (a): In a well-preserved honed surface with N–S finishing lines, a cluster of sharp-edged dents and rounded pits occupy the image center. (b): Sharp-edged plastic deformation, visible at *A* and *B,* and a folded edge at *C,* indicate plastic indentation by sharp hard particles. (c): Tensile fracture surface in a pit forming part of the dent cluster, probably from tearing of a raised edge in adhesive wear.

Suspected Causes: Brittle contaminant (sand, abrasive, process material, etc.) may enter a rolling contact and initiate one of three processes: 1. denting by loose particles (FC 00.18.1.4), 2. denting by embedded debris (FC 00.18.2.2), or 3. shattering and formation of multi-fragment dents as shown.



(a)



(b)



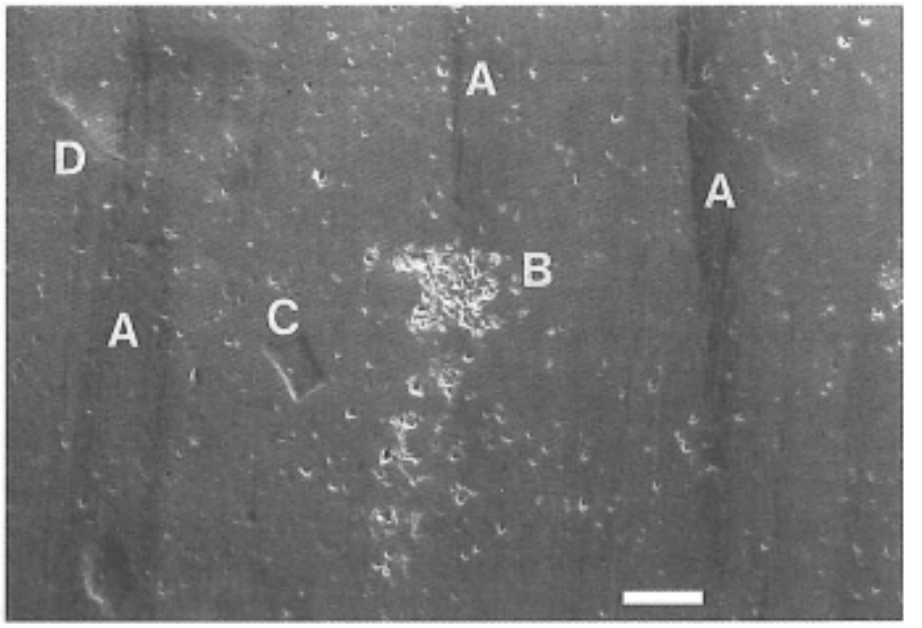
(c)

DATA

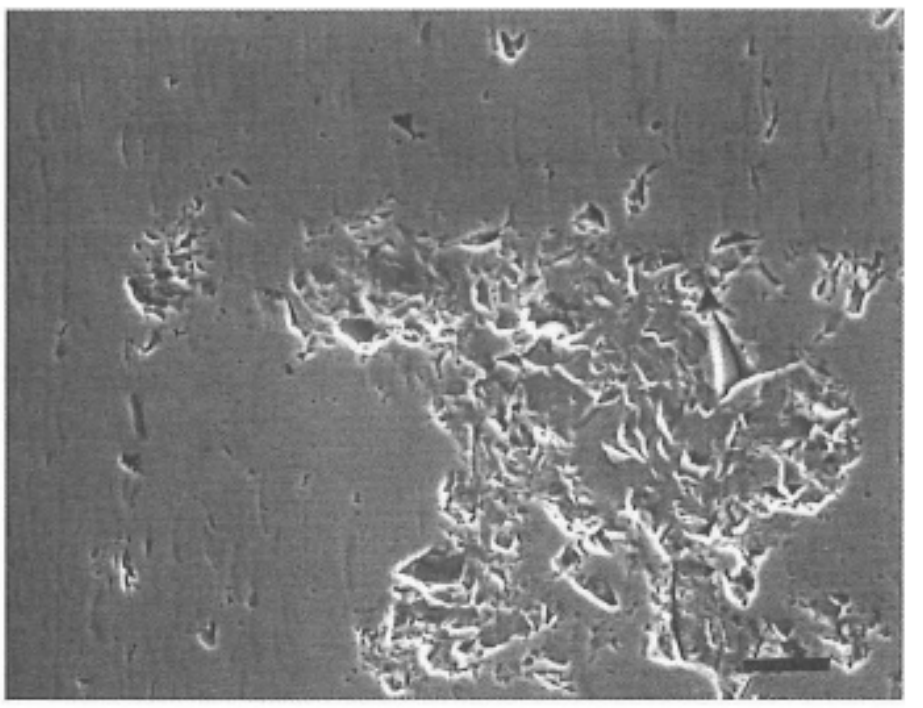
Plate No: 12.7
Archive No: 107-007a&b&c
Image type: a, b, c: SEM
Scalebar = a: 100, b: 20, c: 20 μm
(micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.1.3 Multi-fragment dent (brittle contaminant)
Failure Code 2: 00.18.1.1 Rounded dent (from soft contaminant)
Failure Code 3: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 4: 00.18.01.1.1 Denting of rolling surface, no sliding

DESCRIPTIONS

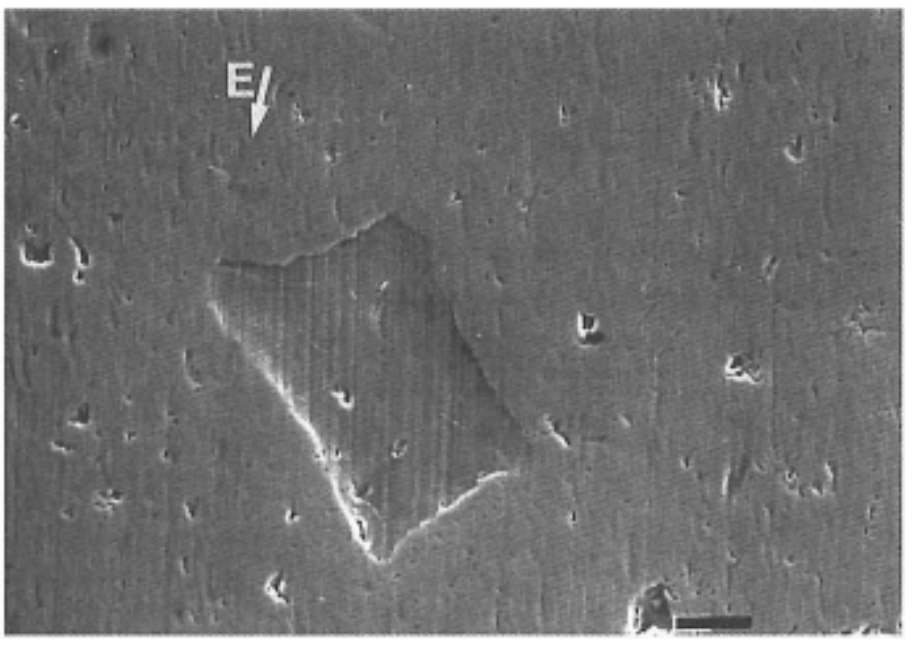
Failure Description: Present are dents from hard contaminant, from soft deformable contaminant (20–60 μm) and a multi-fragment dent from shattered brittle contaminant. Short kinematic wear marks are from earlier running. The bearing was operated at low EHD film (kinematic wear marks FC 00.12) and in contaminated environment with abrasive (brittle), ductile (metal) and soft (organic) debris. The bearing has not yet failed.
Image Description: (a): Overview of 1 mm^2 surface. Dark N–S stripes at *A* are lubricant deposits. The dense cluster of small indentations at *B* is a multi-fragment dent. There are dents from deformed (metal) debris, as at *C*. Gentle depressions were caused by soft particles, as at *D*. Feature *B* is magnified in (b); feature *C* in (c). Note prior fine dents in *C*. Kinematic wear marks ("fingernail marks") at *E* are short (due to low spin/roll ratio) and partly worn off.
Suspected Causes: Deformable (metal) debris flatten but retain their general shape when rolled over (*C*). Soft material, such as plastic trapped in the contact makes a rounded dent (*D*). Grinding grit or other brittle abrasive may shatter upon overolling to make a cluster of fine (multi-fragment) dents (*B*). Hard (overrolled) asperities on the mating surface may make fingernail marks due to ball spin during contact.



(a)



(b)



(c)

DATA

Plate No: 12.8
Archive No: 093-18.1.15
Image type: SEM
Scalebar = 15 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.4 GPa
Lubrication: mineral oil, 60°C
Failure Code 1: 00.18.1.4 Multiple irregular denting from fine, loose hard debris
Failure Code 2: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 3: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 4: 00.17.1.2 Microspalling (advanced surface distress)

DESCRIPTIONS

Failure Description: Multiple denting has occurred on a very small scale, from fine (1–5 μm) contaminant. Light surface distress glazing is visible with obliteration of most finishing lines. Small surface distress microspalls were initiated at the dents. Kinematic wear marking. Damage of this level permits achieving normal life for industrial applications.

Image Description: Background is a honed surface with some finishing lines running N–S, largely obliterated by glazing. Extensive scattered debris denting is visible as at *A, B* and *C,* with surface depressed but not exfoliated. At *D, E* and *F* are microspalls, from the action of surface distress on dents. Isolated kinematic wear ("fingernail marks") are present.

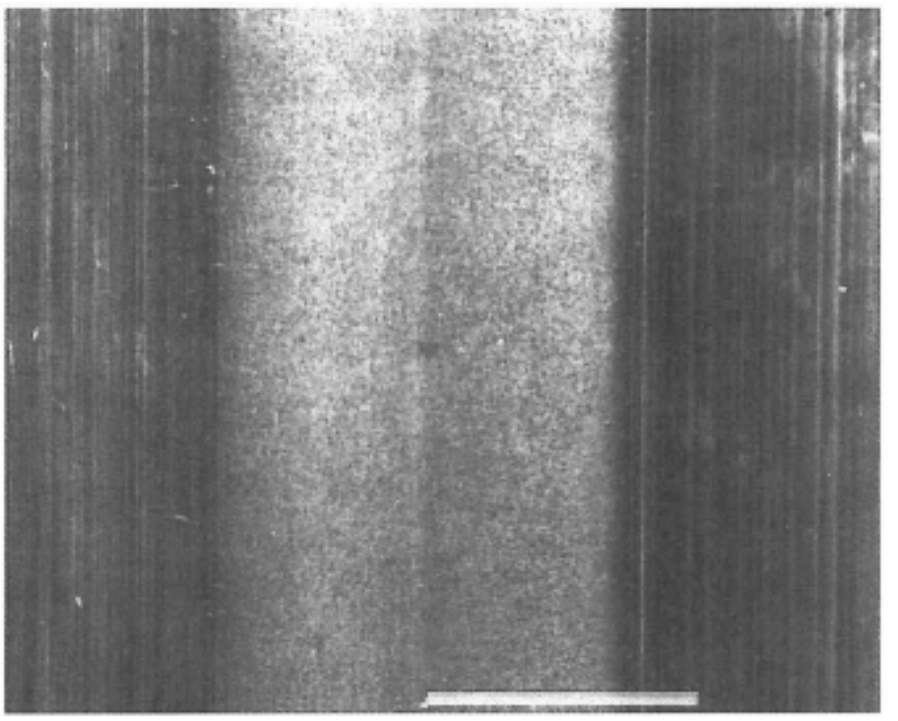
Suspected Causes: Fine denting (and kinematic wear marking) of the size shown are virtually inescapable in most industrial applications with circulating oil due to contaminant ingress past the filters (filtering to less than 10 μm particle size is uncommon). Mild surface distress is not unusual but preventable if ample EHD films can be provided.

DATA

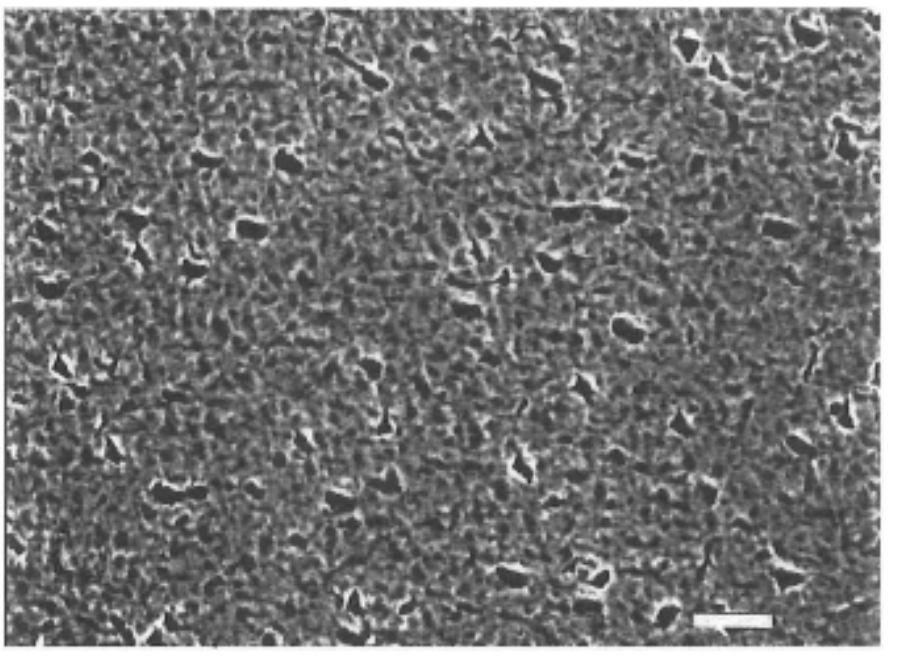
Plate No: 12.9
Archive No: 107-013a&b&c
Image type: a, b, c: SEM
Scalebar = a: 1 mm, b: 10, c: 10 μm
(micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed:
Load:
Lubrication: grease, 30°C
Failure Code 1: 00.18.1.4 Multiple irregular denting from fine, loose hard debris
Failure Code 2: 00.18.01.1.1 Denting of rolling surface, no sliding
Failure Code 3: -
Failure Code 4: -
See also PLATES: 12.10 and 12.14

DESCRIPTIONS

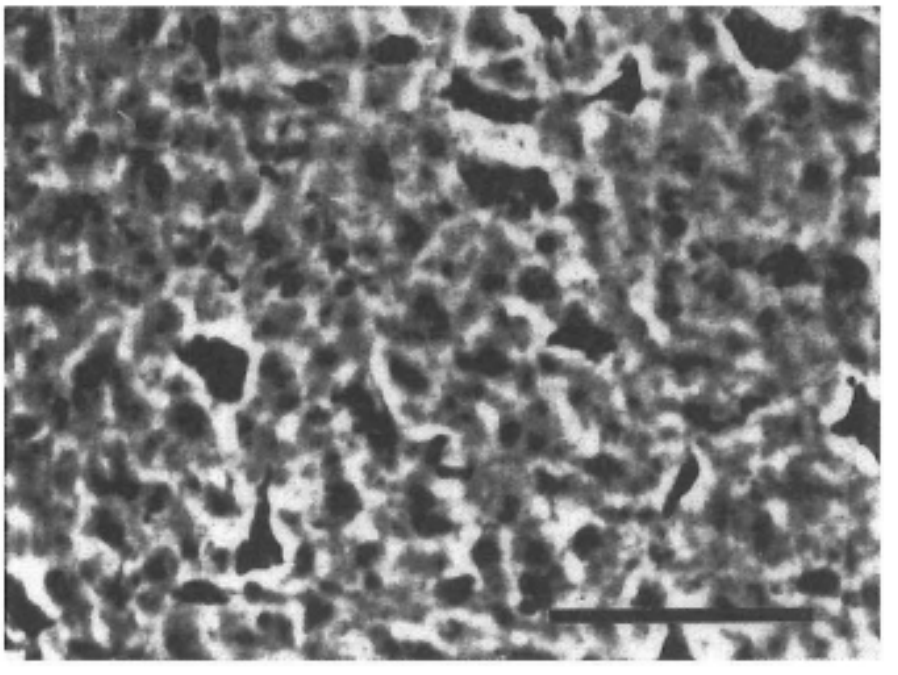
Failure Description: In ball groove of a DGBB is a fine, matte band magnified as dense irregular sharp-edged dents, due to overrolling of fine, loose, hard debris, usually in the lubricant. There was no significant sliding. The surface finish is destroyed and the bearing is noisy. If contamination continues destructive wear is likely, otherwise, early surface origin fatigue is expected. See Plate 12.14 for denting by embedded debris and Plate 12.10 for denting with minor sliding.
Image Description: (a): The background is an undamaged ball groove with N–S running finishing lines. In image center is a N–S band of matte, pebbly appearing surface from debris denting. (b, c): High magnification details of fine (1–5 μm) dents which densely cover the surface on which all signs of original finish have been obliterated. The dent bottoms appear dark; any sharp edges appear light. There is no visible directionality, which indicates no significant sliding.
Suspected Causes: Loose fine debris (wear particles, sand, dust), with the grain size not exceeding 5 μm is suspended in the lubricant. The filter is not fine enough to remove contamination. With little or no sliding, denting of the surface occurs. (With severe sliding, abrasive wear would take place.)



(a)



(b)



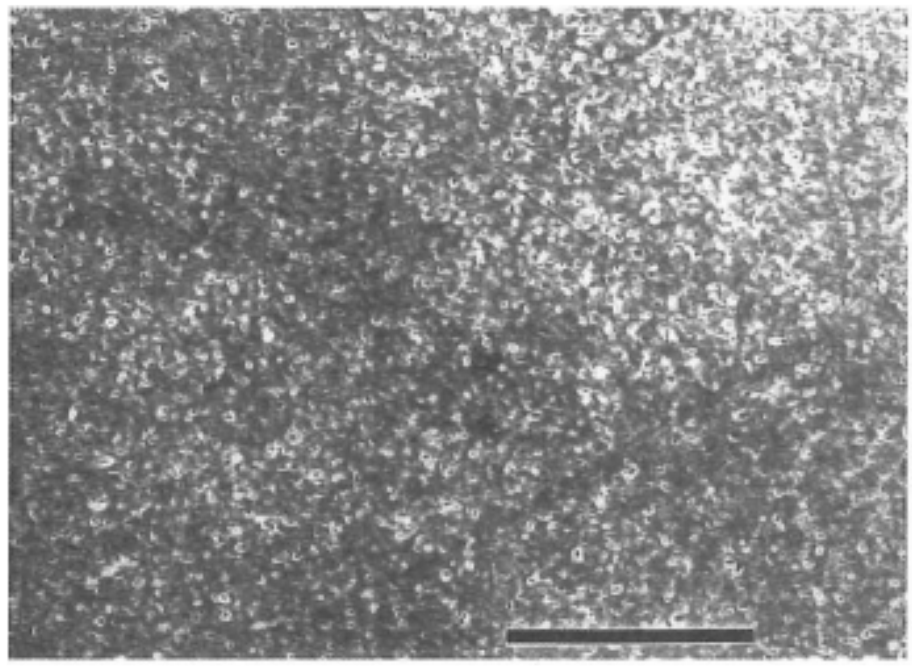
(c)

DATA

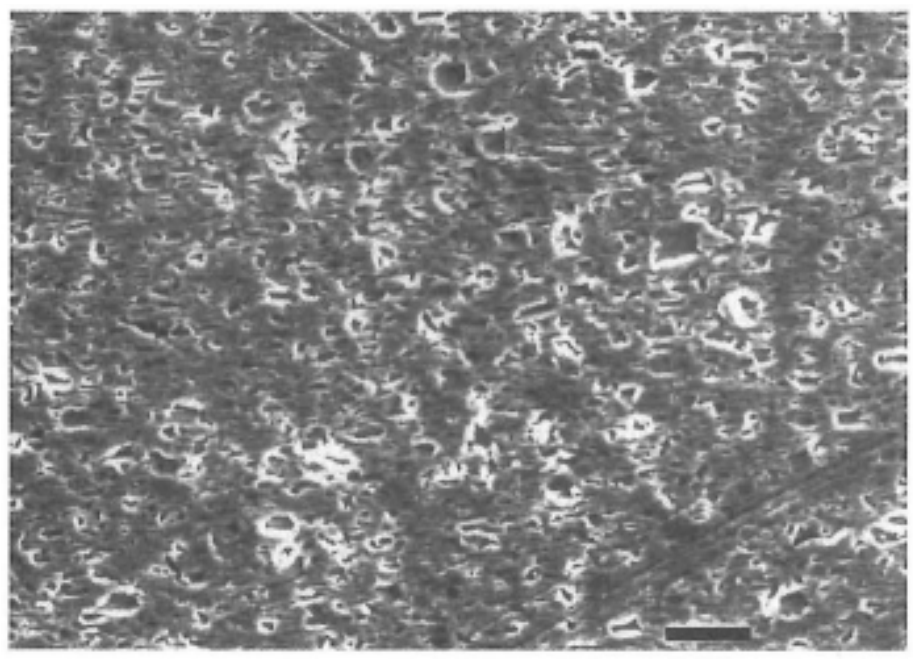
Plate No: 12.10
Archive No: 107-014a&b&c
Image type: a, b, c: SEM
Scalebar = a: 100, b: 10, c: 10 μm (micros: ±20%, others: +100%, −50%)
Component: TRB; R, run with grit added
Speed:
Load:
Lubrication: oil, 30°C
Failure Code 1: 00.18.1.4 Multiple irregular denting from fine, loose hard debris
Failure Code 2: 00.18.01.1.2 Denting of rolling surface, minor sliding
Failure Code 3: -
Failure Code 4: -
See also PLATES: 12.9 and 12.14

DESCRIPTIONS

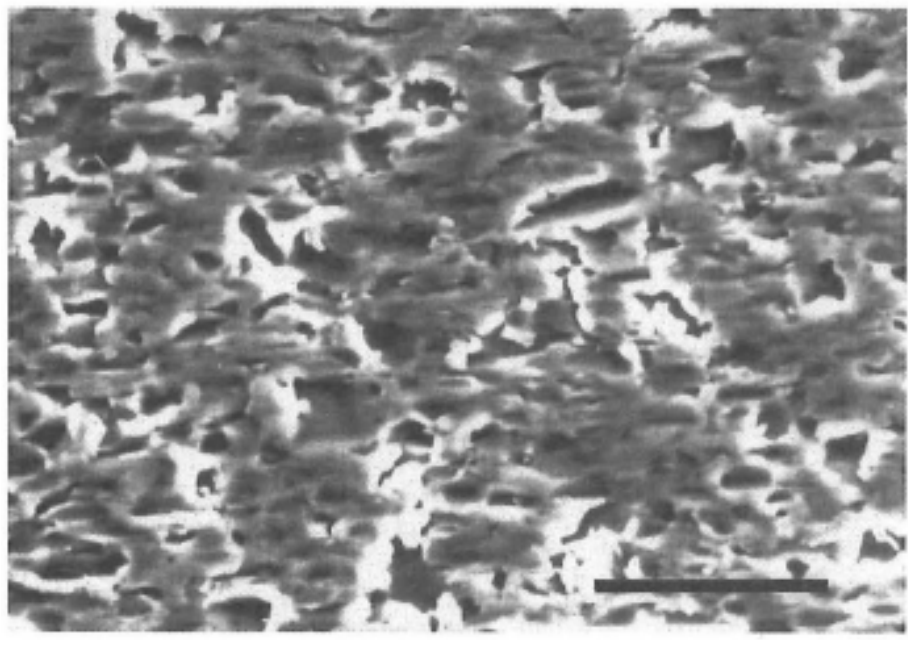
Failure Description: On the rolling path of a TRB roller is a fine, matte band magnified as dense irregular sharp-edged dents, due to overrolling of fine, loose, hard debris, usually in the lubricant. There was some minor sliding. The surface finish is destroyed and the bearing is noisy. If contamination continues, destructive wear is likely, otherwise, early surface origin fatigue is expected. See Plate 12.14 for denting by embedded debris and Plate 12.9 for denting without sliding.
Image Description: (a): Surface covered with dense, irregular, sharp-edged dents (black centers and white, sharp edges). In (a) and (b): few scratch marks NW–SE and SW–NE, made subsequent to denting, are probably incidental. (b) and (c): Population of dents elongated in E–W direction, indicating some sliding (a few μm per contact) in that direction.
Suspected Causes: Loose fine debris (wear particles, sand, dust), with the grain size not exceeding 5 μm is suspended in the lubricant. The filter is not fine enough to remove contamination. With little or no sliding, denting of the surface occurs. (With severe sliding, abrasive wear would take place.)



(a)



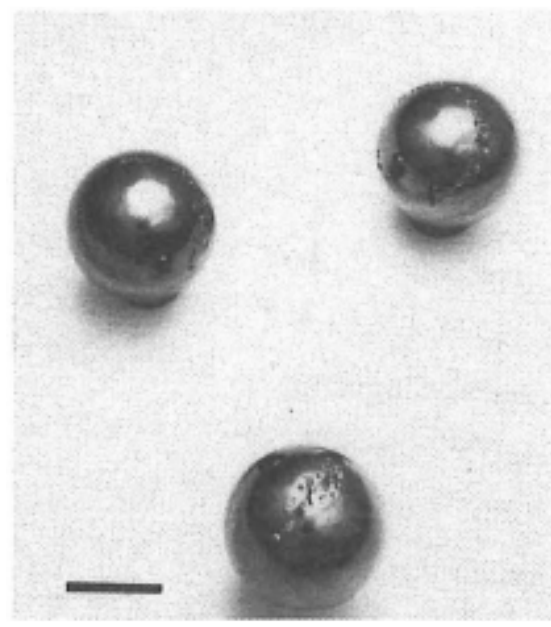
(b)



(c)

DATA

Plate No: 12.11
Archive No: 018-625
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.18.2.1.1 Rolled-in line, one contact edge only
Failure Code 2: 00.16.1.2.2 Shallow entry spall from surface line-defect
Failure Code 3: -
Failure Code 4: -

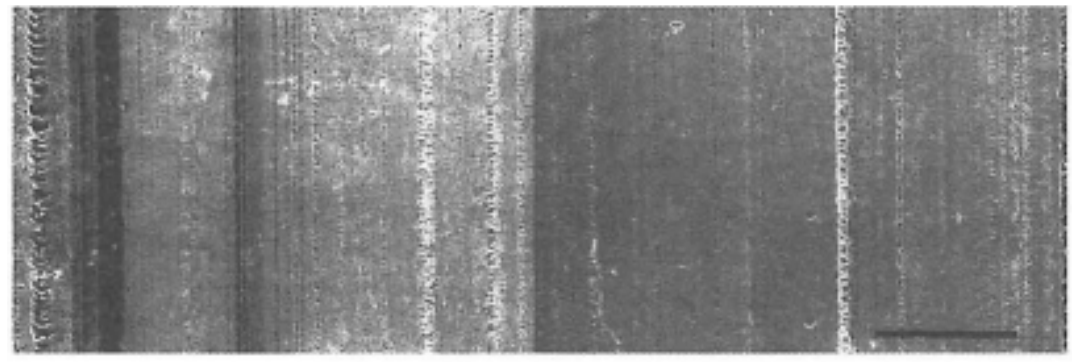


DESCRIPTIONS

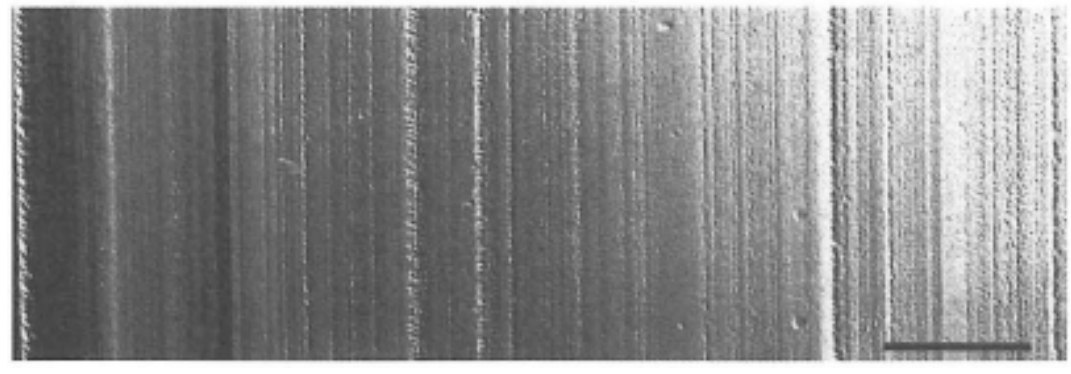
Failure Description: Depressed band along minor circle of balls, with several spall craters. The linear depression results from plastic rolldown against the ball groove edge in the bearing when contact overruns the edge. Spalls arise in the damaged material. The balls have failed.
Image Description: Three balls; on each is a minor circle outlined by spall craters. The unspalled surface in these circles is seen to be depressed below the surrounding material (best visible on ball at image S, near ball center, where a SW–NE running dark line outlines the edge of the depressed band). Dark and bright spots on the ball outside the spalled circle are light reflections.
Suspected Causes: If the contact area extends beyond the physical edge of the available groove, due to geometry error, excess radial looseness or axial overload, then edge loading results, which may generate sufficient stress to roll down the ball (and the groove edge) plastically. Surfaces so damaged are prone to early spalling, especially if the edge load continues. The edge load also tends to prevent balls from indexing, fixing the rolling track.

DATA

Plate No: 12.12
Archive No: 107-010a&b
Image type: SEM, (a) secondary electron, (b) backscatter
Scalebar = a, b: 100 μm (micros: ±20%, others: +100%, −50%)
Component: TRB; R, run
Speed:
Load:
Lubrication: oil, 50°C
Failure Code 1: 00.18.2.2.2 Stippled line(s) or band(s) from rolled-in debris
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



(a)



(b)

DESCRIPTIONS

Failure Description: Multiple parallel wear marks run circumferentially on the rolling path of a TRB roller. Under low magnification these marks appear continuous, as if caused by sliding. At the magnification shown, they resolve into rows of indentations made by the overrolling of hard contaminants embedded in the mating surface. They are classified as 'stippled lines.' Sliding is not evident, but the surface finish is destroyed and fatigue life is shortened.
Image Description: Images (a) and (b) are identical except (a) is a secondary electron image and (b) a backscattered electron image. These create different gray values of the same feature. Viewing both images clearly shows rows of rolled-indents. Each rolled-in stippled line consists of geometrically similar indentations. Most lines are made by fine particles (approximately 3 μm), but a line at image W is about 12 μm wide and a few others are also wider than 3 μm.
Suspected Causes: Abrasive contaminant entering the bearing chamber (in a gearbox bearing) became embedded in a ring track and repeatedly overrolled a line on the roller OD and created circumferential lines composed of multiple identical indentations.

DATA

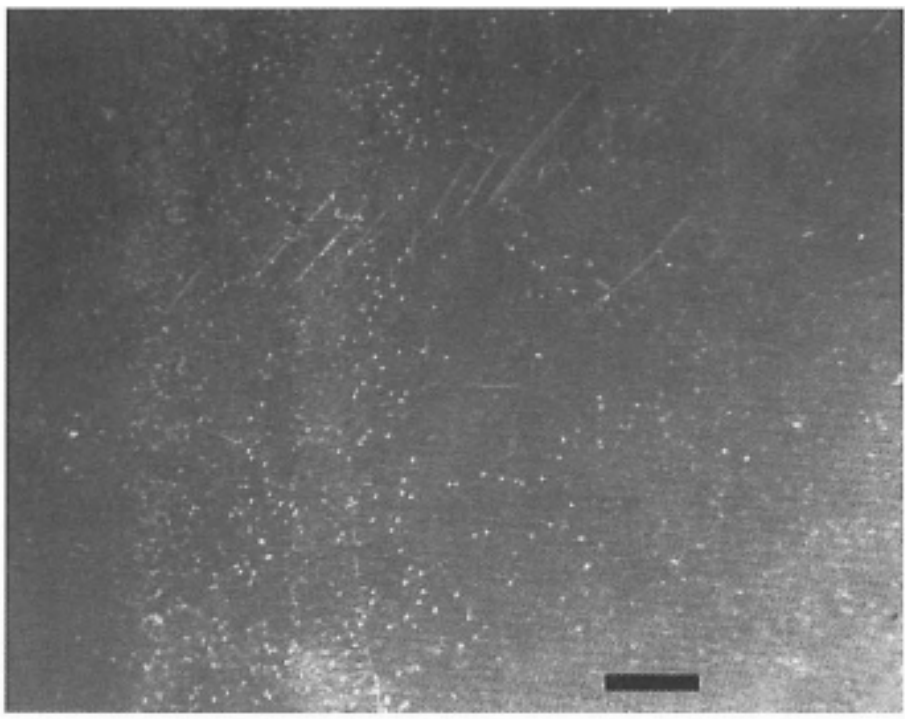
Plate No: 12.14
Archive No: 107-012a&b&c
Image type: a, b, c: SEM
Scalebar = a, b: 100, c: 10 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.2.2.2 Stippled line(s) or band(s) from rolled-in debris
Failure Code 2: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 3: -
Failure Code 4: -
See also PLATE: 12.15

DESCRIPTIONS

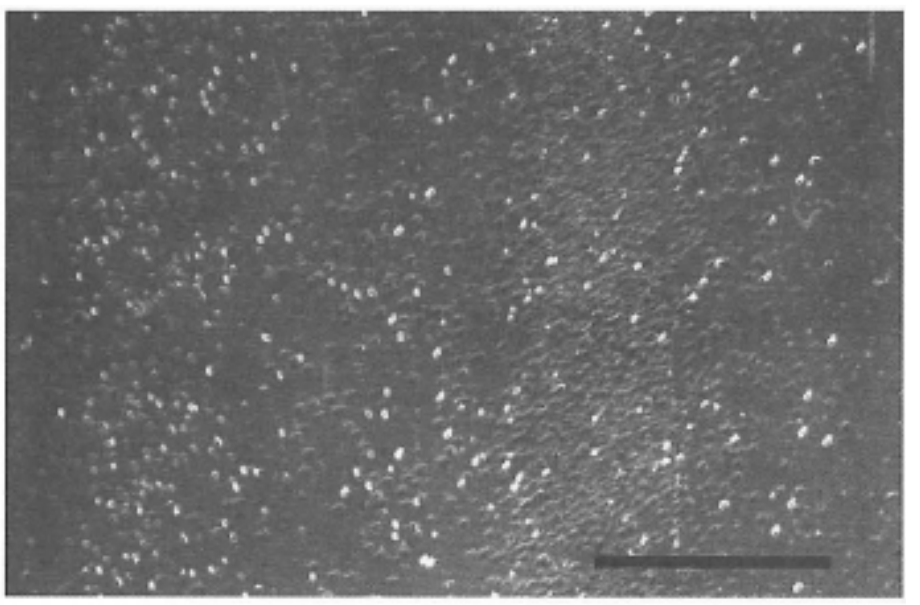
Failure Description: Multiple debris denting of ball surface, including a band of identically oriented dents rolled in by a hard particle embedded in the mating surface. Damage to ball surface promotes surface distress and subsequent surface-origin spalling; with more contamination, damaging wear is also expected. Some scratch marks are visible, probably as a result of disassembly.

Image Description: (a): 1 mm^2 of ball surface. In N 1/3 of image, the SW–NE running light-colored lines are disassembly damage. In N–S band W of image center are multiple debris dents (light-colored points and unresolved light-color bands). (b): Dent bands are enlarged, showing dense marking in E image half. (c): Dense part of dent band, with many identically shaped sharp-edged dents from a particle embedded in the mating surface.

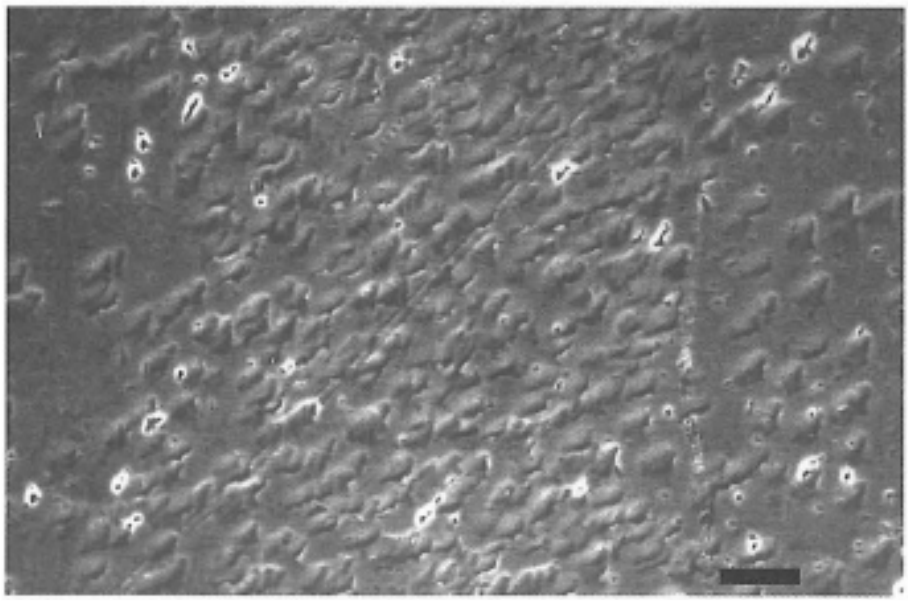
Suspected Causes: When fine, hard contaminant is present, it may embed in a rolling surface and mark the mating surface every time it is rolled over. A given grain continues to make the same shape dent. In a ball contact, in which the ball indexes against the mating surface, numerous rows of parallel dents may form. See also Plate 12.15.



(a)



(b)

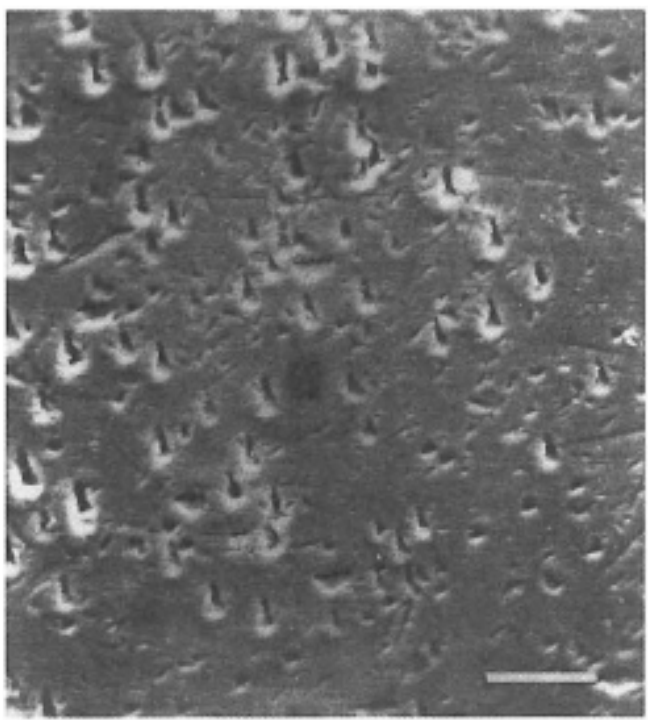


(c)

Failure Code: 00.18.2.2.2
Failure Code: 00.18.3

DATA

Plate No: 12.15
Archive No: 093-18.1.17
Image type: SEM
Scalebar = 20 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed: 300 KdN
Load:
Lubrication: mineral oil, 60°C
Failure Code 1: 00.18.2.2.2 Stippled line(s) or band(s) from rolled-in debris
Failure Code 2: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 3: -
Failure Code 4: -
See also PLATE: 12.14

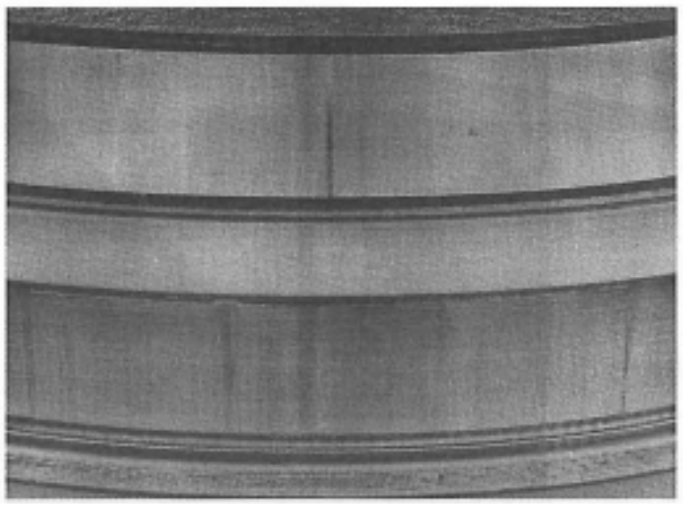


DESCRIPTIONS

Failure Description: Rows of parallel oriented sharp dents with raised edges appear, due to indentation from an abrasive particle embedded in the mating contact surface. Raised edges and undented surface are slightly glazed from surface distress. Denting of this density interrupts EHD film and promotes surface distress with subsequent spalling. Abrasive wear may also take place. See also Plate 12.14.
Image Description: Gray background is the slightly glazed lapped ball surface. Some lapping lines are still visible (E image edge). Rows of dark-bottomed, wedge-shaped dents are elongated in N–S direction, with tip pointing N and with light-colored rims (raised edges). Some differently shaped dents without raised edges (near E and S image edges) are older. The dark square in the image is an imaging artifact.
Suspected Causes: When fine, hard contaminant is present, it may embed in a rolling surface and mark the mating surface every time it is rolled over. A given grain continues to make the same shape dent. In a ball contact, in which the ball indexes against the mating surface, numerous rows of parallel dents may form. Any sliding velocity component will elongate the dents in one direction.

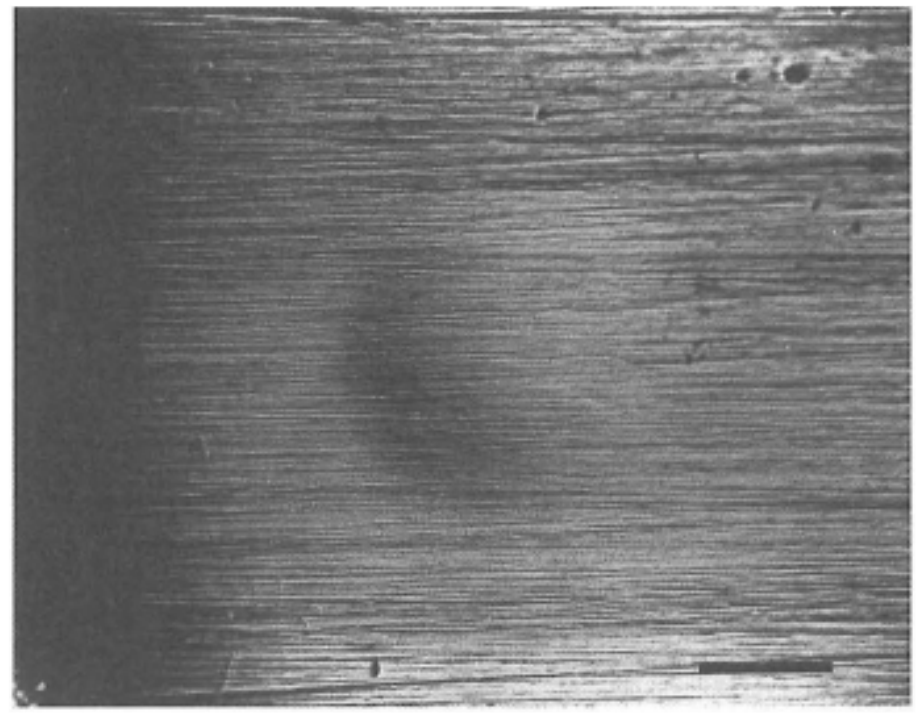
DATA

Plate No: 12.16
Archive No: 018-109
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB, IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.3 brinnelling
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 12.18 and 12.20



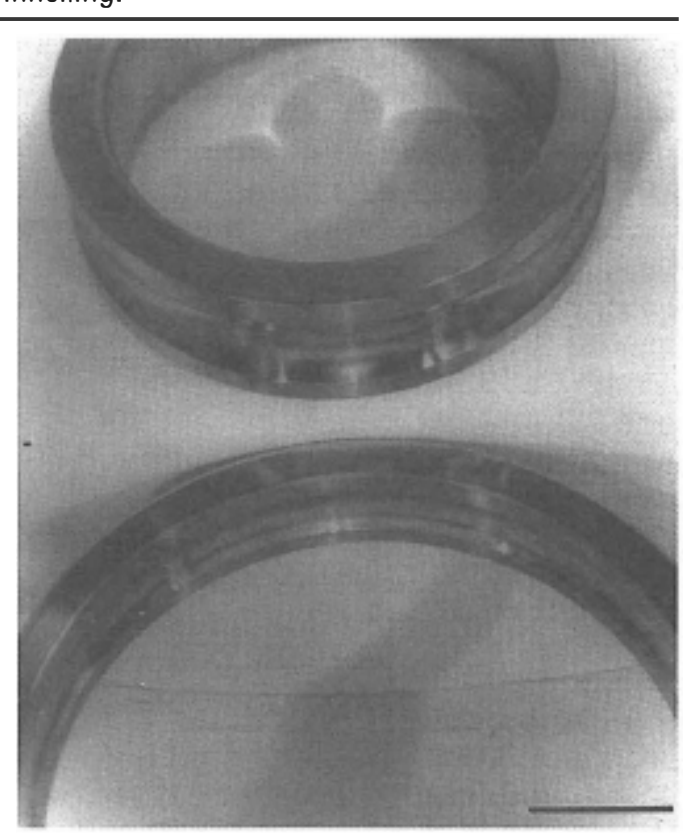
DESCRIPTIONS

Failure Description: Multiple axial brinnell marks on both roller paths of SRB IR were inflicted by a high static load or impact. Marks in one path broaden toward the center flange, suggesting axial loading (possibly when pressing the ring onto the shaft through the OR and the rollers). Such marks may become more visible after running, because they wear differently from the unbrinnelled area. The bearing is noisy and will spall earlier than normal. More severe brinnelling appears in Plates 12.18 and 12.20.
Image Description: Side view of a SRB IR with flanges and undercuts at N and S edge, center flange extending E–W at mid-image. Roller paths are gray. Flaring, fuzzy-edged axial dark marks showing brinnell dents extend across entire path width and, in path at image S, broad toward the center flange. Depending on lighting, a mark may appear dark or light.
Suspected Causes: Assembly of a SRB on a tight shaft may produce static loading, especially if mounting pressure is applied across the roller contacts. A bearing so damaged is noisy, but may run for an appreciable time before failing. Because brinnell marks are depressions, rollers traveling over them undergo load and traction variations which may be reflected in differential wear, highlighting the marks by a change in luster.



DATA
Plate No: 12.17
Archive No: 093-18.1.1
Image type: light micrograph
Scalebar = 150 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 450 KdN
Load: 3.4 GPa
Lubrication: mineral oil, 60°C
Failure Code 1: 00.18.3 brinnelling
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Light brinnell mark in groove of a DGBB IR. The mark is only 0.2 μm deep (by tracing) and oblong with major axis across the ball groove. The bearing is noisy for quiet running applications, but unlikely to fail soon from the brinnelling.
Image Description: Honed groove surface is shown with finishing lines running E–W. At image center, a circular-appearing depression is made visible by shading of highly directional metallographic lighting. The cross-curvature of the groove distorts light reflection further, making part of the oblong mark appear circular. Such marks can be detected by moving the part under a binocular microscope and observing a break in the edge of lighting crossing the mark.
Suspected Causes: Impact loading or high static loading of ball contacts cause brinnelling.

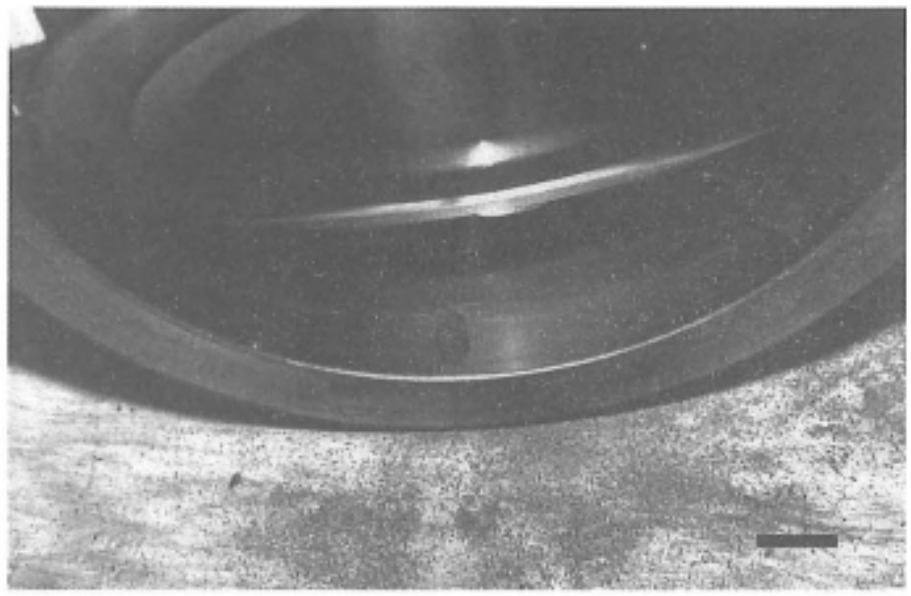


DATA
Plate No: 12.18
Archive No: 087-104
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR & OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.3 brinnelling
Failure Code 2: 00.12.3.2.0.7 Wear track for misaligned outerring
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: brinnell marks are present at ball spacing, extending to ball groove edge in both OR and IR (on opposite sides). The bearing is noisy and may fail in high speed application from separator fracture. Early spalling at brinnell marks is likely.
Image Description: In service, visible IR sideface matches averted OR sideface. OR ball groove edge near averted face shows three indentations at ball spacing (at N-most point and on each side), which are triangular, with base at the dented edge. These are brinnell marks extending across the edge. On the IR, two elliptical brinnell marks at same spacing are gray shadow, in the groove outboard of triangular light reflections. The shifting circumferential lines in the OR groove are the wear track.
Suspected Causes: Assembly or disassembly of bearing on tight fitted shaft, by pressing on OR face, indents ball grooves near edge. The dark wear track which varies in axial location around the ring circumference suggests misalignment in running.

DATA

Plate No: 12.19
Archive No: 031-1501
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: SRB assembly, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 00.18.3 brinnelling
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.18.2.1.2 Rolled-in line, both contact edges
Failure Code 4: -

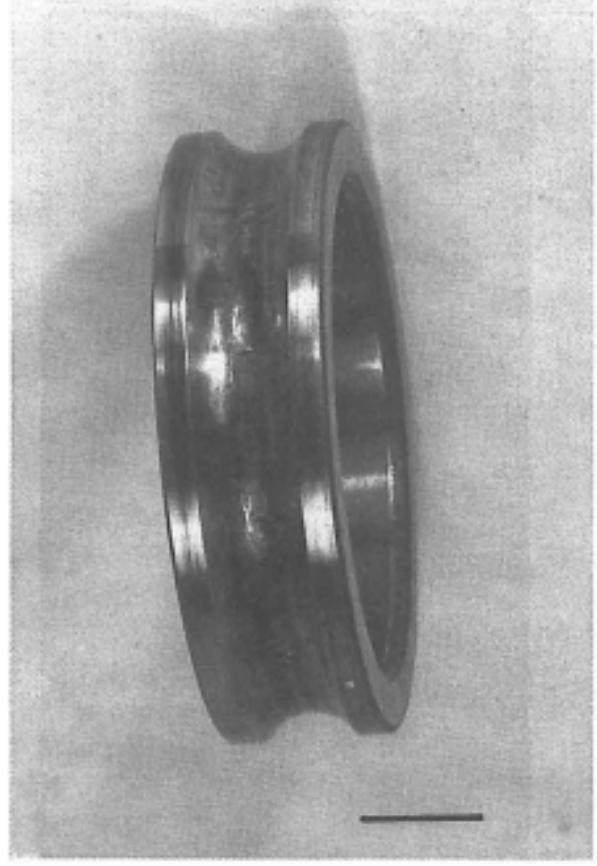


DESCRIPTIONS

Failure Description: In OR roller path, an isolated spall of elliptical contour following a brinnell mark, probably sustained by impact in shipping or mounting of the bearing. Rolled-in circumferential lines are shown emanating from both ends of the spall, probably from dents made by the spall edge on the rollers. The bearing has failed.
Image Description: Bearing is shown with IR/roller assembly swiveled out of alignment, exposing OR roller path at E–W image centerline, just S of IR sideface. At the image center is a barrel-shaped spall crater with sharp contours. It corresponds to the contour of a heavy brinnell mark extending over the entire roller length. Circumferential rolled-in lines of distinct luster extend E and W of the spall.
Suspected Causes: If a bearing is dropped during shipment, or suffers a severe impact load in mounting, heavy brinnell marks may be made on both rings (and one or more rollers). Overrolling of such marks in service is likely to precipitate early spalling-out of the damaged material. The spall edge copies onto the rollers which then may roll-in circumferential lines into the ring contact path.

DATA

Plate No: 12.20
Archive No: 087-118
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.3 brinnelling
Failure Code 2: 01.11.2 Separator fracture, cracking
Failure Code 3: 00.12.3.2.4 Scoring wear (macroscopic gouging without galling)
Failure Code 4: 11.5 Carbonized oil deposit



DESCRIPTIONS

Failure Description: The innerring ball groove is severely brinnell marked at ball spacing. The brinnell marks are gouged and the adjacent area is battered. These are plastic flow events. The discoloration in the groove and on the lands is presumed to arise from oil carbonized in overheating. The brinnelling is attributed to fracture, entrapment and lockup of the separator under the balls.
Image Description: In the groove bottom are four brinnell marks, that the balls have plowed forward circumferentially to form gouges. The adjacent groove surface is plastically battered. Blackish discoloration is visible around the groove bottom (except where worn off) and dark streaks appear on both lands, as from carbonized oil due to overheating.
Suspected Causes: The brinnell-type indentations occurred through a stamped steel separator failure. Sheet steel was entrapped between the balls and OR, and locked them against the IR. The bearing seized. In dissipating momentum, the rotor drove the locked balls along the groove, making plowed gouges. Prior to lockup, the separator material was overrolled, denting the innerring. Overheating during seizure created the black deposit marks (carbonized lubricant).

DATA

Plate No: 12.21
Archive No: 099-132
Image type: light macro
Scalebar = 30 mm (micros: +20%, others: +100%, −50%)
Component: HG; W, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.4.1 Gear tooth peening (irregular local plastic flow)
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 4: -
See also PLATES: 12.22 and 12.23

DESCRIPTIONS

Failure Description: In medium-hard gearing, local plastic flow of macroscopic dimensions occurred in the contact surface due to the interaction of geometric imperfections. This is similar to surface distress glazing except that it is on a larger scale. Surface distress microspalling and incipient macrospalling have followed. The gear may be runnable but is inaccurate, noisy and may be prone to fracture.
Image Description: View of one flank surface in several consecutive gear teeth, with contact extending, as a lighter-gray area, from W tooth edge to within 8 mm of E tooth edge. The patchy variation of hue across the tooth width in the addendum and dedendum represents plastic peening. The dark pinpoints are spall centers, concentrated in dedendum.
Suspected Causes: Cold working of medium-hard gear contact surfaces may occur under heavy, localized or impact loads. Geometric irregularities cause peened appearance. Plastically worked material microspalls in surface distress and subsequently develops macrospall craters. Compare to Plates 12.22 and 12.23 for other forms of local plastic flow in gears.

Failure Code: 00.18.4.2

DATA

Plate No: 12.22
Archive No: 099-133
Image type: light macro
Scalebar = 8 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.4.2 Gear tooth rippling (transverse wavy plastic flow)
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 12.21 and 12.23

DESCRIPTIONS

Failure Description: In the gear contact surface, local plastic flow under vibratory conditions has produced transverse ripples. These are wave surfaces, with phase shifts at radial lines or in a fish-scale pattern. Rippling is believed to result when softer subsurface material flows plastically under repeated loading, distorting the harder surface. The increased roughness produces local stress concentrations which may eventually spall.
Image Description: Gear tooth contact surface is shown, with tip at N image edge and root at S edge. Glancing lighting highlights transverse crests and troughs of waviness with radial lines delineating shifts in crest location (phase). The surface is generally glossy (burnished) in appearance.
Suspected Causes: Rolling contact at very high stresses produces, in softer materials, plastic flow in the rolling direction at the high Hertz shear stress layer. A case hardened or work hardened surface may warp under this flow producing the ripples. The axial phase-shifts may be due to geometric imperfections in stress distribution, causing uneven flow rates. See Plates 12.21 and 12.23 for other forms of local plastic flow in gears.

Failure Code: 00.18.4.3

DATA

Plate No: 12.23
Archive No: 099-134
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: HYG; P, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.18.4.3 Gear tooth ridging (plastic ridges in sliding direction)
Failure Code 2: 00.12.5 Gear tooth wear
Failure Code 3: -
Failure Code 4: -
See also PLATES: 12.21 and 12.22

DESCRIPTIONS

Failure Description: The ridge and valley pattern in a high-sliding hypoid gear set shows ridges following the sliding direction. It arises from combined plastic flow and wear, which is probably initiated by machining imperfections. This is not an imminent failure, but the roughening of the surface may lead to any form of gear failure, such as galling, spalling, wear and eventual tooth fracture.
Image Description: Hypoid pinion teeth cover the image from NW to SE corner. Tips are light gray; flank surfaces dark with light oblique streaks which represent the ridges. These ridging are more sharply defined than the rippling of FC 00.18.4.2.
Suspected Causes: In high-sliding gear sets such as worm gearing or hypoid gearing, a pattern of differential plastic flow and wear develops following the sliding direction. It is believed to result from a variation of contact pressure across the contact width and results in pronounced prominent ridges and valleys. Compare to Plates 12.21 and 12.22 for other forms of plastic flow in gear tooth contacts.

HEAT IMBALANCE FAILURE 13

Failure Code 00.19

13.1 Definition

Heat imbalance failure is a complex sequence of failure events precipitated by a (macroscopic) temperature excursion in the Hertzian contact machine element due to heat generated in excess of the heat simultaneously removed.

Heat imbalance failure is distinct from:

- *Galling* (FC 00.13)
- *Lubricant failure* (FC 11, FC 12)

but may be the precipitating cause and/or the result of either or both of the latter.

Heat imbalance failure is *not synonymous* with overheating, which defines the temperature excursion of the machine element. The latter may or may not precipitate failure. Heat imbalance failure is diagnosed when, as a result of overheating, one or more irreversible changes occur in the contact components.

Heat imbalance failure differs from other contact component failure modes in that it is a *system* failure. The effects may manifest themselves primarily on one or a few components, but the failure mechanism is that of loss of thermal equilibrium of the machine element as a system.

13.2 Nomenclature

Heat imbalance failure (also designated overheating failure) is a recognized failure class in rolling bearing technology (less generally in gear technology). Terms for one of the subclasses of heat imbalance failure are more commonly used, for example: hot plastic flow, temper coloring, permanent hardness loss or overheating seizure.

13.3 Failure Process

Sequence of Failure Events. The failure process in all heat imbalance failures comprises the sequence of four events described below.

Event 1. The steady-state thermal equilibrium in a volume enclosing the Hertzian machine element gives way to an excess of heat generation over heat removal. The heat imbalance can result from any combination of *increased heat generation* in the machine element, and *reduced heat outflow.* See *Causes* below for operating conditions conducive to heat imbalance.

Event 2. The temperature of some or all contact components, and often that of some other components of the machine element (including the lubricant), rises in an excursion above the maximum design level.

Event 3. Depending on the magnitude, location and duration of the temperature excursion, one or more of the following *intermediate* failure occurrences takes place.

Lubrication Failure. (See also FC 11.1 and FC 12.)

- In an organic liquid lubricant (oil, grease), rheological properties change as temperature increases. Most importantly, *viscosity drops*, and EHD film conditions correspondingly deteriorate. Above a limiting temperature, the lubricant evaporates or burns off before reaching high pressure in the contact, and EHD lubrication ceases. These phenomena occur with minimal

time lag behind the temperature change. The direct consequence of deteriorating EHD lubrication is further increased heat generation, providing positive feedback to the heat imbalance failure.

- Grease surrounding the machine element may soften at the increased temperature, causing it to *slump* as a lump into the path of the contact components and undergo violent churning. As a result it may liquefy and escape through the chamber closure, leaving the machine element lubricated only with a thin adhering layer of lubricant, soon lost to decomposition (see below).
- In any lubricant, *decomposition* and oxidation occur at sufficiently high temperatures, if they act over sufficient time. (See FC 11 and FC 12 for details.) Minor changes in lubricant chemistry may have long-term deleterious effects on Hertz contact machine element performance; major changes immediately render the lubricant unserviceable, converting the system to a dry-lubricated or unlubricated system.

The loss of fluid lubrication in the form designed into the machine typically leads to sharply *increased heat generation*, creating rapid and often catastrophic failure of the machine element.

Loss of Operating Clearance. Due to differential thermal expansion of components, operating clearance can be lost in any machine element confined by its design. Examples: rolling bearings may lose internal looseness; gear pairs may lose clearance; and cam systems may lose the gap between cam and follower or tappet at the bottom of the stroke. Clearance loss from thermal expansion is reversible with the temperature and therefore may not be observable in the stopped machine.

Loss of operating clearance generally leads to large parasitic loads on the Hertz contacts. An increased load further increases heat generation, creating rapid, often catastrophic failure.

In steel components with metastable retained austenite, operation at elevated temperature for protracted periods may produce permanent volume growth leading to an irreversible loss of operating clearance.

Loss of component material strength may follow operation at temperatures that exceed the design maximum.

- The hot hardness of *steel* is less than normal ambient temperature hardness, leading to hot plastic flow under load.
- *Hardened steel* loses hardness permanently at temperatures in excess of the tempering temperature used in manufacture, permitting plastic flow under load even after operating temperature has reverted to normal.
- *Plastic materials* (gears and bearing separators) may soften or melt at temperatures tolerated by metals, leading to hot plastic flow or disintegration under load.
- *Ceramic* components are highly resistant to softening at elevated temperature and their thermal expansion coefficient is typically lower than that of steel. Hybrid assemblies (e.g., bearings with ceramic rolling elements and steel rings) may fail by heat imbalance while the ceramic component remains intact, because the steel components change dimensions or hardness, the lubricant or the separator fails from high temperature.

Chemical change in structural component material may result from operation at elevated temperature:

- *Non-stainless steel* develops thin oxide layers when held at elevated temperatures in air. These temper colors can serve to diagnose the order of magnitude of the temperature exposure.

- Some *plastic materials* become embrittled when held at elevated temperature, leading to subsequent cracking during operation.

Event 4. The ultimate failure from heat imbalance, often referred to as a *burn-up*, is a runaway temperature excursion. This occurs when lubrication has been lost and/or softening of the contact material has induced massive galling. Components may be deformed out of all recognition (balls into rollers and vice versa). Components may be welded together (rolling elements, rings and separator pieces from a rolling bearing into a block, forcing rotation at the fit interfaces). The failure process culminates in gross seizure and/or bulk fracture, often extending to the shaft, housing or machine frame.

Arrest of Heat Imbalance Failure. Heat imbalance failure can be arrested at almost any point short of gross seizure or fracture. The following are scenarios with practical significance for the arrest of heat imbalance.

- *Quenching of microscopic thermal instability.* Momentary load peaks, the passage of a contaminant particle or some other local disturbance may overheat *one asperity contact* during operation. If copious liquid lubricant immediately floods the surfaces upon separation, the instability can be quenched leaving, at worst, skidmarking (FC 00.14) or local galling (FC 00.13). Some lubrication methods favor quenching more than others (oil over grease, bulk oil over mist, circulating oil over splash and jet or under-race lubrication over free flow).
- *Resupply of grease through softening* (see FC 12). During moderate overheating, the grease available in the immediate contact area may deteriorate (be contaminated, harden, be expelled), resulting in a loss of lubricating effectiveness. Bulk grease in the warmed grease pack becomes softer, however, and may slump into the contact path and replenish the supply. If the heating, and thus the softening, is moderate, destructive churning of the whole grease pack may be avoided.
- *Moderating operating conditions.* In machinery with variable operating conditions, a temporary overload and/or overspeed may be relieved as the operating cycle progresses, or be deliberately relieved by the operator observing a temperature excursion.

13.4 Distinctive Appearance

A heat imbalance condition may be identified directly by observing temperatures at suitable locations on the machine. Morphologically, heat imbalance failure is recognized as one of the resulting irreversible failure modes, appearing as follows.

Hot Plastic Flow. In metals and heat-softening plastics, hot plastic flow is the decisive indicator of heat imbalance failure. It can be distinguished from cold plastic flow by appearance. Hot plastic flow is generally much more extensive than cold flow; the shapes of components are drastically altered; and surface oxidation is common (but not inevitable) in metals. No causes other than overheating produce hot plastic flow. Compare this to cold flow under FC 00.23.

- Hot plastic flow is a *late* consequence of heat imbalance. Due to its destructive nature, hot plastic flow is likely to obliterate signs of earlier events in the failure process.
- Whereas hot plastic flow is certainly due to overheating, the overheating itself may well be a secondary failure mode. It is advisable to search a plastically deformed component for remaining signs of other failure modes (galling or spalling of contact components, galling or fracture of a bearing separator, etc.).
- In ceramics, the distinctive hot plastic flow is not observed in heat imbalance failure. Indications of overheating may be cracking or fracture of the ceramic or hot plastic flow of adjacent metal components.

- In thermosetting plastics, excessive overheating is manifested as decomposition leading to brittleness, burned surface appearance and disintegration.

Secondary Lubrication Failure

Lubricant outflow from the chamber. Grease, when softened or liquefied by heat, tends to be extruded past seals or shields closing the chamber containing the Hertz contact machine elements. If the outside of the closure is visible, extruded grease may be observed. Only *substantial* amounts of extruded grease, appearing suddenly, are a sign of heat imbalance failure, as gradual modest grease loss may be due merely to imperfect sealing or overgreasing.

Deteriorated lubricant (see FC 11 or FC 12) may be recognizable as having been exposed to excessive temperatures. If the deterioration is severe, then the lubricant appearance may permit distinction between moderate but long-term overheating and unstable heat imbalance. Long-term overheating tends to cause discoloration and acidification; unstable high overheating causes grease liquefaction.

Secondary Galling, Fracture

Galling (FC 00.13) or fracture (FC 00.22) are common final modes of failure initiated by heat imbalance.

In order to be diagnosed as heat imbalance, galling and fracture must be accompanied by other signs of overheating. The most distinctive are hot plastic flow (listed above) and surface changes (see below).

Surface Changes in Structural Components

Low hardness of hardened steel components may be a sign of heat imbalance failure. It may be more pronounced at the working surfaces, thus distinguishing loss of hardness due to overheating, from a heat treatment defect.

Note: Loss of hardness due to overheating is not narrowly localized the way grinding temper (FC 00.08) is.

Temper colors from surface oxidation at elevated temperature are clear symptoms of overheating.

Note: The appearance of early "straw-color" temper is easily confused with that of friction polymer deposit from the lubricant. A special etch test (quick wiping of surface with a cotton tip dipped in 10% dilute HCl acid solution) differentiates the two: temper color is instantly removed but friction polymer is not.

Decomposition of plastics (burned-appearing surfaces, embrittlement, surface cracking, melting, disintegration) results from high overheating and shows differences in appearance depending on the composition of the material.

13.5 Causes

Impaired Lubrication

This is the most common cause of heat imbalance failure and operates by two mechanisms: increase in heat generation (by contact friction and viscous losses) and reduction of cooling via the lubricant.

Increase in Heat Generation

1. *Increase in friction* arises between working surfaces through impaired EHD and/or boundary lubrication. The heat generation goes up while heat removal for a given temperature remains constant, representing heat imbalance. Lubrication may be impaired if:

- Insufficient quantity of (liquid) lubricant reaches the surfaces.
- Lubricant chemistry is impaired by overheating, contamination, or reaction with incompatible materials.
- For lubricant layers formed at the surface (vapor phase lubrication), the reaction intended to form the layer malfunctions.

2. *Increased viscous losses* may be caused by excess oil flow or an excessive or poorly channeled grease pack. With excess oil flow, heat removal may also increase, yet the increased heat generation often outweighs any increase in heat removal, causing imbalance.

Reduction of Cooling by the Lubricant. Especially in oil lubrication, the lubricant normally convects heat away from the working parts of the machine element, at times representing the prime heat removal channel. Cooling by the lubricant is impaired in the following circumstances:

- The quantity of lubricant in a sump is reduced.
- The flow rate of lubricant past the working surfaces is reduced.
- The lubricant entrance temperature to the working surfaces increases.

Whereas heat generation may be reduced as oil volume or oil viscosity decrease, the loss in cooling often dominates.

Reduction of Conductive Cooling

Contact components not operating in a cooled lubricant circulation ultimately reject most generated heat into the environment by transferring it to the surface of the machine from where it is carried into the atmosphere. This heat transfer may be impaired at any of the interfaces along its path. Examples:

- Loose or fretted fit of bearing outerring to housing, bearing innerring or gear to shaft, increasing the interface thermal resistance.
- Inaccurate fit of housing to frame (same effect).
- Insufficient cooling of component by oil (impaired lubrication) or insufficient heat rejection from oil to sump (low oil level) or to heat exchanger (impaired circulation).
- Impaired heat rejection from machine exterior to air (hot environment, sunshine, dust or mud encrusting the surface, loss of forced-air cooling).

Added Heat Generation as Secondary Failure

Galling, spalling with debris generation, separator or rolling body fracture (in rolling bearings), gear tooth fracture, unintended rubbing between noncontact components (mounting parts, etc.) and the ingress of large amounts of solid contaminant are common primary failures that can cause large unexpected additional heat generation and drive a secondary heat imbalance failure of the Hertz contact machine element. For details about each, see the appropriate failure codes.

Machine Temperature Excursion

If another part of the machine undergoes sufficient heating to elevate the temperature of the mounting parts or of the lubricant serving the Hertz contact machine element above a critical level, then heat removal via these elements is reduced and may even be reversed (heat carried to the Hertz contact machine element). This can directly precipitate a heat imbalance failure.

Load or Speed Excursion

A large excursion of component load or operating speed may precipitate a heat imbalance failure. It is likely, however, to cause a galling event first, with a heat imbalance failure following.

13.6 Effects of Heat Imbalance Failure

Major heat imbalance events destroy the component through one of these ensuing failure modes:

- *Galling* (with seizure)
- Hot *plastic deformation*
- *Fracture*
- *Melting* of plastic components

Lesser heat imbalance events, if arrested, may leave no observable effects, or leave one of the following long-term effects causing possible failure later:

- *Loss of lubricant supply* may continue to impair lubrication and/or cooling until replenished.
- *Lubricant decomposition* may impair lubrication until the lubricant is replaced.
- *Friction polymer* is generally harmless and merely a warning sign. Friction polymer has been observed in properly operating bearings (after long service).
- *Temper colors* are a warning sign that component hardness may have been impaired; heavy oxide layers also interfere with component accuracy, can flake off and contaminate lubricant or cause wear.
- *Loss of hardness* in hardened steel parts leave them subject to bulk plastic flow, spalling, wear, brinnelling and galling.
- *Decomposition of plastic components* may cause brittleness, cracking, loss of dimensional integrity, or outright fracture.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.19	16.10
00.19.1.1	16.22 16.33
00.19.1.2	10.27 13.3 13.7
00.19.2	7.21
00.19.2.1	13.14 15.35 18.4
00.19.2.2	16.2
00.19.3	13.4 13.8 13.10 13.15
00.19.4.1	18.12
00.19.5	6.33 8.8 8.23 13.9

PLATES

DATA

Plate No: 13.1
Archive No: 027-135
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar =
Component: 0, specimen
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.1 Heat imbalance, temper colors
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Steel samples with temper colors, tempering temperature (°F) and hardness (RC). Conversion:

°F	300	360	400	450	500	550	750
°C	149	182	204	232	260	288	399
Rockwell C	62	62	61	60	59	58	53
DPH	746	746	720	697	674	653	560

Image Description: Specimens of ground and polished steel tempered at varying temperatures show temper colors ranging from light straw (W) through deeper straw, brown, blue and gray (E). Temperatures (°F) and hardnesses (RC) (for AISI 52100 bearing steel) are shown on labels S of each specimen.
Suspected Causes: Temper coloring depends on tempering time and atmosphere as well as temperature. The colors assume about one hour tempering time in air, and may be used as rough guides only. Hardness indications are strongly alloy dependent and apply to AISI 52100 bearing steel only.

DATA

Plate No: 13.2
Archive No: 087-025
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRB, OR&IR&R&G, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.1.2 Temper colors in contact surfaces
Failure Code 2: 00.22.1 Overstress crack
Failure Code 3: 11.5 Carbonized oil deposit
Failure Code 4: -

DESCRIPTIONS

Failure Description: High-speed CRB operated with substantial axial load. One roller endface on several rollers and one IR thrust flange are severely temper-colored (estimated temperature 220–320 °C). The IR flange is chipped from overrolling of the flange edge by the rollers. The separator is discolored by carbonized oil. The bearing is failed.
Image Description: Intact OR at image NW. IR, at image SW is discolored mostly at or near the severely chipped flange (arrow). All rollers shown are temper-colored on or near the visible end (arrow). The separator is not severely worn but shows dark stains which, on a silver-plated separator, cannot be temper-colored, but consist of carbonized oil deposit.
Suspected Causes: CRB-s, especially in the absence of sufficient radial load, are sensitive to thrust loading. Rollers tend to assume an angled position in the radial plane ('tilting'), causing large local pressures on the flange edge which skews the rollers, producing high sliding. The roller/flange interface overheats under high pressure and edge contact. Galling is likely and, as a secondary effect, the flange may chip.

DATA

Plate No: 13.3
Archive No: 027-143&144
Image type: a, b: color view [SEE IMAGE IN APPENDIX.]
Scalebar = a, b: 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; duplex; IR & B, run
Speed: 100 KdN
Load:
Lubrication: grease, 60°C ?
Failure Code 1: 00.19.2 Hot plastic flow
Failure Code 2: 00.13.02 Extensive galling
Failure Code 3: 00.19.1.2 Temper colors in contact surfaces
Failure Code 4: 00.12.3.2.1.4 Wear track at contact edge

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Duplex ball bearing assembly axially over-preloaded. Contact in one IR overran the groove edge. Overheating caused temper colors, rollout and severe galling with massive material transfer to balls. The second IR was overheated and temper-colored but the contact did not overrun the edge. The bearing assembly has failed.
Image Description: (a): Two IRs mounted in duplex as shown. E IR has a straw temper color (200°C) on the E half. W half is blue (260°C) and the groove edge is rolled out (arrows). W IR is straw colored on the E land and blue in E 1/4 of the groove. (b): Three balls matching E IR. Ball at W has a straw temper color, a blue band of higher heating and, W of this band, a rolled-in line from the edge. Balls at center and E show blue temper color and large masses of welded-on galled steel.
Suspected Causes: Axially preloaded duplex bearing pairs may suffer excess preload if spacing of the bearings is inaccurate. Overheating, loss of lubrication and temper coloring may result. One half may suffer more damage if external axial load adds to preload or if minor profile geometry differences favor overrunning of the groove edge.

DATA

Plate No: 13.4
Archive No: 002-014a
Image type: view
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run & unrun
Speed: 1.7 MdN
Load: 1.5 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.19.2 Hot plastic flow
Failure Code 2: 00.19.3 Scale formation
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Four balls are substantially reduced from original diameter by hot plastic flow and wear of heat-softened surface material. One new ball is shown for reference. A bearing with such balls has lost shaft support accuracy; the balls overroll the groove edge and the separator is damaged. Material was found rehardened, which in tool steel requires local temperatures well in excess of 700°C. This is gross failure.
Image Description: All used balls are visibly smaller than the unused center ball shown for reference. The used balls have streaks from overrolling the groove edge, pits from galling against the separator and scaling from high temperature.
Suspected Causes: In a high speed, high load turbine engine bearing, excessive heat was generated, presumably from excessive IR bore/shaft looseness which permitted relative rotation. The heat caused lubrication to fail; balls galled against the separator pockets, started sliding against rings, were heated to virtual forging temperature, wore greatly, scaled and underwent plastic flow.

DATA

Plate No: 13.5
Archive No: 014-28
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB, complete, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.13.2.1.1 Rolling surface galling, no dent or nick visible
Failure Code 3: 01.14.1 Separator pocket galled
Failure Code 4: 01.13.3 Separator wear from unintended contact

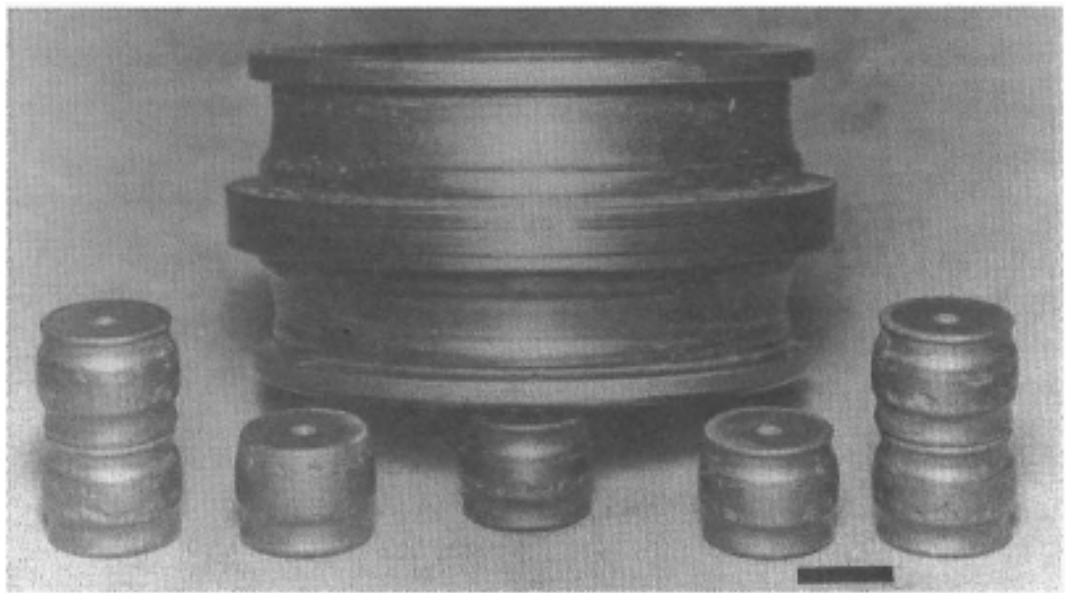


DESCRIPTIONS

Failure Description: Unstable overheating (heat imbalance failure) of bearing after loss of adequate lubrication. OR roller path, roller ends and IR thrust flange ('rib') suffered hot plastic flow (rollout). The roller ends and ODs galled. The separator is bent, its OD is worn against OR. This is a gross failure. Complete seizure is imminent.
Image Description: At image S, IR/roller assembly is viewed from the large sideface. Part of the OR is seen at image N. OR roller path is generally battered, with irregular circumferential bands of galling (light gray) near center plane and near S edge. The roller ends are hot-rolled down to form center protrusions. The IR thrust flange (rib) is rolled thin. Roller OD has galling streaks. The separator is deformed; its OD has light-color wear streaks and galled metal at pocket edges.
Suspected Causes: Loss of adequate lubrication leads to progressive overheating as heat removal fails to balance increased heat generation from friction. The material softens and deforms; the geometry is destroyed; and galling occurs. The separator bends and is pushed against OR, where it wears. The roller end/thrust flange (rib) pressure exceeds reduced yield point and both surfaces roll down, leaving protrusions at the roller axis.

DATA

Plate No: 13.6
Archive No: 018-122
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR & R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.16.01.1.2 Centered spalling, wide track
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: 00.12.4 Wear of guiding-component support surface



DESCRIPTIONS

Failure Description: Unstable overheating (heat imbalance failure) of bearing after loss of adequate lubrication. IR roller paths and roller ODs suffered severe hot plastic flow (rollout), producing deep grooves in IR and near both ends of each roller. Generalized shallow spalling, material removal by wear and continued rolldown proceeded simultaneously. Wear of IR center flange OD occurred against separator.
Image Description: IR design with three flanges. Both roller paths and the flange faces contacting the roller ends are rolled out (depression in roller paths, sharp flange edges). Roller OD has grooves near both end faces; corners and a circle near the edge of the visible end face (not the thrust face) are deformed. Spall craters covering roller paths on IR and roller OD are mostly shallow and rolled down. Circumferential wear scratches appear on the center flange OD.
Suspected Causes: Loss of adequate lubrication leads to progressive overheating as heat removal fails to balance increased heat generation from friction. The material softens and deforms and the geometry is destroyed. Wear and spalling of softened material occurs, removing surface material. This may postpone or prevent gross seizure unless the separator fractures.

DATA
Plate No: 13.7
Archive No: 093-19.1.6
Image type: SEM
Scalebar = 15 μm (micros: +20%, others: +100%, −50%)
Component: DGBB; IR, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, arrested, ? °C
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.19.1.2 Temper colors in contact surfaces
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Ball groove surface of tool steel bearing that suffered heat imbalance failure and plastic flow with total obliteration of original finish. Temper colors were observed. The bearing underwent an "oil shutoff test" to determine its survivability if lubricant is lost. It has suffered gross failure.
Image Description: "Kneaded" surface of ball groove shows material displaced by plastic flow over the entire surface area; laminae formed and rolled on; and total obliteration of the original surface finish. Macro appearance showed temper color. The observed condition is typical of high-temperature overheating during operation.
Suspected Causes: Ultrahigh speed bearings, as shown, rely on lubricating action to control the rate of heat development, and on mass flow of the lubricant (or gas) for removal of generated heat. In an oil shutoff test, heat removal through lubricant convection is lost at once and lubricating effectiveness rapidly degrades. Very high temperatures arise, at which even heat resistant tool steel softens and plastically fails. Survival time is limited to minutes.

DATA
Plate No: 13.8
Archive No: 074-36
Image type: view
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: CRB; R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.19.3 Scale formation
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: -

DESCRIPTIONS
Failure Description: Heat imbalance failure in a (cylindrical) roller bearing. All rollers underwent hot plastic rollout. One roller galled repeatedly against a guide flange and was turned in the separator pocket so that its edges were rolled and worn down to a sphere. Scale has formed on all rollers. This is a gross failure.
Image Description: The roller at image W is battered by rolldown and shows blackish scale. The roller in the center is shorter and shows rounded edges and flat areas on OD from sliding wear. Ball-shaped object at image E originated as similar roller but rolldown of edges is complete to form a sphere.
Suspected Causes: Cylindrical roller bearings exposed to significant thrust load are prone to galling seizure between roller end-faces and guide flanges (for example, by overrolling of the flange edge). Such a seizure forces the roller to slide on the unflanged ring. Sufficient wear, rolldown and skew moment can result in turning the roller endwise in the rolling direction. It may then wear flat or, by repeated turns, be rounded into a sphere.

DATA

Plate No: 13.9
Archive No: 018-617&619
Image type: a: view, b: light macro, section, etched
Scalebar = a: 12, b: 5 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.19.5 Local structure damage from frictional heating
Failure Code 3: 00.13.02 Extensive galling
Failure Code 4: 00.23.2 Plastic distortion of bulk shape



DESCRIPTIONS

Failure Description: Bulk of ring overheated and softened so that rolldown in ball groove extended to deformation of one land, one sideface and the bore. A rehardened and tempered layer has formed under the ball path. Galling and scaling occurred in the ball path. The material folded over the land OD. This is a gross failure.
Image Description: (a): Ball groove radius has increased, land OD at image E is tapered, edge is rounded and folded over. E endface is dished in. E edge of bore shows circular groove from plastic deformation. Ball path surface is battered and shows circumferential jagged line in NW from galling. Scale patches are in the S. (b): Etched section with rolled groove edge at W. White layer at groove surface is rehardened; dark patches beneath are tempered. Light-colored arcs are produced by lighting.
Suspected Causes: Loss of grease lubricant is the most likely failure initiator. Overheating occurs from increased friction. The relatively light load prevents seizure, permitting massive rollout of the entire ring. Galling in the ball path results from ball sliding. Rehardened layer, with underlying retempered zone in cross section indicates that the surface temperature exceeded 900°C.

DATA

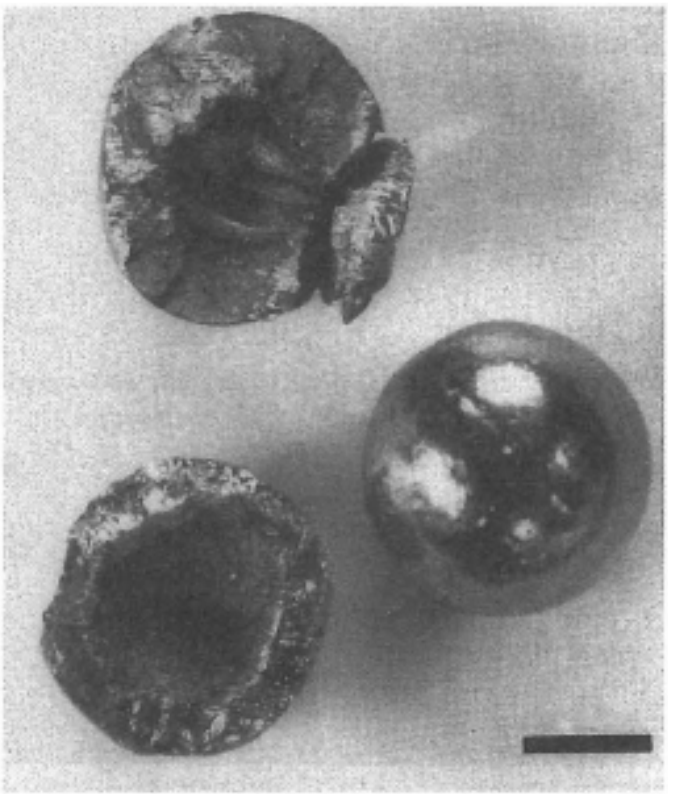
Plate No: 13.10
Archive No: 074-35
Image type: view
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; IR&B&G, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 3: 01.11.2 Separator fracture, cracking
Failure Code 4: 00.19.3 Scale formation
See also PLATE: 13.11

DESCRIPTIONS

Failure Description: Severe heat imbalance failure, probably initiated by a separator geometry error causing the separator to become trapped under a ball. It produced (1) separator fracture; (2) severe hot working of balls (rollout); (3) formation of a concentric hollow in the ball (see Plate 13.11); (4) fracture of the hollowed ball; and (5) scale formation on balls. This is a gross failure.
Image Description: Well-preserved OR is at image E (IR, probably damaged, was not available). The disintegrated stamped steel "ribbon" separator is at NW, with one ball still in a pocket. Five balls, all show hot plastic flow and degrees of scaling. One ball (arrow) has an oblong concentric hollow through which it has fractured.
Suspected Causes: Stamped ribbon separators, if too loose or stretched by high ball forces (misalignment) may become trapped between a ball and ring, locking the ball. Sliding under high pressure occurs; the bearing overheats and the separator breaks. A metal rolling process similar to tube rolling may produce a hollow center in heavily plastically rolled balls under strong tractive surface forces. Cracking under contact load follows.

DATA

Plate No: 13.11
Archive No: 018-621
Image type: light macro
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 00.23.2 Plastic distortion of bulk shape
Failure Code 3: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 4: 00.18.2.2.1 Rolled-in continous line from opposing edge
See also PLATE: 13.10



DESCRIPTIONS

Failure Description: Balls subject to severe plastic strain while overheated have formed a concentric hollow leading to fracture of one ball in service. (The second ball was broken for examination.) The rolling surface of the ball is severely battered, with rolled-down line from edge of contact. See also Plate 13.10.
Image Description: The ball at image E is unbroken, with surface battered throughout, and a heavy rolled-in line running NW–SE along a great circle. The ball at image SW has a large spherical hollow in the center, which is surrounded by fracture surface showing wear (occurred in service). The ball at NW has a smaller hollow in the center, which is surrounded by chipped and cross-cracked impact fracture surface artificially produced in examination.
Suspected Causes: A metal-rolling process similar to tube rolling produced a hollow center in heavily plastically rolled bodies under strong tractive surface forces. Cracking under contact load has followed. The uncracked ball shows plastic battering of the overheated surface and a line rolled-in by the ring groove edge, which was overrolled during uncontrolled overheated operation.

DATA

Plate No: 13.12
Archive No: 027-423
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 2: 12.2 Carbonized grease
Failure Code 3: 00.13.2.1 Rolling surface galling
Failure Code 4: 00.01.1.1 Nick with raised edges

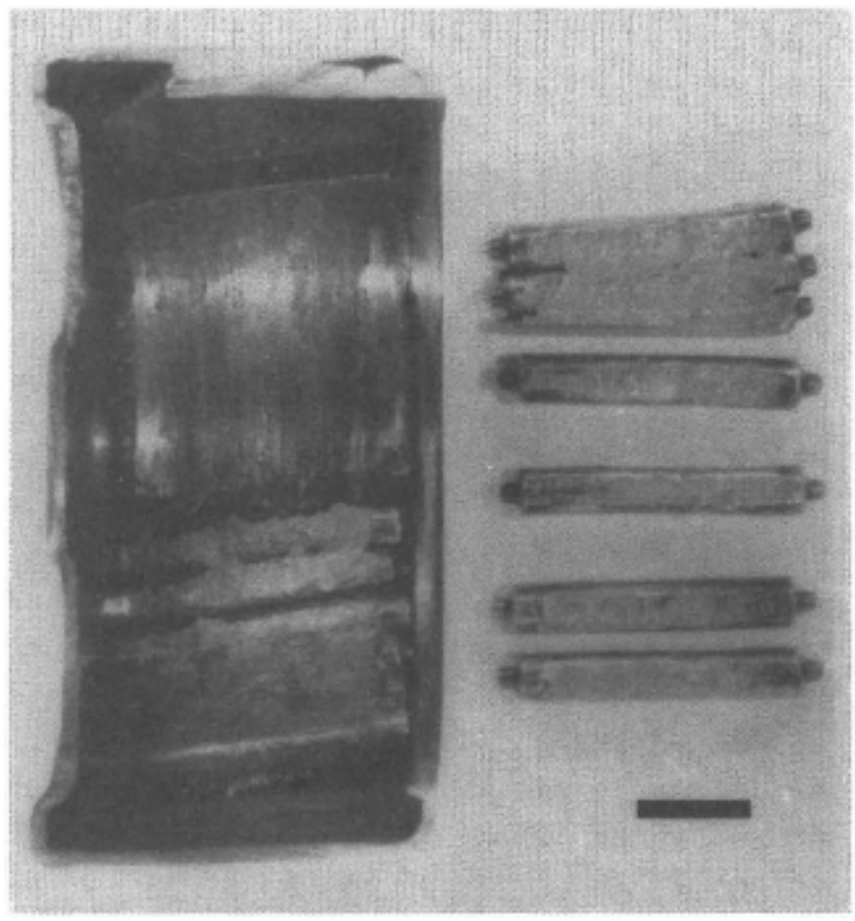
[See Image in Appendix]

DESCRIPTIONS

Failure Description: Severe heat imbalance failure has caused: (1) rolldown of groove; (2) carbonized grease; and (3) severe galling in groove (probably involving pressed steel separator and balls). Severe nicks at the groove edge may have occurred at bearing dismounting. This is a gross failure.
Image Description: Black carbonized grease deposit on both lands and, in streaks, in the ball groove of IR. Circumferential bands of the groove were gouged free of deposit by severe sliding (possibly caused by the separator caught under a ball). At image center, there is a sharp-edged black galling mark where the separator and ball locked on the groove and made a depression later filled in with carbonized grease. E edge of groove shows nicks with raised edges near image N, perhaps from dismounting.
Suspected Causes: Severe heat imbalance failure in bearing, probably due to loss of lubricant, caused high friction; deviation from epicyclic ball speeds; extreme ball-to-separator forces; stamped steel separator distortion with separator caught under a ball; sliding of separator and ball over groove; galling; and possibly seizure. High temperature carbonized the grease. Difficult dismounting of the seized bearing may have caused nicks.

DATA

Plate No: 13.13
Archive No: 018-204
Image type: view, OR sectioned
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: NRB; OR & R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.2 Hot plastic flow with bulk welding
Failure Code 2: 00.13.02 Extensive galling
Failure Code 3: 00.12.3.2.3 Step worn in rolling surface or dimension worn off-spec
Failure Code 4: -

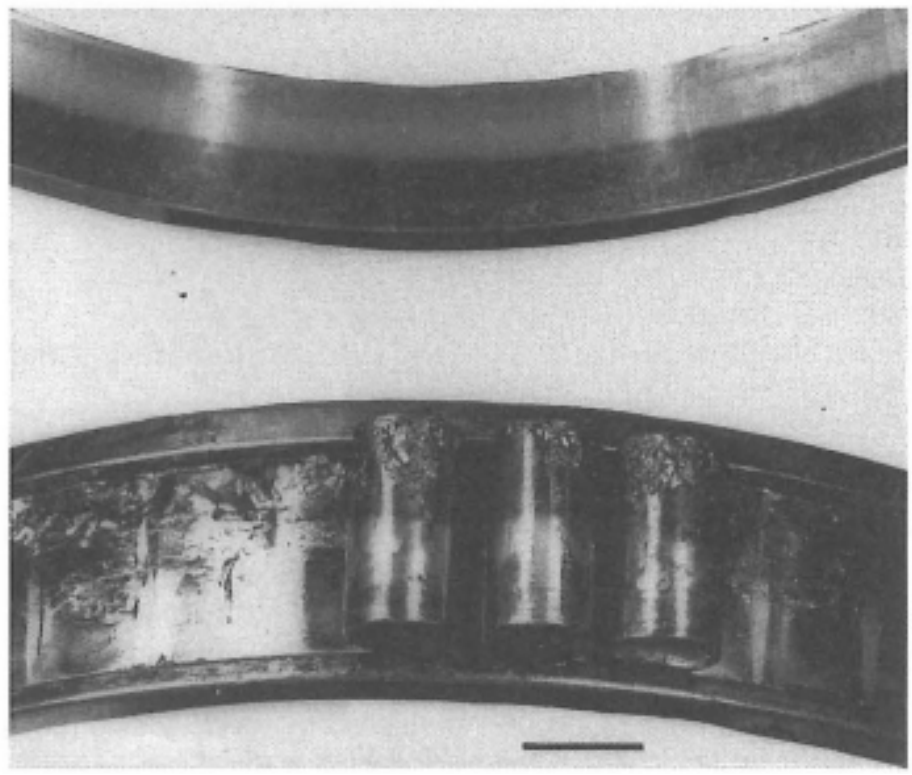


DESCRIPTIONS

Failure Description: Needle rollers misaligned during mounting of separator-less (cageless) drawn-cup needle roller bearing. Rollers have jammed during running and galled against shaft and OR ('cup'). The bearing overheated, losing lubricant; this caused gross plastic flow of rollers and cup followed by heavy galling and wear, probably ending in seizure.
Image Description: W image half shows cross-sectioned OR (drawn cup). Several skewed rollers are welded-in at S cup half. One is at N section edge. The galled, battered and worn cup rolling surface is shown in N image half. E image half shows bent, welded-together needle rollers with a large flat worn on each.
Suspected Causes: Improper installation of cageless needle roller bearing may leave rollers skewed. When load is applied and shaft turns, rollers wedge in, requiring a high torque to turn the bearing by sliding the shaft over the locked rollers. Overheating, material softening, galling, welding and wear follow.

DATA

Plate No: 13.14
Archive No: 093-034
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR & R & OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.19.2.2 Hot plastic flow with bulk welding
Failure Code 2: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 3: 11.5 Carbonized oil deposit
Failure Code 4: -



DESCRIPTIONS

Failure Description: Rollers are severely rolled out and welded to IR track. The OR track is severely rolled down. Dark discoloration is present, as from a carbonized lubricant. All the damage constitutes a severe heat imbalance failure due to loss of lubrication. This is a gross failure.
Image Description: The OR section is at image N, with S half of track rolled out and battered by hot plastic flow. On the S half of the OR track is a carbonized lubricant coating. The IR section is at image S. In it are four rollers welded to the thrust flange due to heat imbalance failure. All of the IR roller track and the rollers are covered with a dark coating of carbonized lubricant. The separator has been ejected and rollers have rolled up against each other.
Suspected Causes: Loss of effective lubrication in a taper roller bearing is rapidly followed by overheating of thrust flange contact with a heavy sliding component under load. That contact will gall and eventually seize (weld). In the process, adjacent rolling contact areas also overheat, soften, gall and suffer rollout. The separator disintegrates during these events, permitting the rollers to roll up against each other.

DATA

Plate No: 13.15
Archive No: 027-424
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B & G, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 00.19.2.2 Hot plastic flow with bulk welding
Failure Code 2: 00.19.3 Scale formation
Failure Code 3: 00.13.2.1 Rolling surface galling
Failure Code 4: 01.11.2 Separator fracture, cracking
See also PLATE: 13.3

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Heat imbalance failure of ball bearing has caused (1) plastic battering of balls; (2) scaling of ball surface; (3) galling and transfer of metal laminae from groove to balls; and (4) fracture of polymer separator. This is a gross failure.
Image Description: Two darkened fragments of machined polymer (phenolic) separator at image W. Two brown-coated battered balls at image E show foil-shaped masses welded onto the balls of galling. Color may be from scaling, grease decomposition products or possibly separator material (more detailed examination needed). Contrast this with Plate 13.3, where the ring at image E shows *moderate* overheating.
Suspected Causes: Severe heat imbalance failure in bearing, probably due to loss of lubricant (or primary separator failure) has caused softening of steel; galling between balls and grooves; deviation from epicyclic ball speeds; extreme ball/separator forces; separator fracture; and overrolling of debris resulting in battering of ball surfaces. High temperature caused scale formation.

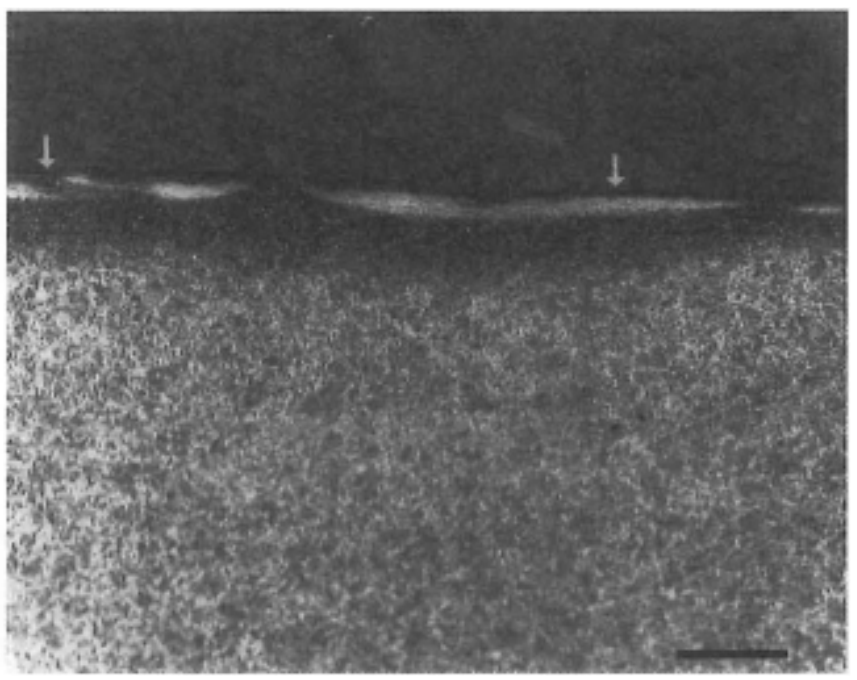
DATA

Plate No: 13.16
Archive No: 027-139
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed: 130 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.19.4.3 Friction polymer on guiding part support surface
Failure Code 2: 12.3 Friction polymer, grease lubrication
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Friction polymer bands of two orientations on ball which has rubbed excessively against separator and was strongly heated. The ball remains serviceable. The high-friction event that produced the overheating may lead to grease loss and resulting bearing failure.
Image Description: The southern hemisphere of ball is covered with coaxial E–W circles of yellow, brown and gray friction polymer bands, as ball rubbed without indexing against (phenolic plastic) separator pocket. The northern hemisphere shows NW–SE-oriented friction polymer circles from another ball orientation. The black diamond in the center of the ball image, and the gray rim of the image are lighting artifacts.
Suspected Causes: Relatively high-speed rubbing of ball in separator pocket, in the absence of sharp asperities to cause wear marks, may heat the contact and promote friction polymer formation, as well as its removal by light wear. The combination of the two effects creates the banded appearance. See chapter introduction for a description of the etch test that distinguishes friction polymer from temper color.



DATA

Plate No: 13.17
Archive No: 005-6
Image type: light metallogram. Nital etch
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Component: C; CF, run
Speed: 7.5 m/sec
Load: 1.4 GPa
Lubrication: mineral oil, 115°C
Failure Code 1: 00.19.5 Local structure damage from frictional heating
Failure Code 2: 26 Support bearing damage (of gear, cam)
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: High-speed, insufficiently lubricated sliding between contact surfaces has caused strong interface heating which retempered and rehardened the near-surface material. Concurrently, galling (FC 00.13) may have occurred. The retempered and rehardened structure resembles a grinding burn tending to cause early spalling failure. Contamination found in the cam follower roller/pin gap caused braking of the roller and contact sliding.
Image Description: In this section, the rolling surface runs W–E (arrows). Extending S from this surface, whitish oblong streaks are light-etching rehardened material. Directly S of them is a wide band of dark-etching overtempered material, blending gradually into the unaltered (mottled appearing) structure. The mottled dark area N of the rolling surface is specimen-mounting material.
Suspected Causes: In cam/follower systems the follower roller separates from the cam in each cam revolution at the end of the lift ramp. If friction of the roller on its pin is high, the roller rotation then slows down and undergoes abrupt acceleration at the start of the next lift phase. The friction forces in the cam/roller interface may not suffice to prevent gross sliding, leading to contact overheating (and possible galling).

CORROSION, ELECTRIC EROSION 14

Failure Code 00.20–21

14.1 CORROSION — FAILURE CODE: 00.20

14.1.1 Definition

Corrosion of contact components is defined broadly in this Atlas as including all failure by chemical (and electrochemical) attacks on surfaces.

The term "corrosion" applies specifically to *metallic* structural materials. Plastics, elastomers and (to a lesser extent) ceramics are also subject to chemical attack which is broadly categorized under corrosion in this Atlas, even though the term does not specifically apply.

Corrosion damage is distinct from:

- *Fretting* (F 00.15), the oxidation of wear particles generated and entrapped in a fit interface undergoing microscopic surface-parallel motion;
- *Pitting* (FC 00.03) as a casting or forming defect;
- *Temper coloring* from overheating (FC 00.19.1); and
- *Friction polymer* deposition (FC 11 or FC 12) from lubricant decomposition.

Protective oxide layers, such as the macroscopically invisible oxide layer protecting stainless steel or aluminum alloys, are not considered corrosion.

14.1.2 Nomenclature

In addition to 'corrosion,' terms used to designate surface damage by chemical action include chemical attack, rust, and staining.

Three distinct corrosion failure modes are designated as follows in this Atlas:

- *Corrosion staining*, which creates a discolored surface without appreciable in-depth attack into the subsurface;
- *Corrosion pitting*, an in-depth attack leaving pits with oxidized surfaces, surrounded by corroded (stained) or uncorroded surface;
- *Intergranular corrosion*, an attack on the grain boundaries of the material, which may leave little macroscopic surface damage, but weakens the cohesion of the material.

14.1.3 Failure Mode

Corrosion of Metals. Corrosion (rust) as originally defined, is the chemical (electrochemical) attack on a steel or cast iron surface by a wet atmosphere, converting some of the near-surface material to oxide or hydroxide. In this Atlas, any oxidizing chemical attack on metal, whether by moisture, acids or the electrochemical effect operating on an assembly of dissimilar metals, is covered under "corrosion of metals."

Depending on the environment, on the condition of the original surface and on exposure time, *steel* corrosion may confine itself to a very shallow layer of material and thus form a *brown stain*; or it may penetrate deeply into the metal from distinct points of origin and thus form *pits*. No clear separation of conditions leading to stain or to pits has been established, but the following circumstances favor one mode or the other:

- Mild corrosive exposure favors staining, and severe or prolonged exposure favors pitting.

- Finely finished surfaces (honed, polished, lapped) corrode less easily and favor staining; rough surfaces corrode more readily and favor pitting.

The following are common forms of corrosion in contact components:

1. *General corrosion,* attacking exposed surfaces of the components indiscriminately. The surfaces on which rolling and sliding contact takes place in service may appear uncorroded, whereas free surfaces are stained. When the corrosion has progressed to pit formation, then contact surfaces may show pits on metallic, uncorroded background.
2. *Contact corrosion,* forming streaks of stain outlining Hertz contact areas. This corrosion appears if a corrosive medium (example: wet oil) coats contact components (example: rollers and rings of a bearing) while at rest. The medium is retained under a meniscus in the narrowing gaps adjacent to contacts and stains the surface there, but may leave other surfaces unattacked.
3. *Corrosion aided by galvanic couple* occurs when an assembly contains dissimilar metals with strongly differing electrochemical potential, such as steel and brass. When an electrolyte is present, such as water or acid in the lubricant or high humidity in the air, corrosion of both parts of the galvanic couple may occur more readily than with either metal alone.

   Some special cases of galvanic corrosion of significance for Hertz contact machine elements are:

   - Corrosion of (hardenable) stainless steel components with surfaces contaminated by adhering nonstainless steel particles. An acid treatment termed 'passivation' protects against this corrosion by removing the non-stainless particles.
   - Corrosion of aluminum components (example: rolling bearing separators) in contact with martensitic steel. Anodizing of the aluminum component has limited protective value but presents tribological problems on working surfaces.

Chemical Attack on Non-Metals. Chemical attack on non-metals may also occur by oxidation, but the agents causing it vary widely.

- Some plastics used as separators are incompatible with certain lubricants (greases) and embrittle when exposed to them for long periods and/or at elevated temperatures.
- Improperly formulated elastomers, as used in rubbing seals, are attacked by mineral oils; more are attacked by synthetic lubricants.
- There is little experience with chemical attack on ceramics in contact components due to their specialized use. Silicon nitride will oxidize at extremely high temperatures. Nonetheless, ceramics are among the most corrosion-resistant materials.

Intergranular Corrosion. Certain chemical environments tend to attack the grain boundaries in metal. These conditions do not commonly affect Hertz contact machine elements, but some examples have been reported, as follows.

- In components used in the petroleum and natural gas industries, a "*sour gas*" environment, which entails exposure to sulphides, can precipitate intergranular corrosion and lead to chemically induced cracking of components. This is generally designated as *stress corrosion cracking* (see FC 00.22).
- Some oxide and phosphate surface treatments used on contact components to aid run-in and protect from rust can produce intergranular chemical attack at manufacture (FC 00.08) and leave the metal surface (under the coating) unsuited to carry contact loads.
- Electroplating of components, especially of hardened steel components can produce *hydrogen embrittlement* (FC 00.08), which leads to cracking or flaking of the surface.

14.1.4 Distinctive Appearance

Corrosion Staining. On *steel* surfaces, corrosion stains are yellow, brown or blackish areas of random shape and extent. Typically, they obliterate the original finishing lines.

Differentiation from light temper color ("straw color") (FC 00.19) may be based on the greater uniformity of the latter over large surface areas (corrosion stain is usually patchy), and on the fact that light temper color does not obliterate finishing marks. Deeper temper color is bluish and seldom confused with corrosion stain.

Friction polymer deposits tend not to obliterate finishing marks and are confined to contact paths. Corrosion stains tend to be polished off contact paths.

Differentiation of corrosion stain from fretting may be possible by observing the more reddish tint of fretting. However, it is more common to differentiate by location. If the stain is limited strictly to fit interfaces, then it is fretting. If the stain is mostly on free or contact surfaces, then it is corrosion.

On *brass* or *bronze* surfaces, corrosion staining is mostly blackish. On *aluminum* surfaces, corrosion may show either as a white or blackish discoloration; the surfaces are usually pitted.

Corrosion Pitting. Corrosion pits tend to be shallow, irregularly shaped and have a blackish surface which, under magnification, does *not* appear as a fracture surface.

Differentiation from spalls may be based on depth, which is typically greater for spalls. Morphology of spall craters and pits differs significantly, especially for fully developed large spalls with their typical fracture surfaces. The difference between corrosion pits and small spalls is easily obscured by oily or greasy residue left on the component after removal from service. Thorough cleaning with solvents and/or detergents suited to the lubricant residue is necessary. (Removal of some grease thickeners without also removing the corrosion stain may be difficult.)

Differentiation of corrosion pits from pores (casting defects) may be based on two criteria: (1) pores are not surrounded by stain whereas corrosion pits *may* be; (2) on metallographic sectioning, open pores are likely to be accompanied by closed voids away from the surface, whereas corrosion pits are not. Examination of corrosion pits by scanning electron microscopy, including electron beam analysis, may reveal the presence of oxides (if the layer is thick enough) and aid in differentiating from small spalls or noncorrosion pits.

Intergranular Corrosion. Intergranular corrosion is discernible under the microscope, by examining the surface or by examining a metallographic section for outlined grain boundaries.

14.1.5 Causes

Causes of corrosion for different types of machine element are not dissimilar. Rolling bearings, gears and cams all can corrode from the same causes. Differences between bearings and gears arise because materials used in gears span a wider range than in bearings (softer steels, cast iron, non-steel metal, more plastics) and so do gear surface finishes. Bearings more often have their own lubricant supply (grease) which may protect them or, if contaminated, attack them.

Corrosion of Metals. A list of common causes follows.

1. *Water.*

   - *Humid air* (condensation on surfaces);
   - *Liquid water in air* (spray, splash);
   - *Water in the chamber* (defective closure, submersion of chamber, leak in cooling coil, etc.);
   - *Water-contaminated lubricant.* Seawater is a particularly aggressive corrosive agent.

2. *Lubricant chemistry.*

   - *Unsuitable lubricant formulation* (example: aggressive EP additives);
   - *Acidified lubricant* (from chemical decomposition by overheating or exposure to active metal);
   - *Incompatible lubricant and system* (example: yellow metal and some polyester lubricants).

3. *Chemical vapors in atmosphere.*
4. *Corrosive chemicals used in manufacture,* or corrosive decomposition products. Manufacturing coolants, process lubricants, lapping compounds, cleaning fluids, and even anti-corrosion preservatives may contain aggressive contaminants or decomposition products. The reactivity of corrosive chemicals increases with temperature. By contrast, condensate may evaporate at high temperature and corrosion may be prevented.
5. *Galvanic couples* set up between metals with different electrochemical potential in the presence of an electrolyte.

   - *Yellow-metal separators in martensitic steel rolling bearings,* in the presence of (water or acid) electrolyte;
   - *Stainless steel surfaces contaminated with martensitic steel;*
   - *Aluminum alloy* components with unprotected surfaces in contact with steel.

6. *Liquid metal* or *salt* environment is violently corrosive. Liquid metal may be present in some nuclear applications; (molten) salt may splash on a component in some heat treating furnaces.
7. *Cyrogenic fluids* are encountered as working environment in some pump applications. The fluid itself is not corrosive, but it promotes condensation and ice formation and has no rust-protective ability.

Chemical Attack on Non-Metals. Two types of chemical attack on non-metals that are likely to cause corrosion are

- *Incompatible lubricants;* and
- *Atmosphere* specifically aggressive to the material.

Intergranular Corrosion. There are many causes of intergranular damage (see [10]), but relatively few commonly affect contact components. Some of these causes are listed below.

1. *Stress corrosion,* which manifests itself only after stress cycling. An aggressive environment weakens the grain boundaries and they fail in cyclic stressing by extensive intergranular cracking (see FC 00.22). Some observed sources of an aggressive environment are

   - *Acidified lubricant* generated by decomposition of lubricant in service;
   - *Sulphide atmosphere* in service.

2. Some (phosphate) *coatings* applied by an etching process during manufacture produce a differential attack on the grain boundaries (FC 00.08).
3. Hydrogen freed at the surface during heat treatment or plating causes *hydrogen embrittlement,* which preferentially weakens the grain boundaries.

14.1.6 Effects of Corrosion

- Destruction of surface geometry, which causes noise, vibration and inaccuracies.
- Formation of surface defects (pits) which precipitate spalling.
- Promotion of wear. Steel or cast iron corrosion product is not wear resistant. It is readily worn off, making way for further corrosion in a mutually enhancing interaction.

- Enhancement of corrosion. Corroded surfaces produce additional rust faster than uncorroded surfaces begin rusting.
- Enhancement of cracking and fracture. Corroded surfaces crack more readily under stress. Intergranular corrosion activates specific cracking mechanisms (stress corrosion cracking) well below normally tolerated stress levels.

14.2 ELECTRIC EROSION FAILURE CODE: 00.21

14.2.1 Definition

Electric erosion is damage to contact surfaces caused by the passage of electric current.

14.2.2 Nomenclature

Electric erosion failure is also designated *electrical pitting, electric current damage, current erosion* or *spark erosion.*

14.2.3 Failure Process

Electric potential difference, developing between components in Hertz contact, meets resistance at the interface from three sources:

1. A non-conducting EHD lubricant film.
   NOTE: Electrically conductive greases are on the market for use where small currents need to be carried by lubricated contacts. To the extent that they suffice to conduct the intended current without building up a substantial potential drop between the contacting surfaces, they may prevent electric erosion.
2. A non-conducting or poorly conducting adsorbed film of boundary lubricant, surface oxide or other deposit.
3. Constriction resistance at metallic asperity contacts of limited diameter.

If the potential difference is sufficiently high, a current will be carried across the contact interface as a *spark*. Sparking is a highly erosive process to the surfaces across which the spark leaps. The severity of the erosive effect is a function of the current carried and the time of exposure to current. When the electric current density passing between the metal surfaces in the Hertz contact exceeds a critical magnitude (not generally established), it creates cratering by the mechanism utilized in spark machining of metals. Small volumes of surface metal are heated and torn off, probably by evaporation. The surface is locally melted and cratered.

The material in the vicinity of the eroded craters is often *tempered* by heating from the spark, and thus softened. If the heating was greater, *rehardened* material may be present. Rehardening may result in *microcracking*.

Note: The insulating layers formed in Hertz contacts are very thin (of the order of 0.1 μm or less) and the area of each asperity contact is very small (of the order of 10^{-3} mm^2 or less). Therefore, even a modest potential difference of several volts sets up a very high electric field strength across the insulating layer. Likewise, even a modest current passes through the asperity contact at very high current density. Electric erosion can accordingly be initiated by conditions that are quite commonplace. Electric erosion may occur between fit surfaces, although, due to the generally lower resistance of that interface, only very large currents produce it.

Initially, electric erosion results in scattered *pits.* As a result of oscillatory effects which may have both an electrical (charge–discharge) and a mechanical vibratory component (but are not fully

explained), severe electric erosion often concentrates in periodically spaced troughs running transversely to the rolling direction, designated as *flutes*.

14.2.4 Distinctive Appearance

Electric erosion can yield two distinct appearances: electric pitting and fluting.

Electric pitting. Electric pits are usually small, approximately conical craters. Under magnification, their surfaces appear melted. They may require some magnification to be resolved.

Fluting. Advanced electric erosion of rolling surfaces may give them a "fluted" or "washboard" appearance, with periodically spaced depressions running transversely to the direction of contact travel. Microscopically, the troughs or flutes consist of a multitude of densely spaced fine pits. The lands separating the flutes may be more or less undamaged.

14.2.5 Causes

In most cases, transmission of electric current across a Hertzian contact is unintended. However, some small rolling bearing applications may be an exception and a small current may deliberately be directed across the Hertzian contacts. A conductive lubricant may be designed in, but may not be used through oversight, or may not suffice to prevent electric erosion.

Most often, the unintended currents are generated by asymmetries in the stator magnetic field of an electric motor or generator. In these machines, the rotor turns in a strong magnetic field which is the vehicle of power transfer to or from the rotor. Ideally the field is symmetrical to the rotor axis and does not generate potential differences between the contact surfaces of the bearings or gears mounted on the shaft. However, unintended asymmetries may exist or develop in service, and these create the potential differences driving the erosive electric currents across the contacts.

Magnetic fields may unintentionally intersect with rotating parts other than the rotors of electric machines.

Static electricity may build up a potential across the Hertzian contact. In large machinery in which non-conductive material moves rapidly over rotors (textile industry, printing industry, conveyors, etc.), the static electric charges may be great enough and be regenerated at a sufficient rate to maintain damaging currents.

Stray currents resulting from incomplete insulation of intended electrical potentials in a machine may discharge across the Hertzian contacts.

Conduction paths including sliprings and brush assemblies are often provided to direct unintended currents away from Hertz contacts. These devices may fail, exposing the Hertzian contacts to current.

14.2.6 Effects of Electric Erosion

- *Noise* and *vibration* of severe intensity is an early effect of electric erosion. The vibration can reach destructive severity, especially if fluting is present.
- The pits and flutes of electric erosion are severe surface defects from which *galling* (FC 00.13), *spalling* (FC 00.16) or *surface distress* (FC 00.17) may proceed.
- The tempered or rehardened structures surrounding electric erosion pits and flutes are prone to *microcracking* and represent low fatigue strength material.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.20	18.17
00.20.01.1	8.24 14.5 14.12 15.22 16.31
00.20.1	9.17 10.1 14.6 14.10 14.13 14.15 14.21
00.20.1.3	7.10 9.18 10.65 10.70 14.11 14.12 14.13 14.14 18.17
00.20.2	5.15 7.10 14.7 14.8 15.2 18.18
00.20.3	14.15

NOTE: FC 00.21 occurs in no other chapter.

PLATES

DATA

Plate No: 14.1
Archive No: 027-211
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB assembly (2), unrun
Speed:
Load:
Lubrication: grease
Failure Code 1: 00.20.01.1 Generalized corrosion
Failure Code 2: 12.4.4 Grease decomposed by chemical agent
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Both bearings are severely corroded in seawater. Corrosion product is on all exposed surfaces. The grease is discolored and made gritty by chemical decomposition in the presence of saltwater and metal surfaces. The bearings are unusable.
Image Description: The bearing at image W shows heavy dark brown rust on all visible surfaces. The grease is of similar color after decomposition and rust admixture. The bearing at image E shows an earlier stage of seawater corrosion. Steel surfaces are partially covered with rust; the grease is decomposed. Note that the rust color is more brown (less reddish) than the color of fretting corrosion.
Suspected Causes: Seawater is known to have found access to these bearings (in storage). Saltwater is extremely aggressive to steel and also decomposes many bearing greases and rust-preventive slushes.

DATA

Plate No: 14.2
Archive No: 064-701
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: HG; P & W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.1 Corrosion stain
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.16.01.3 Tooth spalling
Failure Code 4: -

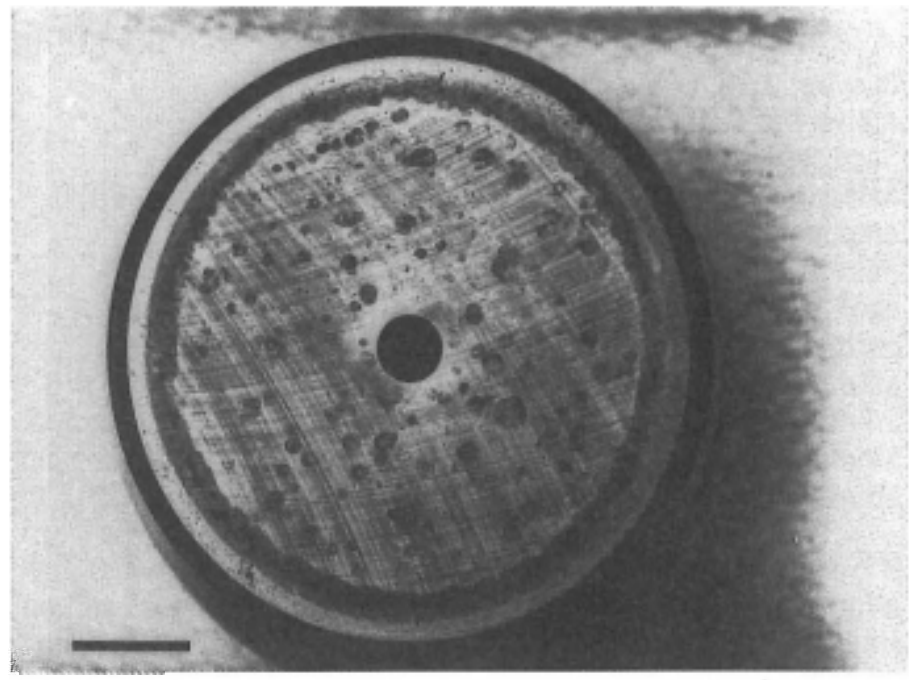
[See Image in Appendix]

DESCRIPTIONS

Failure Description: Corrosion stain spots are in the tooth root radius of pinion. Corroded dents and small spalls are visible on wheel contact surfaces. The corroded indentations and spalls on the contact surface may create a noisy gear and can be sources of more severe spalling and eventually tooth fracture.
Image Description: At N image edge, three tooth flank surfaces of the *wheel* are visible. To the S is the *pinion*. On the wheel, light gray ground flank surfaces show many irregular brown depressions which are dents or small spalls from dents, with corroded bottom. The undented flank surface has worn clean of corrosion. On the pinion, larger, rounded brown marks are corrosion stains in the root radius not subject to wear. The shadow on the two S-most teeth may be a light reflection.
Suspected Causes: Ingress of water into gearbox may cause corrosion staining. The roundish spots on the root radius suggest drops of water on a stationary gear. The dents on the wheel may be due to rolled-over debris and may spall out and/or corrode in the presence of water. Corrosion on the undented contact surface may form, but will wear off in running.

DATA

Plate No: 14.3
Archive No: 093-20.1.2
Image type: view
Scalebar = 6 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; R, black oxide coated, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.1 Corrosion stain
Failure Code 2: 12.4.2 Water droplets in grease
Failure Code 3: 00.12.3.3.2 Wear, centered in sliding contact
Failure Code 4: -

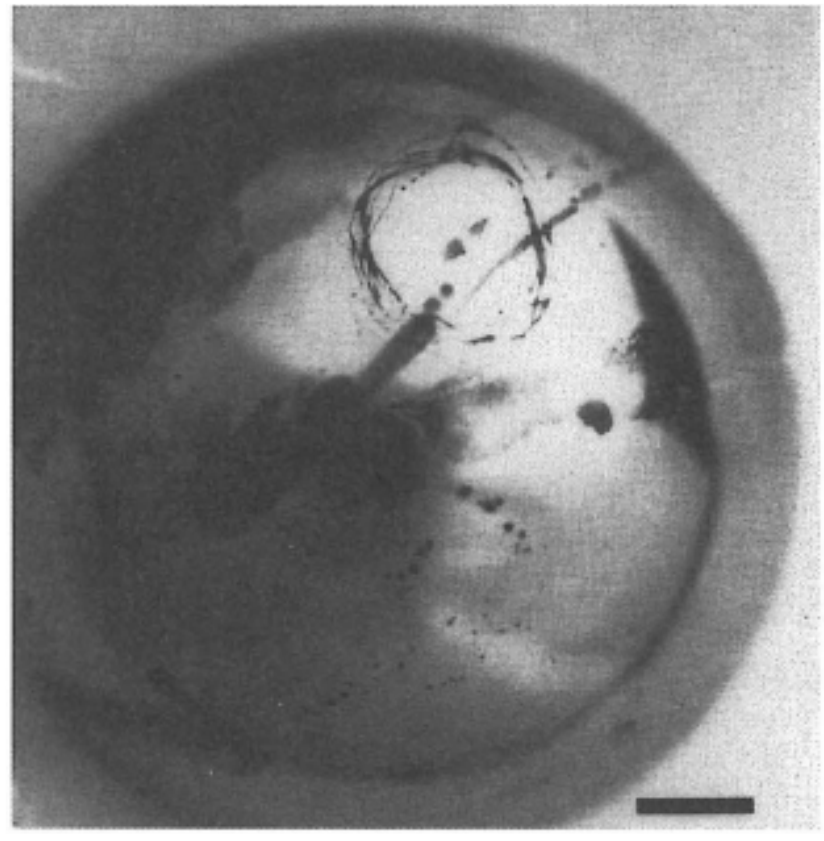


DESCRIPTIONS

Failure Description: A spherical roller thrust face is shown, with scattered, droplet-shaped corrosion stains. Black oxide is seen at the center, and in rings near the endface edge and near the roller OD. The sliding contact areas are worn free of black oxide. Corrosion stains result in lubricant contamination by rust and promote wear. Continued corrosion may form pits acting as failure-initiating surface defects.
Image Description: The roller is black-oxide coated as a run-in aid. Hence the black center spot and OD. On the thrust face, the oxide is polished off by the separator and the guide flange. Proceeding radially from edge: (1) black oxide, (2) wear track from flange contact, (3) dark band of residual black oxide, (4) large area spotted with corrosion stains, (5) black oxide center. Some black oxide streaks are visible in grinding lines across (4).
Suspected Causes: Black oxide coating is a boundary lubricant and corrosion-protective coating used on bearings. In a sliding contact, it wears off during run-in. Corrosion from water droplets in lubricant created the stain spots.

DATA

Plate No: 14.4
Archive No: 018-624
Image type: light macro
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, mounted
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 00.20.1.3 Contact corrosion
Failure Code 2: 00.12.4 Wear of guiding-component support surface
Failure Code 3: -
Failure Code 4: -
See also PLATES: 14.9 and 14.11



DESCRIPTIONS

Failure Description: Small and large corrosion stain spots are visible on ball surface. The small spots are typical of ball corrosion. The large spots appear to follow circumferential wear marks, probably originating from rubbing on the separator during bearing mounting. Corroded balls are prone to early spalling failure. See also Plates 14.9 and 14.11 for ball corrosion.
Image Description: The ball surface reflects dark parts of the lighting apparatus at NW (large area) and at SE along a half-circle concentric with the contour, and the light itself just N of center. Within the bright patch is a black circular pen mark. Small corrosion spots extend S from the ball center. Two faint gray wear bands appear along the great circles, crossing the bright light and the NE dark spots. Large black rust spots are on both wear bands.
Suspected Causes: Due to the fine finish, unworn balls are more corrosion-resistant than other parts of identical material. When corroding in an environment such as water spray, condensation, salt air or acidified lubricant, small stains or pits tend to form. The large rust spots on this ball may be promoted by wear marks from the separator contact. (Large corrosion stains may form preferentially on the roughened surface.)

DATA
Plate No: 14.5
Archive No: 031-1301
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: DRBB; IR, run
Speed:
Load:
Lubrication: grease?, ? °C
Failure Code 1: 00.20.1.3 Contact corrosion
Failure Code 2: 00.20.01.1 Generalized corrosion
Failure Code 3: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 4: -

DESCRIPTIONS
Failure Description: Corrosion pits are in the ball grooves and on the center land. Contact corrosion circles are in one ball groove with spalling outlining the circles. The bearing has failed.
Image Description: Black corrosion deposits are on the E half of the W-facing ball groove and on the center flange. Corrosion pits (with rust worn away) at the bottom of both grooves. Near-circular spalled areas are in the E-facing groove. An isolated spall is in the W-facing groove. The circular outline of heavily spalled areas is the boundary of contact corrosion circles surrounding the balls. The corrosion pitting precipitated the spalling within these circles.
Suspected Causes: This bearing operated in a paper machine. Water (steam) ingress into the bearing causes contact corrosion. Spalls initiate at the corrosion pits, outlining the water-contaminated area bounded by a fluid meniscus surrounding a ball contact. Circular, rather than elliptical spot suggests gel-like lubricant such as grease. Generalized corrosion occurred away from the contact areas.

DATA
Plate No: 14.6
Archive No: 018-101
Image type: view
Scalebar = 90 mm (micros: +20%, others: +100%, −50%)
Component: SRB; IR & OR & R, unrun
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.1.3 Contact corrosion
Failure Code 2: 00.20.1 Corrosion stain
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Corrosion stain ‘haloes’ at each roller contact on both rings and on the mating roller ODs. The stain is darkest at the contour of the haloes where the lubricant meniscus and the humid air meet. The bearing is runnable but likely to fail early from spalling.
Image Description: Angular-shaped ‘haloes’ at each roller/OR contact show dark contour and occasional dark centerline. The haloes are rectangular on the S row of the IR and triangular on the N row, due to unequal roller loading in the bearing as it rested on its side during storage. Stains on center flange thrust surface are barely visible. The roller endfaces and flange OD are stained.
Suspected Causes: Storage of SRB in humid atmosphere without adequate corrosion protection permits moisture to collect at the meniscus of lubricant forming around the contacts. The existence of contacting metal bodies (enhanced by a separator of different metal) sets up an electric potential gradient accelerating the corrosion.

DATA

Plate No: 14.7
Archive No: 080-104
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: HG; P, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.1.3 Contact corrosion
Failure Code 2: 00.20.2 Corrosion pitting
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: The tooth flank surfaces of the gear are covered by small scattered corrosion pits, with clean metal surface between them. No pitting is visible on the gear OD. This type of corrosion is attributed to an aggressive substance in the lubricant, such as an aggressive EP additive, acting chiefly in the high pressure contact environment. The gear is not failed but may spall prematurely or deteriorate further if the corrosive environment continues.
Image Description: The image is of a portion of a helical pinion with integral shaft. All contact surfaces show evenly scattered fine brown-black corrosion pits. The gear OD shows no pits, just circumferential machining marks (which may be corroded).
Suspected Causes: EP additives in some gear oils may become aggressive if water is admixed or temperature is excessive. They corrode the steel, especially where high local temperatures arise due to contact loading and sliding.

DATA

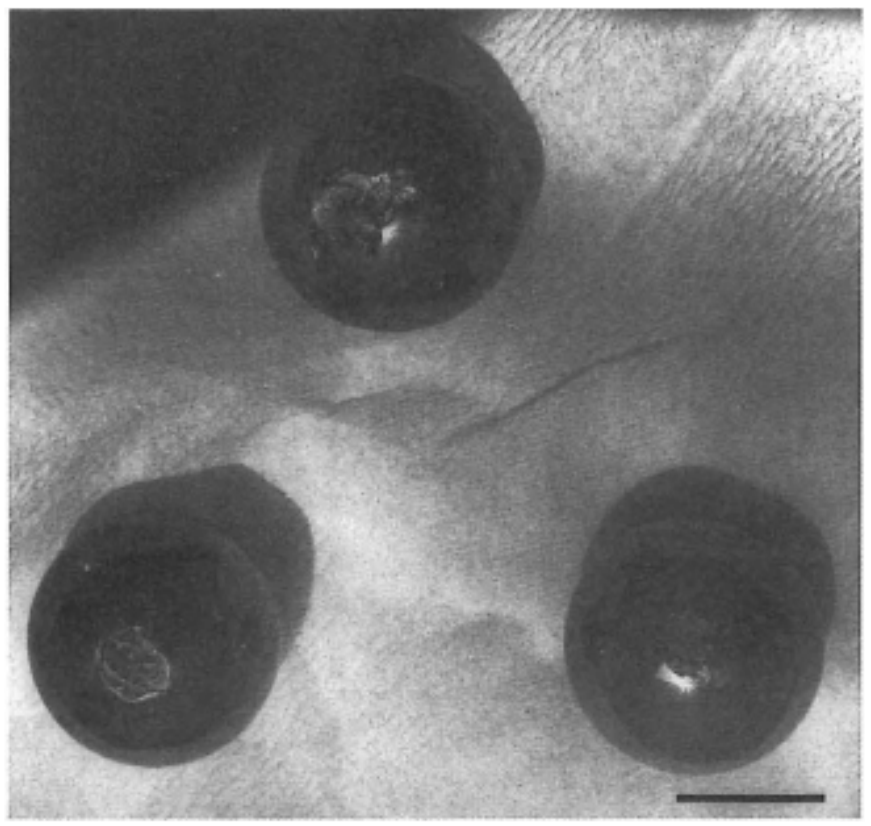
Plate No: 14.8
Archive No: 031-1101
Image type: view (partial)
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubricant: mineral oil, ? °C
Failure Code 1: 00.20.1.3 Contact corrosion
Failure Code 2: 00.20.2 Corrosion pitting
Failure Code 3: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 4: 00.12.4 Wear of guiding-component support surfaces

DESCRIPTIONS

Failure Description: Numerous contact corrosion streaks are visible at roller spacings with more than one roller set position. Corrosion pits appear in and outside the contact areas. Spalls follow the contact corrosion outlines. Circumferential wear marks are on the separator guide surface (OD) of the center flange. The bearing has failed.
Image Description: OD of SRB IR (partial view), showing both roller paths and three flanges. Rectangular axial bands extend across both roller paths where the original surface is destroyed. Black corrosion pits are in and outside the bands. Spall craters follow straight edges of the contact bands on the roller path facing image N. Circumferential (shiny) wear marks are on the OD of the center flange.
Suspected Causes: This bearing operated in a paper machine. Water (steam) ingress into the bearing causes contact corrosion outlining the area within the fluid meniscus adjacent to each contact. Spalls initiate at the corrosion pits concentrated within the liquid-filled area near the contacts. Wear on the separator guide surface may be due to abrasion by debris.

DATA

Plate No: 14.9
Archive No: 087-117
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.16.03.2 Spall propagating by re-initiation at surface
Failure Code 4: -
See also PLATES: 14.4 and 14.11

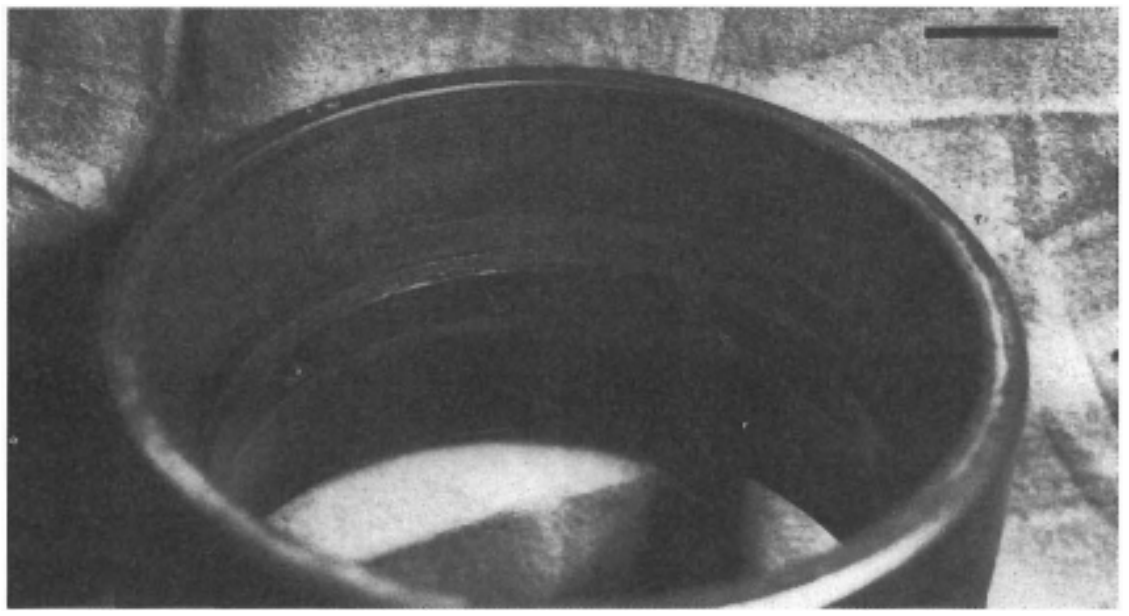


DESCRIPTIONS

Failure Description: Dense corrosion pitting on balls has precipitated spalls on each. Irregular propagation suggests multiple spall starts from several corrosion pits. The balls have failed.
Image Description: Fine corrosion pitting on all three balls, best seen near the contour, where dark spots contrast with reflection from the white background. Corrosion is most advanced on the ball at image N, least on the ball at image SE. One spall crater is visible on each ball; the most advanced is on ball at N, which shows several initiation points with ridges dividing the crater bottom.
Suspected Causes: Due to fine finish, unworn balls are more corrosion-resistant than other parts of identical material. When corrosion occurs in an environment such as water spray, condensation, salt air or acidified lubricant, small stains or pits tend to form. Pits are major sources of early spalling. See also Plates 14.4 and 14.11.

DATA

Plate No: 14.10
Archive type: 031-502
Image type: view
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: TRB (multirow); OR, run
Speed:
Load:
Lubrication: mineral oil, ? °C
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.20.1 Corrosion stain
Failure Code 4: 02.13 Rubbing seal counterface wear

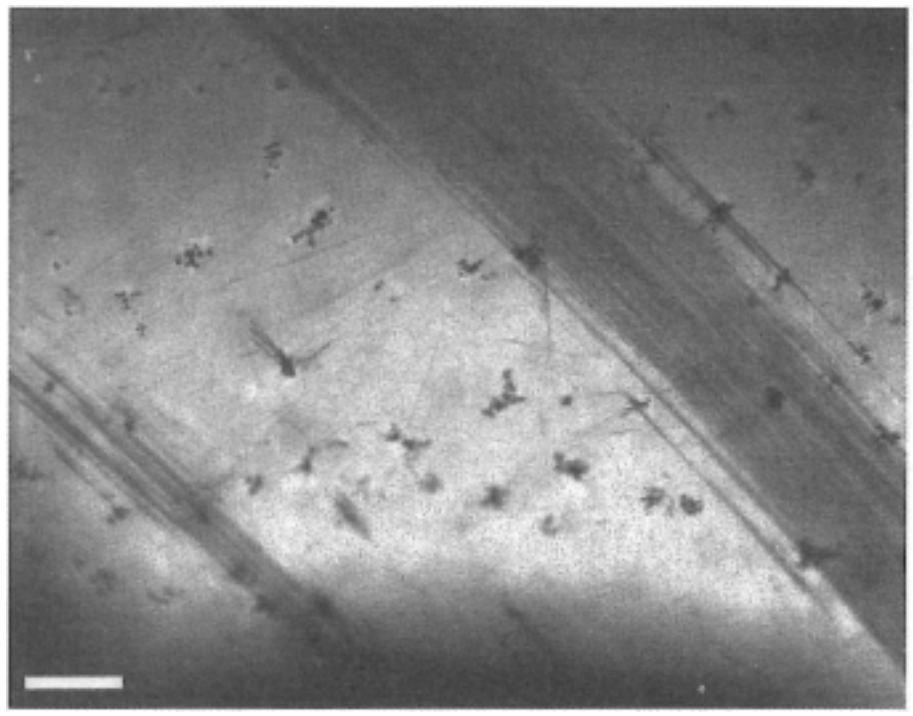


DESCRIPTIONS

Failure Description: Generalized corrosion of free surfaces (stains) and contacts (pits) with subsequent extensive spalling composed of small craters emanating from pits. Spalling covers the rolling contact surfaces. The flange contact surface is heavily corrosion pitted, and may be galled. The bearing may still turn but has no useful life left.
Image Description: The ring sideface (facing image N) and the ID of the center flange (with oil holes) show dark corrosion stains. The roller path is densely peppered with pits and spalls (details not discernible in the image) indicating corrosion followed by spalling. The N-facing thrust face of the center flange is corrosion-pitted, and may be galled. On the contact surface, adjacent to the N edge, circular wear bands are visible, which may be due to seal wear.
Suspected Causes: This bearing operated in a paper machine, in wet environment. Water ingress (possibly steam) past damaged seal, caused corrosion, followed by spalling. On the flange thrust surface pits and rust are visible, and galling is suspected.

DATA

Plate No: 14.11
Archive No: 001-10
Image type: light microgram
Scalebar = 400 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, run
Speed: 1 MdN
Load: ? (axial)
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.20.1.3 Contact corrosion
Failure Code 3: 00.12.4 Wear of guiding-component support surface
Failure Code 4: -
See also PLATES: 14.4 and 14.9



DESCRIPTIONS

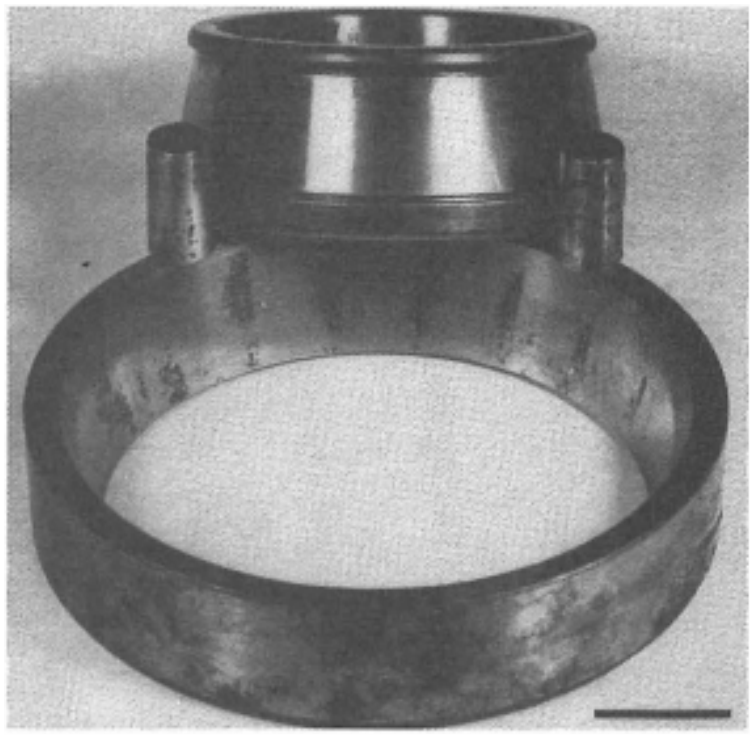
Failure Description: (1) Random corrosion pits on ball surface; (2) parallel scratchmarks along a great circle and a nearby minor circle, inflicted later than the corrosion pits. Exposure to an aggressive environment caused by corrosion. The scratchmarks appear to be due to contact with abrasive particles of asperities in the separator. This is incipient failure in a high-speed bearing. See also Plates 14.4 and 14.9 for ball corrosion.

Image Description: Gray background is ball surface. Lapping marks are not visible. Clusters of dark spots are corrosion pits. The band of dark parallel arcs across the NE image quadrant consists of scratchmarks. Similar bands are in the SW quadrant. Centered between the two sets of bands is one corrosion pit from which scratches in identical direction emanate, showing that scratches covering pits or emanating from a pit were made after the pits had formed.

Suspected Causes: Due to the fine finish, balls are intrinsically more corrosion-resistant than other parts of identical material. When corrosion occurs in an environment such as water spray, condensation, salt air or acidified lubricant, pits, rather than stains tend to form. The scratch marking appears to be caused independently of the corrosion, except where it originates at a pit that may have provided corroded debris.

DATA

Plate No: 14.12
Archive No: 014-13
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR & OR & R, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.20.1.3 Contact corrosion
Failure Code 3: 00.20.01.1 Generalized corrosion
Failure Code 4: -
See also PLATES: 14.5, 14.6 and 14.12



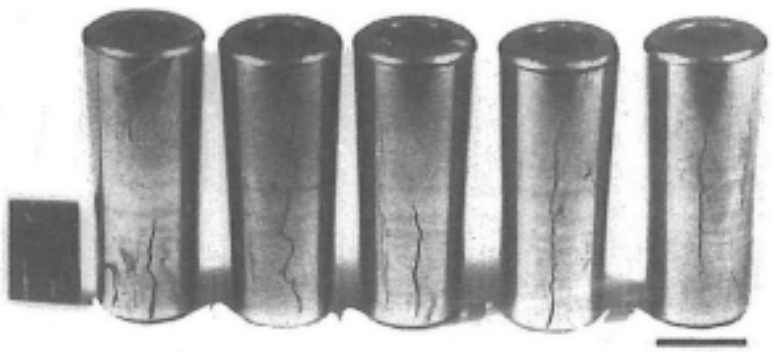
DESCRIPTIONS

Failure Description: In the OR roller path, on the rollers and (less) on the IR roller path, axial bands of macroscopic corrosion pits have formed from trapped condensation surrounding the stationary contacts. On the OR OD, general corrosion and/or fretting is visible. Corrosion is diagnosed because of the random, spotty appearance extending across the entire OD width. Contact corrosion pits form severe spall-initiating surface defects. See Plates 14.5, 14.6 and 14.12, for comparison.

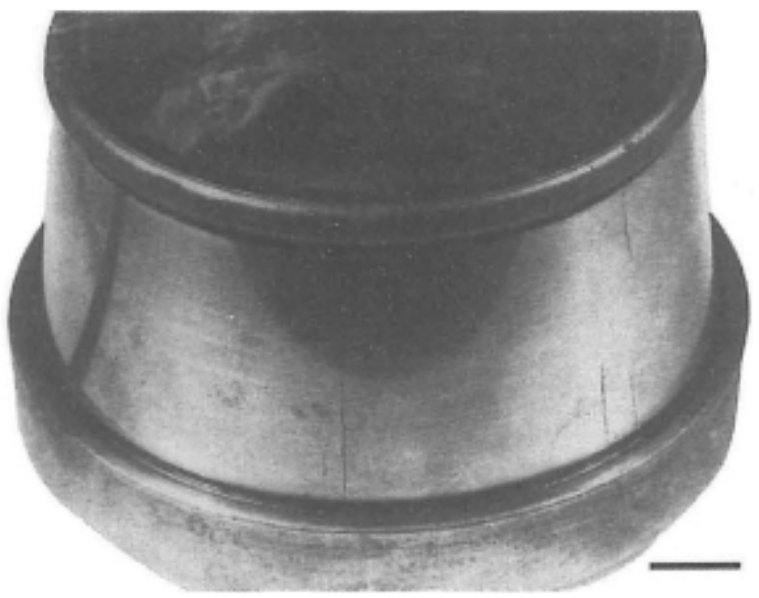
Image Description: An IR ('cone') at image N is flanked by two rollers. The OR ('cup') is at image S. Corrosion pit bands at roller spacing are near N (small) edge of IR track and at extreme E. Many pit bands are on the roller OD. Heavy bands appear at roller spacing in the OR track. The OR OD is diffusely rust stained. (Fretting is possible but less likely across full width and in small diffuse spots. In color view, fretting tends to be more red; corrosion more blackish.)

Suspected Causes: This bearing was grease lubricated and used in a road vehicle wheel. Condensation may accumulate at contacts when vehicle stands in the cold, and produce the staining if grease is unsuitable to protect contacts.

DATA
Plate No: 14.13
Archive No: 014-19&20
Image type: a, b: view
Scalebar = a, b: 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB: IR & R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.20.1.3 Contact corrosion
Failure Code 3: 00.20.1 Corrosion stain
Failure Code 4: 00.15.1.1 Generalized fretting, radial fit surface
See also PLATES: 14.6 and 14.12



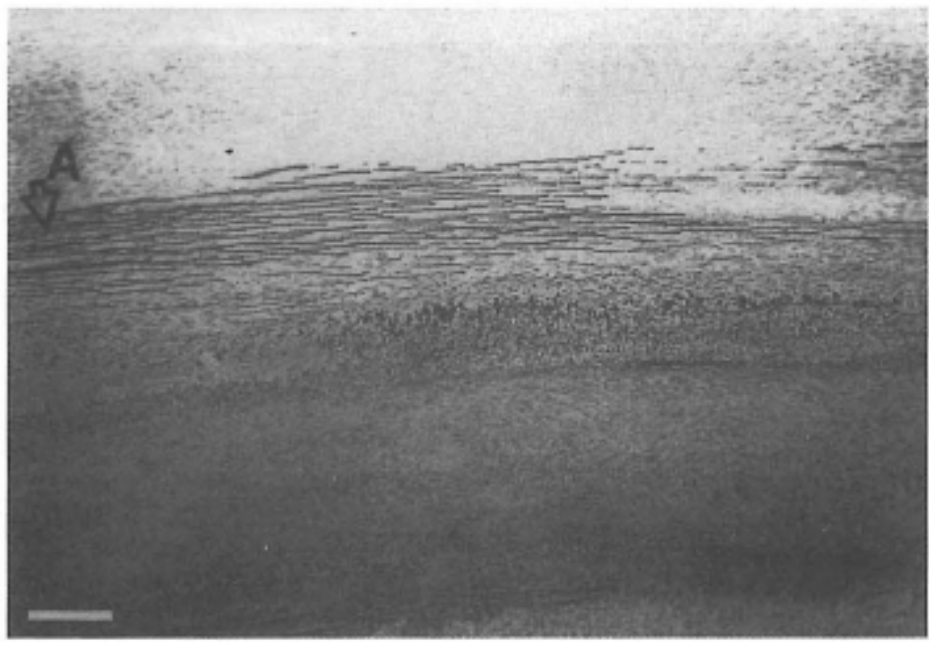
a



b

DESCRIPTIONS
Failure Description: Thin wavy lines of corrosion micropitting are on the IR ('cone') and the roller contact surfaces. Compared to Plate 14.6, the corrosion pitting indicates more aggressive (or more long-term) corrosion over small surface areas. There are some corrosion stains. Pits are spall-initiating surface defects. Early spalling failure is expected. Incidental fretting is present in IR ('cone') bore. See also Plate 14.12 illustrating significant TRB corrosion.
Image Description: (a): rollers with wavy axial dark lines formed by corrosion micropits (discernible under magnification). Some diffuse corrosion staining is visible near N end of rollers. (b): Thin, straight dark lines formed by corrosion pits near S roller path edge in image center and 1/5 from image E. Minor staining exists at image W. Broad curved dark band at W is artifact. Heavy dark spotting in the bore is fretting.
Suspected Causes: If an aggressive agent (water, acidified preservative or lubricant) enters contacts in small quantity but remains in place for long, localized corrosion pitting may develop. Lesser concentrations may cause stains. Heavy bore fretting indicates that the bearing ran extensively. Corrosion may be a late occurrence; otherwise spalls would have formed.

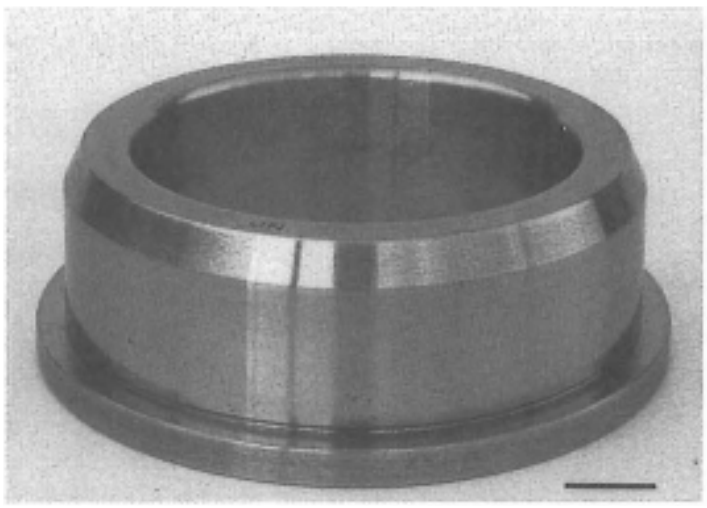
DATA
Plate No: 14.14
Archive No: 093-20.1.4
Image type: light micrograph
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.20.1.3 Contact corrosion
Failure Code 3: 11.2 Water in oil
Failure Code 4: -



DESCRIPTIONS
Failure Description: The lubricant in this SRB contained a modest concentration of water which formed fine droplets on the stationary contact surface. It appears that a small amount of relative motion took place in the contact. Where pure rolling occurred, the droplets formed round pits. Where a sliding component existed, the points were smeared out into streaks. Extensive corrosion produces many spall-initiating surface defects.
Image Description: Image shows SRB IR roller path with rolling direction E–W. At image S, dark points densely pepper the surface. Progressing to N, they coalesce into bands and then, near *A* into individual streaks about 600 μm long. It is assumed that water droplets in oil were wiped over the surface by sliding.
Suspected Causes: Water in the lubricant is a serious source of corrosive attack when its concentration exceeds a maximum dependent on the ability of the lubricant's anti-oxidant to prevent corrosion. Corrosion pits cause loss of contact fatigue resistance.

DATA

Plate No: 14.15
Archive No: 087-102&103
Image type: a: view, b: light micrograph
Scalebar = a: 10 mm, b: 500 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, unrun
Speed: -
Load: -
Lubrication: -
Failure Code 1: 00.20.2 Corrosion pitting
Failure Code 2: 00.20.3 Corrosive fingerprint-mark
Failure Code 3: 00.20.1 Corrosion stain
Failure Code 4: -



a



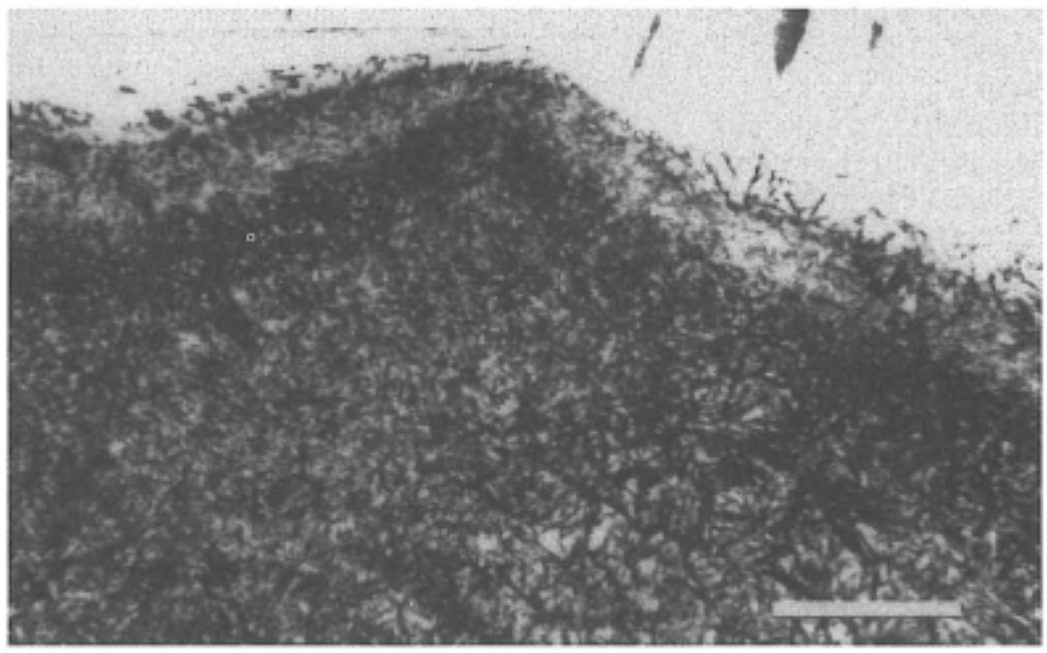
b

DESCRIPTIONS

Failure Description: Incipient corrosion pitting on contact surface of unrun IR due to inadequate preservation for existing humidity. Corrosion pits (as distinct from stains) have significant depth and form serious spall-initiating surface defects. In bore, light staining is visible, and possibly fingerprint marks.
Image Description: (a): Roller path of IR is at the image center; undercut and guide flange to the S. Dark spots at the image center near undercut and 1/5 from W contour are corrosion pits. Irregular fine stain is near N edge of roller path, (1/5 from W contour) and on flange contact surface, at W. Fingerprint-shaped stains are visible in the bore, near image centerline. (b): Corrosion pitting on surface. Pit contains oxides, the depth is not resolved. There are E–W finishing lines.
Suspected Causes: Inadequate rust preventive for the humidity condition prevailing at storage permits corrosion stains or (if exposure is longer) pits. Water droplets in grease (FC 12.4.2) are likely sources of pitting. Pits may have significant (several μm) depth, which becomes apparent in efforts to remove the corrosion by light polishing. Fingerprint marks arise from human touch of degreased steel surfaces.

DATA

Plate No: 14.16
Archive No: 014-145
Image type: light metallogram. Nital etch.
Scalebar = 40 μm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.21.1 Electric erosion pitting
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 14.21 and 14.22



DESCRIPTIONS

Failure Description: The material was overheated in electric erosion damage. A rehardened layer has formed at the pit bottom surface; and an overtempered layer is beneath that. Electric erosion creates extremely noisy bearings which tend to fail rapidly by spalling, or (in case of fluting) seizure or separator fracture. See Plates 14.21 and 14.22 for the appearance of eroded surfaces.
Image Description: The image is an etched metallographic section through the electric erosion-damaged part. The white area at image N is protective plating applied for examination. The scalloped interface adjacent to the white area represents two eroded pits. Light-etching crescents S of surface are rehardened. Dark etching crescents next S of these are overtempered. Normal material extends to S image edge.
Suspected Causes: Electric current passing through the rolling contacts of a bearing (with insulating lubricant) makes sparks which erode (melt) the surface. Depending on current intensity, fine pitting, gross pitting or fluting may result.

DATA
Plate No: 14.17
Archive No: 027-165
Image type: light macro
Scalebar = 5 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed: 100 KdN
Load: <1.6 GPa
Lubrication: grease, 60°C
Failure Code 1: 00.21.1 Electric erosion pitting
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: A band of fine electric erosion pits is in the IR ball groove. A cluster of incipient surface-origin spalls was initiated by some of the pits. Additional spalls are likely to be initiated from other pits. The bearing has failed as spalling is expected to progress rapidly.
Image Description: The dark area of the image is the ball groove. There are reflected highlights near E and W image edges and a reflected light streak below letter *B*. One land faintly visible above *B*. An extensive band of fine electric erosion pits is marked by arrow *A*. Fan-shaped (surface origin) spall craters are at arrow *B* and to the W.
Suspected Causes: Electric current passing through the rolling contacts of a bearing (with insulating lubricant) makes sparks which erode (melt) the surface. Depending on current intensity and other variables, fine pitting (as shown), large pits or 'flutes' (axial bands of pitting) may be caused. Pits are serious spall-originating surface defects.

DATA
Plate No: 14.18
Archive No: 027-179
Image type: light macro
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed: 110 KdN
Load:
Lubrication: grease, 60°C
Failure Code 1: 00.21.1 Electric erosion pitting
Failure Code 2: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 3: 00.16.02.4 Incipient spalling, multiple spalls
Failure Code 4: -

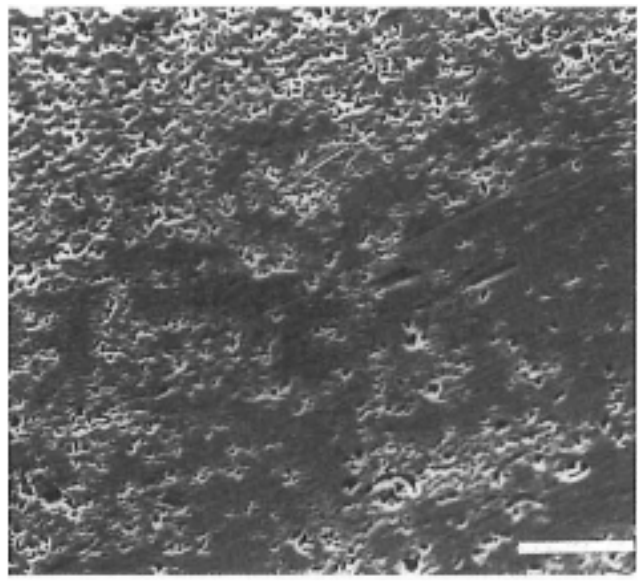
DESCRIPTIONS
Failure Description: A line of electrical pits from passage of moderate current, with possible incipient spalling, is visible along a great circle. The bearing is very noisy and the separator will wear. Spalling failure is imminent.
Image Description: The ball appears dark in the image, with multiple bright light reflections. An E–W band of pits is indicated by two arrows. Some of the pits appear irregular as if spalls had been initiated.
Suspected Causes: Electric current passing through the rolling contacts of a bearing (with insulating lubricant) makes sparks which erode (melt) the surface. Depending on current intensity, fine pitting may occur (as shown). With other current densities and operating conditions, large pits or 'flutes' (pitted axial troughs) may form. Pits are serious spall-originating surface defects.

DATA

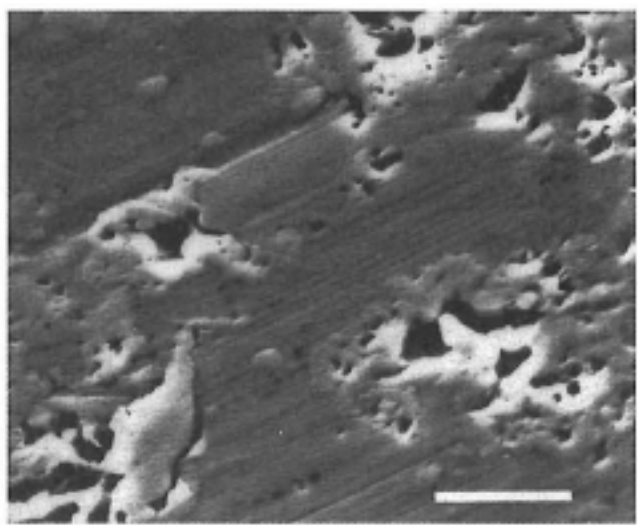
Plate No: 14.19
Archive No: 107-006a&b
Image type: a, b: SEM
Scalebar = a: 50, b: 10 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication: oil, 50°C
Failure Code 1: 00.21.1 Electric erosion pitting
Failure Code 2: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 3: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 4: -
See also PLATES: 14.17 and 14.23

DESCRIPTIONS

Failure Description: Microscopic pitting of contact surface through long-time passage of small current. Raised pit edges are being rolled down (surface glazing). The surface has suffered damage comparable in its effect to surface distress (asperity-scale spalling) and is prone to early spalling failure. The few wearmarks are incidental.
Image Description: (a): Background is dark gray rolling surface. Finishing lines run SW–NE. Many dense, small, black-centered electric erosion pits with light (raised) rims are visible. Near image center E, are two short deep wear scratches. (b): High magnification. Gray rolling surface shows darker, SW–NE running finishing lines. Black irregular electric pits with surrounding raised (light color) edges, which are rolled down by contact passage. There are no fracture surfaces as found in spalls.
Suspected Causes: Electric current passing through the rolling contacts of a bearing (with insulating lubricant) makes sparks which erode (melt) the surface. Depending on current intensity, fine pitting (as shown, see also Plate 14.17) or massive fluting (see Plate 14.23) may result.



a



b

DATA

Plate No: 14.20
Archive No: 107-005a&b
Image type: a, b: SEM
Scalebar = a: 1 mm, b: 100 μm (micros: +20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.21.1 Electric erosion pitting
Failure Code 2: 00.18.1.2 Sharp individual dent(s) from metal debris, asperities
Failure Code 3: 00.16.1.2.1 Shallow entry spall from surface point-defect
Failure Code 4: -
See also PLATE: 14.23

DESCRIPTIONS

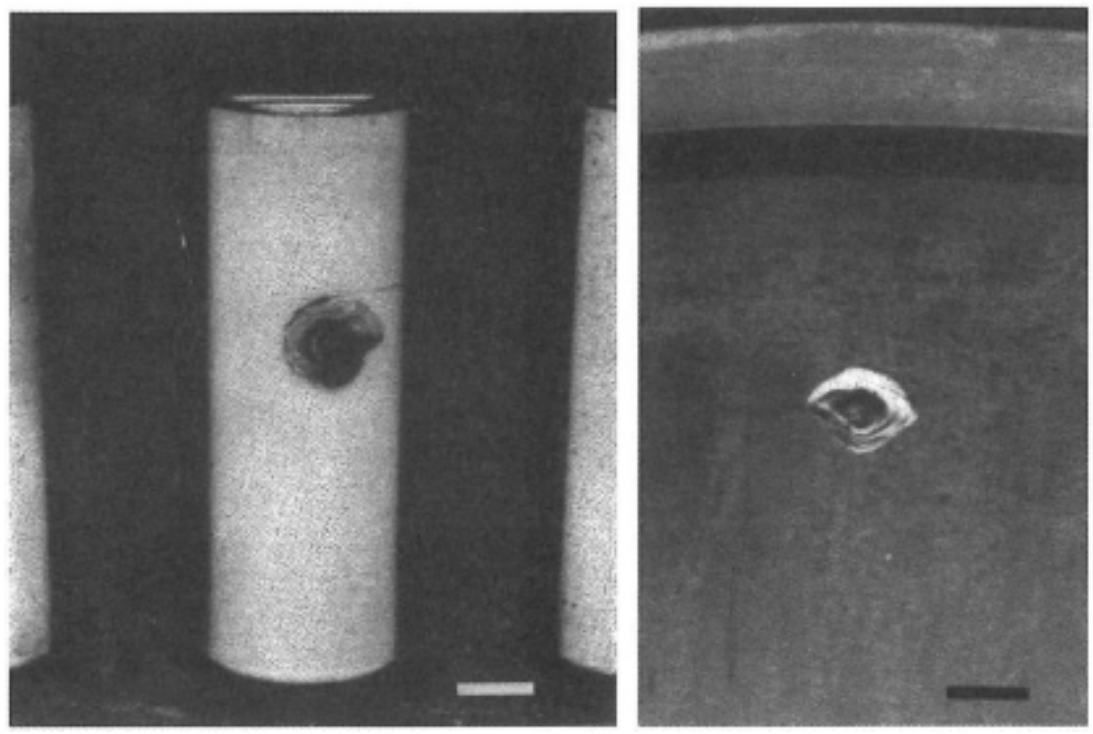
Failure Description: (a): Circular platelets of surface material were removed by electric current passage through the contact. Sharp-edged cratering was caused by local melting. Removed platelets were rolled over to form circular dents. (b): Erosion craters with rolled-down edges are shown, possibly starting to spall. A platelet begins to form. Pits from electric current erosion are major noise sources and tend to lead to very early spalling.
Image Description: (a): The dark gray background is the rolling surface with finishing lines running N–S. Identical-sized circular light and dark spots are dents of about 200 μm diameter. (b): Near center of S image edge: remelted erosion pit with striated bottom and raised loosened platelet at S. Flat circular depressions in SE, NW and SW quadrants are dents. At image N are erosion pits, with rolled-down edges. These possibly initiate spalls.
Suspected Causes: Electric current passing through the rolling contacts of a bearing (with insulating lubricant) makes sparks which erode (melt) the surface. Depending on current intensity, fine pitting (as shown) or massive fluting may result. See Plate 14.23.

a

b

DATA

Plate No: 14.21
Archive No: 014-70&71
Image type: a: view; b: light macro
Scalebar = a, b: 5 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; a: R&G; b: IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.21.1 Electric erosion pitting
Failure Code 2: 00.20.1 Corrosion stain
Failure Code 3: -
Failure Code 4: -



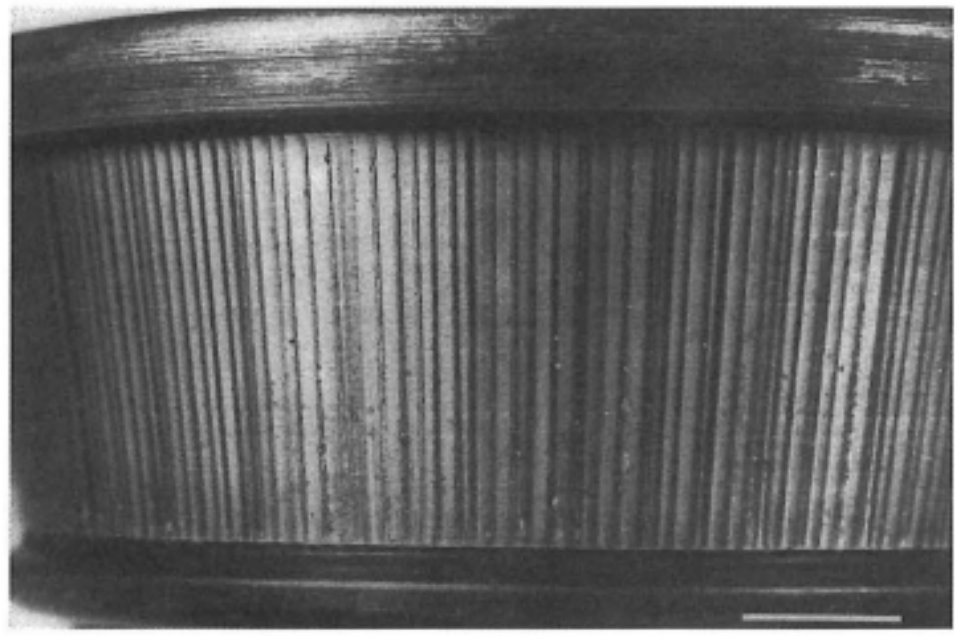
a b

DESCRIPTIONS

Failure Description: One large electric erosion pit each is in the roller and the IR, due to one-time passage of high-intensity current in the stationary bearing. Incidental corrosion staining is visible on the IR. The bearing has failed.
Image Description: (a): The rollers appear light gray in the dark stamped-steel separator. On the center roller, midway along the contact is a large, circular dark pit with raised rim. (b): IR ('cone') roller path with the thrust flange at N image edge. At image center, is a large pit matching that on image (a). The rim of the pit is raised. Incidental corrosion stain streaking appears on the roller path.
Suspected Causes: This bearing supported a rotor on which electric arc welding was performed while grounding the machine through the stator. The full welding current passed through the bearing, creating massive electric sparking and erosion pitting. The bearing is unusable.

DATA

Plate No: 14.22
Archive No: 014-68
Image type: light macro
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.21.2 Electric erosion fluting
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 14.23



DESCRIPTIONS

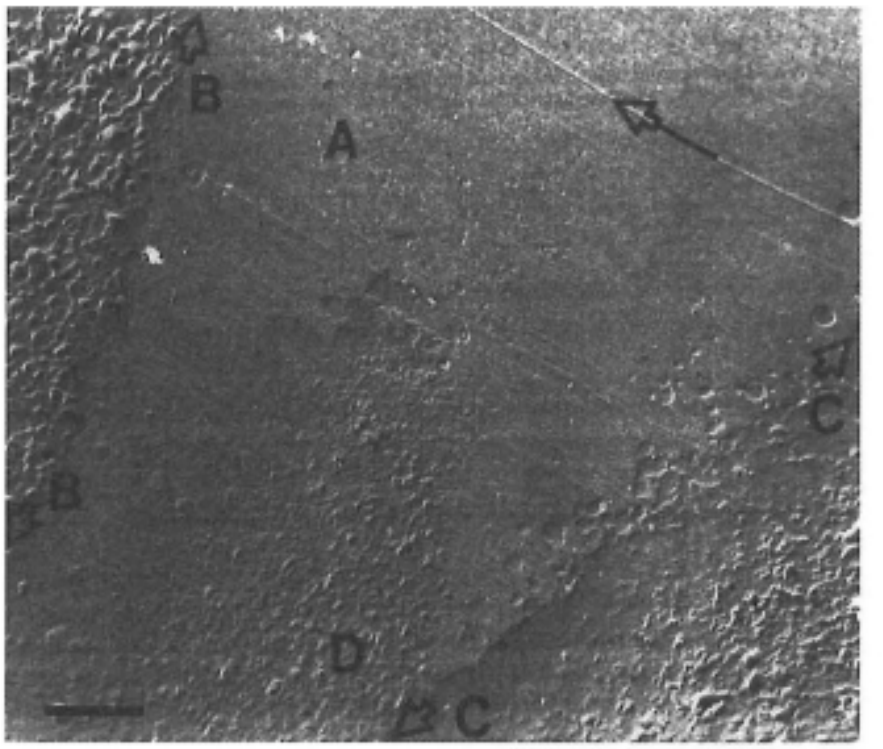
Failure Description: 'Fluted' electric erosion damage is shown,
with transverse depressions in rolling surface, in which considerable pitting took place, alternating with relatively undamaged bands between flutes. Fluting requires continuing current flow above a minimum strength. Fluting erosion creates extremely noisy bearings which tend to fail rapidly by seizure or separator fracture. See Plate 14.23 for detailed appearance of the fluted surface.
Image Description: At the N image edge is the thrust flange ('large-end rib') of a TRB OR ('cone'); at the S edge is the small-end flange (rib) and undercut. Between these, the roller path is covered by approximately periodic sharp-edged axial valleys ('flutes') of 1–3 mm width and extending completely across roller path.
Suspected Causes: Fluting under electric erosion is not fully explained. Apparently, vibratory conditions lead to concentration of current flow at minimum surface separation points occurring during the vibration and flutes form there. Less current flows near maximum separation points. Existence of flutes apparently locks in the vibration phase so that fluting is reinforced. See magnified images of flutes in Plate 14.23.

DATA

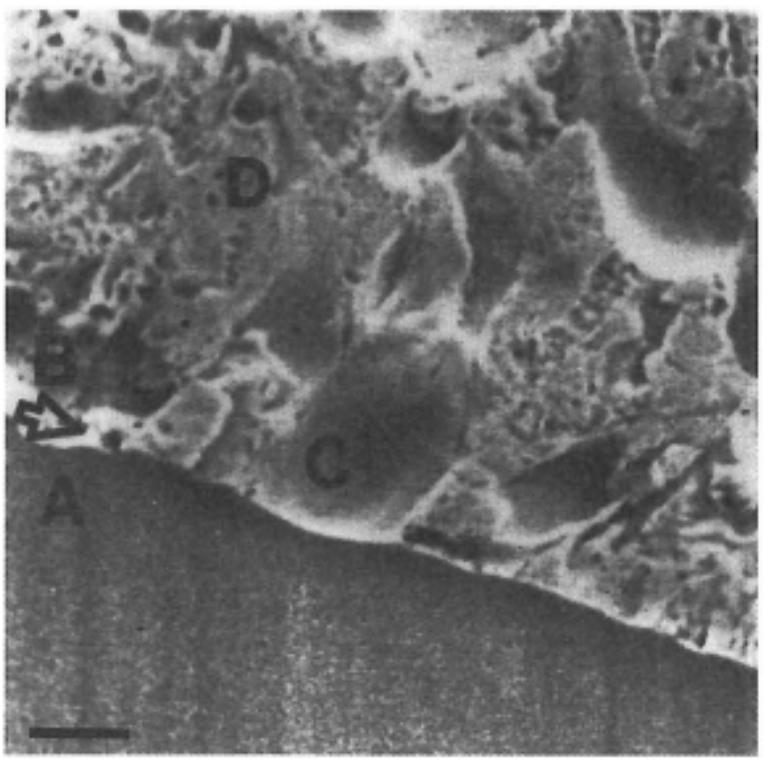
Plate No: 14.23
Archive No: 093-21.1.8&7
Image type: a: SEM, b: SEM with section
Scalebar = a: 250, b: 8 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.21.2 Electric erosion fluting
Failure Code 2: 00.17.1.1 Glazing (incipient surface distress)
Failure Code 3: -
Failure Code 4: -
See also PLATE: 14.22

DESCRIPTIONS

Failure Description: 'Fluted' electric erosion damage with transverse depressions in rolling surface. There is dense cratering in flutes, and no damage or damage of considerably lower depth between flutes. The crater bottoms in the flutes are molten surfaces; crater edges have been rolled over and are surface-distressed. Fluting creates extremely noisy bearings which tend to fail rapidly by seizure or separator fracture.
Image Description: (a): Portion of a ball groove. The surface at *A* is unfluted. Finishing marks and rolling direction run along the arrow in NE corner. The leading edge of a flute is at *B–B*, with craters extending to the NW. SE of line *C–C* is the trailing edge of another flute, with cratering. There is minor damage at *D*. (b): A section plane begins at *A*; the edge of the fluted surface is at arrow *B*. A molten crater bottom is at *C*; raised, overrolled, glazed rims are at *D*.
Suspected Causes: Fluting from electric erosion is not fully understood. Apparently a vibratory occurrence concentrates current along the thinner film areas, forming flute bottoms. The existence of flutes appears to lock in the vibratory phase so that flutes are reinforced. For appearance of the fluted surface, see Plate 14.22.



a



b

BULK CRACKING, FRACTURE, PERMANENT DEFORMATION 15

Failure Code 00.22–23

15.1 BULK CRACKING OR FRACTURE FAILURE CODE 00.22

General Note on Ceramics. Ceramics, especially silicon nitride, are used as Hertz contact components. Ceramics as a class are crack-sensitive due to their relative brittleness compared with metals. Non-experimental use of ceramic Hertz contact elements accordingly favors components such as rolling bodies (balls and rollers) and gears integral with stub shafts, in which bulk tensile stresses are minimized and which therefore do not tend to form bulk cracks in service. As a result, documented cracking failures of ceramic Hertz contact elements in service are not available for use in this Atlas, and thus the cracking of ceramics is addressed in this text, but not illustrated. Refer to FC 00.01 for nicking (chipping) of ceramic components, which represents local (but not bulk) cracking.

15.1.1 Definition

In a contact component, *bulk cracking* designates cracks extending beyond the stress field of the Hertz contact. Bulk fracture is fracture leading to separation of a volume of material by a bulk crack. Examples of bulk cracks and fractures of Hertz contact components follow.

1. *Rolling Bearings and Cams*

   - Cracks starting in the contact zone but extending in depth into the component, beyond the Hertzian stressed volume.
   - Cracks of integral flanges; fracture of flanges.
   - Cracks of an entire cross-section; breakage of component into separate pieces.

Note: Cracking of bearing separators is covered under FC 01.1.

2. *Gears*

   - Tooth cracking (bulk); tooth fracture.
   - Cracking or fracture of gear body (web or hub).
   - Cracking of spline (tooth or body).

Note: Cracking or fracture of integral shafts, away from the gear itself, is covered under FC 22.

15.1.2 Diagnostic Objective

Bulk cracking and fracture are, by far, the most common *ultimate* failure modes in mechanical components as a broad class. The causes and types of cracking are a wide field of study [10]. In this Atlas, the description of bulk cracking and fracture of contact components is limited to cases encountered as service failures of these tribological components.

Engineering diagnosis is aimed at the identification of engineering causes for failure. When diagnosing cracking, three questions must be answered to identify causes:

1. *Basic cracking mechanism:* Is the cracking initiated by overload, fatigue or chemical attack? (This is diagnosed from the crack surface topography.)
2. *Crack propagation direction*: Where did the stress field initiating the crack operate and in what direction did it drive the crack? (This is diagnosed by identifying the crack origination point and observing marks of crack growth.)
3. *Crack age*: How much of the crack is recent and at what rate did it propagate? (This is diagnosed from the oxidation and wear condition of the crack surfaces.)

15.1.3 Nomenclature

There are no designations other than "cracking" and "fracture" for this failure mode. However, there is a large number of differentiating adjectives for failure mechanisms, fracture appearances, etc. To avoid repetition, these are identified in the description of the failure process which follows.

15.1.4 Failure Process

Cracking may be categorized, according to its cause, as mechanical stress cracking, thermal stress cracking, and chemically promoted cracking.

Mechanical Stress Cracking. This category includes both overstress (ductile and brittle) and fatigue cracking, which are often intermingled.

Rolling Bearings

1. *Cracking under* (tensile) *hoop stress* occurs in rings interference-fitted on shafts and in the rotating innerrings of high speed bearings, due to centrifugal forces.

   If excessive, hoop stress alone may cause fatigue or even overload cracking, starting at a nick or edge in the bore or the rolling track. A lesser tensile hoop stress may divert a fatigue crack starting from Hertzian stressing into progressing radially inward, so that a bulk crack rather than a spall forms.
2. *Cracking under bending stress*. Rings may be under bending stress if their mounting part (shaft or housing) is thin, soft, distorted or interrupted (for example, by a hole or keyway). *Balls* or *rollers* may be under bending stress if the balls are hollow, or if the rollers are drilled or axially mislocated, so that they overrun the track edge.
3. *Impact or overload cracking* may occur in hardened, especially through-hardened steel (and even more, ceramic) material, which is inherently of low toughness. Impacts or overloads in manufacture, mounting or service can propagate cracks. Local defects can create overloads and be potent crack initiators.

   Impact or overload cracking may occur on bearing rings and rolling elements (especially balls). Particularly vulnerable to impact or overload cracking are integral flanges of rings. These flanges can come under high load or impact from improper mounting practices, from axial service loads (cylindrical roller bearings) or excessive roller skewing. Cracks that chip or break flanges are common.
4. *Cracking after spalling.* Spalls are stress raisers, and rolling over spalls creates impacts. When the spalls are large, the condition may become sufficiently severe to propagate a mechanical stress crack in a ball, roller or ring, under the action of otherwise well-supported bulk stresses in the component (hoop stress, bending stress, etc.). Through hardened components are more vulnerable than case hardened components.

Notes:
1. Cam follower rollers, which are bored to accommodate a supporting pin bearing, may undergo cracking due to some of the same causes from which bearings crack.
2. Silicon nitride balls have not been noted for developing bulk cracks from spalling.

Gears

1. *Tooth bending* fatigue fracture is a primary failure mode in gears.
   - *Tooth root fracture* is the result of stress concentration at the tooth root.
   - *Tooth chipping* removes portions of the tooth tip, as a result of concentrated stress in that area, such as from a local defect.
2. *Web* or *hub cracking* or both may occur as a sequel to tooth cracking.
3. *Splines* may crack when transmitting excessive torque or impacts.
4. *Impact* or *overload cracking* of gears may occur as it does in rolling bearings.
5. *Cracking from spalling* is not uncommon. Spalls are stress raisers, and rolling over spalls creates impacts. When the spalls are large, the condition may become sufficiently severe to drive a fatigue crack through a tooth, under the action of tooth bending stresses.

Note: Cams may undergo cracking for many of the same causes as do gears, except for tooth fracture modes which do not apply.

Thermal Stress Cracking.

Rubbing cracks. Cracks may form on (hardened steel) surfaces in *sliding* contact under heavy load, as a result of cyclic local overheating. This failure mode is in competition with galling and may dominate, if the lubrication, the surface coating or finish succeed in preventing the welding necessary for galling. The cyclic heating and cooling can result in thermal stress fatigue cracking designated rubbing cracks.

For forging cracks and heat treat cracks, see FC 00.07. For grinding cracks see FC 00.08.

Chemically Promoted Cracking.

Stress corrosion cracking and *hydrogen embrittlement* cracking both result from otherwise well-tolerated stresses applied to weakened intergranular bonds caused by chemical reactions. For a description of the hydrogen embrittlement process see FC 00.08, for that of stress corrosion, see FC 00.20.

15.1.5 Distinctive Appearance

Three appearance features of cracks are important in diagnosing cracking processes and causes: (1) crack progression features, which provide indications of the nature of the stress driving the crack; (2) crack initiation features and location, which can identify weak points and the direction from which the stress attacked; and (3) changes in crack surface appearance from events after cracking, which are indications of crack age and progression rate. They are preferably examined in the order listed, because interpretation of each is needed to shed light on the next appearance feature.

Crack Progression Features. The following comments apply to the recognition of crack progression features.

Extensive fractography literature [22] covers crack progression features in general. However, the body of data published on fractography of hardened steels is quite limited. In this Atlas, only appearance features relevant to Hertz contact machine element diagnosis are covered.

Great differences in crack surface appearance arise from the structure, toughness and residual stress of the component material and also from differences in the applied stress condition. In hard steels, the features are very fine and may require (scanning electron) microscopy for identification. The features may be less well developed in ceramics than in steel.

The classic distinguishing features of crack propagation follow.

Transgranular Cracking is the normal cracking mode in the absence of grain boundary weakness:

- *Fatigue cracks* resulting from repeated application of stress below the ''ultimate strength,'' show ''beach marks'' which are ridges in roughly concentric arcs centered on the initiation point. Fatigue cracks may, if allowed to continue in service, convert to overstress cracks when the cross section has been weakened by the fatigue crack to the point where stresses exceed the ultimate strength.
- *Ductile cracks* are comparatively slow moving cracks resulting from stress slightly in excess of the ''fracture stress.'' They occur in materials with sufficient ductility under the prevailing stress conditions and show microscopic ''dimples,'' that is, conical depressions where plastic flow has taken place during cracking. Ductile cracks may occur in tension or in shear. In tension, the dimples are non-directional; in shear they are oriented in the slip direction. Ductile cracking is clearly identifiable in tough, lower-hardness materials, but in hard steels, the distinguishing features are very subtle and may be unidentifiable.
- *Brittle cracks* are fast moving cracks with little plastic flow which occur in material with low ductility under the existing stress conditions. They are driven by the applied stresses plus the elastic energy released by the crack from the stressed material (including residual stress). These cracks are flat-faceted (undimpled). The facets are cleavage planes across each grain. Cracks in ceramics typically show brittle characteristics.

Intergranular Cracking

Intergranular cracking occurs when grain boundaries are weakened, often by chemical effects (see FC 00.08 and FC 00.20). These cracks follow the grain boundaries. There may or may not be signs of corrosion on the surface.

In ceramics that include binders, intergranular cracking in the binder is common.

Crack Initiation Features. Crack initiation points may be surface defects (nicks—in ceramics, chips—dents, furrows, galling or rehardened areas), material defects (inclusions, voids, large carbides, cold worked volumes, binder weak points in ceramics), edges or previous macro- or microcracks or spalls. Often, the initiating feature is lost in cracking or is indiscernible.

Crack initiation location may be identified by the following criteria, depending on the nature of crack propagation.

- In *fatigue cracks:* if the bulk fatigue crack initiates from a point (surface or subsurface defect), then the initiation point is the center of the beachmarks (striations) of the crack surface. If the bulk fatigue crack initiates from a spall (or a Hertzian fatigue crack), then the visible remnants of the spall are the initiation zone. A bulk fatigue crack may initiate outside the Hertzian stressed volume, traverse the cross section to arrive at the rolling track and there serve as the initiation point of a spall. This can be verified by observing the beachmarks.
- In *ductile cracks:* The initiation area may be a fatigue crack, a local defect or other identifiable feature. If the ductility of the material is high, the crack may end in a *lip,* that is, a rim at an angle to the main cracking direction, at the surface it reaches *last.* The initiation point is then to be sought on the opposite side of the cracked section.

- In *brittle cracks:* Macroscopic *chevron marks* may be found on the crack surface, which point with their tip to the crack initiation point. This means that the crack progresses toward the open end of the chevrons. Microscopic *river marks* may be observable by SEM on the crack face, consisting of depressions with the appearance of a river bed with tributaries. The crack progresses *downriver*—the initiation point is at the upriver end of the river marks.

The location of the initiation point on the component can indicate the *initiating stress condition*, as detailed below.

In *bearing parts:*

Cracks due to Hertzian stressing originate in the vicinity of the rolling track, most often at depths comparable to the maximum Hertz shear stress. Cracks initiating from *subcase failure* initiate at the case/core interface.

Cracks due to *mounting damage* originate from nicks, scuffmarks or in the undercut adjacent to an overloaded flange.

Cracks due to *tensile hoop stresses* in rings tend to initiate at the bore where these stresses are highest.

Cracks due to *bending* (in rings or hollow rolling elements) originate at the side of the component where the bending stresses are tensile.

Cracks in flanges due to *overload* of *flange contacts* are bending or shear cracks, originating on the contact side of the flange (tensile bending stresses), often in the undercut or at the outside edge.

Rubbing cracks are initiated on a surface undergoing overheating in sliding contact.

For heat treat crack initiation see FC 00.07.

For grinding crack initiation see FC 00.08.

In *gears:*

Cracks due to Hertzian stressing originate in the vicinity of the tooth profile surface, most often at depths comparable to the maximum Hertz shear stress. Cracks initiating from *subcase failure* initiate at the case/core interface.

Tooth root cracks initiate from high bending stress at the root blend radius, on the (tensile stressed) contact side of the tooth. The crack typically begins at the tooth radius, travels down below the tooth root, then veers and ascends to the tooth radius on the unloaded side of the same tooth.

Note: Tooth root crack initiation near an axial edge indicates a misaligned contact. Off-center initiation not near an edge may indicate contact geometry error.

Tooth shear cracks may occur along with, or in place of, tooth bending cracks if a high impact force is applied to the tooth contacts. The crack initiates at the root radius but instead of traveling downward into the web, cuts across the tooth dedendum.

Web and *hub cracks* may originate from tooth cracks (usually as a result of overstress generated by the tooth cracking), or from the bore of the hub. Crack propagation direction must be established.

Cracks due to *mounting damage* originate from nicks or scuffmarks.

In splines, *torsional cracking* due to moment overload or to impact initiates cracks just outside the loaded area, running at about 45° across the spline tops and with connecting axial cracks at the spline sides.

Changes in Preexisting Crack Face. *Freshly formed* crack faces are metallic. When exposed to air or to lubricant, especially at elevated temperature, they oxidize and become discolored. Discoloration

of a *part* of a crack face indicates initiation of a crack which was subsequently arrested and recently restarted.

An extreme case of oxidation is a *heat treat crack* (FC 00.07), which develops a scaled face if it occurs in the first half of a two-stage heat treat cycle (example: carburizing with rehardening). A crack face which develops after (last stage) quenching but before tempering, may show temper color (see FC 00.19).

- Cracks that undergo cyclic stressing after formation may experience rubbing of the crack faces. If so, fine fracture features may be worn away and fretting or polishing appear.
- The fracture surface of a spall bottom may experience direct contact with a rolling element or with spall debris and acquire a hammered appearance.

15.1.6 Causes

A list of common causes of bulk cracking follows.

1. Casting or forming defects (FC 00.04 and FC 00.05).
2. Heat treatment defects (FC 00.07).
3. Residual stresses, such as
   - *Forming stresses* (especially in cold formed parts).
   - *Heat treating stresses*. These may be deliberate (the compressive stresses in carburized cases) or unintended (residual stresses from uneven quenching).
   - *Grinding stresses* from the cutting forces and heat applied in grinding. Extreme case: grinding burns.
   - *Service-induced stresses.* Rolling (or sliding) contact at high pressures builds up residual stresses in the Hertz stress field (from plastic flow and the decomposition of austenite).
4. Applied tensile or shear stress (steady-state, cyclic or impact), such as
   - Hoop stress in tight fitted bearing rings, gears or cams or in centrifugally stressed rotating high speed bearing innerrings.
   - Bending or shear stress in bearing flanges or gear teeth under working load; in bearing rings fitted to out-of-round or interrupted housings or shafts.
   - Torsion overload in splines.
5. Secondary failure to spalling or galling.
6. Chemical intergranular attack.

15.1.7 Effects of Bulk Cracking or Fracture

Destruction of component is the most common consequence of a bulk crack. The crack grows at an accelerating rate and the component becomes grossly unserviceable through fracture. This may occur almost immediately in high hardness steel components or be more delayed in medium-hard or case hardened components.

Spalling may occur in bearing components. Small bulk cracks may be open to the rolling surface and be the originating defect for spalls.

Destruction of other components. Pieces broken off one component may wedge other components and cause them to fracture or deform. A split (but not disintegrated) bearing ring will turn on the shaft and damage it by galling.

15.2 PERMANENT BULK DEFORMATION FAILURE CODE: 00.23

15.2.1 Definition

A contact component suffers permanent bulk deformation if any of its macroscopic dimensions is permanently altered from the as-installed condition.

Elastic deflection or thermal expansion are not permanent deformation.

Nicks, dents, and rolled-in marks are permanent deformation, but not *bulk* deformation.

15.2.2 Nomenclature

Permanent bulk deformation is also designated permanent set, permanent distortion, permanent bending or twisting (depending on shape assumed).

The following terms designate various types of permanent bulk deformation:

- bulk plastic deformation;
- rollout;
- material volume instability (structural transformation);
- distortion by residual stress.

15.2.3 Failure Process

The three failure processes commonly producing permanent bulk deformation are listed as follows.

Plastic Flow. A portion of the component is subjected to plastic deformation. Other portions deflect elastically to maintain coherence. If the plastically flowed volume is sufficiently large, macrogeometric changes of shape or size occur in the component. Examples are

- *Bulk bending* of a gear tooth, ring gear, rolling bearing ring or cam follower roller, under service overload.
- *Rolldown* of the track in a rolling bearing ring or cam follower roller under very heavy load, resulting in circumferential plastic expansion. The parts of the cross section not affected by rolldown stretch elastically, and this results in overall diameter increase.
- *Hot deformation* of rolling elements or gear teeth in heat imbalance failure (FC 00.19).

Note: Ceramic components are not observed to fail from bulk plastic deformation because of their limited ductility.

Distortion by Residual Stress. Part of a component contains residual stresses (from heat treatment, cold working, high-load operation). These and the counterbalancing stresses in the rest of the component together cause shape distortion. Examples:

- A carburized component with asymmetrical cross section is often distorted in heat treatment.
- A component with symmetrical cross section undergoes dimensional change in heat treatment.

Deformation by Phase Change of Material. Changes in the structure of the material may cause a change in specific volume, leading to permanent deformation. For example: the retained austenite phase in hardened martensitic steels can decompose with time, elevated temperature or cyclic mechanical stress. The resulting martensite phase is of greater specific volume causing dimensional growth, or, if the phase transformation occurs locally, distortion.

15.2.4 Distinctive Appearance

Permanent bulk deformation is identified by dimensional measurement of size and shape of the component. Severe permanent deformation may be visible to the unaided eye. Differentiation from other failure modes is needed in two cases:

1. When the as-installed dimensions are unknown and a dimensional error may be due either to bulk plastic deformation or to manufacturing error. Diagnosis is generally possible by examining a second surface. For example: the fit of a rolling bearing innerring on the shaft is too loose. There is no interface wear. The loose fit may be (a) a manufacturing error, (b) due to rollout from running under heavy load, or (c) due to volume growth from retained austenite transformation. *Differentiation:* (1) If the roller path and ring width are both in tolerance, and the roller path is undamaged, manufacturing error is likely. (2) If the roller path shows local plastic flow (e.g., a lip formed at the corners), then rollout is likely. (3) If the width of the ring also exceeds tolerance, then volume growth due to austenite transformation is likely.
2. When bulk permanent deformation is accompanied by wear which has added to or counteracted some dimensional growth. In these cases diagnosis is possible if depth of wear can be measured and subtracted from or added to the permanent deformation. For example: A rolling bearing innerring is loose on the shaft and the width is above tolerance, but internal radial looseness is correct. The roller track is worn. It is likely that track wear has offset some of the volume growth effect on internal radial looseness.

15.2.5 Causes

Each of the three major processes producing bulk permanent deformation has its own set of possible causes.

Bulk Plastic Flow

- *Overload* exceeding the bulk strength of a component can lead to bulk plastic flow.
- *Overheating* to a temperature where the material looses hardness, with continued application of load, leads to bulk plastic flow. The overheating may be caused by excessive ambient temperature, but more often by heat imbalance in the machine element, where more heat is generated tribologically than is removed by all means of heat dissipation combined.

Distortion by Residual Stress

- Residual stresses due to *forming,* in components not undergoing hardening heat treatment, may remain and cause distortion of the finish-machined part.
- *Heat treat* residual stresses from carburizing, nitriding, case hardening or through hardening treatments may be intentional (as the compressive stresses in a carburized case) or unintended (stresses left from uneven quenching), but each may cause distortion or dimensional change.
- *High contact load* produces residual overrolling stresses which may combine with plastic deformation of the rolling track to create bulk permanent deformation.

Deformation by Phase Change in the Material. Carburizing and hardening of steels inherently creates volume change as the unhardened (pearlitic) structure differs in specific volume from the hardened (martensitic) structure. Manufacturers allow for anticipated volume changes in dimensioning the parts. If heat treat errors occur, volume changes may differ from those anticipated, creating deformation or dimensional error.

Hardened and tempered martensitic steels generally contain a metastable structural element; *retained austenite,* which can transform prior to or during service into martensite, with volume growth. The transformation is promoted by the following factors:

- *Elapsed time.* At normal operating temperatures, retained austenite tends to transform spontaneously. The percentage of volume growth is proportional to the percentage of *transforming* retained austenite. Manufacturers select heat treatments aimed at holding austenite transformation within permissible limits for the application. However, total dimensional stability of hardened steel is seldom achieved. Heat treat errors may cause more austenite to be retrained than was allowed for, resulting in dimensional error as time elapses.
- *Component temperature.* The temperature at which the component dwells is a rate-controlling factor in austenite transformation. Operation at temperatures in excess of design values may create unacceptable volume growth rates.
- *Cyclic stress.* Cyclic stressing induces austenite transformation. Hertzian contact operation generally results in reduced retained austenite in the stressed material volume. With modest levels of retained austenite, normal component dimensions and loading, the volume of Hertz stressed material generally does not suffice to cause significant bulk permanent deformation. In heavily loaded thin-walled rings it may nonetheless happen.

15.2.6 Effects of Permanent Bulk Deformation

The functional effect of bulk permanent deformation is generally that of any deviation from design dimensions or shape. The severity of the effect depends in obvious ways on its magnitude.

- *Massive permanent deformation* renders the component unfit for use through seizure, loss of positioning accuracy, loss of assembly integrity or interference with other components.
- *Permanent change (growth) in size,* especially in diameter, even when moderate, may result in loss of interference fit on a shaft, unwanted interference fit with loss of axial alignment in a housing, loss of internal clearance in a rolling bearing or loss of play in a gear or cam set.
- *Permanent distortion* in contact components may lead to alignment errors, roller skew and, if severe, edge contact.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
00.22.01.1	5.10 15.37
00.22.01.2	15.3
00.22.01.3	6.15 10.46 10.51 10.52 10.53 13.10 13.11
00.22.01.4	5.5 6.9 7.37 10.25 11.9 12.5
00.22.01.42	7.35
00.22.01.43	15.17
00.22.01.44	7.36 15.17
00.22.1	9.2 10.16 10.39 13.2 15.18 15.20
00.22.2	5.23 6.9 6.21 9.2 10.2 15.4 15.5 15.6 15.9 15.10 15.11 15.12 15.13 15.14 15.15 15.20 15.23
00.22.3	15.15
00.22.4	10.66
00.23.1	15.7 15.26
00.23.1.1	10.17
00.23.2	10.39 13.9 13.11

PLATES

DATA

Plate No: 15.1
Archive No: 018-602&601
Image type: a: light macro, b: light macro, magnetic particle test
Scalebar = a, b: 10 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed: 150 KdN
Load: 1.2 GPa
Lubrication: mineral oil, 68°C
Failure Code 1: 00.22.01.1 Axial cross section crack in ring
Failure Code 2: 00.16.1.1.2 Spall from subsurface defect
Failure Code 3: 22.5 Shaft deformed
Failure Code 4: 00.15.1.2.0.3 Excessive fretting, loose or inaccurate radial fit

a **b**

DESCRIPTIONS

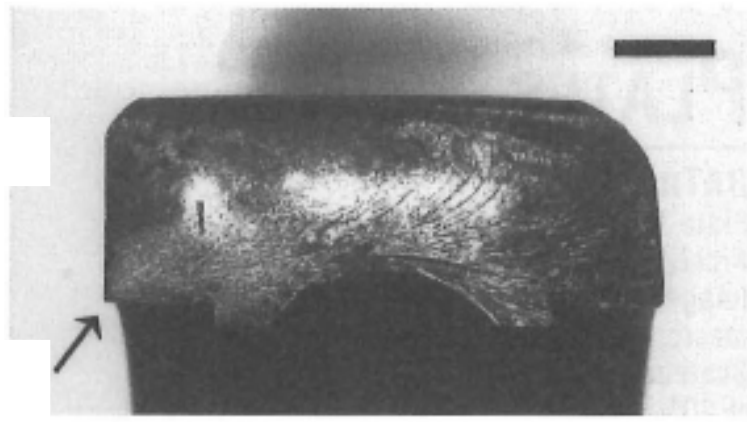
Failure Description: (a): Several axial-radial crack indications are shown, from magnetic particle test. One cross-section crack shows a small spall. (b): Crack face of cross-section crack is shown propagating from the contact through the section into the bore. The shaft underwent large bending deflections, which caused hoop stresses in the IR. These, combined with the contact stress, initiated axial-radial cracks, and eventually a cross-section crack failure. Heavy fretting occurred in the IR bore.
Image Description: (a): The IR is viewed on roller paths. Heavy black axial line 1/4 from N image edge is a cross-section crack. Oblong widening in E roller path is a spall. Fine axial black lines on E roller path are incipient cracks highlighted by magnetic particles. (b): Cracked section at image center. Crack initiation is from the track at image W. There is dark fretting on the crack face, from extended running; also, heavy fretting in IR bore.
Suspected Causes: Shaft is known to have undergone heavy deflection in bearing seat. Hoop stresses were generated in the IR. A contact path under tensile stress is known to form axial-radial cracks on overrolling (even at the light stress of this service). One crack has split the cross section, fretted and spalled out. Bore fretting is secondary.

DATA

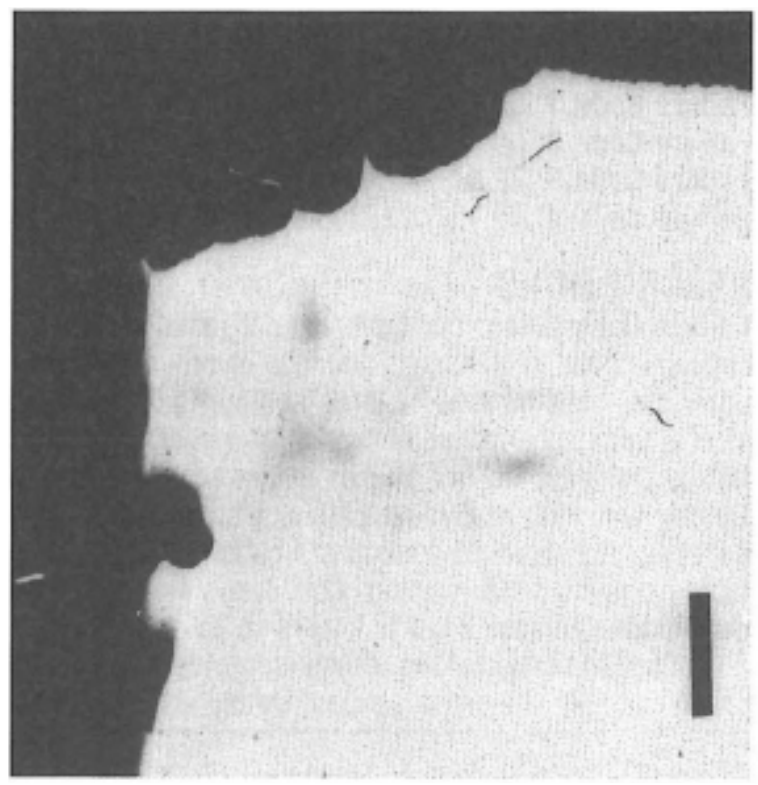
Plate No: 15.2
Archive No: 074-73&74
Image type: a: light macro, b: metallogram (unetched)
Scalebar = a: 10 mm, b: 100 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB (mast support roller); OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.1 Axial cross section crack in ring
Failure Code 2: 00.20.2 Corrosion pitting
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Axial/radial bulk fatigue fracture of OR in DGBB used as mast support roller with rolling contact on OR OD. The crack initiated at the ID corner, at corrosion pitting, from cyclic tensile stresses caused by bending under OD contact load. This is a gross failure.
Image Description: (a): Axial/radial fatigue fracture surface with striations centered on ID corner (arrow). (b): Unetched polished section at crack-initiating corner shows a scalloped edge around the corner, due to corrosion pitting.
Suspected Causes: OR used as a support roller is subjected to cyclic bending under contact stresses at the OD, which are reacted against the ball complement. Tensile stresses arise at the ID which have, at the sharp corroded corner, initiated bulk fatigue fracture of the ring.



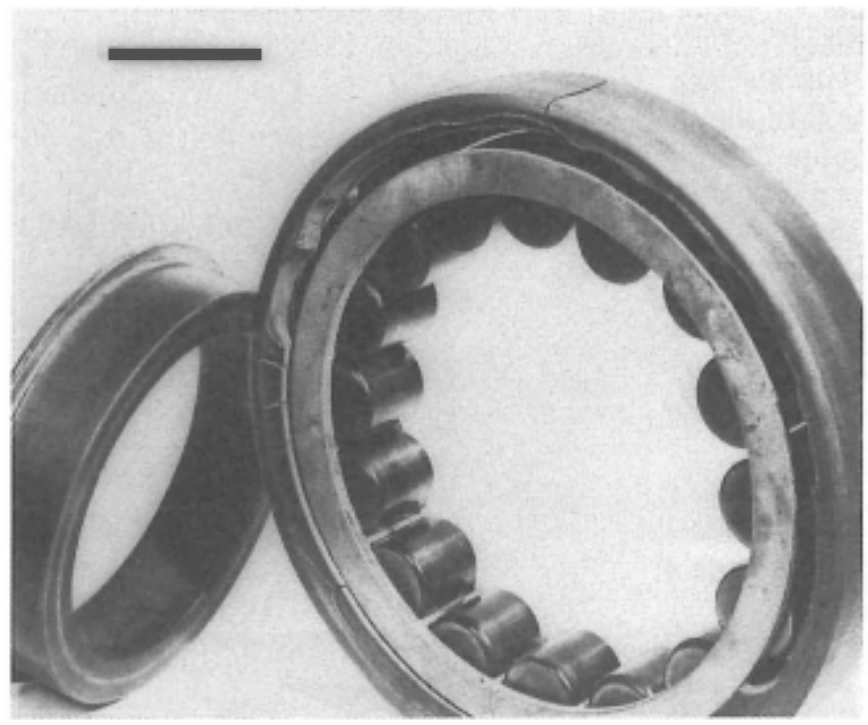
a



b

DATA

Plate No: 15.3
Archive No: 087-023
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRBB; assembly, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.1 Axial cross section crack in ring
Failure Code 2: 00.22.01.2 Circumferential crack
Failure Code 3: -
Failure Code 4: -

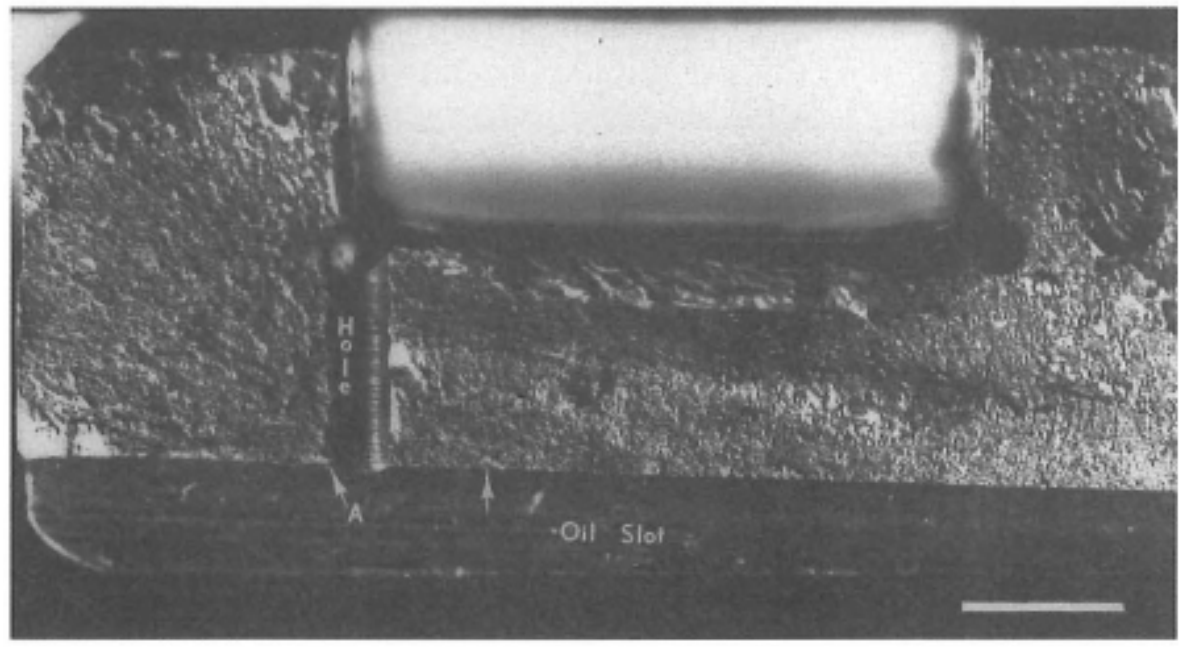


DESCRIPTIONS

Failure Description: Flange fracture and axial cross section crack in the OR of a CRB is due to thrust impact load or greatly excessive axial load. This is a gross failure.
Image Description: IR at image W, OR/R/G assembly at image E. 180° of thrust flange on OR (N–facing half) is fractured (chipped) off. An axial cross-section crack is visible at N. There is no evidence of roller damage or separator fracture in this image. No clear evidence of IR damage is found in this image, although the flange thrust surface may be worn down past the undercut under the axial load.
Suspected Causes: In a thrust loaded CRB, integral ring flanges (with undercuts) are subject to overload cracking, especially if radial load is too low to prevent roller tilt. Axial cracking of ring occurs secondarily. Ring cracking may occur also if the axial load causes heavy flange galling with roller skewing. However, separator and roller damage should then be visible.

DATA

Plate No: 15.4
Archive No: 002-013c
Image type: light macro
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, tool steel, run
Speed: 3.0 MdN
Load: 1.2 GPa
Lubrication: synthetic polyester oil, 204°C
Failure Code 1: 00.22.01.1 Axial cross section crack in ring
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Bending fatigue crack was initiated at the surface of the oil slot located in the IR bore. Further cracking was initiated at the oil hole/slot corner. Eventually, the IR disintegrated.
Image Description: Image is the fractured cross section of an IR. Flanges are at image NE and NW; the ring body at image center; the oil slot (labeled) at image S. The roller path and thrust surfaces are at N center. An oil hole (labeled) connects the roller path undercut and oil slot. Fatigue crack was initiated at (unlettered) arrow. Further cracking extends from oil hole/slot corner (arrow *A*).
Suspected Causes: High speed CRB are subject to high centrifugal hoop stresses. Oil slots and oil holes may have sharp edges or machining marks. Bending fatigue can initiate at the oil slot where the cross section of the ring is weakened. Further cracking at oil hole/slot intersection is promoted by sharp edges. Tool steel bearing rings are especially crack sensitive.

DATA

Plate No: 15.5
Archive No: 074-61
Image type: light macro
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.1 Axial cross section crack in ring
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Fatigue fractured cross section of IR with crack originating at bore, from excessive hoop stress acting on a minor surface imperfection. This is a gross failure.
Image Description: Axial/radial fatigue crack propagating through ring from an initiation point (arrow) at the bore and extending to an arc connecting the seal grooves. Striations, first parallel to the bore and then arcing, indicate fatigue. The fracture surface of the remaining part of the cross section is coarse, indicating rapid overstress cracking.
Suspected Causes: Excessive hoop stress, as from too great an interference fit between IR and shaft, combined with cyclic contact stressing, may initiate bulk cracking. Hoop stresses are greatest at the bore. A surface imperfection may initiate cracking at that surface.

DATA

Plate No: 15.6
Archive No: 074-64&65
Image type: a: view, b: light macro
Scalebar = a: 10, b: 1 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.2 Circumferential crack
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: 00.01.2 Scratch, tool mark, scuffmark
Failure Code 4: -

DESCRIPTIONS

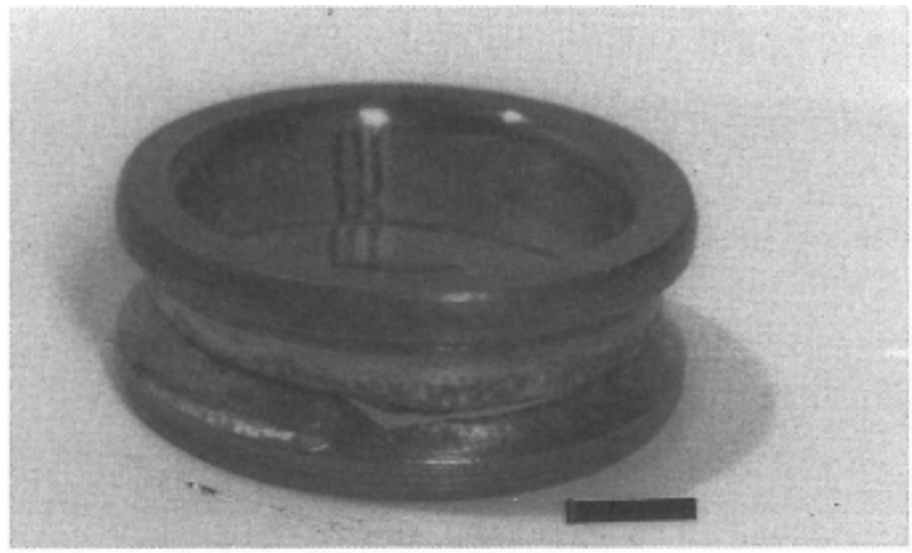
Failure Description: Circumferential bulk fatigue fracture of a ring, connecting the snap-ring groove with the ball groove. A sharp corner or tool mark in the snap-ring groove may have initiated the crack. This is a gross failure.
Image Description: (a): OR was cut in half by axial/radial cut for examination. Circumferential fracture has separated the ring, connecting a corner of the snap-ring groove with the ball path. (b): Fracture surface shows arced striations of crack propagation around the initiation point at the snap ring groove corner.
Suspected Causes: Snap ring grooves, provided to receive rings locating the bearing axially, cause reduced cross section. If they have sharp corners, damaged surfaces or grinding burns, circumferential bulk fatigue cracks can initiate across these reduced sections.

a

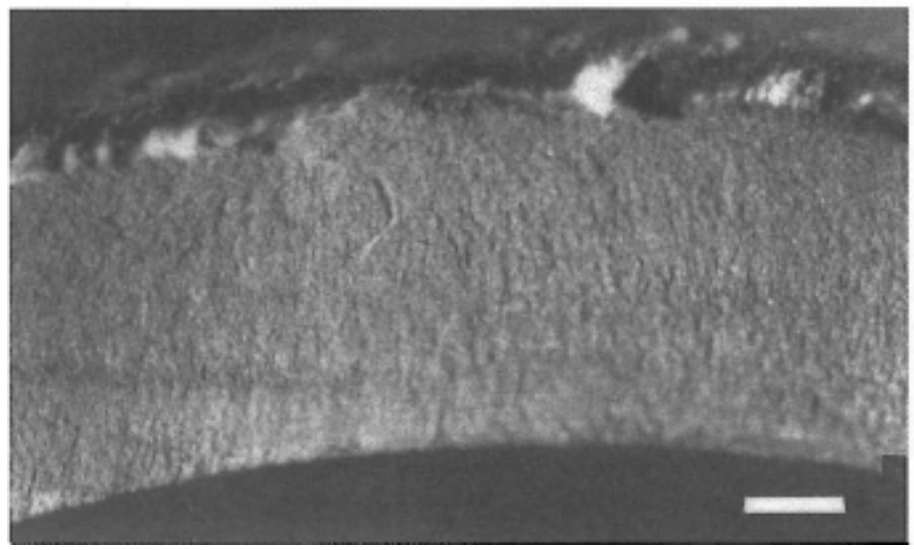
b

DATA
Plate No: 15.7
Archive No: 074-62&63
Image type: a: view, b: light macro
Scalebar = a: 10, b: 1 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB, IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.2 Circumferential crack
Failure Code 2: 00.23.1 Plastic rolldown of contact path
Failure Code 3: 00.16.02.3 Incipient spalling, single spall
Failure Code 4: -

DESCRIPTIONS
Failure Description: Plastic rolldown occurred in the groove, due to excessive load. An incipient spall is followed by circumferential cracking. This is a gross failure.
Image Description: (a): Plastically worked (battered) groove surface. A circumferential fracture separates the two ring halves. (Black penmarks in bore register the halves.) There is a deep gouge from a fragment on the groove surface (at SW). The initiating spall is not shown. (b): Fracture surface near initiating spall. (Shallow craters are out of focus, about 1/4 image width to either side of image center.)
Suspected Causes: Long-term, high-load over-rolling may produce plastic rollout resulting in compressive stresses in the contact surface. Balancing tensile stresses arise elsewhere in the cross section. A spall relieves the compressive stress at a point; tensile stress, acting from the spall bottom and aided by continued overrolling, may drive a circumferential crack. (Cross-section cracks are more common.)



a



b

DATA
Plate No: 15.8
Archive No: 074-78
Image type: light micrograph of section; Nital etch
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; R, induction hardened, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 2: 00.07.5.02 Heat treat crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Twisted cracks in core of an induction hardened small roller. Cracks do not emerge to the surface. The unhardened core of the roller is in high tensile residual stress due to heat treatment. Cracks may form before running and/or propagate under high cyclic contact loading. The roller is likely to fracture upon continued running.
Image Description: Etched cross section of a roller shows induction hardened case as light gray and unhardened core as darker gray. The S-shaped black line with a side-branch is the crack in the core.
Suspected Causes: Small rolling element with deep induction hardened case contains high compressive case stress and high tensile core stress due to volume growth in the martensitic case. Spontaneous heat treat cracks may exist in the core. Cracks may initiate or grow in the high tensile stress environment of the core due to the rotating stress field imposed by contact loading.

DATA

Plate No: 15.9
Archive No: 074-80&81
Image type: a: view, b: light microgram
Scalebar = a: 10, b: 1 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Spiral fracture of a ball in fatigue under contact loading, from material defect below the surface. High heat treat stresses may contribute to this gross failure.
Image Description: (a): Mating fracture surfaces on two halves of a fractured ball. Radial steps on the two halves match. The failure origin is the small circular area with an irregular fracture surface, close below the ball surface (arrow). Cracks have propagated in both directions around the periphery and have met in a step. (b): Failure origin on W ball-half. Ball surface is at N, and is chipped. A dark patch is visible at the crack origin, followed by dark/light striations of fatigue propagation.
Suspected Causes: Water quenched balls may contain substantial heat treat stresses. If a material imperfection is present and contact loads are heavy, bulk fatigue cracking may result.

a

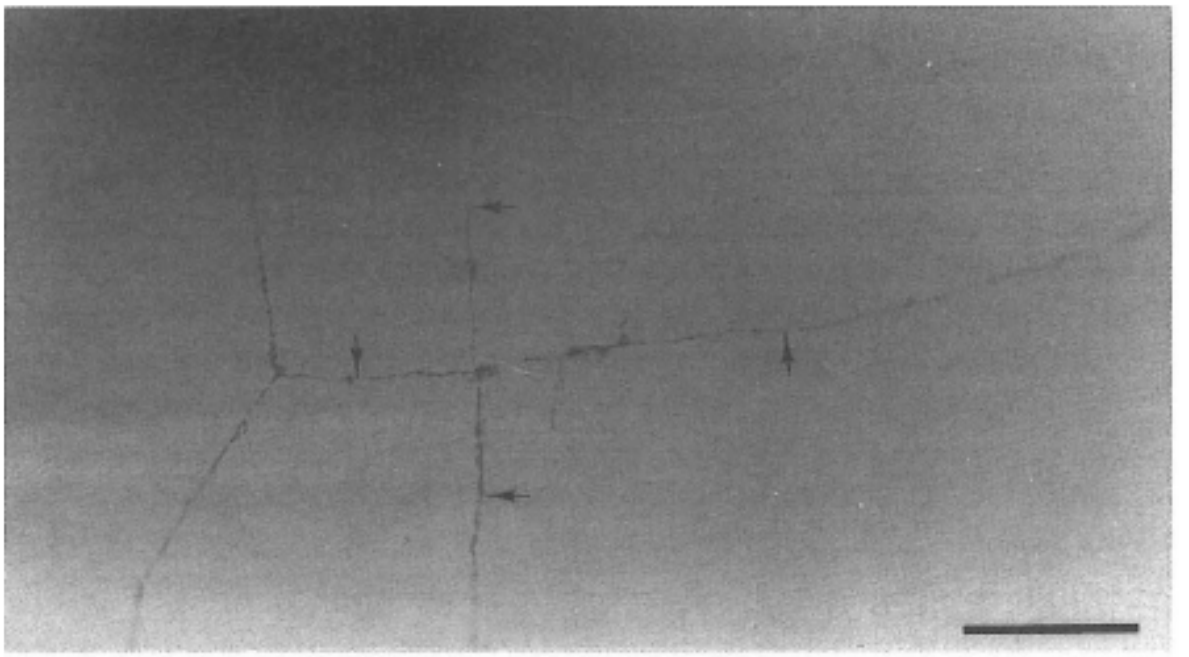
b

DATA

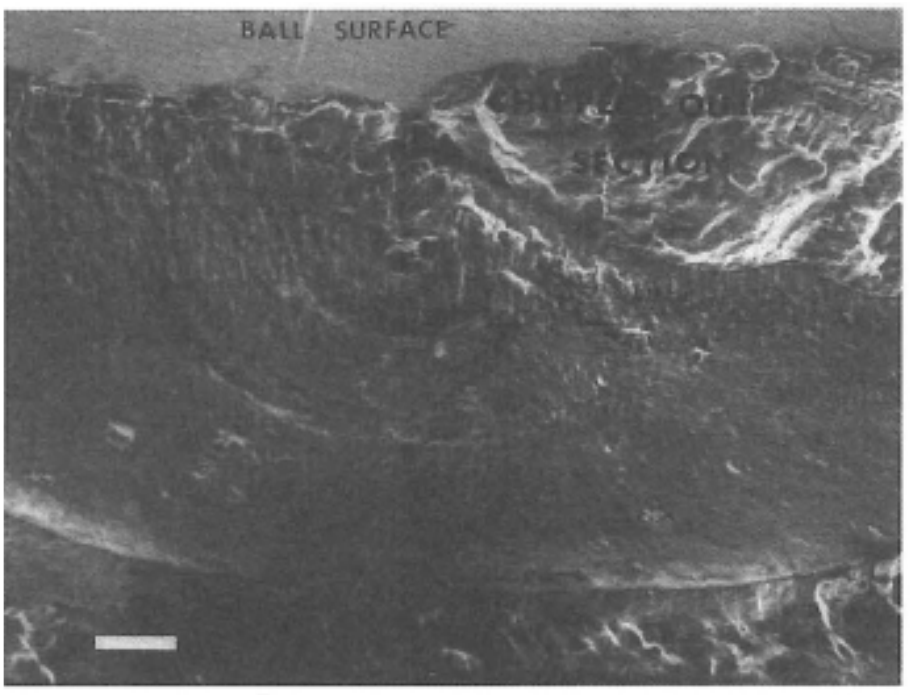
Plate No: 15.10
Archive No: 002-019b&d&e
Image type: a: light micrograph, b, c: SEM
Scalebar = a: 2 mm, b: 50, c: 20 μm
(micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 0.8 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

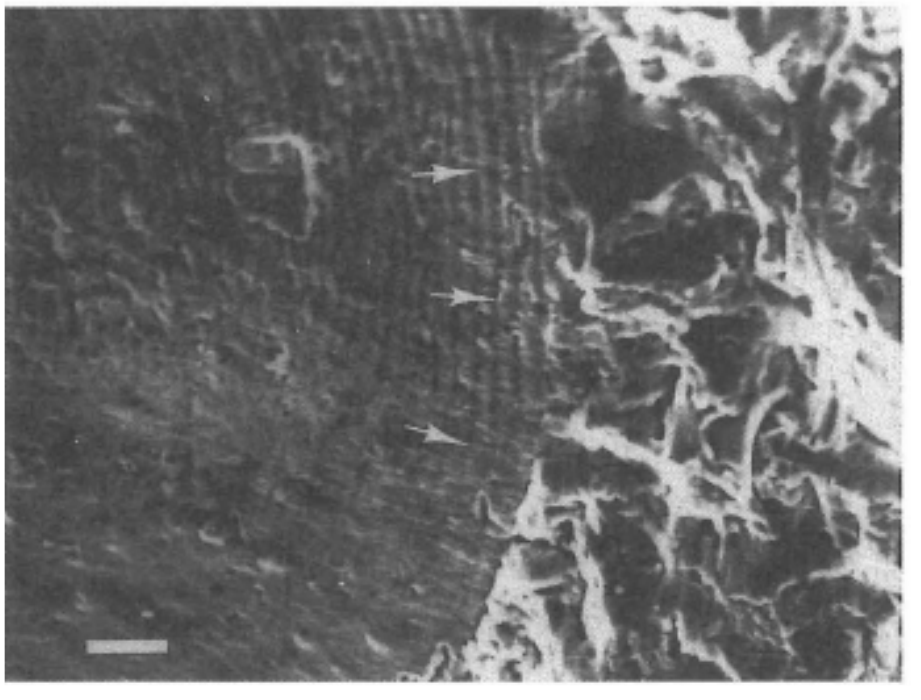
Failure Description: Bulk fatigue cracking of a ball, forming crossing straight crack openings at the surface (minimal spalling) and extending radially inward. Tool steel balls of aerospace bearings occasionally exhibit such bulk fatigue rather than conventional spalling, for reasons not ascertained. Occasionally, coarse martensite is suspected. The ball has failed.
Image Description: (a): Crossing, dark, straight-line cracks on the ball surface (arrows), with minimal spalling (broadened patches). (b): Fatigue crack propagated from spall (labeled "chipped out section") at (labeled) ball surface, to artificial fracture at image S (curved boundary). (c): Fatigue striations visible near a crack tip (arrows).
Suspected Causes: Tool steel used in aerospace rolling bearing occasionally exhibits crack sensitivity, especially under tensile hoop stressing. Tool steel balls (not hoop stressed) may fail in bulk fatigue. Forming and heat treating of heavy-section tool steel balls appear to be difficult and critical operations, occasionally causing brittleness. The crossing crack pattern at the surface is not explained.



a



b



c

DATA
Plate No: 15.11
Archive No: 074-75
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; R, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: 00.09.2 Galling from forcible assembly or mounting
Failure Code 4: -

DESCRIPTIONS
Failure Description: Axial bulk fatigue crack in a roller OD following an axial galling streak inflicted in assembly or mounting. The roller is likely to fracture or spall in continued running.
Image Description: Cylindrical roller surface of varying hue of gray due to magnetic particle inspection. At roller centerline is a light gray axial galling mark in the center of the W roller half. A black, slightly curved line following the galling mark to the S is the magnetic particle indication of a bulk crack.
Suspected Causes: Galling due to mounting damage creates high local residual stresses and surface damage. Most commonly, such a defect will spall in running. However, if a roller contains high tensile residual stresses (possibly from the quench), then bulk fatigue cracking may occur.

DATA
Plate No: 15.12
Archive No: 026-12&19
Image type: a, b: light macro
Scalebar = a: 60, b: 30 mm (micros: ±20%, others: +100%, −50%)
Component: CRB (multirow); R & G, run
Speed:
Load:
Lubrication: mineral oil mist, ? °C
Failure Code 1: 00.22.01.3 Rolling element (ball, roller) crack
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: 00.16.1.1.2 Spall from subsurface defect
Failure Code 4: 00.18.02.2 Severe or advanced denting

DESCRIPTIONS
Failure Description: Rollers with bore accommodating pin-type separator. Cross-section cracking in fatigue is probably initiated from machining defect or decarburization at the bore which is subjected to cyclic tensile stress in bending. The crack penetrates to the rolling surface; it spalls, creates extensive debris which are rolled over and eventually the roller splits. This is a gross failure.
Image Description: (a): In N image half, a row of rollers is held between two rings of the separator by pins through the bore along each roller axis. Three rollers to W are intact; the next roller is fractured, then one is cracked and spalled. Parts of the broken roller are at S. (b): Four cracked, spalled and chipped rollers are held in the separator.
Suspected Causes: Rollers with bore for a separator pin are crack-prone. The bore is usually in the as-machined condition. Unfavorable residual stresses may exist. Bending under cyclic stressing tends to initiate cross-section cracking, with subsequent spalling. These rollers are carburized, with bores usually masked from carburizing atmosphere. Incomplete masking may cause patchy carburizing, resulting in high local residual stresses.

a

b

DATA

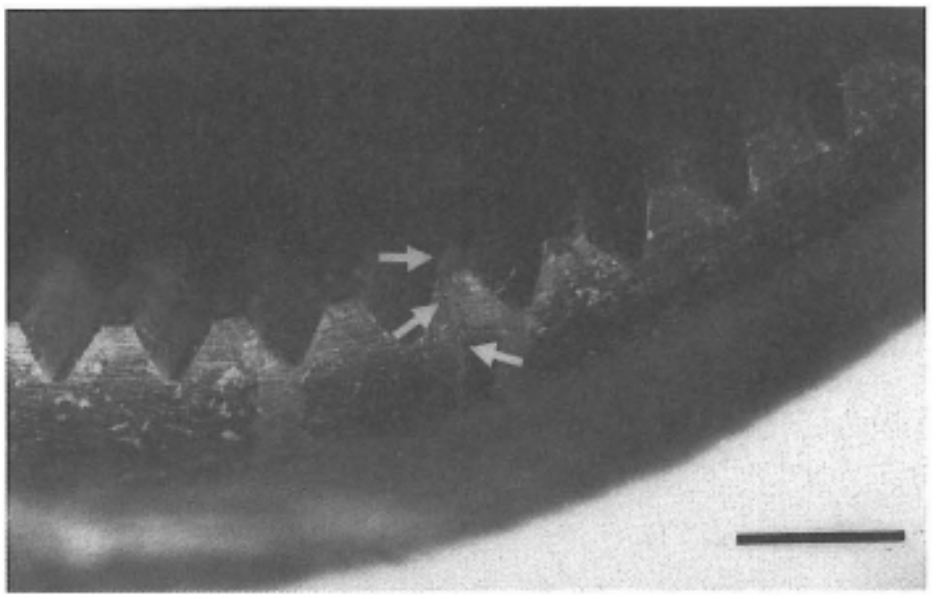
Plate No: 15.13
Archive No: 002-009c&d&e&g
Image type: a, b, c: light macro, d: metallogram, etched
Scalebar = a, b: 3, c: 2 mm, d: 20 μm (micros: ±20%, others: +100%, −50%)
Component: SLG, run
Speed: 106 m/sec
Load: 0.5 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.22.01.4 Gear tooth crack or fracture
Failure Code 2: 00.07.5.01 Forging crack
Failure Code 3: 00.22.2 Bulk fatigue crack
Failure Code 4: -

DESCRIPTIONS

Failure Description: Forging crack extending along 7 mm of spline tooth, to full tooth height. Crack face details in (d) show minimal fatigue crack propagation. Oxide layer is in main crack which occurred prior to final heat treatment; fatigue cracks are not oxidized. The spline may eventually fracture from these cracks.

Image Description: (a): Spline viewed from endface. Three arrows show a radial crack from spline tooth tip past tooth roots. (b): In the sectioned spline, the same crack is the white, axial jagged line (magnetic particle indication) (arrows). White spots are loose magnetic particles. (c): The tooth is fractured along the crack (dark area with arrows). (d): Section across the crack. The heavy branching line is a forging crack. Fine branches may be bulk fatigue cracks.

Suspected Causes: Forging of the gear introduced cracks in the blank. When the spline was machined, cracks remained in the tooth. The gear has been run extensively, but only minimal fatigue crack propagation has occurred.



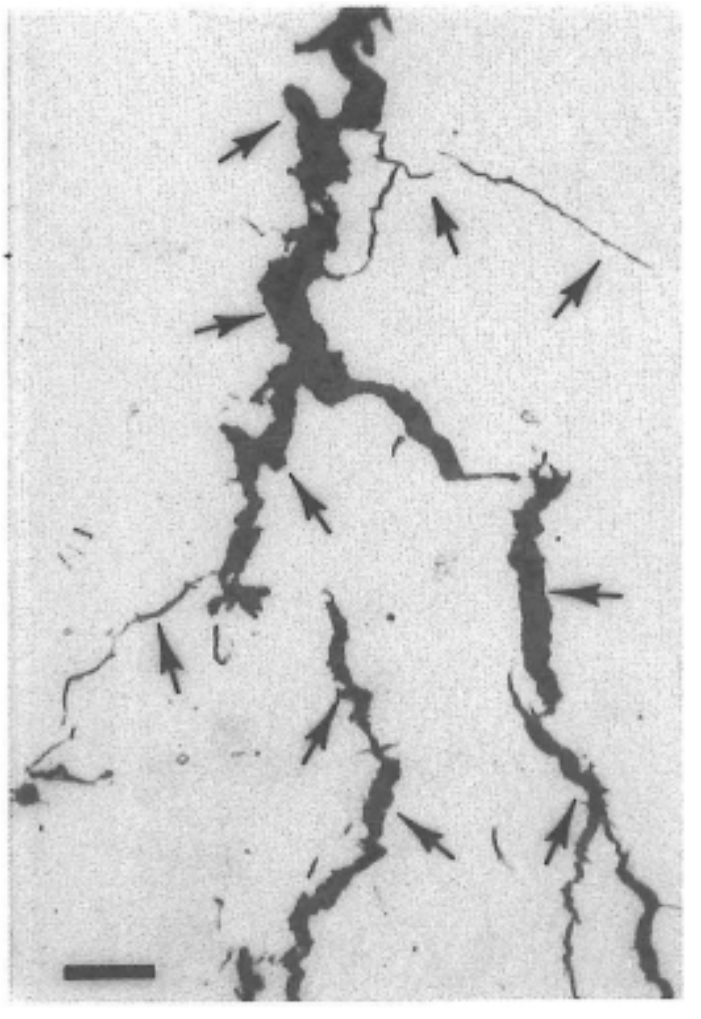
a



b



c



d

DATA

Plate No: 15.14
Archive No: 080-107
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.4 Gear tooth crack or fracture
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: -
Failure Code 4: -
See also PLATES: 15.17 and 15.18

DESCRIPTIONS

Failure Description: Fractured segment of a tooth, from bulk fatigue crack which has propagated across the section. Fatigue striations are visible. This is a gross failure. See Plate 15.18 for an overstress crack and Plate 15.17 for a fatigue crack with no striations.
Image Description: Segment of a tooth with artificially cut surface averted. The contact surface is at image S, followed by the bulged fracture surface toward image N. The arrow *A* indicates crack initiation. Elliptic fatigue striations extend over W, N and E border areas of the fracture. They are most clearly seen near arrow *B*. The fracure surface is smooth, not fibrous. This is typical of *fatigue* cracking, especially in hard materials.
Suspected Causes: Tooth fatigue cracking under contact loading may initiate from a surface or subsurface defect and gradually extend to sever the tooth.

DATA

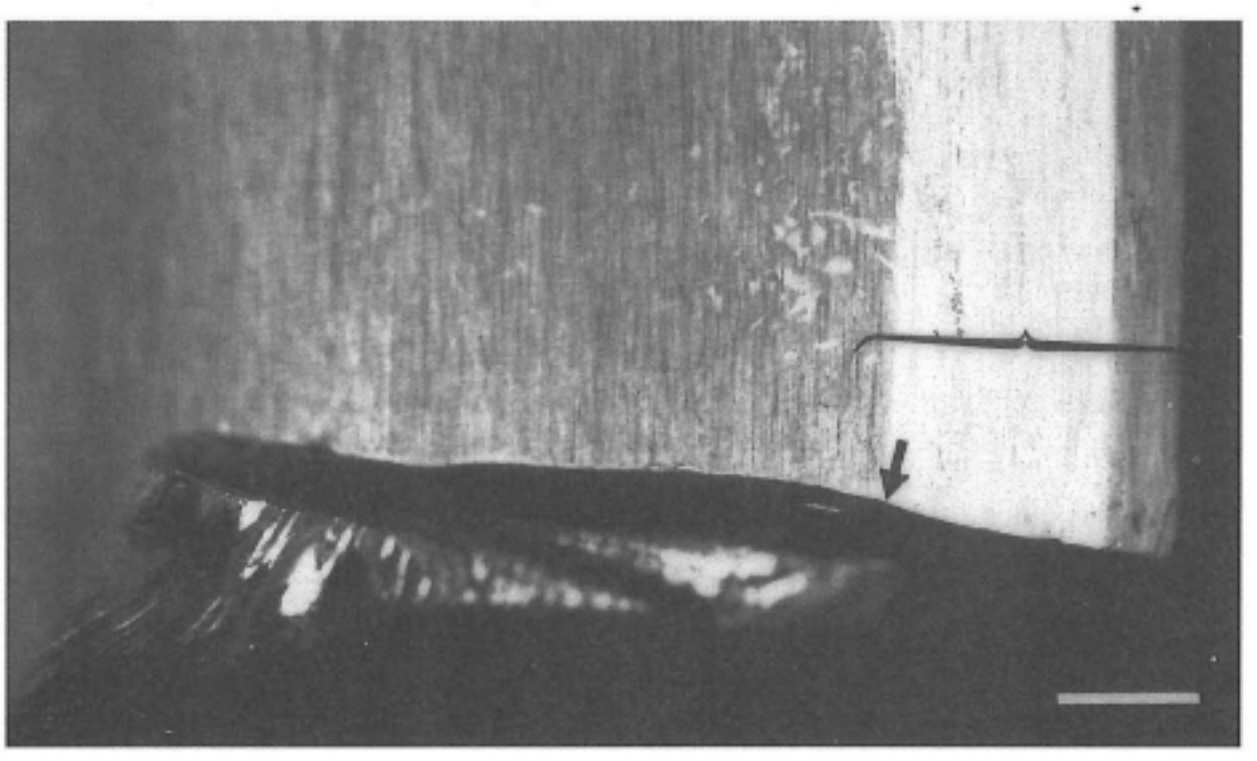
Plate No: 15.15
Archive No: 002-010c&d&e
Image type: a, b: macro, c: light metallogram, Nital etch
Scalebar = a: 2, b: 3 mm, c: 20 μm (micros: ±20%, others: +100%, −50%)
Component: BG; W, high hardness, run
Speed:
Load: 0.5 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.22.01.4 Gear tooth crack or fracture
Failure Code 2: 00.22.3 Rubbing crack
Failure Code 3: 00.22.2 Bulk fatigue crack
Failure Code 4: 00.12.6 Wear at unintended surface contact

DESCRIPTIONS

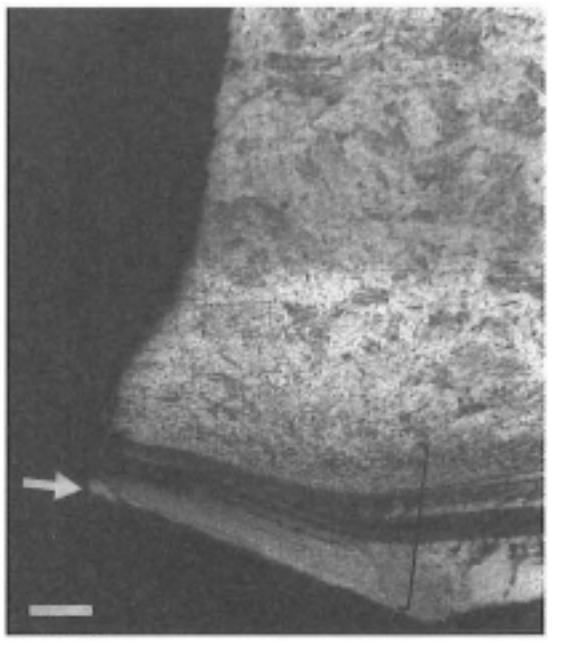
Failure Description: A crack propagated through the bevel gear tooth root from initiation at the back of the gear disk which unintentionally rubbed against a stationary part. Rubbing created plastic working, overheating and crack initiation, and propagated through the tooth by fatigue, disintegrating the gear. This is a gross failure.
Image Description: (a): Fractured gear disk; tooth face is in NE quadrant, followed by crack surfaces. A rubbing crack initiated at the arrow (see view (b)), propagated in fatigue through much of the disk and finally fractured the disk in overload. (b): Gear disk bottom surface (at arrow of (a)); rubbed the area at the bracket; crack initated at the arrow. (c): Etched section through rubbed area (bracket); the worked material appears light, the tempered zone dark. The crack starts at the arrow.
Suspected Causes: The back face of the gear disk unintentionally rubbed against a stationary component, creating high heat, plastic working and eventually a 'rubbing crack,' from which fatigue drove a crack in depth toward the teeth. Eventually the weakened gear disk fractured at a tooth root radius.



a



b



c

DATA
Plate No: 15.16
Archive No: 099-140
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: WG; W, bronze, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.41 Tooth root fracture
Failure Code 2: 00.12.5.1 Tooth polishing
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Fatigue cracking from the tooth root corners into the wheel rim. There is light polishing of contact surfaces. The rim is likely to fracture in further running.
Image Description: Worm gear wheel viewed obliquely. On second tooth from image E, fine dark crack lines extend from both root corners two-thirds into the machined rim. Light polishing marks (arced lines and bands of different luster) are on the tooth flank surfaces.
Suspected Causes: Bulk overload of the tooth rim in bending, combined with stress concentration at sharp tooth root corners, has initiated fatigue cracking. The mild contact wear indicates no abusive operation.

DATA
Plate No: 15.17
Archive No: 080-108
Image type: view
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: SG; P, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.41 Tooth root fracture
Failure Code 2: 00.22.01.43 Mid-tooth fracture
Failure Code 3: 00.22.01.44 Tooth tip chipping
Failure Code 4: 00.16.01.3 Tooth spalling
See also PLATES: 15.14 and 15.18

DESCRIPTIONS
Failure Description: Extensively chipped, fractured and spalled teeth. One tooth is fractured at the root in fatigue, but without striations. This is a gross failure. See also Plate 15.14 for tooth fatigue fracture and Plate 15.18 for overstress tooth fracture.
Image Description: Counting from image S, teeth No. 1, 4, 5, and 7 are chipped. Tooth 7 has spall cratering in the dedendum. Tooth 6 is broken off at the root, showing a smooth, fine fracture surface (not fibrous), typical of fatigue in hard material, but no fatigue striations.
Suspected Causes: Heavily loaded gear suffered spalling and (probably from impacts and/or debris passage) tooth chipping and breakage. The missing tooth was broken in fatigue.

DATA

Plate No: 15.18
Archive No: 080-106
Image type: light macro
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.41 Tooth root fracture
Failure Code 2: 00.22.1 Overstress crack
Failure Code 3: -
Failure Code 4: -
See also PLATES: 15.14 and 15.17

DESCRIPTIONS

Failure Description: Overload fracture of a gear tooth, with signs of bulk plastic flow during fracture. This is a gross failure. See Plates 15.14 and 15.17 for fatigue fracture of teeth.
Image Description: The center tooth of the gear segment shown is broken at the root. Fracture began at W flank of the tooth with fibrous, uniform texture. About midway through the fracture, a "hump" begins, as material plastically bent and was sheared. This hump and the absence of fatigue striations distinguishes overstress fracture.
Suspected Causes: Overstress fracture from accidental overload or following a severe material defect occurs in one or a few load cycles.

DATA

Plate No: 15.19
Archive No: 002-004a&c
Image type: a: view, b: light macro
Scalebar = a: 40, b: 2 mm (micros: +20%, others: +100%, −50%)
Component: BG; W, high hardness, run
Speed: 106 m/sec
Load: 0.5 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.22.01.42 Tooth corner fracture
Failure Code 2: 00.06.2 Inclusion stringer
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

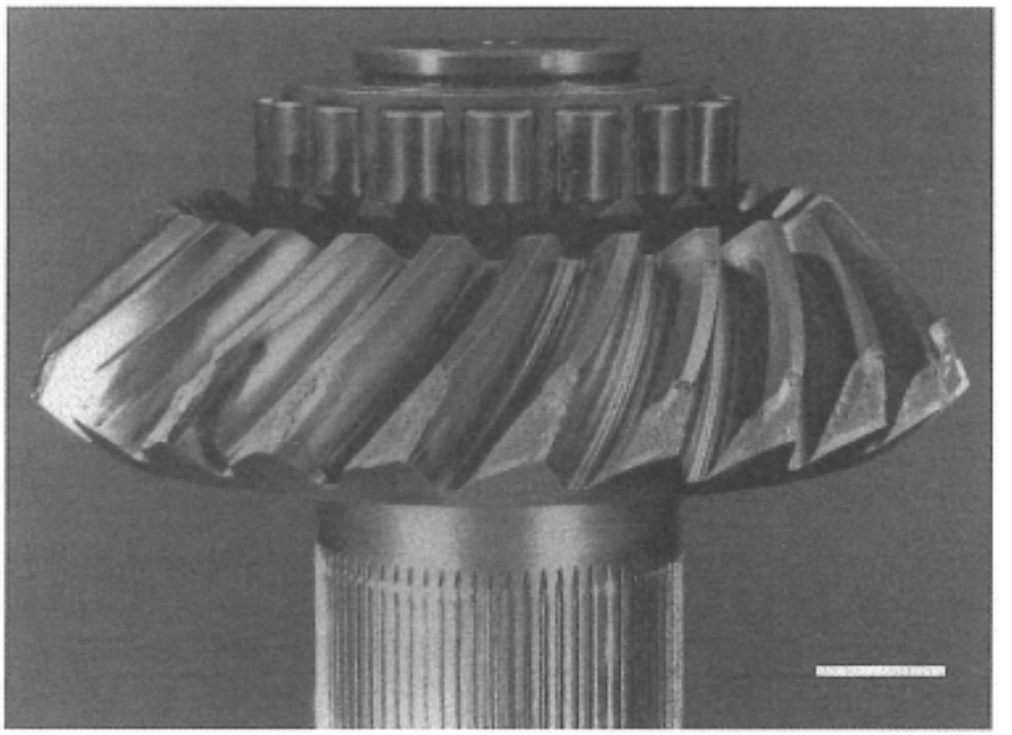
Failure Description: Two consecutive gear teeth are fractured in fatigue across the small-diameter edge. Both teeth were found to contain large (2 mm long) alumina inclusion stringers in the core material, from which the fracture is seen to initiate. The gear has failed.
Image Description: (a): Entire gear, with two teeth marked by arrows having fractures at small-diameter edges under arrows. (b): Fracture surface of one tooth, showing crack spreading from long nonmetallic stringer indicated by opposing arrows.
Suspected Causes: Large inclusion stringers are severe stress concentrators which may initiate fatigue failure. The inclusion in this gear was so deep beneath the surface that it initiated bending fatigue, and not contact fatigue.

a

b

DATA

Plate No: 15.20
Archive No: 080-109
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: BG; P, high hardness, & CRB, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.42 Tooth corner fracture
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: 00.09 Geometry, assembly or mounting defect
Failure Code 4: 00.22.1 Overstress crack

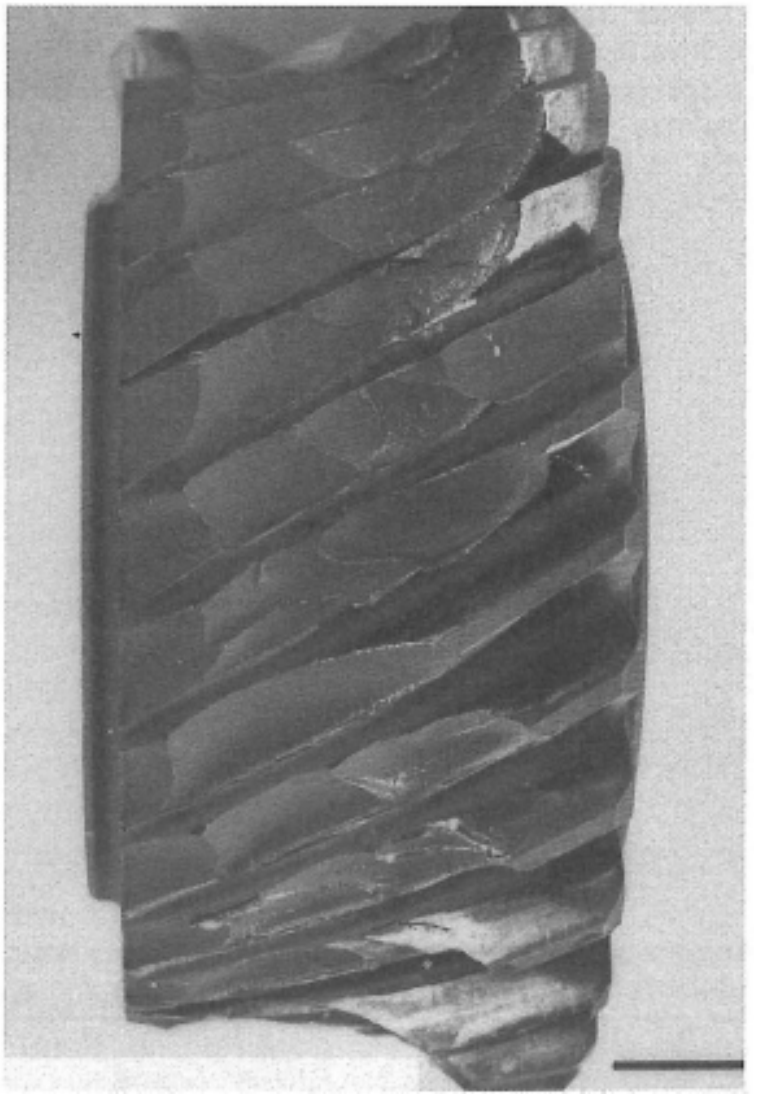


DESCRIPTIONS

Failure Description: Fatigue fracture of the corner of several teeth in a spiral bevel gear, due to a misaligned mesh causing overloading of that corner. The misalignment results from improper mounting geometry. Other teeth are then broken in impact. This is a gross failure.
Image Description: Spiral bevel pinion is in image center; supporting CRB at N. Corners on the large-diameter end of all visible gear teeth are broken off in a diagonal line from (or near) root level (at the gear face) to the tooth tip (further inboard). In this case-hardened gear, the case shows fatigue striations; the core is a woody fracture.
Suspected Causes: Improper relative position of the wheel and pinion, due, for example, to excess looseness in the support bearings or wrong position adjustment leads to misaligned mesh which may place most of the tooth load at one corner of the mesh. Fatigue cracking of several teeth may result, with the others then broken by impact.

DATA

Plate No: 15.21
Archive No: 099-141
Image type: view
Scalebar = 60 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.42 Tooth corner fracture
Failure Code 2: 26 Support bearing damage (of gear, cam)
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Tooth corners broken away in three consecutive incidents due to mislocation of pinion resulting from support bearing failure (not shown). The load was shifted in each case to a tooth sector which failed to support it. This is a gross failure.
Image Description: A pinion is viewed on OD. Tooth corners facing image W were broken away. The pinion then shifted to image W and another length of tooth tip broke away, extending from the first fracture to roughly the gear center plane. After a second shift, a third row of fractures occurred, now extending to the E half of the face width.
Suspected Causes: Gross support-bearing failure was observed to have dislocated the gear mesh, causing local overload in repeated passes.

DATA

Plate No: 15.22
Archive No: 064-204&902
Image type: a, b: color view [SEE IMAGE IN APPENDIX.]
Scalebar = a: 30, b: 20 mm (micros: ±20%, others: +100%, −50%)
Component: HG; P, high hardness, & TRB; IR&R&G, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.43 Mid-tooth fracture
Failure Code 2: 00.16.01.3 Tooth spalling
Failure Code 3: 00.12.5.3.2 Adhesive (destructive, non-galling) tooth wear
Failure Code 4: 00.20.01.1 Generalized corrosion

[See Image in Appendix]

DESCRIPTIONS

Failure Description: (a): Mid-tooth fractures cover entire contact length of all pinion teeth, starting from multiple initiation points. Corrosion is visible. The shell-shaped chipping in the fractures suggests case/core interface failure. (b): Wear step and axial line of spalls near one tooth edge. General corrosion has occurred after failure. (a, b): Gears are no longer serviceable.
Image Description: (a): In image center is a HG on integral shaft, with a TRB at S. The teeth show many mid-tooth fractures, with concentric striations, initiated by spalls. Shell-like shapes suggest case/core failure. A brown rust color is apparent. Purple dye is used for examination. (b): HG from same application. Wear step and heavier spalling near W tooth edge indicate misaligned loading. There are brown rust deposits.
Suspected Causes: (a): Massive failure of gear results from long running after spalling and chipping was initiated. Rust stains in fractures negate instant catastrophic failure. A possible heat treat defect contributing to deep spalling at case/core interface requires metallurgical examination. (b): Similar, earlier stage failure. Misalignment of mesh caused edge loading; failure initiated there and propagated across the tooth width. Rust is incidental.

DATA

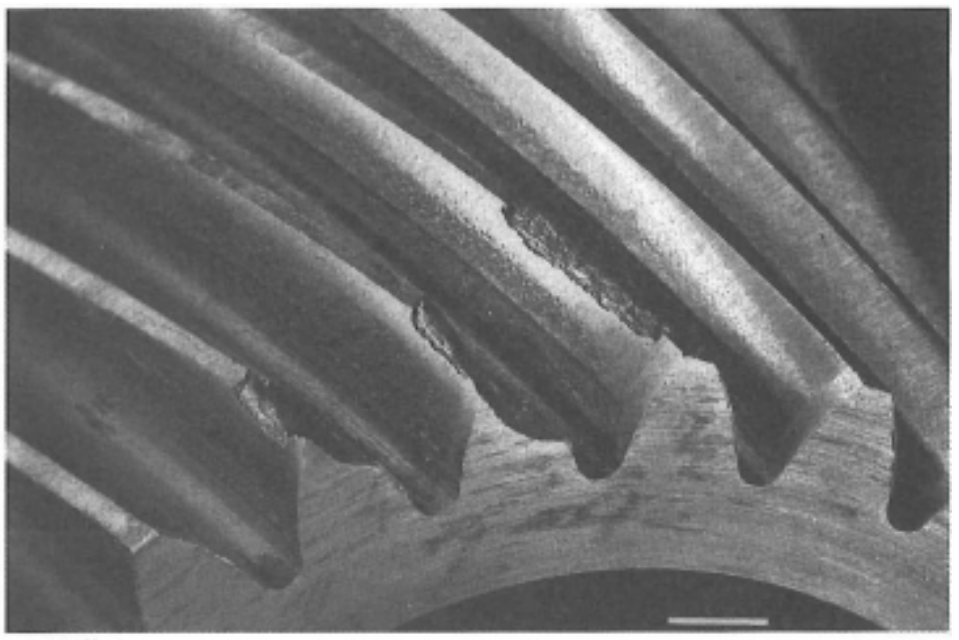
Plate No: 15.23
Archive No: 099-238
Image type: light macro
Scalebar = 5 in = 127 mm
(micros: ±20%, others: +100%, −50%)
Component: HG; P, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.43 Mid-tooth fracture
Failure Code 2: 00.22.2 Bulk fatigue crack
Failure Code 3: 00.16.01.3.1 Tooth pitchline or dedendum spalling
Failure Code 4: 00.18.4.2 Gear tooth rippling (transverse wavy plastic flow)

DESCRIPTIONS

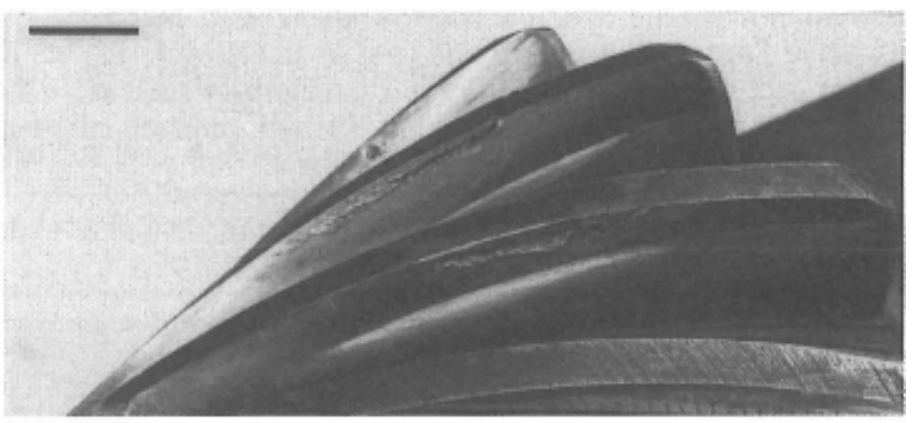
Failure Description: Multiple mid-tooth fracture on one tooth of a wide, medium-hard pinion. The primary fracture initiated from a pitchline spall. Slow crack progression is indicated by fretting of the early fracture surfaces. Radial plastic surface flow (rippling) occurred on several contact surfaces indicating high load. Metallurgical examination showed impaired structure with less fatigue resistance than specified. This is a gross failure.
Image Description: The third tooth from N shows a large midtooth fracture, with primary and secondary fracture origins labeled. A spall and tooth tip chipping are visible at E end of second tooth from S. Rippling is (faintly) visible on E quarter of the first tooth from S. A dark half-moon on the crack face below the primary fracture origin appears fretted.
Suspected Causes: The gear was found, in metallurgical examination, to have a marginal structure. Combined with loading sufficient to cause plastic surface flow, spalling and eventual mid-tooth fracture were produced.

DATA
Plate No: 15.24
Archive No: 099-138&139
Image type: a, b: light macro
Scalebar = a: 25, b: 10 mm (micros: ±20%, others: +100%, −50%)
Component: a: HG, medium hard, b: BG, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.44 Tooth tip chipping
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Appearance comparison of tooth tip chipping between medium-hard and high hardness (case hardened) gear. (a): Medium-hard gear with tooth tip chipped, probably from edge contact. (b): Case hardened gear with cracks in tooth tips at mid-contact, possibly due to geometry error, failing at case/core interface. In both gears, progressive failure is likely.
Image Description: (a): Gear is viewed obliquely, with the three tooth corners (in center) chipped off at the tip. Fracture surfaces are coarse in medium-hard material. (b): Gear is viewed on OD. Of the three tooth tips fully shown, the two toward image N show cracks and some spalling on the contact surface, extending onto the tooth OD. Proximity to the tooth tip suggests that the failure is at the case/core interface.
Suspected Causes: Tooth tip overload from geometry error, or passage of hard contaminants may combine with material weakness (as in the case hardened gear where case/core interface appears weak) to cause tooth tip chipping.



a



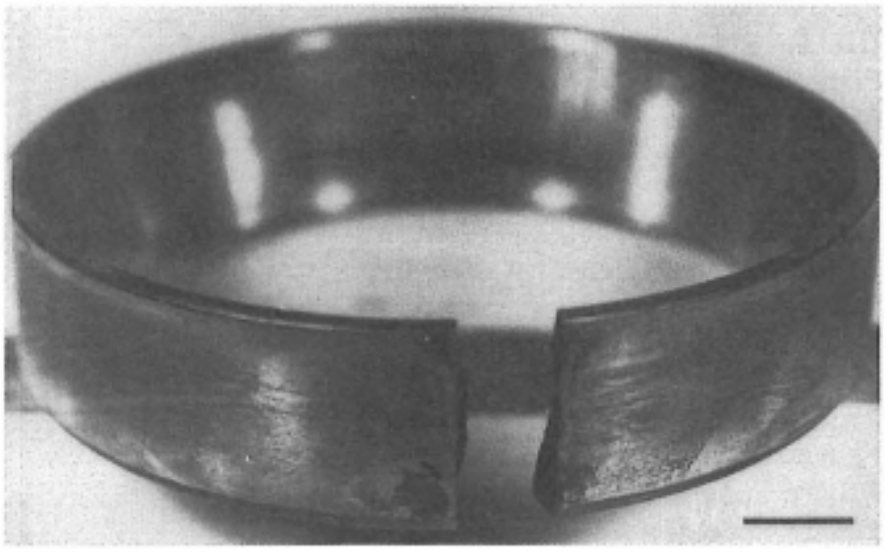
b

DATA
Plate No: 15.25
Archive No: 080-110
Image type: light macro
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.01.44 Tooth tip chipping
Failure Code 2: 00.16.01.3 Tooth spalling
Failure Code 3: 00.16.1.1.3 Subcase-fatigue spall
Failure Code 4: -

DESCRIPTIONS
Failure Description: Portions of tooth tips are chipped off following extensive spalling, penetrating to the case/core interface. In this high-hardness gear, the spalling has lead to bulk fatigue fracture. This is a gross failure.
Image Description: Three teeth at image N have lost much of the contact surface. At N-most tooth, spalls have reached the case/core interface. The next two teeth to S are heavily spalled, and chips have fractured out of the tooth tips.
Suspected Causes: Severe spalling, as from overload, possibly combined with insufficient case depth, have caused subcase spalling (also referred to as 'case crushing') in this carburized gear. Subsequent bulk fatigue cracking has produced chipping of tooth tips.

DATA

Plate No: 15.26
Archive No: 014-59
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; OR, carburized, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 00.22.1 Overstress crack
Failure Code 2: 21.4 Housing worn
Failure Code 3: 00.23.1 Plastic rolldown of contact path
Failure Code 4: -

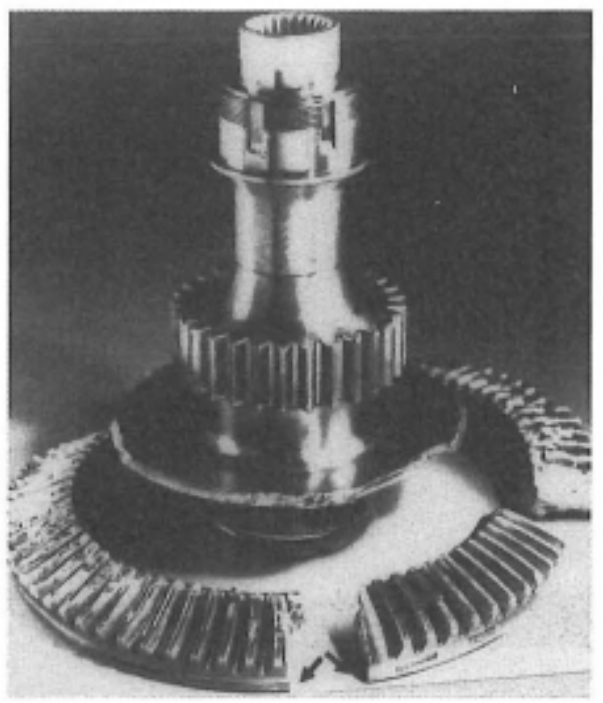


DESCRIPTIONS

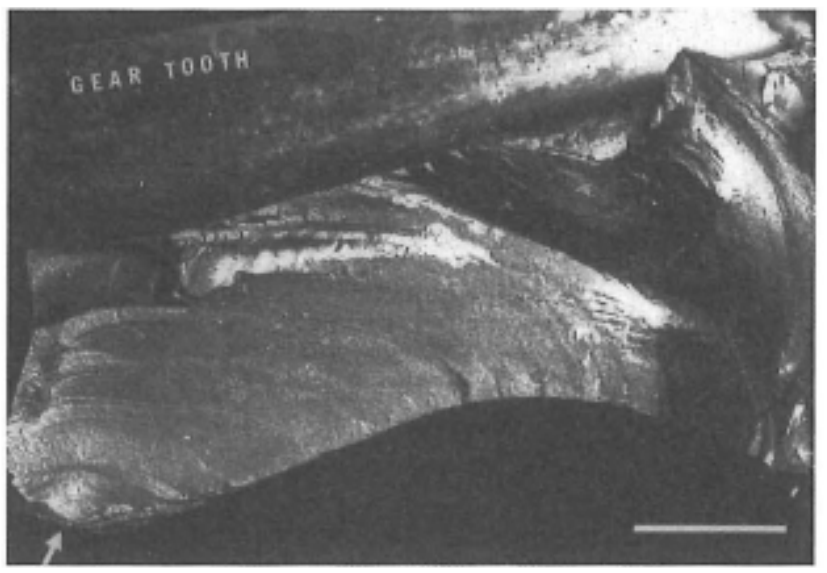
Failure Description: Radial/axial overstress crack across OR ('cup') section has resulted from plastic rolldown of the cup roller track in a housing worn oversize by the cup turning in a loose seat. This is a gross failure.
Image Description: OR (cup) viewed from OD shows axial/radial fracture, with surfaces widely separated. Cup OD finishing lines are worn off. Housing bore (not shown) was severely worn.
Suspected Causes: The bearing was used in a wheel hub and the housing to OR OD fit was loose. The OR turned and wore the housing bore. Subsequent rolldown of the roller path stretched the contact path circumferentially, causing increased residual compressive stress in the contact path case, and increased core tension. Eventually, the core ruptured, causing cross-section fracture. Case stress relief opened the fracture.

DATA

Plate No: 15.27
Archive No: 002-008a&b
Image type: a: view, b: light macro
Scalebar = a: 40, b: 5 mm (micros: ±20%, others: +100%, −50%)
Component: BG; W, high hardness, run
Speed: 91 m/sec
Load: 0.6 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 5.10



a



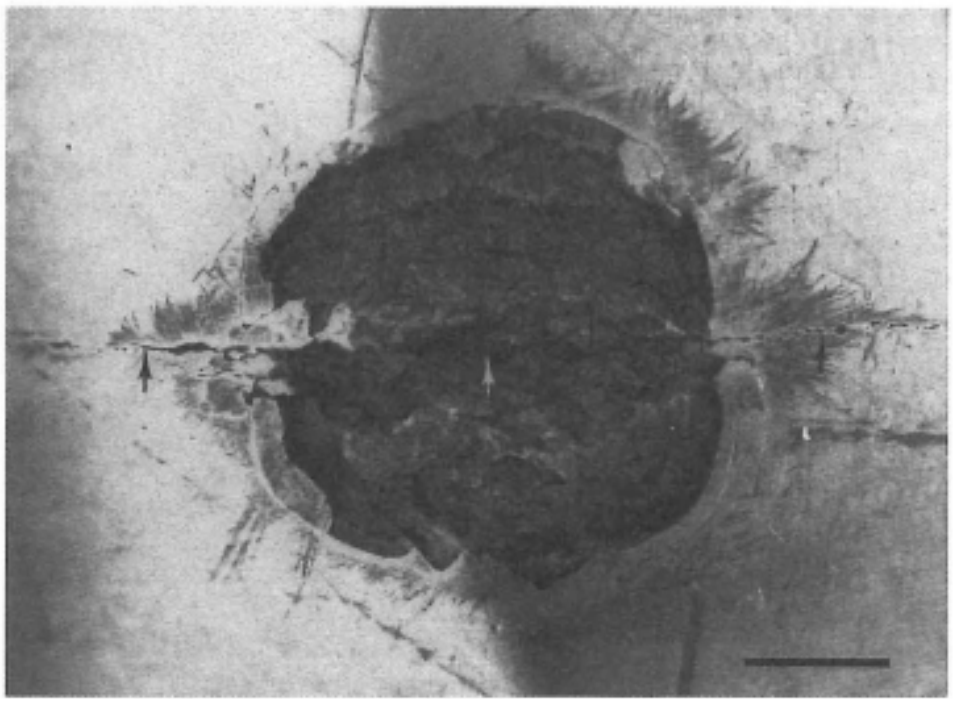
b

DESCRIPTIONS

Failure Description: Radial and circumferential disk fracture of a bevel gear is from fatigue originating at a sharp machining discontinuity. See PLATE 5.10 for originating defect. This is a gross failure.
Image Description: (a): Shaft with two integral gears, of which the larger, to image S, is a bevel gear. This has fractured at three points radially across the teeth and around 360° of arc in the disk. Arrows point to the fracture origin, shown in detail in (b): An edge, left in machining acted as a stress raiser. (See defect in Plate 5.10.) From this origin, a striated fatigue crack extended NE across the disk, to the tooth root, ending in overload fracture.
Suspected Causes: The highly loaded bevel gear ring undergoes high alternating bending stresses. The (off-specification) machining marks acting as stress raisers precipitated bending fatigue.

DATA

Plate No: 15.28
Archive No: 002-024b
Image type: light macro
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.04.2 Forming seam
Failure Code 3: 00.16.1.1.2 Spall from subsurface defect
Failure Code 4: 00.17.2 Localized surface distress (halo at defect)
See also PLATES: 5.23 and 5.24

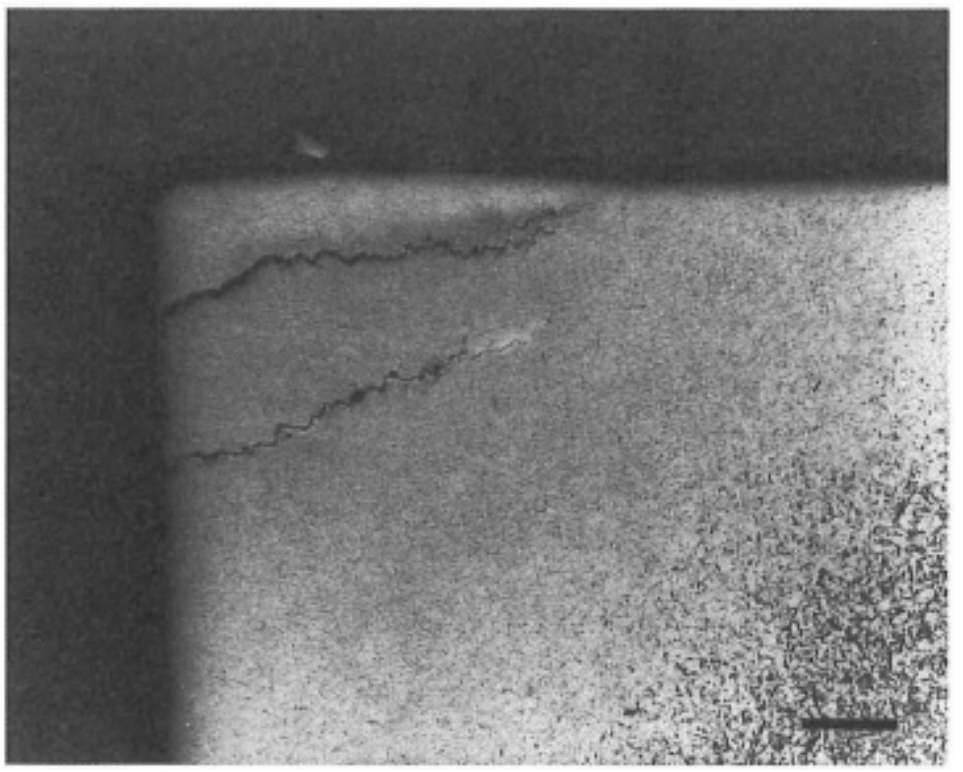


DESCRIPTIONS

Failure Description: Bulk fatigue crack in ball, resulting in a spall and surrounding halo of surface distress during continued running. Metallography has found a forming seam which originated the crack. See also Plates 5.23 and 5.24 for material defects in this ball. The ball has failed.
Image Description: At image center is a circular spall crater, exfoliated from a straight-line bulk crack (along arrows). Burnishing marks around crater edge are from over-rolling of the edge.
Suspected Causes: Forming seam and other material structure defects in ball have originated a radial fatigue crack which subsequently spalled out.

DATA

Plate No: 15.29
Archive No: 005-11
Image type: light metallogram. Nital etch
Scalebar = 250 μm (micros: ±20%, others: +100%, −50%)
Component: C; CM, case hardened, run
Speed:
Load: 2.1 GPa
Lubrication: Diesel fuel, ? °C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.07.5.02 Heat treat crack
Failure Code 3: 00.07.2 Off-specification martensite platelet size
Failure Code 4: -

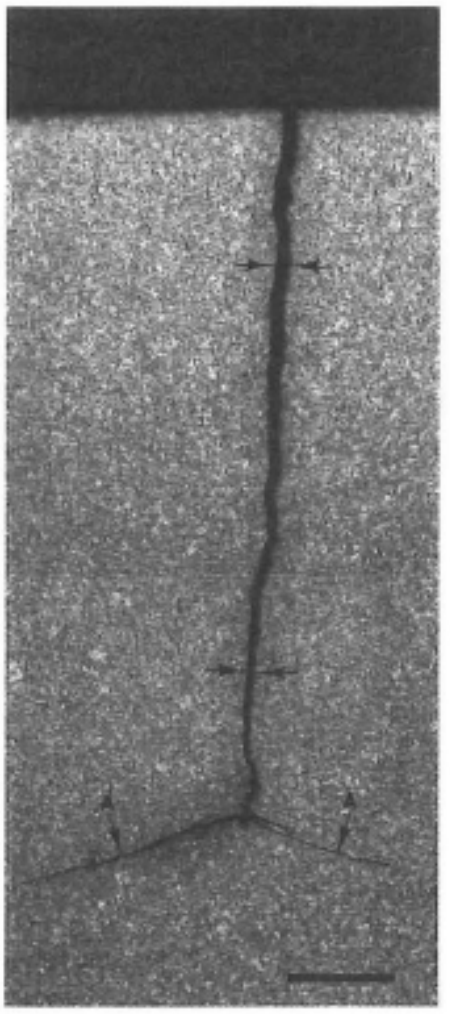


DESCRIPTIONS

Failure Description: At the edge of the cam lobe, two large cracks in the case are attributed to defects of the heat treated structure, and possible intergranular heat treat cracks, which have propagated in fatigue. The cam has failed.
Image Description: The image is an etched metallographic cross section of a cam lobe, including sideface at W image edge and contact surface near N image edge. The core transition zone (dark mottled area) is in the SE corner. The dark area at N and W edges is mounting material. Two twisting (dark) bulk cracks extend from the sideface in E–NE direction into case but do not reach contact surface. The highly tortuous crack path indicates intergranular crack.
Suspected Causes: A heat treatment error led to a coarse structure after heat treatment, with weakened intergranular bonds. Intergranular heat treat cracks may have been initiated, and were extended by intergranular fatigue cracks (rare in contact devices). The origin of the cracks at the sidewall suggests edge-loading and weakened (perhaps decarburized) sidewall surface.

DATA

Plate No: 15.30
Archive No: 002-007g
Image type: light metallogram, Zephiran etch
Scalebar = 200 μm (micros: ±20%, others +100%, −50%)
Component: ACBB; B, tool steel, run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.07.5.02 Heat treat crack
Failure Code 3: 00.07.5.1 Crack with oxidized surface
Failure Code 4: -
See also PLATE: 6.17

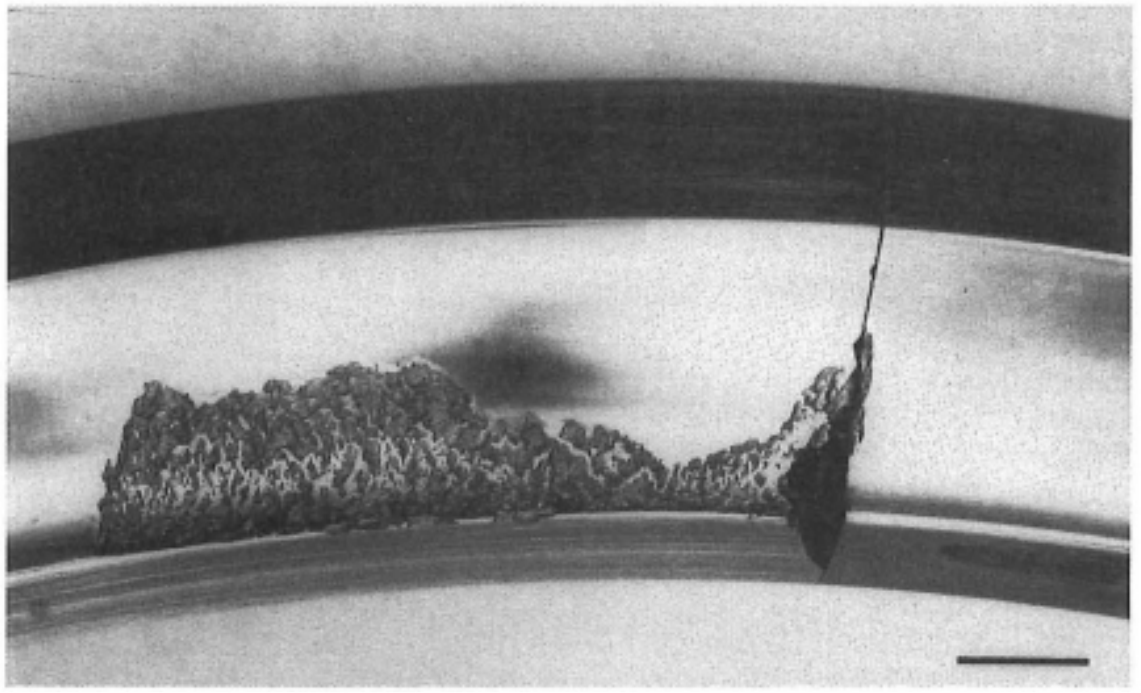


DESCRIPTIONS

Failure Description: An open crack, probably formed during heat treatment, runs from the ball surface toward center. Closed bulk fatigue cracks have extended the crack front during running. Heat treat cracking creates a severe defect which precipitates both spalling and bulk fatigue cracking. See Plate 6.17 for surface view and crack surface appearance.
Image Description: The etched, mottled metallographic section is fine-structured steel. N image edge is mounting material. Wide N–S crack between opposing arrows is a heat treat crack. Branching cracks at arrows *A* are bulk fatigue cracks which have propagated during running.
Suspected Causes: The oxidized surface of the primary crack suggests causation by forging or heat treatment. The tortuous course of the crack (see Plate 6.17) suggests a heat treat crack. The severe defect represented by the heat treat crack initiated the bulk fatigue cracks shown here.

DATA

Plate No: 15.31
Archive No: 003-001
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed: 1.1 MdN
Load: 1.9 GPa
Lubrication: synthetic polyester oil, 110°C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.08.2 Rehardened grinding burn
Failure Code 3: 00.16.1.1.2 Spall from subsurface defect
Failure Code 4: 00.16.02.5 Advanced spalling

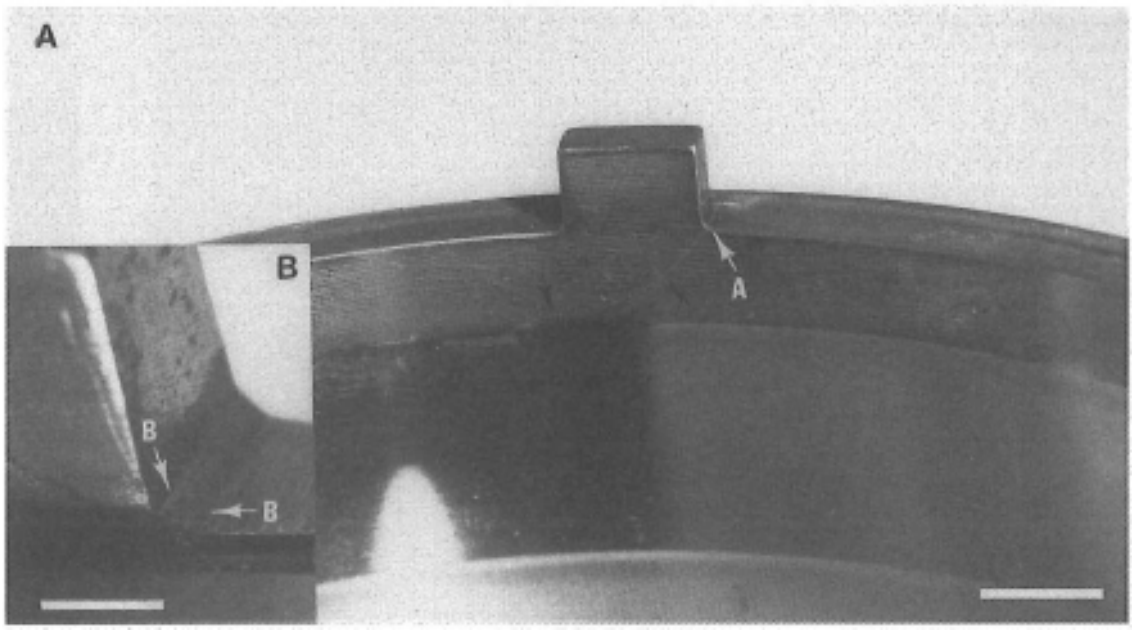


DESCRIPTIONS

Failure Description: Cross-sectional fatigue crack in an ACBB (split) IR, found to have originated from a grinding burn (FC 00.08.2) in the bore, through the action of high centrifugal hoop stresses in the ring. The spall has propagated in the rolling direction from the crack. The bearing has failed.
Image Description: One of two parts of a split innerring from an ACBB, with land (dark band) bordering ball groove on image N and split-face at S. A black axial crack crosses the entire ring, ¼ of the image width from E edge. Extensive spall cratering extends from crack toward W (in rolling direction). In width, the spall reaches a split-face edge. Reported grinding burn is not shown.
Suspected Causes: Grinding with excessive pressure overheats material and causes rehardened grinding burn at the surface. High residual stresses and brittleness of untempered martensite may serve as an initiating defect for bulk fatigue cracking, which then initiates spalling.

DATA

Plate No: 15.32
Archive No: 002-016b1&016b2
Image type: a, b: light macro
Scalebar = a: 9, b: 2 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; OR, run
Speed: 0.9 MdN
Load: 0.8 GPa
Lubrication: synthetic polyester oil, 149°C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.09.0 Geometry defect
Failure Code 3: -
Failure Code 4: -

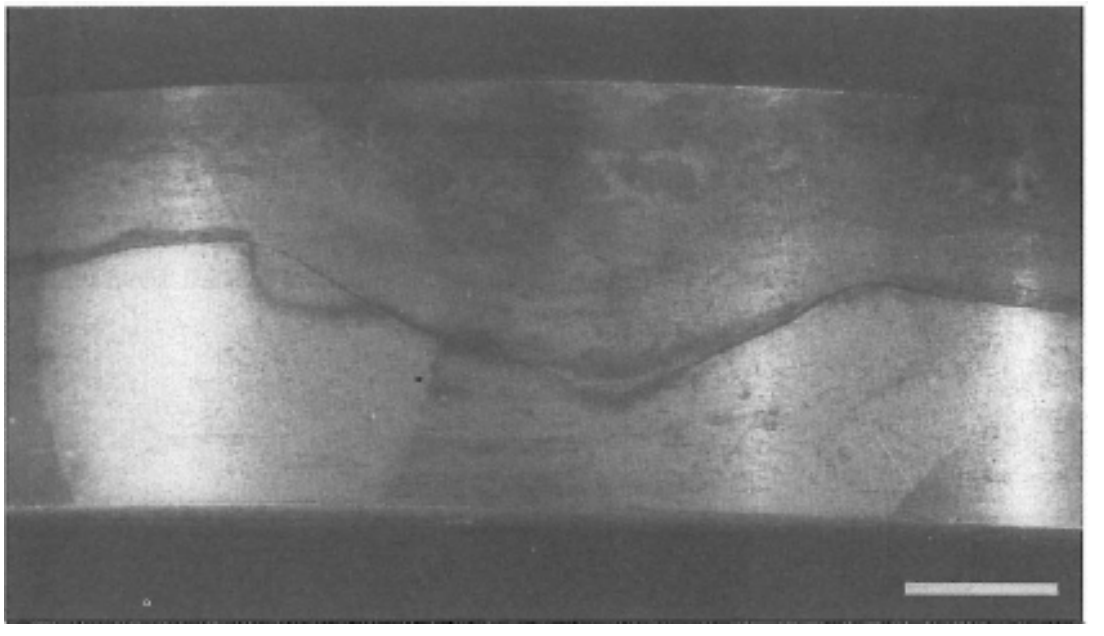


DESCRIPTIONS

Failure Description: Fatigue crack across section of IR, from an inadequately blended corner of the anti-rotation lug exposed to bending forces during service. The lug may break off with a chip out of the ring.
Image Description: (a): OR with one of four anti-rotation lugs facing image N, followed, going S, by a free ID band, then the roller track (lustrous) and another free band. At *A*, inadequate corner blend (not full radius), as shown in (b), as the detail between arrows *B*. A light-colored fine crack line extends on the ring ID, running from *A* in SW direction and then curving W (black arrows). Crack also extends N from *A* across ring face.
Suspected Causes: Some aerospace bearings have anti-rotation lugs engaging notches to prevent creep of thin OR under moving load direction. Forces driving ring creep may cause sizeable stresses in the lug. At the lug root, the corner is a stress concentrator which requires corner blending. The chamfered blend achieved in this bearing left small radii at *B* and was insufficient to prevent cracking.

DATA

Plate No: 15.33
Archive No: 116-001
Image type: light macro
Scalebar = 7 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.15.1.2.0.6 One-sided radial fit fretting from taper
Failure Code 3: 00.15.1.2.0.7 Irregular fretting in distorted radial fit
Failure Code 4: -



DESCRIPTIONS

Failure Description: OR with OD fretting in irregular circumferential band covering roughly one ring half, indicating taper and circumferential irregularity in the housing seat. A ring-splitting circumferential crack follows the edge of the fretting. The ring has failed.
Image Description: The OR is viewed on the OD. A dark, blotchy band of fretting covers half of the ring width to image N, with a wavy line of heavier fretting delineating this half from the unfretted S half. A circumferential crack in or near the fretting boundary is a sharp dark line.
Suspected Causes: A housing with taper in the bore fitted the OR more tightly where not fretted. The irregularity of the fretting boundary indicates that the housing was not round. Poorly supported (fretted) half underwent cyclic bending against the supported half as balls rolled over the track, creating tensile stresses in the axial direction in the OD and, with surface damage caused by fretting, eventually lead to cracking.

DATA
Plate No: 15.34
Archive No: 074-34
Image type: view
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; OR (Sendzimir-mill bearing), run
Speed:
Load:
Lubrication: mineral oil mist, ? °C
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.16 Spalling (Hertzian contact fatigue)
Failure Code 3: 00.13.2.1 Rolling surface galling
Failure Code 4: -

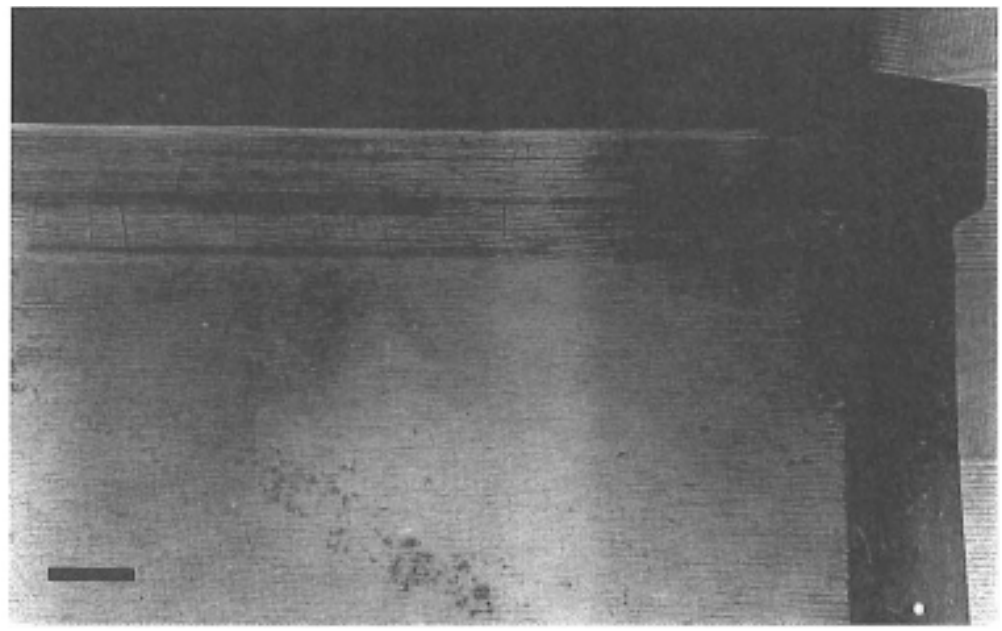
DESCRIPTIONS
Failure Description: Gross material removal to about 7 mm depth, from contacting OD of a Sendzimir mill bearing, apparently initiated as contact spalling. The lobed crack propagation and uniform-width flat band at spall bottom are not explained, in the absence of failure history from the mill. This is a gross failure.
Image Description: The short cylindrical part shown is the thick-walled OR of a CRB, with the OD used as a roller supporting a cluster roll in a sheet mill. The center and E-facing end of the ring are missing a deep layer of material removed by surface-parallel cracks running about 7 mm below the original surface. The center shows a smooth, flat band. The sides of the spall are lobed. Deep axial galling marks are on the unspalled OD.
Suspected Causes: Sendzimir mills are cluster mills with two small-diameter work rolls supported by layers of backup rolls, of which the outermost consists of CRBs stacked on long shafts. Rolling forces are great, contamination is possible and temperatures may be high. A specific analysis of the peculiar failure appearance requires detailed machine failure history, which is lacking.

DATA
Plate No: 15.35
Archive No: 018-114
Image type: view
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.2 Bulk fatigue crack
Failure Code 2: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 3: 00.19.3 Scale formation
Failure Code 4: 22.9 Geometry or assembly defect in shaft

DESCRIPTIONS
Failure Description: An improper taper angle on the bearing seat of the shaft has supported only one ring half. The other half failed by circumferential cracking in bending fatigue, causing massive overheating, plastic rollout and scaling. This is a gross failure.
Image Description: A fracture surface from circumferential cracking bounds the ring at image N. The adjacent roller path is severely rolled out, and the fracture surface is battered. The N ring half is scaled. Shaft contact (circumferential wear marks) is visible in the S half of the bore. The N half of the bore is scaled but unworn; it probably had no or little shaft contact. This suggests an angle error in the shaft seat.
Suspected Causes: Severe angle error in a tapered shaft seat creates support only under one ring half (the large-bore end in this case). The other ring half is cantilevered and undergoes severe bending fatigue stressing. Circumferential fatigue cracking may result. As this crack progresses, normal bearing geometry is destroyed, parts (such as a separator) break, overheating and plastic flow occur.

DATA

Plate No: 15.36
Archive No: 018-117
Image type: light macro of cut ring
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; IR, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.3 Rubbing crack
Failure Code 2: 00.12.1.2 Advanced mild wear of fit surface
Failure Code 3: 22.9 Geometry or assembly defect in shaft
Failure Code 4: -

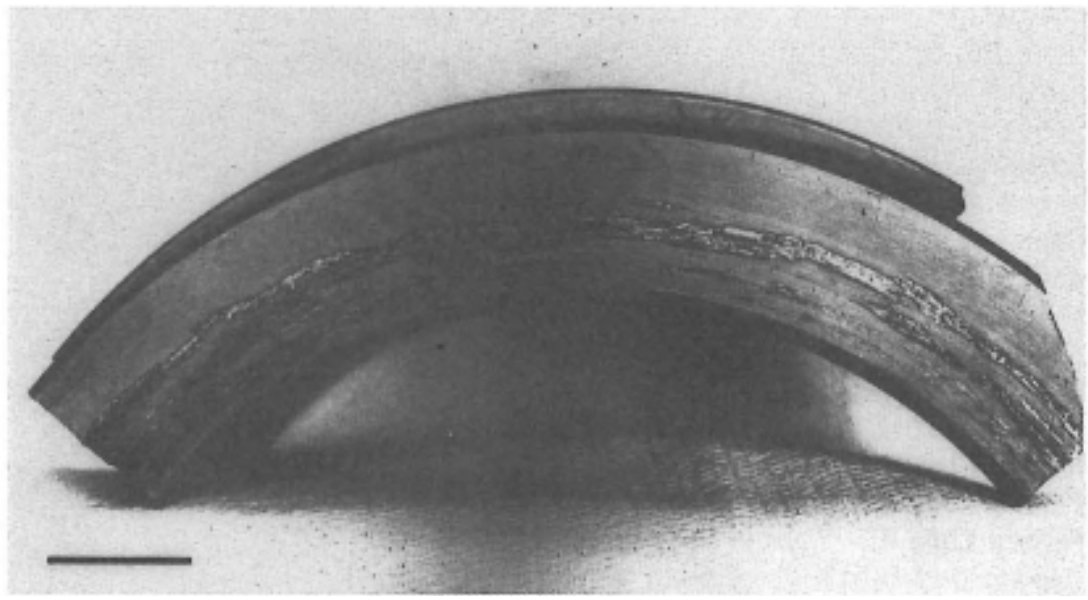


DESCRIPTIONS

Failure Description: Multiple, generally axially running fine rubbing cracks are visible in the IR bore, near the sideface. Circumferential wear marks are crossing the cracks. The ring has rotated on the shaft, creating severe local heating in the band where the cracks arose. The ring is likely to crack through, if it is mounted with an interference fit.
Image Description: IR, cut to expose the bore is viewed on the bore. The corner radius is near the N image edge, a section plane is near the E edge. A band S of the corner radius shows (dark) circumferential wear marks and multiple, dark axial crack lines. Wear markings (dark interrupted circumferential lines) elsewhere in the bore are less pronounced.
Suspected Causes: Interference fit between IR and shaft was insufficient for the loading and severe sliding occurred. Wear marks resulted. In the band near the corner radius (presumably with tighter fit than elsewhere), heating was excessive and thermal and structure transformation stress caused cracking. Such cracks are typically axial in radial fit surfaces due to the interaction of rubbing-induced stresses with mechanical (hoop and/or contact) stresses.

DATA

Plate No: 15.37
Archive No: 093-018a
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR (segment), run
Speed:
Load:
Lubrication:
Failure Code 1: 00.22.3 Rubbing crack
Failure Code 2: 00.13.1 Fit surface galling
Failure Code 3: 21.7 Housing mismounted
Failure Code 4: 00.22.01.1 Axial cross section crack in ring



DESCRIPTIONS

Failure Description: Rubbing cracks and galling on the sideface of an IR, from unintended rubbing against the stationary end cover attached to the housing, leading to material transfer in unlubricated sliding. Overheating of surface and cracks from thermal stresses or stresses induced by structural transformation. Heat imbalance failure may be in progress. The ring is fractured by axial/radial crack emanating from a rubber crack. This is a gross failure.
Image Description: The IR is viewed on the sideface. There are circumferential galling marks (light and dark, irregularly bounded streaks) and dark fine radial rubbing cracks. The E contour of the ring is an axial/radial fracture.
Suspected Causes: Mislocation of the shaft assembly in the housing, or of the bearing on the shaft, or of the end cover in the housing, has produced unintended rubbing between the stationary end cover and the rotating bearing IR endface. Galling and severe local overheating caused sufficient thermal stress or structural transformation stress to initiate cracks. One has penetrated across the ring and broken it.

Failure Code: 00.22.3
Failure Code: 00.23.1.1

DATA

Plate No: 15.38
Archive No: 001-40
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = 6 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR, run
Speed: 700 KdN
Load: 1.2 GPa
Lubrication: mineral oil, 70°C
Failure Code 1: 00.22.3 Rubbing crack
Failure Code 2: 00.13.2.1.1.2 Contact galling from high acceleration
Failure Code 3: 00.12.3.2.1.4 Wear track at contact edge
Failure Code 4: 11.1 Friction polymer, oil lubrication

[See Image in Appendix]

DESCRIPTIONS

Failure Description: On contact surface of IR are several axial/radial cracks, initiated from an extensive galling streak near the contact center. Also, wear bands appear near both roller ends. In a high-speed CRB innerring, acceleration-caused galling may injure the centrifugally stressed OD to cause cracking. Wear streaks may indicate roller skew. Friction polymer indicates high temperature. Continued running is likely to cause ring fracture.
Image Description: Center portion of the image is a CRB IR roller path. Two interrupted light brown bands near N edge of rolling track are wear bands with friction polymer. Two interrupted bands with dark brown edging, near the rolling track center, are wear bands with galled metal (white-and-brown patchy deposit) along their centerline. Dark and light, irregular axial lines across the galling bands and beyond are bulk cracks penetrating radially.
Suspected Causes: Very high speed bearing IR, especially CRB IR, are subject to high centrifugal hoop stress. Roller sliding (from high acceleration, skewing, or both) may cause wear, and if severe, galling, which is a severe tractive stress in the surface. Thus, the damage done to surface integrity by galling, and the centrifugal hoop stress can combine to form radially going axial cracks, and eventually cross-section fracture.

DATA

Plate No: 15.39
Archive No: 001-4
Image type: light macro, section
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; IR, run
Speed: 1.1 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 00.23.1.1 Contact path rolldown in bearing
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATE: 10.5

DESCRIPTIONS

Failure Description: Overrolling of the contact path at extreme pressures causes plastic flow in Hertzian dimensions. If the contact is well centered, the result is profile distortion and residual stresses in the subsurface material. If the contact extends to the track edge (as shown), a lip or ridge forms at the edge. Operation under a load sufficient to cause plastic rolldown destroys geometry and leads to early spalling.
Image Description: The image shows a cross section of an ACBB innerring against a black background. At image E is the edge of the ball path; the straight line from center to W is a land. The edge between track and land, which should be rounded, shows a protrusion above the land caused by plastic flow of material from under the ball path.
Suspected Causes: In a ball bearing, contact overriding the track edge results from (1) severe overload; (2) insufficient land height for the load condition; or (3) excessively tight conformity as built or due to plastic rolldown. In any of these cases, plastic rolldown occurs as a result of very high Hertzian pressures. Plate 10.5 shows rolled-in lines on one of the mating balls.

DATA
Plate No: 15.40
Archive No: 099-131
Image type: light macro
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: SG; W, medium hard, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.23.1.2 Gear tooth contact rolldown
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Excessive contact pressure in medium-hard gear causes plastic flow in the contact surface. Pressure was evenly distributed to the contact edge, and lips formed protruding past the tooth face and the tooth tip. Geometry was lost. Gear is noisy and if flow progresses, may suffer tooth fracture.
Image Description: Side view of gear. Tooth contact surfaces facing image W form lips protruding past the sideface. (Black streak on sideface is paint mark.)
Suspected Causes: Excessive contact pressure produces continued plastic flow of surface material. In a medium-hard material, sufficient plasticity is available to produce substantial gross deformation before fracture.

DATA
Plate No: 15.41
Archive No: 080-126
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: SG; G, high hardness, run
Speed:
Load:
Lubrication:
Failure Code 1: 00.23.1.2 Gear tooth contact rolldown
Failure Code 2: 00.07.1.1 Insufficient bulk hardness
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Overloaded teeth of insufficiently hardened gear have plastically deformed by rolling down the contact surface and extruding material at the tooth tips and ends. The insufficiently hardened gear is unable to carry the design load. Plastic deformation destroys the geometry and may be followed by galling, spalling or tooth fracture as possible further failures.
Image Description: Gear segment (three teeth) is viewed from gear face. The E-facing tooth flanks are more-or-less unchanged. The W-facing (loaded) tooth flanks are hollowed out and material is extruded, forming extensions ('lips') at the tooth tips and also at the tooth-end edges facing the viewer.
Suspected Causes: On unhardened or insufficiently hardened gears, heavy continous or impact loading may roll or hammer out the tooth surfaces. (In properly hardened high-hardness gears, tooth fracture is more likely.)

GUIDING-COMPONENT FAILURE 16

Failure Code 01

General Description

This chapter covers failures of *separators* and *guiderings*—components unique to rolling bearings. Separators are also known as *cages* or *retainers*, and are the components placed between the rings to hold and space the rolling elements. Guiderings are ring-shaped components (loosely) fitted to a contact component (ring). They are used in some (multirow) roller bearings to provide axial guidance to roller ends in the absence of a fixed flange, and (in some cases) to provide separator guidance.

16.1 SEPARATOR FAILURE FAILURE CODE: 01.1

A separator consists typically of one or more *rings*, some or all with *pockets* for the rolling elements. Individual *bars* (crossbars) attached to the separator rings may separate the rolling elements instead of pockets machined into a separator ring. If there is more than one separator ring, they (as well as any crossbars) are fastened together by welding, rivets, prongs or bolts.

Separators have many failure modes in common with Hertz contact components, and others, which are unique to them. In this general description of the failure class, *nomenclature* and *failure process* are referred back to the definitions for the corresponding contact component failure mode wherever possible, with differentiating features given where they exist. *Distinctive appearance*, *causes* and *effects*, being very different for separators, are generally treated without back-reference.

Separators may be made of (mostly unhardened) steel or a variety of other metals including powder metals. Plastic materials (polymers) or composites of polymers and reinforcing fibers are also used.

Separators (other than those consisting of undersize rolling elements) have sliding contacts only. All separators have such contacts with the rolling elements. Some separator designs also have contacts with guiding surfaces on the Hertz contact rings or on guiderings. Unusual separators may consist of individual *inserts* placed between adjacent rolling elements and unattached to each other or to separator rings. Undersize rollers or balls can be used as separator inserts.

Some multirow bearings have more than one separator.

16.1.1 Separator Bulk Discontinuity Failure Failure Code: 01.11

16.1.1.1 Definition

The term "separator bulk discontinuity failure" is used as the generic designation for all failures involving separation or voids in separators, or melting and disintegration of separator material. It includes the following failure modes:

1. *Melting* or *burning* (in polymer separators);
2. *Casting* or *molding defect*;
3. *Weld failure*;
4. *Cracking* and *fracture* (separator body);
5. *Fastener failure* (rivets, prongs, bolts).

16.1.1.2 Nomenclature

Bulk discontinuity failures are commonly designated by their specific failure modes as listed in Definition, above.

16.1.1.3 Failure Process

Melting occurs in thermoplastic materials when the separator is operated at excessive temperature. It can range from partial melting, with resulting distortions of the separator, to near-total disintegration. *Burning*, which represents a chemical decomposition due to excessive temperature, occurs in polymers that do not melt first.

Cracking or *fracture* is a common failure mode of separators. These are generally slender, sculptured shapes subject to substantial stresses in bending, torsion and tension. Many metal separators are cold-stamped from sheet, with opportunity for sharp corners, scratches, work hardening and microcracking during manufacture. Most separator cracking is due to overload or fatigue. Chemically promoted cracking occurs in polymer separators, operating in aggressive atmospheres. Chemically promoted cracking is also known to occur in metals as a result of electroplating defects. Manufacturing macrocracks may occur in the fabrication of stamped separators or during the "closure" of separators around rolling elements in assembly (stamped separators in taper roller bearings, retainer-tang designs in machined aircraft bearing separators). See *Fastener failure* below for cracks in prong-assembled stamped separators.

Weld failure occurs in separators welded from separate parts. Spot welding in lieu of riveting is common for light sheet steel separators; some heavier stamped separators have line-welded construction. Welds may crack from tensile or shear overloading or fatigue, which are possibly aided by residual stresses, weaknesses or brittleness in the weld. Welding cracks may also be manufacturing defects.

Casting or *molding* defects of manufacture occur in sandcast, centrifugally cast or diecast metal separators and in molded plastic separators. Common defects include *voids, seams, structure defects, underfill* and *incomplete bonding* at interfaces where melt flows meet, such as in injection molding.

Fastener failure (deformation, cracking or fracture) occurs in riveted, prong-assembled or bolted separators. The failure of a fastener may lead to weakening or disassembly of the separator or loss of separator geometry (with subsequent rubbing on moving parts) and possibly eventual fracture of the separator body.

16.1.1.4 Distinctive Appearance

Separator bulk discontinuities, if sizeable, are readily recognized visually. Difficulty may arise with microcracks or the cracking of fasteners in concealed areas. Crack-revealing techniques, such as die-penetrant inspection, are available. Knowledge of the points in the separator design where manufacturing stresses are likely to lead to cracks may depend on experience with failures of a given design. Design features with a history of vulnerability are listed below.

16.1.1.5 Causes

Separator bulk discontinuity may arise from manufacture (or design) or from service.

Manufacturing and Design Causes

1. *Sharp edges* in stamped separators tend to work-harden and crack.
2. *Sharp bends* in retaining prongs and tangs may crack during or after the bending operation.
3. *Rivet heads* and necks may be malformed, or crack in forming or service.
4. *Large, thin walled sand castings* for machined separators may contain voids or inclusions.
5. *Interfaces* in injection moldings, where melt material coming from two directions must bond, may remain weak.
6. *Welds* in both steel and plastic separators may be incompletely fused, contain residual stresses, inclusions, be brittle or microcracked.

Service Causes

1. Operation at *excessive temperature* as a result of bearing heat imbalance failure (FC 00.19) or insufficient separator cooling may cause melting or chemical decomposition (also galling, see FC 01.14).
2. *Excessive* separator/rolling element (or ring) *forces* may cause cracking or fracture of separator body, fasteners or welds. They can also cause overheating (see above), permanent deformation, wear or galling (see FC 01.12, FC 01.13 and FC 01.14 later in this chapter). Separators transmit forces to rolling elements while maintaining their relative position. Ring land riding separators also transmit forces to the rings. When these forces exceed design levels, bulk permanent deformation (see FC 01.12) or bulk discontinuity may result.

   Causes for abnormal levels of separator/rolling element forces (in ring land riding separators, also ring forces) include conditions that necessitate increasing sliding between rolling elements and rings, namely:

   - *Misalignment* between bearing rings;
   - *Axial* bearing *loads* in excess of design levels;
   - *Diameter* sorting *error* among rolling elements;
   - *Skewing* of rollers in excess of design levels;
   - Off-specification (insufficient) *pocket clearance* between separator and rolling element.

   Another set of causes for abnormal separator/rolling element forces is represented by any condition that increases friction between separator, rolling elements and rings, notably, *impaired lubrication.*
3. *Inertial forces* on the separator may cause cracking or fracture. High-speed operation imposes centrifugal hoop stresses on the separator body which act similarly to the rolling element forces described under 2. Additionally, high speed on an unbalanced separator displaces it from the centered position or causes instability in separator motion, which increases rolling element (and ring) forces. This may create unintended contacts (between separator and a ring) with corresponding forces.
4. *Geometry errors* of the separator may cause cracking or fracture. Distortions may cause roller skewing, maldistribution of contact loads or unbalance. Excess clearance may allow the separator to make unintended contacts. Rolling element riding separators can become land riding, and separator elements may be caught under a rolling element, wedge in the Hertz contact and cause catastrophic fractures.
5. *Chemical attack* (see FC 01.15) can weaken a metal separator and promote cracking under stress. Chemical attack on a plastic separator (from atmosphere or incompatible lubricant) can cause embrittlement and cracking.

16.1.1.6 Effects of Separator Bulk Discontinuity

Separator discontinuity eventually leads to gross machine element failure.

16.1.2 Separator Permanent Bulk Deformation — Failure Code: 01.12

16.1.2.1 Definition

Permanent bulk shape or size changes of separators fall in this failure class (as distinct from wear or galling, which change local microgeometry).

16.1.2.2 Nomenclature

Commonly used designations are *bending, distortion, twisting,* and *stretching* of the separator.

16.1.2.3 Failure Process

- *Imposed bulk stresses* exceeding the elastic limit cause permanent bulk plastic deformation in (metal) separators.
- Bulk deformation may be caused by unrelieved *residual stresses*.
- In plastic separators, *chemical* influences may cause bulk deformation.
- *Softening* of separator material, usually due to bearing overheating (FC 00.19) may cause permanent deformation under forces otherwise well supported.

16.1.2.4 Distinctive Appearance

Permanent bulk deformation may be detected in the *assembled* bearing:

- By direct visual evidence of misshapenness (example: out of roundness);
- By signs of wear at unintended contact surfaces or uneven wear at intended contact surfaces (see FC 01.13);
- By measurement of excessive or uneven separator looseness (radial, axial or circumferential (in the pocket)).

Note: Stroboscopic observation of separator motion in the running machine may provide indications of permanent bulk deformation.

Permanent bulk deformation may be detected in the separator *removed* from the bearing: by dimensional measurement, and by signs of wear as described above.

16.1.2.5 Causes

Either of the following causes may bring about permanent bulk deformation.

Any of the *imposed stresses* listed as causes of cracking or fracture under FC 01.11.

Residual *stresses* caused by any of the following:

- *Cold forming,* including stamping, drawing, rolling as manufacturing operations.
- *Forging, casting* or *molding* operations if not effectively stress relieved.
- Bulk or surface *heat treatment* for hardening or tempering of metal separators.
- *Assembly of separator* or its parts by riveting, prong-closure, or welding, snapping over rolling elements, tang or body closure by cold deformation.

16.1.2.6 Effects of Separator Permanent Bulk Deformation

- Unintended changes in separator clearances;
- Distortion of contacts with rolling elements and/or rings;
- Increased wear in contacts;
- Wear at unintended locations;
- Wear or galling of rolling elements and/or rings;
- Entrapment of separator in a rolling contact with catastrophic failure of the bearing.

16.1.3 Separator Wear — Failure Code: 01.13

16.1.3.1 Definition

Mild wear of a separator is defined as under failure code FC 00.12 for wear of contact components.

Surface distress, being a form of fatigue limited to *rolling* contact, is not a failure mode of separators.

Galling, a common failure mode of separators, is described under FC 01.14: *Separator galling.*

16.1.3.2 Nomenclature

Nomenclature of separator wear is the same as given for contact components under FC 00.12.

16.1.3.3 Failure Process

Failure modes of separator wear are the same as given for Hertz contact components under FC 00.12. Because separator contacts are almost always *simple sliding* contacts, wear is a predominant failure mode. According to the types of contact in the separator, the following wear locations can be distinguished:

1. *Pocket wear* between the rolling element and its containing separator pocket. More specifically:
   - *Pocket bore wear* between the rolling surface of the roller (any surface of the ball) and the mating surface of the separator.
   - *Pocket bottom* or *endring wear* between roller endfaces and mating separator surfaces in the pocket, or on a separable endring.
2. *Guideland* wear between a cylindrical surface of the separator (bore or OD) and a Hertz contact ring or guidering surface.
3. *Wear* of *unintended contact,* when the separator contacts another component at an unintended location due to separator displacement or deformation.

Composites (such as fiber reinforced plastic separators or solid-lubricant filled metal separators) can suffer especially damaging wear if the plastic or solid lubricant layer wears through to the reinforcing material. This reinforcing material is harder; it is generally not selected for tribological capabilities; and it may protrude as jagged points or edges. Separator wear can then give rise to wear of the mating contact component.

16.1.3.4 Distinctive Appearance

Separator material is almost always softer than the mating contact component. The wear scar on the separator is expected to be deeper than on the Hertz contact component whenever they contact along *surfaces.* Contacts along *edges* are possible, however, and then wear scratches on the Hertz component may be more pronounced than the wear of the separator edge. If hard contaminant particles are embedded in a soft separator, then the mating surface on the Hertz contact component may be severely worn.

As described under FC 00.12, wear on a separator surface typically consists of ''kinematic wear marks'' in the form of *circumferential* scratches indicating the sliding direction. Typical wear patterns indicative of operating conditions are listed below (on the assumption that the direction of bearing rotation does not reverse).

Pocket Wear

- *One-sided pocket bore wear* on front or back of the pocket but not both, indicates normal radial pocket clearance and wear under the rolling element/separator load.
- *One-sided pocket end wear* indicates normal axial pocket clearance and wear under axial load.
- *Two-sided pocket bore wear* indicates low radial pocket clearance.
- *Two-sided pocket end wear* indicates low axial pocket clearance.
- *Edge wear* indicates geometry error of the separator (including geometry change by bulk deformation or surface wear).
- *Cross-corner wear* in a roller separator pocket indicates skewing of the roller.

Guideland Wear

- *Even wear* around the circumference indicates rotating separator loading or low land clearance.
- *Uneven wear* around the circumference indicates one-sided separator loading or separator unbalance.
- *Uneven wear* (one land more than the other) indicates separator misalignment.
- *Localized guideland wear* indicates geometric distortion of the separator.

Wear at Unintended Contacts

This wear type indicates excess separator looseness (including increased looseness from wear), separator geometry error or high distorting forces on the separator.

Note: Retaining tang wear, on separators equipped with roller or ball retaining tangs, indicates excess separator clearance or off-specification tangs.

16.1.3.5 Causes

- *Contamination*. Solid contaminant in lubricant or the chamber rapidly wears the sliding contacts of the separator.
- *Inadequate lubrication*. Separator contacts are the bearing's most vulnerable contacts under inappropriately selected lubricant or insufficient quantity of lubricant.
- *Off-specification separator clearance.* Low or zero pocket (or guideland) clearance creates high separator contact pressures and rapid wear.
- *Separator geometry error* may cause edge contact (not reliably lubricatable), uneven distribution of rolling element loads on separator, or contact at unintended locations.
- *Rolling element sorting error* causes differentials in rolling element epicyclic orbiting speeds necessitating rolling element sliding, which requires high driving forces from the separator.
- *Bearing misalignment* causes cyclically varying rolling element epicyclic speeds necessitating rolling element sliding, which requires high separator driving forces.
- *Insufficient* (mounted) *bearing clearance* causes 360° load zone in bearing and accumulating phase errors between rolling elements, necessitating rolling element sliding, which requires high separator driving forces.
- *Bearing axial load* (in excess of specification). High axial load causes 360° load zone in bearing and accumulating phase errors between rolling elements, necessitating sliding which requires high separator forces.

16.1.3.6 Effects of Separator Wear

- *Run-in* by self-limiting mild wear can produce improved surface finish, especially in large bearings and in designs where coined edges must contact rolling elements.
- *Edge contacts* may form as a result of wear, impairing lubrication and accelerating wear or causing galling.
- *Separator geometry* may be impaired, leading to secondary failures (separator unbalance, entrapment under rolling element).
- *Structural strength of separator* is eventually lost due to wear, causing fracture.

Depending on separator design, considerable mild wear may be acceptable without impairing service. Machined metal and molded plastic separators tolerate appreciable wear, owing to their heavy sections. Stamped sheet metal separators, especially those contacting rolling elements along coined edges, tolerate only minimal wear.

16.1.4 Separator Galling — Failure Code: 01.14

16.1.4.1 Definition

Galling in separators is defined as under FC 00.13 for galling in contact components. Galling in separators is distinguished from mild wear, a common failure mode of separators, described under FC 01.13.

16.1.4.2 Nomenclature

See FC 00.13: *Galling in contact components,* for nomenclature.

16.1.4.3 Failure Process

As described under FC 00.13, this failure mode consists of the transfer of surface material between separate locations on the contacting surfaces by friction welding of contacting asperities, and their subsequent separation along a plane other than the weld interface.

A separator galls against contact components, which are of different material (different composition and/or hardness), and thus transfers foreign material (mild steel, yellow metal, etc.) onto the (hard steel) contact component.

Separator contacts are highly vulnerable to galling, because: (a) motion in them is *simple sliding,* so that an asperity contact is not interrupted by surface lift-off as in a rolling contact; (b) separators have complex shapes including sharp edges; (c) if metallic, separators are made of relatively soft metals; and (d) separators are manufactured by methods including stamping, milling and turning, none of which produce as fine a surface finish as that on contact components of rolling bearings.

The forces acting on separators are widely variable and their control is more problematic than that of the Hertz contact forces; galling is often the result of unanticipated force excursions.

Miscellaneous Notes on the Failure Process

- Although it is more common for the (softer) separator material to transfer onto the contact components, *reverse* transfer of hard steel onto separators has also been observed.
- Separators made of plastics do not usually suffer galling failure. However, some thermoplastic materials are capable of transfer to the mating contact surface and this transfer may be considered galling. Unintended transfer of plastic separator material to a contact part may cause noise, inaccuracies and overheating, in addition to placing large forces on the separator.
- Separators in contact with rolling elements made of ceramics are much less likely to suffer galling than with steel rolling elements. Nonetheless, separator material can transfer onto ceramic rolling elements and this transfer may be considered galling.
- Bearings operating in cryogenic fluids may be equipped with separators made of reinforced teflon. Controlled transfer of teflon to the rolling surfaces is a design requirement aimed at supplying dry lubrication and thereby improving the functioning of such bearings. This intentional transfer is not considered to be a failure.

16.1.4.4 Distinctive Appearance

The appearance of galling in a separator is similar to that described for contact components under FC 00.13, with the following special features:

- *Galled material wears* at once in the sliding separator contact, therefore wear marks will appear on it.

- *Dissimilar material* may appear on the galled surface, if separator and Hertz contact component materials are visually different (example: a brass separator against steel rolling elements).

16.1.4.5 Causes

The *common* causes of galling listed under FC 00.13 also apply to separator contacts.

Causes specific to separator galling include the load-increasing conditions listed under FC 01.13 and additionally the following:

- *Overheating* of the separator contact, precipitating the loss of lubrication and facilitation of welding postulated in Blok's flash temperature theory [14].
- *Loss of clearance* in the separator contact due to deformation, contamination, entrapment of the separator under rolling elements, etc.

16.1.4.6 Effects of Separator Galling

Separator galling may be arrested (*healed*) if the precipitating condition is alleviated before material transfer has destroyed significant areas of contact interface.

Unless there is relief in the severity of operating conditions to permit healing, separator galling typically leads to the following failure modes:

- *Bearing noise and vibration* may be caused by the material transferred through galling.
- *Heat imbalance failure* (FC 00.19).
- *Separator fracture* (FC 01.11).
- *Seizure* of the bearing (FC 00.13), possibly with bulk cracking or fracture (FC 00.22).

16.1.5 Separator Corrosion — Failure Code: 01.15

16.1.5.1 Definition

Chemical attack causing failure in a separator is designated in this Atlas as *separator corrosion.* This is analogous to the definition of corrosion for Hertz contact components under FC 00.20. The damage categories distinguished from corrosion under FC 00.20 (fretting FC (00.15), pitting as a casting defect (FC 00.05), temper coloring and friction polymer deposition (FC 00.19)) must also be distinguished from corrosion when they occur in a separator, although fretting is not a likely separator failure.

16.1.5.2 Nomenclature

The nomenclature for subclasses of corrosion (corrosion staining, corrosion pitting, intergranular corrosion), cited under FC 00.20 equally applies to *metallic* separators. In nonferrous separators, the staining is often designated 'discoloration.'

Chemical attack on plastic separators include *dimensional change* (swelling) due to humidity and *embrittlement.*

16.1.5.3 Failure Process

See FC 00.20 for a general description of failures by chemical attack.

Metal Separators. Separators made of *steel* corrode under conditions and by mechanisms similar to steel contact components.

Because of the rougher surfaces and lower hardness of steel separators, they are likely to be more sensitive to corrosion than the surfaces of contact components.

Separators made of *yellow metal* (bronze, brass) corrode by electrochemically enhanced corrosion in the presence of steel components and an electrolyte. *Ester base* synthetic lubricants of some formulations are aggressive to yellow metal. Yellow metal must be excluded from systems using such ester lubricants.

Aluminum alloy separators, if used, are protected by an anodizing surface treatment. This layer may wear away and the exposed metal forms an electrolytic couple with steel that can precipitate corrosion of the aluminum alloy leading to cracking.

Plastic Separators. Chemical attack on plastic separators can assume many forms, depending on material and attacking chemical. The most common are

- *Dimensional change in nylon* due to change in absorbed water content (not strictly a chemical reaction, but included here as being the effect of an environmental chemical).
- *Embrittlement of plastic* due to incompatible lubricants or aggressive atmosphere. When embrittlement occurs, micro- or macrocracks are likely to result under deflections otherwise readily tolerated by the material.

16.1.5.4 Distinctive Appearance

- Separators made of *steel* show corrosion similar to steel contact components, except for the appearance differences due to dissimilar original surface finishes.
- Separators made of *yellow metal* (brass, bronze) usually show brown or blackish stains under chemical attack.
- Separators of *aluminum alloy* show a disruption of the anodized coating, possibly with cracking.
- *Plastic* separators, when embrittled, tend to show discoloration, possibly cracking.

16.1.5.5 Causes

The causes of separator corrosion are similar to those listed under FC 00.20 for contact components.

16.1.5.6 Effects of Separator Corrosion

Metal Separators. The corrosion product on *steel* separator surfaces is abrasive. When worn off by contact with the rolling elements, it contaminates the lubricant and causes wear of contact components, of the separator and of guidering or seals (if present).

Separator corrosion may change separator clearance. Separator corrosion may weaken the separator (especially a thin stamped sheet metal separator) and cracking may result.

Corrosion of any part in the chamber containing the separator tends to enhance corrosion of other components in the chamber. Corrosion of contact components may result.

Plastic Separators. Embrittlement of plastic separators produces substantial weakening and typically leads to cracking, especially as plastic separators are often designed utilizing their great tolerance for deflection, much of which may be lost due to embrittlement.

16.1.6 Separator Heat Imbalance Failure — Failure Code: 01.16

Heat imbalance failure of contact components generally involves separator interaction, that is, these components cooperate to generate the excess heat. For a description of heat imbalance failure, see FC 00.19.

16.1.7 Separator Spalling — Failure Code: 01.17

On rare occasions, spalling is seen in the contact between a (machined metal) separator pocket and a rolling element. This contact fatigue failure arises from repeated application of normal contact pressure as the rolling element (usually a ball) is pressed against the separator pocket bore, upon changes in rolling element orbital speed (e.g., when the load zone is entered and left), or upon misalignment of the bearing. See FC 00.16 for a description of spalling.

16.2 GUIDERING FAILURE — FAILURE CODE: 01.2

This section covers failures of *guiderings* in rolling bearings. Guiderings are *separate* rings, loosely fitted to one of the Hertz contact rings of the bearing. They serve to guide the other components. Guiderings serve two distinct functions, as described below. In some designs, the guidering performs only one of the functions; in others, it performs both.

Separator guiderings participate in the positioning (centering) of separators. Such guiderings have conforming (non-Hertzian) sliding contact with separators.

Roller guiderings are used to provide a face for axial guidance of rollers in designs where integral flanges are not provided at all required roller-end contact points.

Examples:

1. Combined separator- and roller-guiderings are used in some designs of spherical roller bearings. They are usually loosely fitted over a center land of the innerring and help center the separator(s) with their OD, while axially guiding the rollers with their sidefaces. They feature sliding contact with the separator bore and sliding/rolling contact with the roller endfaces. They are commonly made of cast iron, powder metal or plastic.
2. In some single-row cylindrical roller bearings, integral flanges are supplemented by loose end-rings with an L-shaped cross section which guide the roller ends. This arrangement permits axial mounting, with both bearing rings mounted on shaft or in housing before insertion of the rotor.
3. In some designs of multirow cylindrical roller bearings, spacing rings between rows guide rollers axially with their sidefaces and also center the separators with their OD. Such rings are made of materials similar to Hertz contact rings—most often hardened steel.

Guiderings have similar failure modes as the flanges of Hertz contact rings. If the guidering is made of plastic, the failure modes of plastic separators may also occur.

16.2.1 Definition

The failure modes listed in Table 16.1 are defined by reference to failure codes for contact components or separators.

16.2.2 Nomenclature

Nomenclature of failure modes is the same as for the corresponding failure codes covering Hertz contact components or separators.

16.2.3 Failure Process

Failure processes are the same as for the corresponding failure codes covering Hertz contact components or separators. Because some guiderings are of thin section, cracking or fracture of guiderings is not uncommon.

Table 16.1 CORRESPONDENCE OF GUIDERING FAILURE CODES

Guidering Failure Code	Guidering failure mode description	Correlated Failure Code
01.2.1	Guidering manufacturing defect	00.01–08
01.2.2	Guidering bulk discontinuity failure	00.22
		01.11
01.2.3	Guidering bulk permanent deformation	01.12
01.2.4	Guidering wear	00.12
		01.13
01.2.5	Guidering heat imbalance failure	00.19
		01.16
01.2.6	Guidering galling	00.13
		01.14
01.2.7	Guidering denting	00.18
01.2.8	Guidering corrosion	00.20
		01.15

16.2.4 Distinctive Appearance

Guiderings of *spherical roller bearings* are typically rings of trapezoidal cross section (cylindrical bore and OD and angled sidefaces) which slide on the innerring land along their ID, slide on the separators along their OD and undergo compound rolling/sliding against roller ends on their sidefaces. *Wear* or *galling* may appear on any of these surfaces. Bore and OD marks will be circumferential, as in a separator. Sidefaces will show epicyclic marks, as in the contact between a roller end and the flange of a bearing ring.

Guiderings of *cylindrical roller bearings* may have rectangular or L-shaped cross sections. L-shaped guiderings of single-row cylindricals have a side surface intended for contact with roller ends. In spacing rings of some multirow cylindricals, the OD or the bore surface serves to guide a separator, and side surfaces guide roller ends. Failures of the type appearing on bearing ring flanges are seen on the roller-contact surfaces. Separator support surfaces show circumferential marking.

16.2.5 Causes

Separator Guide Surface Failures

- *Manufacturing defects*: casting errors, geometry errors (especially those of sideface angle), incorrect clearance between guidering ID and innerring land OD or between guidering OD and separator, or incorrect surface finish.
- *Excessive sliding speed over the innerring* (excessive clearance between guidering and innering land; geometry errors leading to high roller end loads from roller rows contacting *both* sidefaces).
- *Contaminant* ingress into the guidering/land or guidering/separator interface gap.
- *High roller contact load.*
- *High separator radial loads* from large differences in epicyclic roller speeds.
- *Inadequate lubrication.*
- *Chemical attack.*

Roller Guide Surface Failures. Failures may arise from any of the causes of roller end/flange contact failure. When the guidering also carries a separator guiding surface, the two sets of failure causes may interact.

Because guiderings are separate parts, misalignment between the roller-end guide surface on the guidering and the ring carrying the rolling track may arise in mounting or in service. This source of misalignment may cause failures in the roller end contacts, for example, roller skew and edge contact with resulting wear and galling.

16.2.6 Effects of Guidering Failure

- The effects of *separator* guide surface failure are similar to those of separator failure.
- The effects of *roller* guide surface failure are similar to those of the failure of integral flanges on Hertz contact rings.

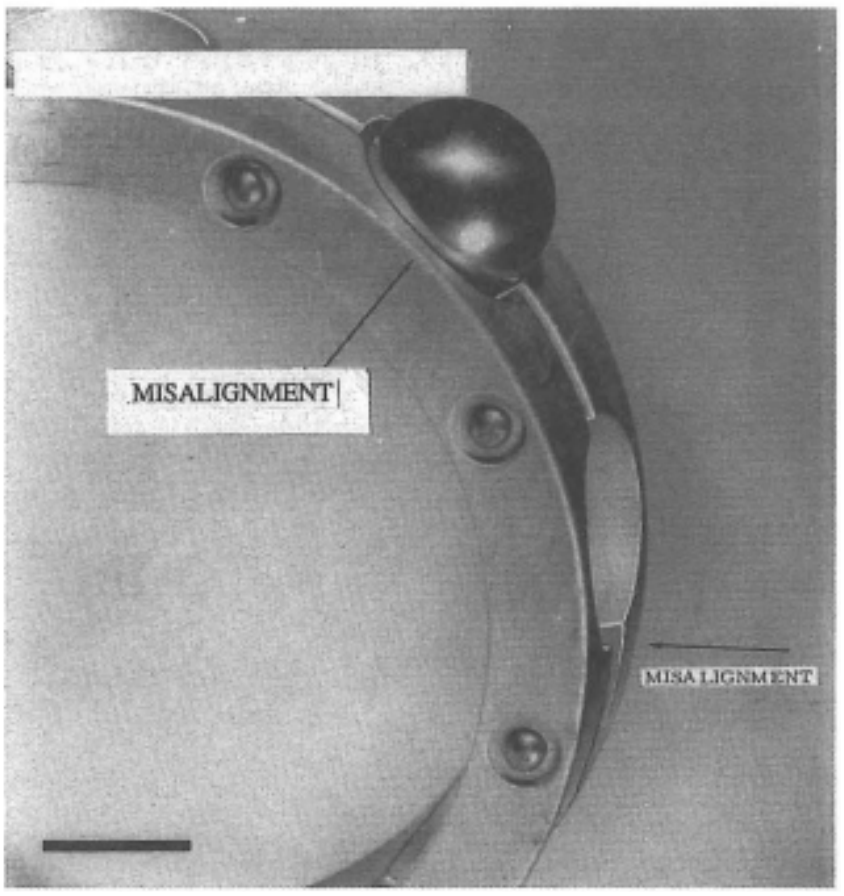
Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
01.10	16.4 16.23
01.11.2	7.20 12.20 13.10 13.15 16.26 16.29 18.4
01.11.4	16.5
01.11.5	16.6
01.11.6	16.24
01.12	16.6 16.10 16.12 16.33
01.13	7.14
01.13.1	16.7 16.8 16.9 16.15 16.16 16.30
01.13.1.2	16.10 18.19
01.13.1.3	7.21
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01.13.2.2	16.11 18.19
01.13.3	13.5 16.12 16.13 16.25 16.28
01.14	16.13
01.14.1	13.5 16.25 16.34
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01.16	16.11
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PLATES

DATA

Plate No: 16.1
Archive No: 087-011
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B&G (riveted machined separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.10 Separator manufacturing geometry defect
Failure Code 2: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 3: -
Failure Code 4: -

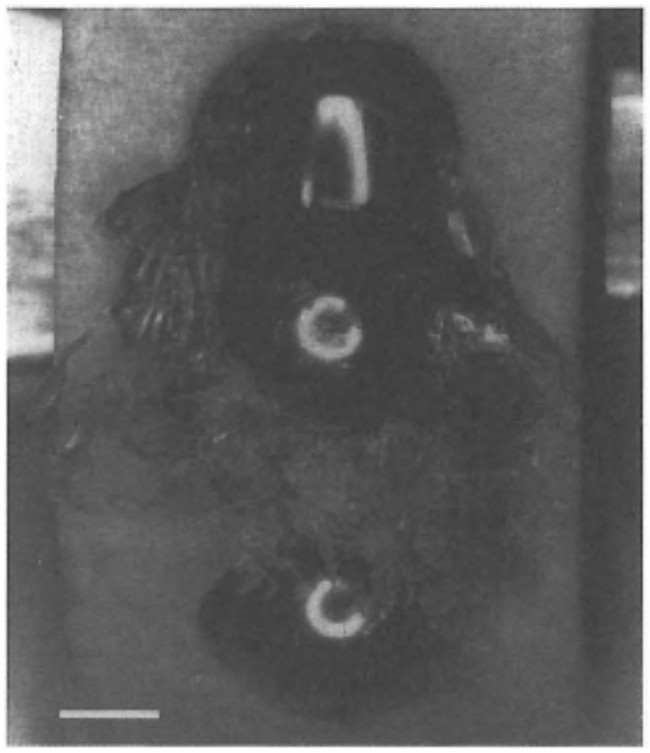


DESCRIPTIONS

Failure Description: Mis-registry of riveted separator halves has caused mislocation of ball pocket halves, with sharp edge at the dividing plane. During a dynamic test run, the bearing did not rotate freely. The balls were scratched. The bearing is not serviceable.
Image Description: A two-part, machined, riveted separator is viewed obliquely on the sideface. The pocket halves are not properly aligned by the rivets. A step exists between the halves at the arrows (labeled "misalignment"). The ball at image NE shows many faint circumferential wear marks from separator contact in a tight pocket.
Suspected Causes: Error in fixturing for drilling of rivet holes may result in mis-registry of separator halves. If extreme, the balls jam in some of the pockets and the bearing will not turn. In lesser cases, a sharp edge in a pocket scratches the ball. The separator wears prematurely.

DATA

Plate No: 16.2
Archive No: 103-003
Image type: light macro
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB&G (porous nylon separator), run
Speed: 600 KdN
Load:
Lubrication: mineral oil impregnated separator
Failure Code 1: 01.11.1 Separator melting (polymer)
Failure Code 2: 00.19.2.2 Hot plastic flow with bulk welding
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Melting of porous nylon separator material from high-speed friction at a ball/pocket contact. The ball pocket was elongated by about 1/2 of the ball diameter through melting and extrusion of softened nylon. The two balls shown were melt-bonded to the retainer and the retainer was bonded to the IR upon stopping. The steel components were not damaged. This is a gross heat imbalance failure.
Image Description: View on retainer OD, with two (glossy black-appearing) balls in pockets. Glossy black IR is visible through the N half of the greatly elongated pocket at image N. Patches of nylon adhere to the ball surface in N pocket. Much fibrous-appearing light and dark nylon material from N pocket was thrown out onto the separator OD and onto the ball at image S.
Suspected Causes: Operation at excessive speed created an imbalance between the heat generated in the ball/retainer contacts and the heat removal. The nylon overheated, melted, darkened and was extruded. The cooling nylon bonded the balls to the IR.

DATA

Plate No: 16.3
Archive No: 031-806
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: BB (maximum complement); G (stamped separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Two halves of stamped, 'ribbon type' ball bearing separator are shown, with riveted staves. One half is fragmented across the rivet holes, and many staves are missing. There is fatigue cracking of weak cross sections with rectangular, sharp-cornered rivet holes, probably from bearing misalignment. This is a gross failure.
Image Description: View of the ball-contact side of both side-rails of a maximum-complement ball bearing separator, with a few crossbars (staves) remaining riveted to each side-ring. Fatigue fracture of one side-ring occurred across rivet-holes of rectangular shape with sharp corners, which receive stave prongs serving as rivets.
Suspected Causes: Riveted ball bearing separators may break in bending fatigue if exposed to excessive ball/separator forces, mostly through misalignment of the bearing. Failing lubrication may contribute to the high separator forces.

DATA

Plate No: 16.4
Archive No: 002-026a&b
Image type: a, b: view
Scalebar = a: 15, b: 30 mm
(micros: ±20%, others: +100%, −50%)
Component: ACBB; G&OR, run
Speed: 1.7 MdN
Load: 2.6 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 00.16.01.2.3 Spalling at contact edge from thrust load
Failure Code 3: 00.16.02.5 Advanced spalling
Failure Code 4: 01.10 Separator manufacturing geometry defect

DESCRIPTIONS

Failure Description: Extensive spalling on OR, near groove edge, under heavy thrust load and high speed. As a secondary failure, the separator broke into two ring-shaped halves by fracturing each crossbar at sharp edges of the ball retaining tangs.
Image Description: (a): An OR is at image center, with two halves of the broken separator on either side. All separator crossbars are broken. The OR ball groove shows large spall crater area near image N, extending to S-facing groove edge. (b): Separator, with two broken halves, is shown replaced in alignment. All cracks were initiated at corners where ball-retaining tangs connect to crossbars. Two broken-off retaining tangs are at image S.

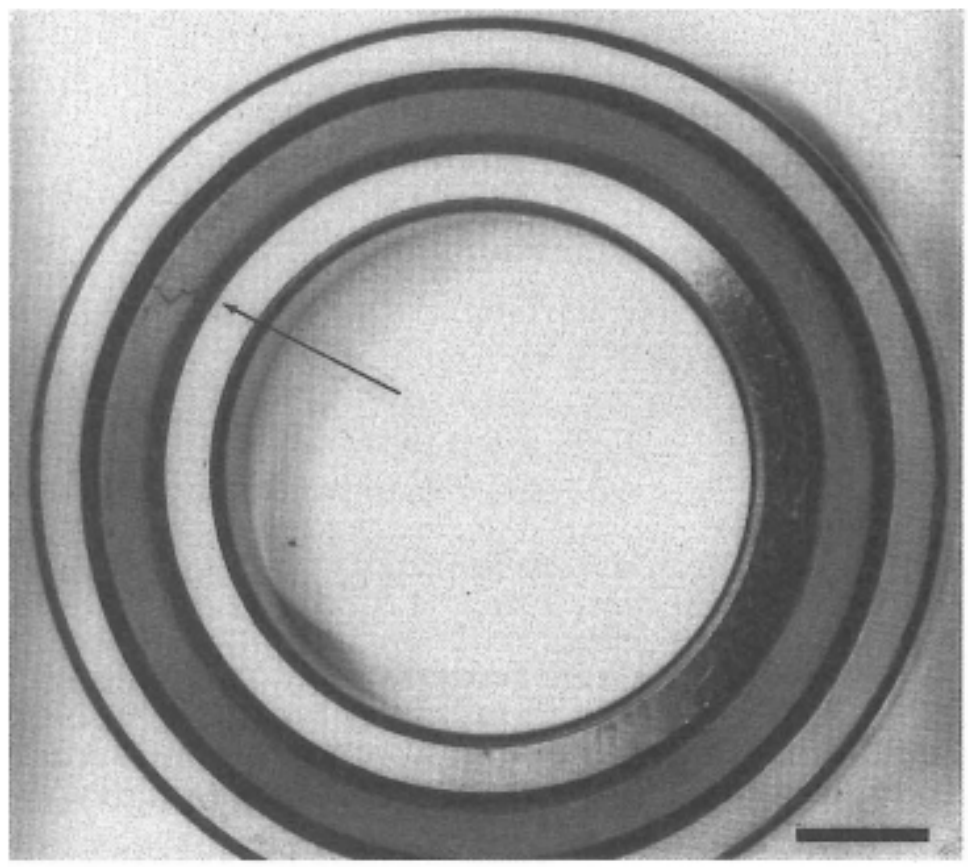
a

b

Suspected Causes: The bearing operated at extreme speed and load in a test, resulting in massive spalling. Large separator forces resulted from this failure, causing fracture of each ball pocket crossbar at the stress-concentration of the (sharp) corner between retaining tangs and crossbars.

DATA

Plate No: 16.5
Archive No: 087-002
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB (with machined bronze separator), unrun
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.11.4 Separator casting or molding defect
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

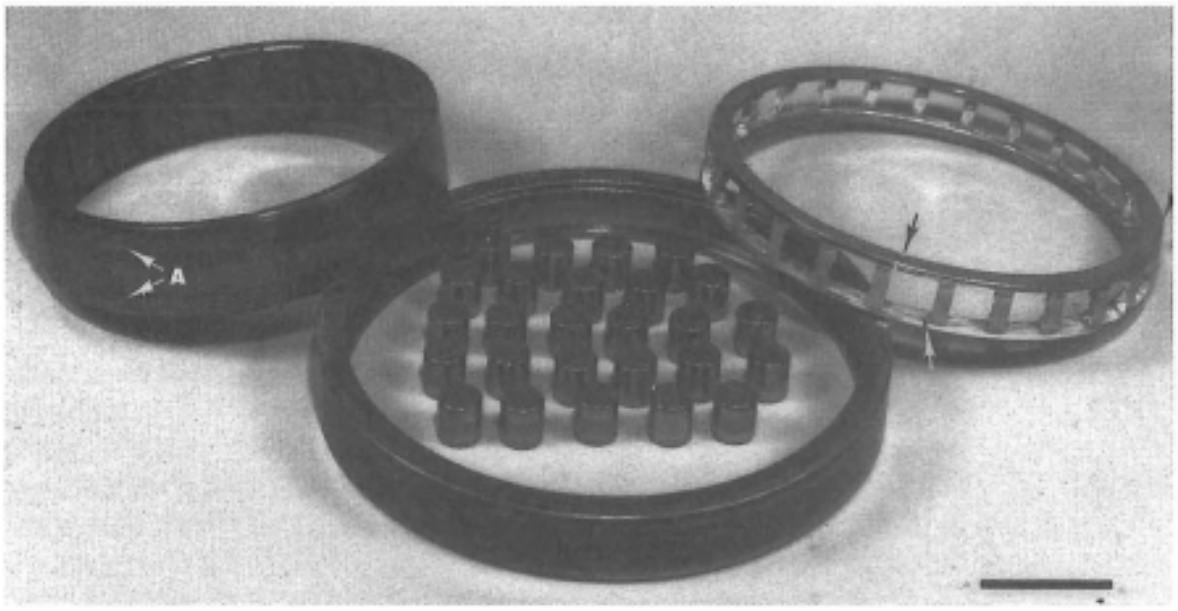
Failure Description: The manufacturing crack across the sideface of the one-piece machined bronze separator has probably resulted from casting stress. This is a gross failure.
Image Description: ACBB viewed on sideface. The machined separator is the gray center ring between light-gray IR and OR. Shown at the arrow is a jagged cross-section crack in the separator, probably extending to the ball pocket.
Suspected Causes: Machined bronze separators are generally made from centrifugally cast bronze tubing. A casting defect can create a weak cross section and/or high residual stresses which precipitate a crack. Cracking has probably occurred after bearing assembly and during storage; otherwise it is unlikely to have escaped detection.

DATA

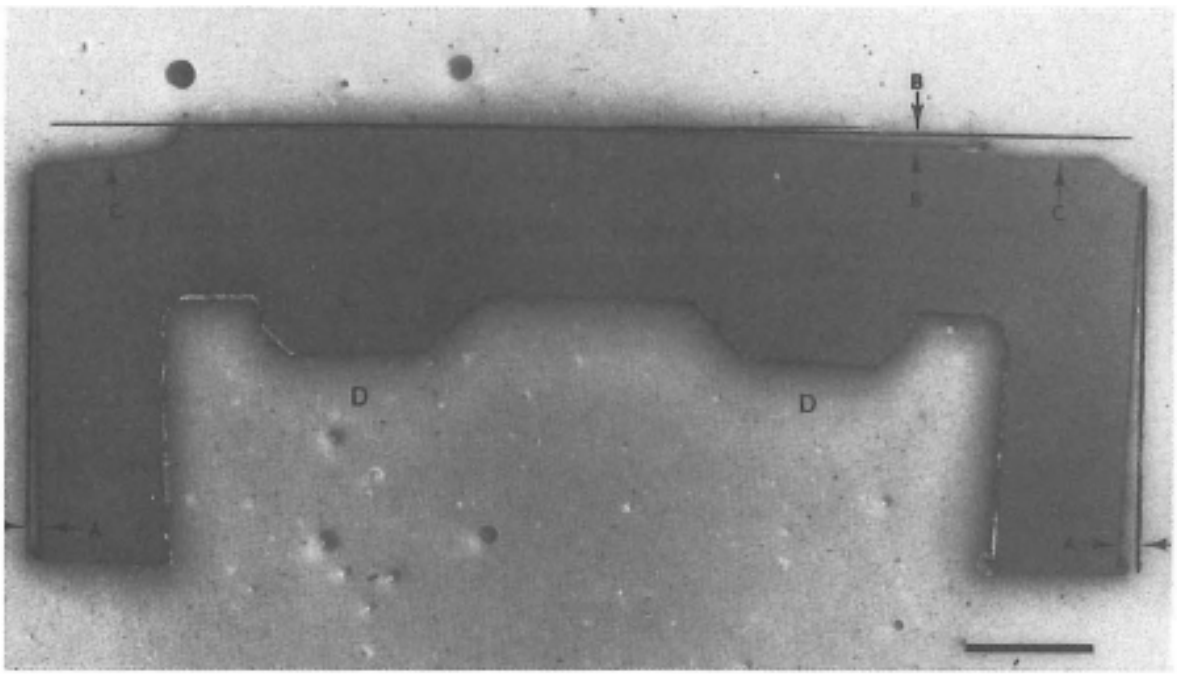
Plate No: 16.6
Archive No: 002-020a&c&e
Image type: a: view, b: light micrograph, c: metallogram
Scalebar = a: 100, b: 10 mm, c: 200 μm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR&OR&R&G (silver-plated steel separator), run
Speed: 0.6 MdN
Load: 0.9 GPa
Lubrication: synthetic polyester oil, 162°C
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.11.5 Separator rivet, prong, tang or bolt failure
Failure Code 3: 01.12 Separator plastic deformation
Failure Code 4: 00.12.4 Wear of guiding-component support surface

DESCRIPTIONS

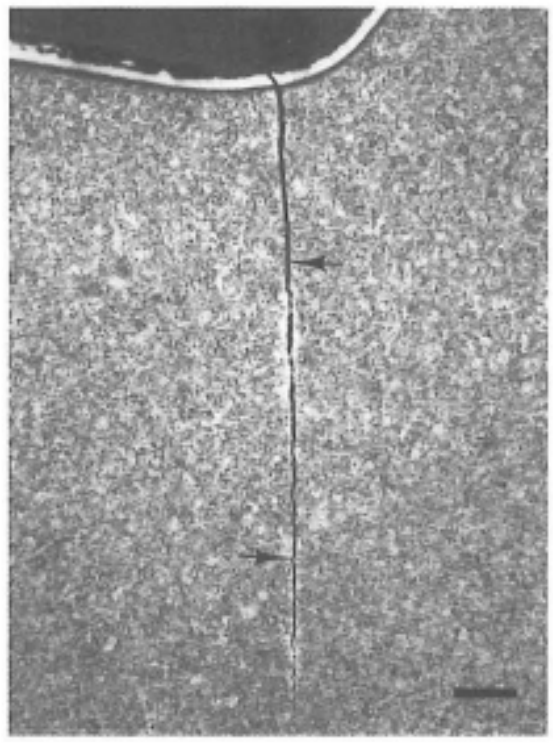
Failure Description: Roller retaining tangs in the separator were improperly staked in assembly. The separator suffered bulk deformation (crossbars are bent, siderails dished). Wear occurred on the separator surface guided on the OR. The separator rails have fractured. The separator contacted the innerring unintentionally and the IR wore. The bearing has failed.
Image Description: (a): View of disassembled bearing. At image NW: IR with wear tracks from separator contact at arrows *A*. At image NE: separator with cracks through siderails at arrows. Wear lines on siderail OD (near arrow). (b): Cross-section of separator. Two roller retaining 'tangs' at *D*; bowed crossbar at *B*; dished siderail at *A*; material worn off at *C*. (c): The section shows crack (arrows) through the siderail/crossbar blend radius.
Suspected Causes: The rollers are retained in this separator by staking (plastically deforming) the two tangs on each crossbar ID. Poor support in the staking tool has bent the crossbars, which in turn dished the siderails. The separator is guided on the OR lands. The deformation resulted in poor contact geometry and wore the separator at the OR guide surface. Unintended IR/separator contact wore the IR. High forces cracked the separator.



a



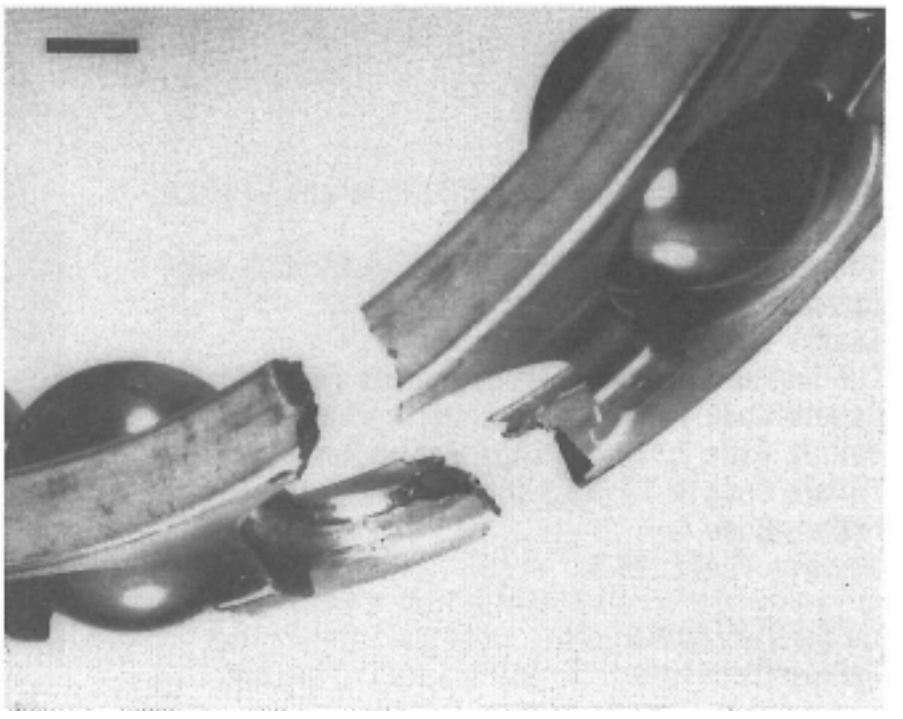
b



c

DATA

Plate No: 16.7
Archive No: 018-629
Image type: light macro
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: ACBBB & G (S-monel separator), run
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.1 Separator pocket worn
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Total fracture of separator siderails at their minimum thickness in the ball pocket, preceded by heavy ball/pocket contact wear. Failure is attributed to excessive ball/separator forces, probably from a misaligned bearing. This is a gross failure.
Image Description: Oblique view of a segment of machined S-monel ACBB separator, on sideface. Total fracture of both siderails occurred across the ball pocket at image center. The tensile fracture appears "woody." There is a lustrous, dark-edged white wear patch N of the fracture, covering one-half the pocket width near ID.
Suspected Causes: Strongly variable ball contact angles arose in operation under heavy, excentric axial load. They caused the large orbiting velocity differences among the balls, placing excessive tensile stresses on the separator, which fractured at its weakest cross section. High ball/separator contact pressures are indicated by heavy pocket wear.

DATA

Plate No: 16.8
Archive No: 004-1
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; G (polyimid separator) run
Speed: 1.2 MdN
Load:
Lubrication: Ga-In-WSe solid, graphite weave, 300°C
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.1 Separator pocket worn
Failure Code 3: -
Failure Code 4: -
See also PLATE: 16.9

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Wear of separator pocket with eventual breakout of a crossbar. Siderails have worn, with deformation near the fracture. OD has worn against the guide surface. The self-lubricating, graphite fiber reinforced polyimid polymer separator was tested at high temperature and speed, resulting in this failure mode. See Plate 16.9 for another failure image of the same bearing type.
Image Description: View on separator OD. Dark and shiny striations on OD show OD wear on the shiny bands. Two ball-pockets at image center are connected through wear and fracture of crossbar. The siderails adjacent to the missing crossbar are distorted.
Suspected Causes: This is an experimental separator for a dry lubricated high-speed, high-temperature application, using graphite fiber 3-D weave reinforcing for the polyimid polymer separator carrying a solid lubricant. The separator failed during exploration of limiting failure modes. In this case, these modes are excessive ball/pocket forces resulting in wear and fracture. The separator is land-guided and shows wear on the contacting OD.

DATA

Plate No: 16.9
Archive No: 004-12
Image type: light macro
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: BB (assembly); Si-N B, polymer G, run
Speed: 1.2 MdN
Load:
Lubrication: Ga-In-WSe solid, graphite weave, MoS_2, 300°C
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.1 Separator pocket worn
Failure Code 3: 13 Solid or gas lubricant failure
Failure Code 4: -
See also PLATE: 16.8

DESCRIPTIONS

Failure Description: Two ball pockets in separator are connected by fracture of crossbar. Pocket wear occurred. Wear marks are on the separator ID. Ball surfaces are partly coated with solid lubricant and separator debris. The bearing has silicon nitride balls and a reinforced polymer separator. MoS_2 is sputtered on rings and balls and is a powder filler in the separator. The bearing was tested at high load and speed, without external lubrication, resulting in this failure mode.
Image Description: Bearing assembly with one IR half removed is viewed on bore. Housing with cutout N of separator obscures the OR. Two separator pockets are connected by fracture of the crossbar, and worn open. Separator ID shows axial wear stripes (possibly related to separator whirl). Balls show a peppered surface, found to result from deposits of separator and lubricant material.
Suspected Causes: This is an experimental bearing with graphite fiber reinforced polymer separator carrying solid lubricant, for a dry lubricated high-speed, high-temperature application. The separator failed in a test for the exploration of limiting failure modes. In this test excessive ball/pocket forces resulted in wear and fracture. See also Plate 16.8.

DATA

Plate No: 16.10
Archive No: 014-31
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; G (stamped steel separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.1.2 Separator crossbar worn, both pocket sides
Failure Code 3: 01.12 Separator plastic deformation
Failure Code 4: 00.19 Heat imbalance failure

DESCRIPTIONS

Failure Description: Fractured stamped steel roller separator, following heavy wear of crossbars on both sides of pockets. Lubrication was inadequate; rollers exerted great friction forces on the separator. These wore the contacts, plastically extruded the metal past the edges in the pocket corners and eventually fractured the siderails in bending fatigue. Heat imbalance of the bearing is conjectured. This is a gross failure.
Image Description: A stack of broken separator segments is shown. Light gray wear areas appear along the ID edge of all crossbars. Separator material is plastically flown at the corners of two pockets at image E. Fracture surfaces of the siderails are plastically battered.
Suspected Causes: The bearing was observed to have inadequate lubrication, producing excessive separator/roller forces and wear. The separator becomes looser and drops down in the bearing, further increasing roller forces. The separator bending stress may be so large that bending fatigue of the rails results. The separator may become trapped between a roller and the OR. (There is no direct evidence in this image.)

DATA

Plate No: 16.11
Archive No: 027-257
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (phenolic one-piece separator), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.2.2 Land guided separator, guide surface worn, local
Failure Code 3: 01.16 Separator heat imbalance failure
Failure Code 4: -

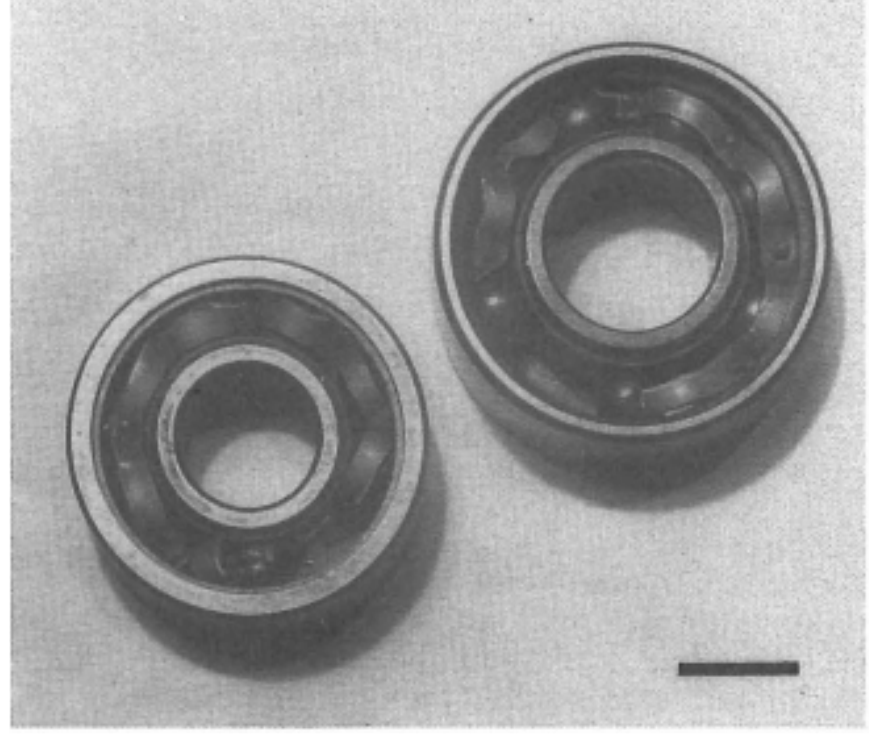
[See Image in Appendix]

DESCRIPTIONS

Failure Description: Fragmented phenolic plastic one-piece land-riding separator, with OD wear over one area and ID wear over another area of the circumference. The separator, likely to have been unbalanced, ran progressively more excentrically and eventually fractured due to competing guiding forces from balls and land. Darkening in one pocket indicates high temperature due to large friction force.
Image Description: Three fragments of the broken separator are at image NW, NE and S. Extreme NW and NE pockets show a dark spot, probably from overheating. The surfaces on the OD of the NE fragment and on the ID of the S fragment are ablated by wear.
Suspected Causes: Land-guided plastic separators are used in high-speed angular contact ball bearings, especially in low noise applications. If separator forces are not symmetrical (dynamic unbalance, inaccurate pocket geometry, heavy combined bearing load), then the separator forces at the guidelands rise, resulting in wear and distortion. The separator may make unintended contact on the opposite ring land, accelerating wear. Hoop stresses may cause fracture.

DATA

Plate No: 16.12
Archive No: 087-017
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB (assembly) (2), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.3 Separator wear from unintended contact
Failure Code 3: 01.12 Separator plastic deformation
Failure Code 4: -



DESCRIPTIONS

Failure Description: Disintegrated 'ribbon-type' riveted stamped steel ball bearing separators. The separator OD was stretched and touched the OR land unintentionally. Separator wear occurred at the OR contact. The failure is attributed to misaligned operation creating excessive ball/separator forces stretching the separator, causing unintended contact and bending fatigue fracture. This is a gross failure.
Image Description: Two DGBB viewed on sideface. The separators are deformed and fractured in both. The separator edge touches the OR land ID at E in both bearings and is worn irregularly. The separator is fractured at SE (in the bearing at image W). The separator is fractured at W and S (in the bearing at image E).
Suspected Causes: Heavily misaligned operation of DGBB results in "cross-corner loading" of the balls by a high overturning moment. Contact angles and ball orbital speeds vary drastically around the circumference, placing excessive hoop stresses on the separator. The separator stretches, touches the OR or IR land, creating additional forces. Eventually, fatigue fracture occurs.

DATA

Plate No: 16.13
Archive No: 014-49
Image type: view
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR&R&G (stamped steel separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.2 Separator fracture, cracking
Failure Code 2: 01.13.3 Separator wear from unintended contact
Failure Code 3: 01.14 Separator galling
Failure Code 4: 21.9 Geometry or assembly defect in housing

DESCRIPTIONS

Failure Description: Gross wear, galling and eventual fracture on (small-end) sideface of separator, resulting from unintended contact with housing end-cap. High friction generation and high temperatures prevailed during running. This is a gross defect resulting in gross failure.
Image Description: The TRB IR/roller/separator assembly is viewed obliquely on its small endface. The separator siderail is severely worn, battered and galled on its entire circumference. At image N, total separator fracture occurred. At image SW, partial fracture of small-end siderail is visible. Rollers have fallen into the separator at image E.
Suspected Causes: A design error of the housing end-cap failed to allow clearance for a separator normally protruding above the IR ('cone') sideface. Rubbing contact between separator and end-cap produced gross wear, overheating and fracture.

DATA

Plate No: 16.14
Archive No: 093-201
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; G (cast bronze separator), unrun
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.4 Separator casting or molding defect
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: "Repaired" macro-porosity in the separator crossbars was due to casting defect. An attempt was made to repair the porosity by filling the pores with weld material. Porosity weakens the cross section and, if exposed on working surfaces, may lead to galling. Weld repair is generally unsatisfactory, due to poor bonding and high residual stresses. This is an unacceptable separator blank.
Image Description: CRB separator with one integrally cast siderail and crossbars is viewed on its ID. Milled recesses are on each crossbar. Of the three crossbars shown, those at image N and S show large, irregularly shaped pits, from macro-porosity filled with arc-weld material (hence the rippled surface).
Suspected Causes: Sand casting of large bronze components of complex shape such as this separator is a difficult process. Clearing of gas during mold filling may fail, leaving bubbles entrapped which create macro-porosity. As a salvage operation, tungsten-inert-gas (TIG) arc welding is at times attempted to fill the pores.

DATA

Plate No: 16.15
Archive No: 087-045
Image type: light micrograph
Scalebar = 1 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; G (glass fiber/nylon separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.11.4 Separator casting or molding defect
Failure Code 2: 01.13.1 Separator pocket worn
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: In a glass-fiber reinforced nylon ball bearing separator ball pocket, protruding glass fibers were uncovered from the nylon matrix by a molding error, and by wear in service. Such fibers scratch balls, break off and cause indentations in rolling surfaces. The bearing runs with high torque and noise, and it may spall prematurely.
Image Description: NW image quadrant shows a quarter-circle from a ball pocket, with dark background. Light gray material is a reinforced nylon separator. Glass fibers protrude into the ball pocket.
Suspected Causes: Glass-fiber reinforced nylon separators are used in aerospace (instrument) and other ball bearings. When properly made, an uninterrupted nylon contact surface is presented to the balls. If the separator was improperly molded or after heavy wear, glass fibers may become exposed, scratch balls, break off and dent rolling contacts.

DATA

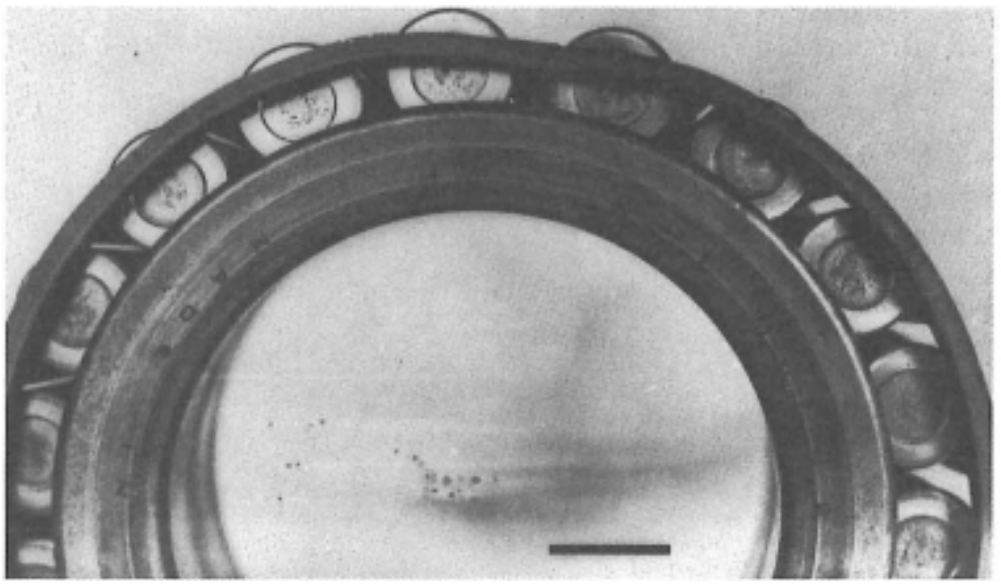
Plate No: 16.16
Archive No: 018-609
Image type: light macro
Scalebar = 3 mm (micros: ±20%, others: +100%, −50%)
Component: ACBBB; B & G (silver plated steel separator), run
Speed:
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 01.11.6 Separator plating defect
Failure Code 2: 01.13.1 Separator pocket worn
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Silver plated steel separator of ACBB with blistered plating in ball pockets. The plating is elevated above surrounding surface and wears. Pocket galling or separation of plating flakes is likely upon continued running. Flakes may indent the rolling surfaces.
Image Description: Machined, silver plated steel ACBB separator is viewed on OD.The ball pocket facing image S shows two crescent shaped, rough-edged dark areas where silver plating has blistered up above the surrounding surface and is worn. The ball is visible further S, in a dropped-down position relative to its operating position.
Suspected Causes: Silver plating of steel separators requires a thin copper under-plating for good adhesion. This was found to be missing in the present case, permitting the blistering. Wear of the elevated, poorly supported silver plate has occurred at the ball contact.

DATA

Plate No: 16.17
Archive No: 014-47
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR&R&G (stamped steel separator), unrun
Speed:
Load:
Lubrication:
Failure Code 1: 01.12 Separator plastic deformation
Failure Code 2: 00.09 Geometry, assembly or mounting defect
Failure Code 3: -
Failure Code 4: -

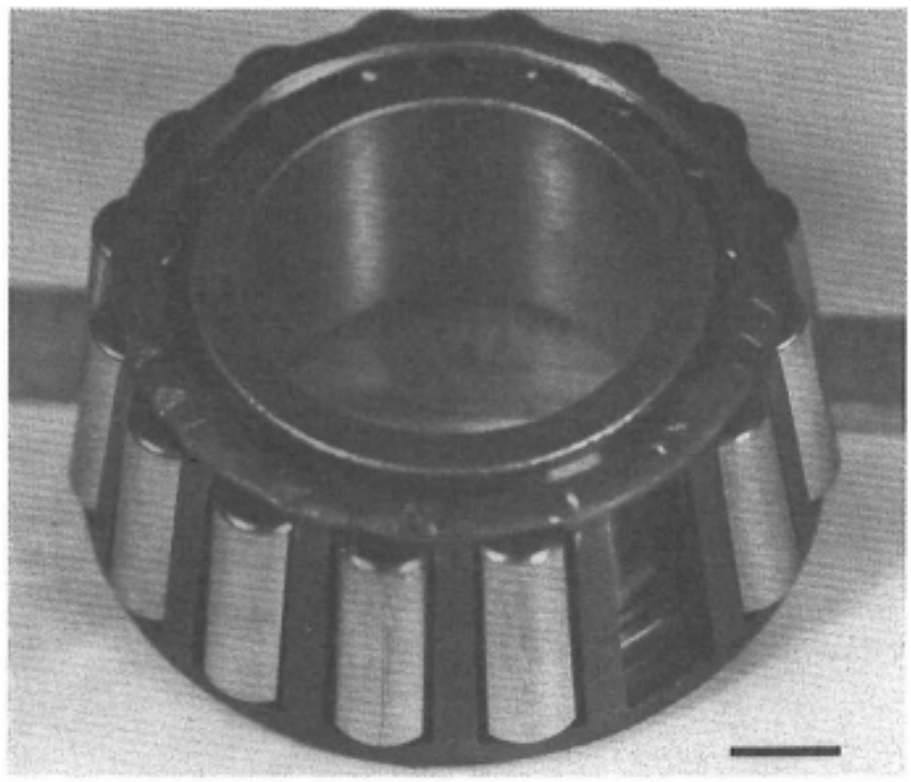


DESCRIPTIONS

Failure Description: Siderail of stamped steel separator at large-end of TRB IR ('cone') is stove in from dropping of the IR/roller assembly during mounting. The deformation results in mislocation of the crossbar, insufficient roller pocket looseness, excess wear, and possibly heat imbalance failure.
Image Description: TRB IR/roller/separator assembly is viewed from (large) sideface. Between two rollers at image N center, the circular shape of the separator siderail is bent inward.
Suspected Causes: Accidental dropping of an assembly is likely to cause brinnell damage between the rollers and IR. In this case, separator deformation has resulted because impact was on the separator edge.

DATA

Plate No: 16.18
Archive No: 014-48
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; IR&R&G (stamped steel separator), unrun
Speed:
Load:
Lubrication:
Failure Code 1: 01.12 Separator plastic deformation
Failure Code 2: 00.09.1 Scoring from forcible assembly or mounting (no galling)
Failure Code 3: -
Failure Code 4: -

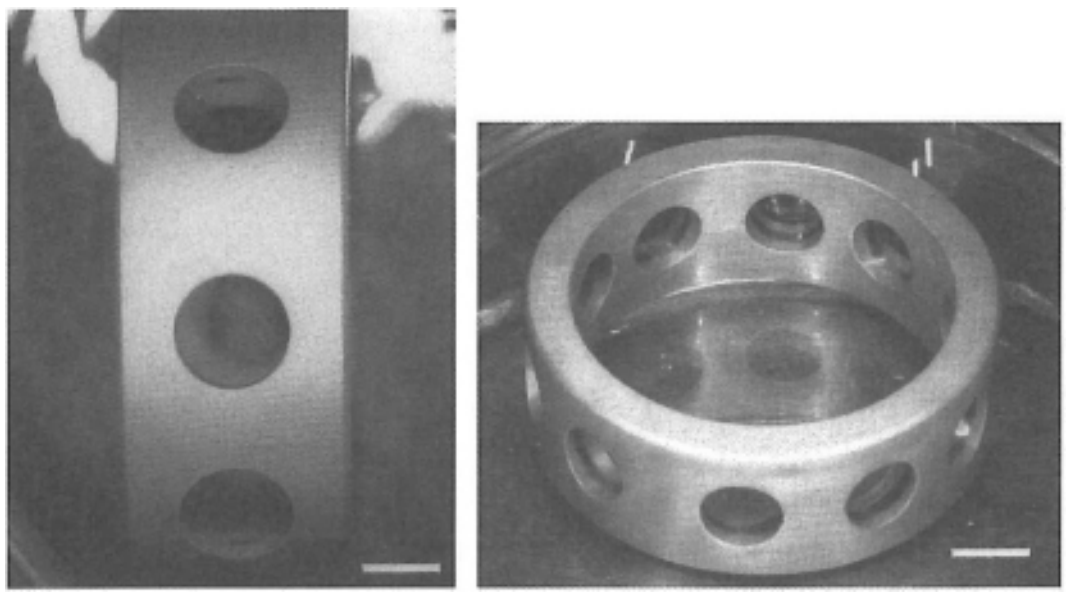


DESCRIPTIONS

Failure Description: Severe sharp indentations in the (small-end) sideface of the separator, from 'drift' used to mount the IR onto a tight seat. The separator suffered overall deformation and local bending of siderail into roller pockets, causing local rubbing. The bearing is likely to run with high friction and overheat. The separator may break at nicks from normal roller forces.
Image Description: An IR/roller/separator assembly is viewed obliquely from small-end. Numerous sharp nicks across the separator sideface from a sharp-edged driving tool ('drift'). At three rollers in SW quadrant, the rail is bent in toward rollers.
Suspected Causes: Mounting of interference-fitted IR (cone) requires a tubular driver contacting the IR sideface. Use of a drift damages the separator and, by driving through the separator and rollers to the thrust flange, may cause roller-end and/or flange damage.

DATA

Plate No: 16.19
Archive No: 103-001&002
Image type: a: view, b: light macro
Scalebar = a: 3, b: 2 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (porous polyimide separator), run
Speed:
Load:
Lubrication: synthetic hydrocarbon impregnated separator, 25°C
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



a b

DESCRIPTIONS

Failure Description: (a): 360° circumferential wear in the separator pockets due to dynamic instability causing high-speed whirl of the separator in a high-speed gyro spin-axis bearing. (b): Pocket wear, chiefly at leading and trailing contact points of the balls in the pockets of a separator in stable operation. Separator whirl is an unacceptable gyro bearing operating mode.
Image Description: (a): One-piece separator with cylindrical pockets is viewed obliquely on sideface. Dark circle of wear extends 360° around pockets, as the result of separator whirl. (b): Similar separator, partial view on OD. An elongated but localized dark contact area is visible at N in the pocket at image N, and at S in the pocket at image S. A faint contact mark extends circumferentially in both pockets. This separator has operated without whirl.
Suspected Causes: Porous, oil impregnated polyimide separators are used in gyro spin-axis bearings. They are land guided, with clearance to permit free motion. Normally, separators run excentrically but stably. Excitation by friction forces can lead to a whirling motion consuming energy, increasing separator forces and wear and degrading the required smooth, constant-torque operation.

DATA

Plate No: 16.20
Archive No: 002-007d2
Image type: light microgram
Scalebar = 2 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (silver plated steel separator), run
Speed: 1.7 MdN
Load: 1.4 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Even-spaced 'impact wear' in the silver plating of a separator pocket, along with normal polishing wear in the silver plate. In high-speed aerospace bearings, ball/separator contact under EHD conditions was observed to cause periodic wear marks attributed to intermittent ball impact on the plating. The normal wear area is adjacent. The bearing has not failed.
Image Description: Ball pocket surface of (sectioned) separator. Sliding direction is S to N. Separator retaining prong is at image N. Dark-appearing polished ball contact patch is in S image half. Arrows indicate light/dark N–S "fingers" worn in silver plating by 'impact wear.'
Suspected Causes: Normal (smooth) plating wear is expected in a separator pocket. Data are limited concerning periodic 'impact' separator wear attributed to intermittent lubricated ball contact. The kinematics of the periodic wear marking are not clearly understood.

DATA
Plate No: 16.21
Archive No: 087-111
Image type: light macro
Scalebar = 5 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; B&G (stamped steel separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
Failure Code 3: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 4: 00.16.02.4 Incipient spalling, multiple spalls

DESCRIPTIONS
Failure Description: Concentric wear scratches in a separator ball pocket, concentrated near the separator ID. Matte, worn ball surface with linear bands of surface distress microspalls and incipient macroscopic spalling. The failure appearance suggests solid contamination. The bearing runs noisily, has lost accuracy and is likely to fail from early spalling.
Image Description: In N image half is a ball with uniformly matte, worn surface. Linear, narrow bands of microspalls extend from N pole southward, and in SE quadrant of ball image. At ball center and in SE quadrant, some macro spall craters are developing. The non-circular ball contour is an imaging artifact. In the S image half is the ball pocket of a stamped 'ribbon' separator, with light and dark concentric wear scratches near both edges; strongest near N (ID) edge.
Suspected Causes: Generalized wear on ball and retainer suggests fine solid contaminant in the lubricant. Overrolling of the ball surface damaged by wear produces surface distress microspalling and eventually macroscopic spalls.

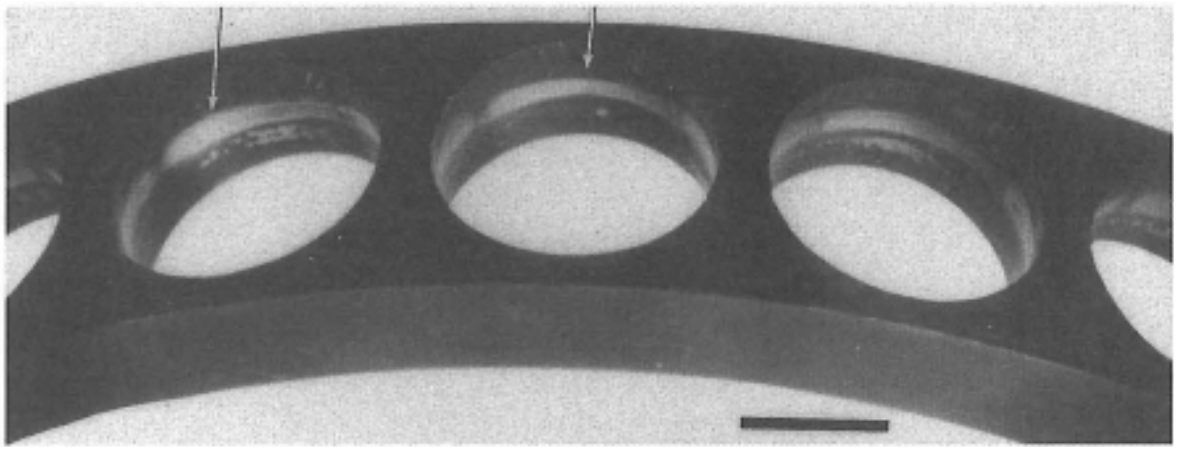
DATA
Plate No: 16.22
Archive No: 027-181
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B & G (stamped steel separator), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: 00.19.1.1 Generalized temper colors
Failure Code 3: 12.5.02 Severe grease contamination
Failure Code 4: -
See also PLATE: 13.1

[See Image in Appendix]

DESCRIPTIONS
Failure Description: Temper color on separator and ball. From Plate 13.1, the exposure temperature was approximately 210°C. The ball shows scratch marks from abrasive wear by a contaminant (covered by temper color). Fresh heavy scratch marks are in the separator pockets. Severe grease contamination by abrasive solids is suspected. Bearing is noisy, may run hot.
Image Description: DGBB 'ribbon' separator half is viewed on the inside face. One ball is shown. Both components show brown temper color. The ball shows random wear marks under the temper color. The separator ball pockets show fresh, metal-colored concentric wear marks (arrows).
Suspected Causes: Severe contamination of lubricant with contaminant (probably extraneous abrasive) causes abrasion between balls and separator ball pockets. Concentric scratch marks in the separator pocket are the result. Scratch marks on the ball may not be concentric if the ball has indexed. Overheating of the bearing results from high friction in the presence of a contaminant.

DATA

Plate No: 16.23
Archive No: 087-006
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (machined bronze separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: 01.10 Separator manufacturing geometry defect
Failure Code 3: 11.1 Friction polymer, oil lubrication
Failure Code 4: -

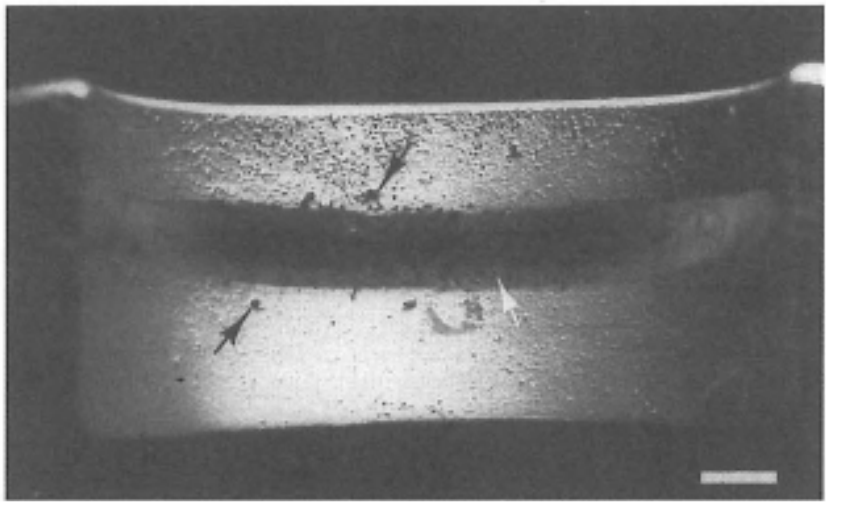


DESCRIPTIONS

Failure Description: 360° circumferential wear band in all ball pockets of a machined bronze separator, indicating insufficient pocket clearance due to dimensional error in manufacture. Bearing is likely to run at excessive temperature leading to heat imbalance failure. Decomposed oil coating ('friction polymer') on non-contacting retainer surfaces indicates high-temperature operation.
Image Description: A segment of a machined bronze separator that has ball pockets cylindrical at OD and spherical at ID to retain balls. Dark coating (possibly friction polymer) is on the surfaces, except in a 360° circumferential shiny wear band (arrows) in the cylindrical part of the pockets, and a few wear patches in the spherical part of the pockets.
Suspected Causes: Normally dimensioned ball pockets show wear marks near front and rear center, where ball forces produce contact under load. A pocket with insufficient clearance rubs over entire circumference. Contact in spherical retaining part of pockets does not appear excessive.

DATA

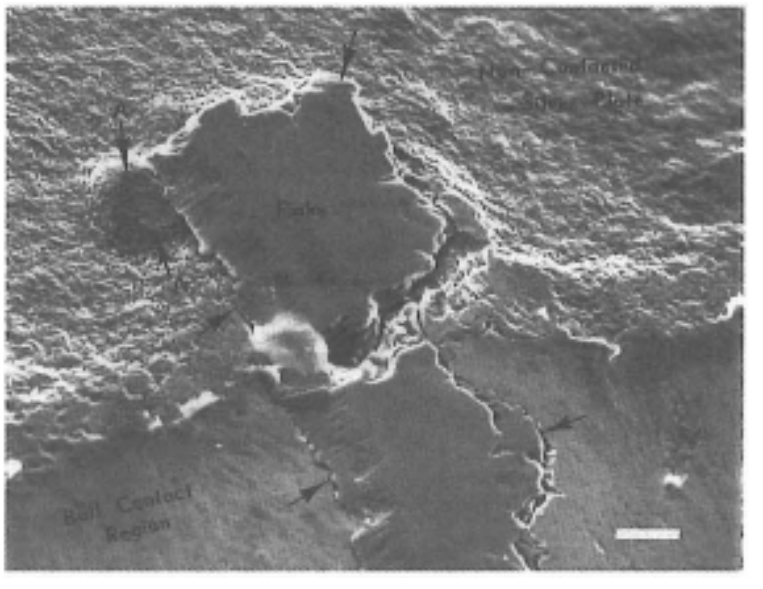
Plate No: 16.24
Archive No: 002-012c&d
Image type: a: light microgram, b: SEM
Scalebar = a: 1 mm, b: 20 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (silver plated steel separator), run
Speed: 0.5 MdN
Load: 2.2 GPa
Lubrication: synthetic polyester oil, 137°C
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: 01.11.6 Separator plating defect
Failure Code 3: 11.3 Solid contaminant in oil
Failure Code 4: -



a

DESCRIPTIONS

Failure Description: Separator ball pockets damaged by (1) embedded solid contaminant, (2) wear, and (3) irregular plating ('nodules'). The contaminated pockets were found to damage balls and hence races. The irregular plating wears prematurely. Ball surface damage is expected to result, and bearing failure may follow.
Image Description: (a) Sectioned separator pocket is shown, exposing ball contact surface. The dark E–W band near the pocket centerline is the ball contact path. Inside and to N of this band, the many small grainy protrusions are plating 'nodules.' Arrows show embedded metal contaminant. (b): Edge of the ball contact path (labeled) runs E–W just S of image center, with the smooth surface of the band to the S. Extraneous metal flakes are rolled in at the arrows. *A* is a plating nodule.
Suspected Causes: The plating nodularity is due to a processing deficiency. The embedded metal flakes come from extraneous contamination. The contaminant has been observed to damage balls.



b

DATA

Plate No: 16.25
Archive No: 027-256
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 20 mm (micros: +20%, others: +100%, −50%)
Component: DGBB (cartridge); IR&G (stamped steel), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 01.13.1 Separator pocket worn
Failure Code 2: 01.13.3 Separator wear from unintended contact
Failure Code 3: 00.12.4 Wear of guiding-component support surface
Failure Code 4: 01.14.1 Separator pocket galled

[See Image in Appendix]

DESCRIPTIONS

Failure Description: The ball pockets are worn and galled. Wear and chipping (FC 01.11.2) occurred on separator ID in unintended contact with IR land, which is also worn. The circular shape of the separator is distorted (FC 01.12). High separator/ball forces caused pocket wear, increased separator looseness and unintended contact with the IR land. The separator was temporarily caught between ball and groove edge causing greater forces, pocket galling, chipping, and distorted shape.
Image Description: At image W is the IR, with dashed dark wear marks on lands and a dark contact band in the groove. The separator half at image E has lost its circular shape. The W-most pocket is chipped at the ID. All pockets are worn. Galled patches in the S-most pocket, in two pockets to its E, and in one to its W.
Suspected Causes: The separator may have been distorted in assembly or lubrication may have failed causing high separator/ball forces, resulting in complex wear, galling and distortion. Erratic orbital separator motions may occur, causing the dashed marks on the IR. Cartridge-type (wide) DGBB are grease lubricated. Bearing may have been run past functional grease life, precipitating lubricant failure.

DATA

Plate No: 16.26
Archive No: 003-007
Image type: light macro
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; G (machined bronze separator), run
Speed: 2.2 MdN
Load:
Lubrication: synthetic polyester oil, ? °C
Failure Code 1: 01.13.1.1 Separator crossbar worn, one pocket side
Failure Code 2: 01.13.1.4 Roller separator, pocket bottom worn
Failure Code 3: 01.11.2 Separator fracture, cracking
Failure Code 4: -

DESCRIPTIONS

Failure Description: Wear of separator crossbar and siderails. Plating on the crossbar is worn through. The plating peeled and the crossbar probably cracked through. Roller forces from a skewed roller produced "dog-bone" wear pattern. The bearing is likely to fail soon due to separator fracture.
Image Description: Oblique view of separator pocket from OD. The siderails are at E and W. The roller contact face of the crossbar is at S center, with retaining tangs at S. A second crossbar is out-of-focus at N image edge. Sharp wear marks (gouges) are at both corner radii of the crossbar. A "dog-bone"-shaped dark wear scar is in the crossbar sideface, with plating worn through (dark). A jagged dark crack line appears near the W corner. The edge of the plating is lifted at the crack.
Suspected Causes: High-speed CRB at times suffer severe roller/separator loading when rollers skew (example: from unbalance). Loads between roller end and siderail cause roller end and separator wear (see the sharp cut into corner radius). Load on the crossbar from roller edge contact (skewed roller) causes "dog-bone" wear pattern and, secondarily, cracking.

DATA

Plate No: 16.27
Archive No: 003-003
Image type: light macro
Scalebar = 4 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; B&G (silver plated steel separator), run
Speed: 2 MdN
Load:
Lubrication: synthetic polyester oil, 120°C
Failure Code 1: 01.13.1.1 Separator crossbar worn, one pocket side
Failure Code 2: 01.17 Separator contact spalling
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Wear through the silver plate of a separator pocket. Spalling in the underlying steel separator material. This unusual failure mode is attributed to high ball-contact loads from bearing misalignment, under very good lubrication of the separator ball contact, which limited wear and prevented galling, allowing the contact load to produce a spall. Bearing failed by separator fracture initiated at another spall (not shown).
Image Description: View is on separator OD, with balls dropped below normal position by removal of the IR. The pocket toward image S shows light crescent-shaped ball contact with silver plate over 180° angle. At the pocket center, a dark, feathered ellipse has worn through to steel. The central area of the ellipse shows the fracture surface of a spall crater. An additional small spot of silver plate removal is 1/4 from W image edge, in the same pocket.
Suspected Causes: Misalignment of bearing was observed, leading to severe angular velocity and phase differences among balls and very high ball contact forces on the separator. Wear, galling, possibly heat imbalance would be expected. Spalling of the medium-hard steel separator is unusual and indicates excellent cooling and lubrication of the contacts.

DATA

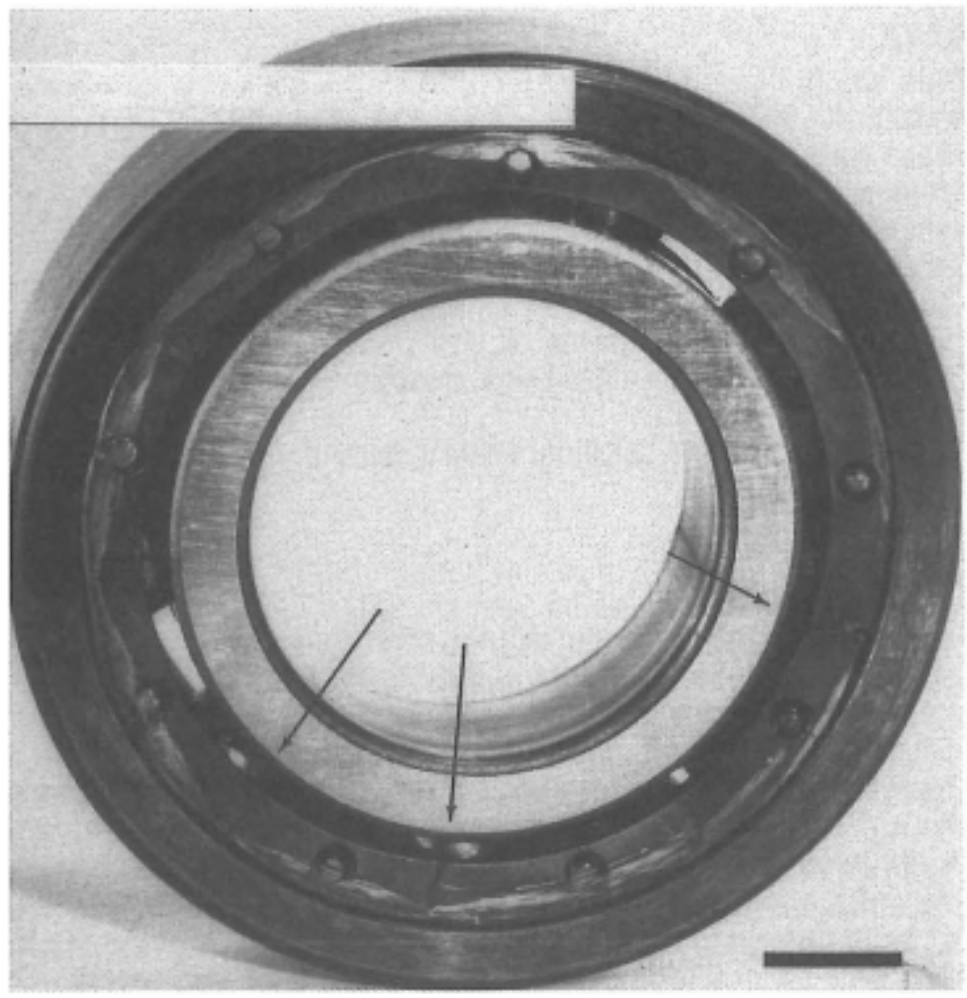
Plate No: 16.28
Archive No: 018-127
Image type: light macro
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: SRB; G (machined bronze separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.13.2.1 Land guided separator, guide surface worn, general
Failure Code 2: 01.13.3 Separator wear from unintended contact
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Machined bronze land-guided SRB separator with center ring and cantilevered prongs is worn heavily on center ring guide surface contacting IR center flange OD. The resulting radial displacement has caused IR contact at the ID of the prongs, and wear. Separator fracture or bearing seizure is likely.
Image Description: One-half of a two-part machined bronze SRB separator is shown, with center ring facing to image S and prongs to N. The sideface at the S made contact with the other separator half and shows slight polishing near the ID. The adjacent cylindrical ID was originally at the prong ID level; now it is heavily worn down. The prong ID shows dark wear pattern. Corresponding wear of the prong sides contacting the rollers is not visible in this image.
Suspected Causes: Inadequate lubrication, probably with contaminated lubricant, possibly combined with rough IR center flange OD surface, can cause heavy wear. The separator will drop down on the rollers as the roller contact surfaces wear, eventually contacting the ID roller path at the prong ID, causing wear.

DATA

Plate No: 16.29
Archive No: 087-010
Image type: view
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: BB (maximum complement); G (2-piece separator), run
Speed:
Load:
Lubrication:
Failure Code 1: 01.13.3 Separator wear from unintended contact
Failure Code 2: 01.11.2 Separator fracture, cracking
Failure Code 3: 20.01.2.1 Fouling of mounting part by other moving part
Failure Code 4: -

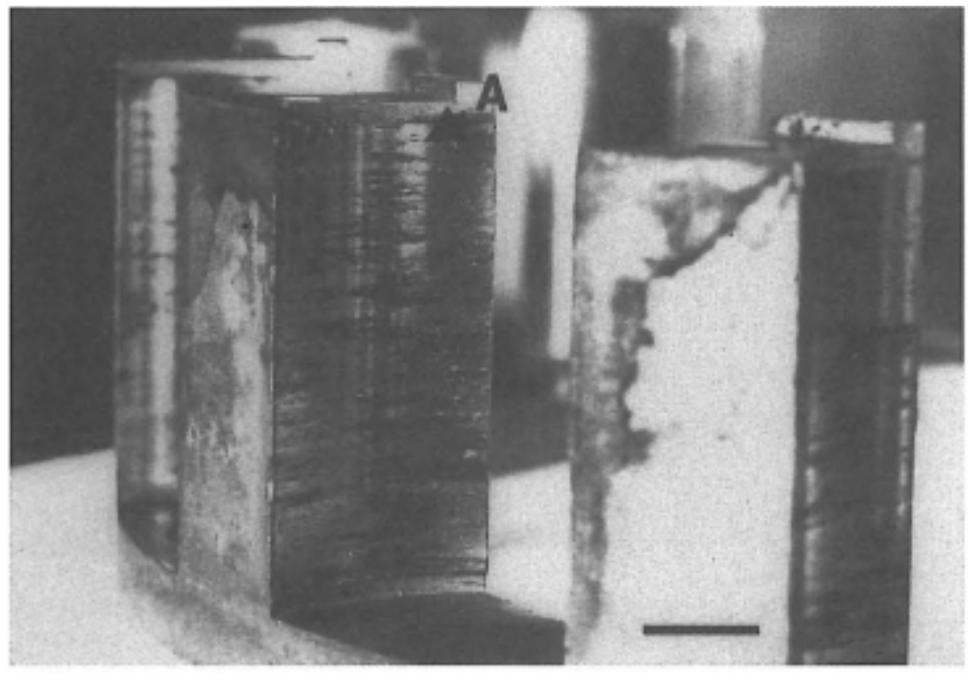


DESCRIPTIONS

Failure Description: Separator sideface and rivet head wear from unintended contact with stationary mounting part. Three cracks run across the thin cross sections over the ball pockets. This is a gross failure.
Image Description: Maximum complement ball bearing with machined, riveted two-piece separator is viewed on sideface. The dark gray separator sideface (including rivet heads) shows deep wear, with plastically flown edges. The worn areas are of lighter color. Black, jagged cross-section cracks are at the arrows.
Suspected Causes: Incorrect dimensioning of housing or end-cap allowed contact of the separator sideface with a stationary part. (In most ball bearings, the separator is wholly contained in the OR outline, but not in this design.) Heavy wear and large ball/separator forces resulted, which have ultimately led to cross-section cracking under the hoop stresses.

DATA

Plate No: 16.30
Archive No: 093-13.1.12
Image type: light macro
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; G (2-piece machined bronze separator), run
Speed:
Load:
Lubrication: oil, ? °C
Failure Code 1: 01.14.1 Separator pocket galled
Failure Code 2: 01.13.1 Separator pocket worn
Failure Code 3: -
Failure Code 4: -



DESCRIPTIONS

Failure Description: Extensive galling (and wear) of separator prong/roller contact surface, probably initiated by solid contaminant. Galling of this severity causes a large volume of debris, adding to the contamination. This may precipitate continued wear, galling, heat imbalance failure and seizure.
Image Description: The machined bronze separator consists of a siderail with integral prongs and a separate closing ring (not shown), attached by rivets passing through the prongs. The image views the separator from the OD. The entire prong surface marked *A* is covered with circumferential streaks of light-appearing galled metal on a dark background of the original material. The transferred metal is higher than the original surface and is polished by wear against the rollers.
Suspected Causes: This very large multirow CRB worked in a steel rolling mill in a severely contaminated environment (both water and solids). Galling at high-speed sliding contacts between the separator and rollers can result and is progressive, since contamination continues and water degrades the oil mist lubrication.

DATA

Plate No: 16.31
Archive No: 027-209
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B & G (stamped steel separator), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 01.15 Separator corrosion
Failure Code 2: 00.20.01.1 Generalized corrosion
Failure Code 3: 12.4 Water in grease
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Generalized corrosion of accessible surfaces on balls and separator. Riveted separator fit surfaces are not corroded. This degree of corrosion causes friction and wear; on continued running, corroded rolling surfaces are likely to spall. Water (seawater) in the grease is the most likely source of corrosion.
Image Description: One half of riveted 'ribbon' separator, disassembled, is viewed on ball contact surfaces. Pocket surfaces are covered with brown corrosion. Three balls are also corrosion-covered. The separator fit surfaces with rivet holes show a few stains only, where water seeped in. The grease pack may show the presence of water (FC 12.4).
Suspected Causes: The bearing was operated in shipboard environment and may have been exposed to seawater spray or mist. Grease contaminated with seawater is a severe corroding influence.

DATA

Plate No: 16.32
Archive No: 027-142
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (phenolic separator) (2), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 01.16 Separator heat imbalance failure
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Comparison of as-manufactured and overheated phenolic plastic separators for ACBB. Overheating produces chemical decomposition of the plastic, revealed by discoloration. Decomposition causes the plastic to lose strength and it may become brittle. Separator fracture may result.
Image Description: Two phenolic plastic ACBB separators are viewed obliquely on OD. The separator at W is of the as-manufactured tan color. In the separator at E, color has changed to greenish-black from exposure to excessive temperature. Recognition of the color change requires a baseline of as-manufactured color.
Suspected Causes: Plastic separator materials are sensitive to elevated temperature. Different plastics may melt (thermoplastic materials) or chemically decompose (thermosetting materials) at excessive temperature. Embrittlement and loss of tensile strength tends to occur as a result of chemical changes even in the absence of melting, in both classes of plastics.

DATA
Plate No: 16.33
Archive No: 027-141
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 15 mm (micros: +20%, others: +100%, −50%)
Component: DGBB; G (stamped 'ribbon' separator), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 01.16 Separator heat imbalance failure
Failure Code 2: 00.19.1.1 Generalized temper colors
Failure Code 3: 01.12 Separator plastic deformation
Failure Code 4: -
See also PLATE: 13.1

[See Image in Appendix]

DESCRIPTIONS
Failure Description: Dark brown temper color is on the entire separator surface, from sustained overheating of the bearing. From Plate 13.1, the temper color corresponds to approximately 230°C overheating temperature. While at high temperature, the separator is weakened and stretches. This may cause contact with ring lands, wedging and seizure.
Image Description: One-half of a two-part, riveted, 'ribbon-type' stamped ball bearing separator, removed from bearing, is viewed on the face. Color of the entire visible surface is dark brown, indicative of exposure to high temperature (temper color). The ball pockets are plastically elongated from their original semicircular shape (see S-facing pocket).
Suspected Causes: Inadequate lubrication, overloading or lack of internal looseness are likely to overheat the bearing. If sustained, temper coloring may result.

DATA
Plate No: 16.34
Archive No: 002-014b&c
Image type: a, b: light macro
Scalebar = a: 20, b: 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; G (silver plated steel separator), run
Speed: 1.7 MdN
Load: 1.5 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 01.16 Separator heat imbalance failure
Failure Code 2: 01.14.1 Separator pocket galled
Failure Code 3: 11.5 Carbonized oil deposit
Failure Code 4: -
See also PLATE 13.4

a

DESCRIPTIONS
Failure Description: Bearing has suffered heat imbalance failure, resulting in galling and hot plastic flow in the separator pockets, a carbonized lubricant deposit on the separator and oxidation of the silver plating. This is a gross failure. See also Plate 13.4 for damage to the balls.
Image Description: (a): Separator is viewed on its OD. The entire visible surface is darkened and patchy where the silver plate has oxidized and peeled off and where carbonized oil was deposited. The pocket edges are peened (arrows). (b): Section exposing the pocket surface, with heavy carbonized oil deposit (black flaking deposit) covering galled transferred material. The edge at the arrows and the light-colored material W of the arrows is galled transferred metal.
Suspected Causes: Mounting error was observed on the bearing, leading to IR rotation on the shaft, high overheating and destruction of balls, separator and lubricant.

b

Integral Closure Failure

17

Failure Code 02

General Description

Integral closures are part of some rolling bearings, intended to keep lubricant in the bearing and/or keep contaminants out. Typically, they are firmly attached to one of the bearing rings, while the other ring rotates past an edge or lip of the closure. The two main types of integral closures are *seals* and *shields*.

Seals, that is, rubbing seals, have a (flexible) lip in sliding contact with a surface of the relatively moving part. These seals typically consist of the following:

- *A seal contact surface* provided on one of the bearing rings and consisting of a cylindrical, conical or toroidal, mostly ground or polished, surface for the flexible seal lip to slide over.
- *A seal body* made of an elastomer, and comprising: (a) one or more *lips* that slide over the seal contact surface under some pressure, and (b) a flat, ring-shaped body, often reinforced with a metal insert, with an edge that is snapped, staked or crimped into a recess in the bearing ring, forming a stationary sealing interface with that ring. Seal bodies are often designed with sharp edges on the lips to ensure tight contact with low friction. A common method of producing these sharp edges is *tear-trimming*, in which a thin sheet of elastomer is allowed to protrude into a gap in the mold and is subsequently removed by tearing over a sharp metal edge.

Shields are simple gap seals, with a narrow space between the relatively moving surfaces. These shields are generally made of sheet metal or sheet plastic. They are attached to one ring as is a seal and have an edge forming a narrow but finite gap against a rotating surface of the other ring. Non-contact shields are not leak-free closures. They serve two purposes:

1. Protect the inside of the bearing from accidental ingress of sizeable foreign bodies;
2. Limit egress of grease.

Rotating flingers are (rotating) shields attached to the innerring of the bearing and placed outside a (stationary) shield or seal to expel impinging solid contaminants.

Note on Image Material Limitation: Photographic images of failed integral seals are not available for this Atlas. As a substitute, a Plate with *sketches* of seals illustrates the distinctive appearance of some failure modes. Chapter 19, 'Mounting part failures,' comprises some images of failed *external* seals. The failure modes of external and integral seals are similar, therefore some guidance as to the appearance of integral seal failures may be obtained from Chapter 19.

17.1 Definition

The failure modes in Table 17.1 apply to integral closures.

17.2 Nomenclature

The designations used in this Atlas are common in bearing technology.

Table 17.1 FAILURE MODES OF INTEGRAL CLOSURES

Failure description	Failure Code
Rubbing seal defects	**02.1**
Pre-service defect (seal)	02.11
Wear (seal)	02.12
Torn lip (seal)	02.13
Leakage (seal)	02.14
Chemical attack (seal)	02.15
Non-contact shield defects	**02.2**
Pre-service defect (shield)	02.21
Wear (shield)	02.22
Leakage (shield)	02.23
Chemical attack (shield)	02.24

17.3 RUBBING SEAL FAILURES — FAILURE CODE: 02.1

17.3.1 Failure Process

17.3.1.1 Pre-service Defects of Seals — *Failure Code: 02.11*

1. *Geometry defects* of the seal:
   - *Distortion* of metal parts;
   - *Molding error* in elastomer;
   - *Defect in tear-trim* of elastomer.
2. *Microgeometry errors* of seal contact surface (excentricity, waviness, rough surface finish);
3. *Elastomer integrity defects* (tears, gaps);
4. *Elastomer material defects* (off-specification composition, embrittlement, tackiness, high friction coefficient, low wear resistance).

17.3.1.2 Wear of Seals — *Failure Code: 02.12*

Both the seal contact surface and the seal lip may wear, in either the two-body (adhesive) or three-body (abrasive) wear mode. Seal *lips* are particularly sensitive to wear failure as their precise geometry is decisive for effective sealing action without excessive friction.

Note: Some seal lips are designed for controlled wear during run-in to provide a contact band of suitable width for the support of the seal lip pressure.

17.3.1.3 Torn Seal Lip — *Failure Code: 02.13*

Elastomeric seal lips are fragile. Initial damage (e.g., during tear-trimming), abrasion or momentary adhesion to the contact surface may start a tear in the lip edge which progresses during operation. A tear may leak and may eventually separate a piece of the lip leaving a gap.

17.3.1.4 Seal Leakage — *Failure Code: 02.14*

Leakage past a seal may occur whenever the contact between seal body and bearing ring (at the installation interface or in the seal contact) is inadequate. Leakage includes two failure modes:

- Leakage of *contaminant* into the bearing;
- Leakage of *lubricant* out of the bearing.

Sources of leakage are

- Unintended *openings*;
- Insufficient *lip pressure*;
- *Pressure differential* across the seal;
- "*Screw pump effect*," where finishing marks on the contact surface have a screw-thread type "lead," moving lubricant or contaminant axially under the seal.

17.3.1.5 Chemical Attack on Seal *Failure Code: 02.15*

The elastomeric seal body is subject to chemical attack by lubricant or atmosphere, especially when operated hot. The elastomer may embrittle or become tacky, causing the lip to stick to the contact surface and to tear.

The metal seal contact surface may corrode, resulting in higher friction and in abrasive corrosion products in the seal gap that may cause wear of seal or contact surface. See FC 00.20 and FC 01.15 for sources of chemical attack on the contact surface.

17.3.2 Distinctive Appearance

Geometry errors and distortion (FC 02.11) may be observed as irregularities in the seal contact. Leakage may be an indication of geometry error, to be confirmed by dimensional measurement.

Wear (FC 01.12) may leave visible wear marks on the seal body, or polish the seal contact surface. Lip wear of magnitude sufficient to cause leakage or high friction may be discernible by inspection of the lip edges under magnification.

The *torn lip* (FC 02.13) of a contact seal is best observed on the dismounted seal.

Leakage (FC 02.14) of lubricant out of the bearing is manifested as beads of grease outside the seal (at the insertion interface or the seal gap). Greater leakage causes grease to be flung away by rotating parts. Leakage of contaminant into the bearing is usually detected after removal of the seal. See FC 11 and FC 12 for diagnosis of lubricant contamination.

Chemical attack (FC 02.15) on metal seal parts is recognizable as rust. Chemical attack on elastomers and plastics is generally not morphologically discernible except as follows:

- *Embrittlement* may result in visible cracking;
- *Tackiness* of elastomers may be felt by touch.

17.3.3 Causes

Pre-service defects (FC 02.11) can occur in the manufacture of the seal or the finishing of the seal contact surface. Insertion of the seal into a bearing ring may lead to distortion or lack of tight fit, permitting leakage.

Wear (FC 02.12) is commonly due to the following causes:

- Seal *geometry* error causing excessive seal pressure;
- Improper *surface finish* of contact surface. Rough surfaces, but also relatively smooth unpolished ground surfaces which have sharp-edged asperities, promote wear;
- Defective *elastomer* material with low wear resistance;
- Lack of *lubrication.* A contact seal requires a thin film of oil (from the rolling bearing grease) to avoid wear.

A *torn lip* (FC 02.13) may arise from

- *Manufacturing* defect;
- *Tacky* elastomer adhering to contact surface;
- Inadequate seal lip *lubrication.*

Leakage in the moving interface (FC 02.14) between lip and contact surface may be caused by

- *Manufacturing* defect in seal or contact surface;
- Defective *installation* of seal;
- *Wear;*
- *Torn* seal lip;
- Excessive *grease* charge or unsuitable grease in the bearing;
- *Overheating* of the bearing;
- Bearing *misalignment.*

Leakage at the stationary interface (FC 02.14) where the seal body is mounted into the bearing ring, may result from

- *Manufacturing* defect in seal or bearing ring;
- Defective *installation* of the seal;
- Excessive *grease* charge or unsuitable grease in the bearing;
- *Overheating* of the bearing;
- *Pressure differential* across the seal (in pumps or in chambers in which closed air volumes change temperature).

Chemical attack (FC 02.15) is caused by aggressive lubricant or atmosphere.

17.4 NON-CONTACT SHIELD FAILURES — FAILURE CODE: 02.2

17.4.1 Failure Process

17.4.1.1 Pre-service Defects in Shields — *Failure Code: 02.21*

- *Geometry* errors of the shield, the holding groove, or the mating surface forming the gap may increase leakage or cause rubbing.
- *Installation* defects may cause leakage at the installation interface or distort the shield and cause rubbing.

17.4.1.2 Wear of Shields — *Failure Code: 02.22*

Non-contact shields wear in two circumstances:

- *Unintended contact* with moving ring due to deformation or geometry error;
- *Contamination* with abrasive material that enters the shield gap.

In either case, the shield as well as the mating surface may wear.

Note: A rarely used shield design requires initial shield wear to form the shield gap.

17.4.1.3 Leakage at Shields — *Failure Code: 02.23*

Non-contact shields are not leak-free in normal operation. *Excessive leakage* (contaminant ingress or lubricant egress) may have the causes listed in section 17.4.3.

17.4.1.4 Chemical Attack on Shields — *Failure Code: 02.24*

See FC 00.20 and FC 01.15 for sources of chemical attack.

17.4.2 Distinctive Appearance

Geometry errors and *distortion* (FC 02.21) may be observed as irregularities in the shield gap. Leakage may be an indication of geometry error, to be confirmed by dimensional measurement.

Wear (FC 02.22) may leave visible wear marks on the shield body, or on the (unintentionally) contacted surface of the ring across the shield gap.

Leakage (FC 02.23) of lubricant out of, or contaminant into the bearing is manifested the same as for seals (see Section 17.3.2).

Chemical attack (FC 02.24) on metal shield parts is recognizable as rust.

17.4.3 Causes

Pre-service defect (FC 02.21). See FC 02.11.

Wear (FC 02.22) is due to geometry error in shield or bearing rings.

Leakage (FC 02.23) in excess of permissible level may result from

- *Geometry* error (wide gap);
- Excessive *grease* charge (for the design);
- Excessive *contaminant* outside the shield;
- *Overheating* of the bearing;
- Excessive *vibration* of the bearing causing grease to slump.

Note: A non-contact shield is suitable for use if it is *intended* to bleed off a pressure differential across the closure.

Chemical attack (FC 02.24) is caused by aggressive lubricant and/or atmosphere.

17.5 Effects of Integral Closure Failure

This section covers both rubbing seals and shields.

Loss of lubricant may result in the following failures:

- *Insufficient lubricant* remaining in bearing, with resulting failure from inadequate lubrication;
- Lubricant *contamination* of parts outside the bearing.

Contaminant ingress into bearing may cause failures of the lubricant or of bearing components.

Excess heat generation may occur in the bearing due to seal friction.

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
02.1	17.1
02.12	17.1
02.13	14.10
02.19	17.1

PLATES

DATA

Plate No: 17.1
Archive No: 117-1&2&5
Image type: a, b, c: drawing
Scalebar = -
Component: BB; S (molded integral elastomer seal)
Speed:
Load:
Lubrication:
Failure Code 1: 02.11 Rubbing seal wear
Failure Code 2: 02.12 Torn rubbing seal lip
Failure Code 3: 02.19 Geometry or assembly defect in rubbing seal
Failure Code 4: 02.1 Rubbing seal defect
See also PLATES: 19.12 and 19.13

DESCRIPTIONS

Failure Description: Sketches (a) through (c) show cross sections of integral rubbing bearing seals. *A:* seal lip wear (FC 02.11); *B:* torn seal lip (FC 02.12); *C* deformed seal geometry (FC 02.19). Other failure modes (not shown) are counterface wear (FC 02.13) and chemical attack (FC 02.15). Seal leakage (FC 00.14) from any of the above failures may result in bearing failure. Excess heat generation may cause heat imbalance failure (FC 00.19).
Image Description: (a): Automotive wheel seal with metal casing (white) and elastomer body (black). Lip worn down to line *A*. (b): Seal for pillow blocks. Radial tear in lip, to line *B* (c): Molded rubber ball bearing seal with steel insert (white). Insert bent down to line *C*, preventing tight sealing at OR insertion. Not shown: Counterface on shaft may show wear band. Chemical attack may cause tackiness or brittleness.
Suspected Causes: Seal failures may be due to manufacturing defects, insertion errors, damage in bearing mounting, unsuitable counterface (rough, out-of-round), shaft misalignment (FC 02.11, 02.12, 02.13, 02.19), excess temperature or speed, incompatibility or inadequacy of lubricant (FC 02.11 or 02.15) or contaminant ingress (FC 02.11, 02.12, 02.13). Any of these may cause leakage (FC 02.14). PLATES 19.12 and 19.13 show *external* seal failure.



LUBRICANT FAILURE 18

Failure Code 11–13

General Description

Lubricants covered in this Atlas fall into three classes:

1. *Oil* (FC 11). In this class fall all (organic) fluid lubricants whose rheological properties (increase of viscosity with pressure) permit EHD films in Hertz contacts.
2. *Grease* (FC 12). This class of lubricants consists of oils blended with thickeners forming semi-solid gels that can be packed around moving components and can be channeled by their motion.
3. *Other lubricants* (FC 13). All lubricants that are neither oils nor greases fall in this class. It includes solid lubricant compounds and coatings, particulate (powder) lubricants, reactive gases and fluids without the ability to form EHD films, and unreactive or reactive vapors which form lubricant films by condensation or chemical reaction with the contact surfaces. Also included are solid gel entrapped oils which are molded around moving parts but do not channel.

Many lubricant failures are chemical in nature (decomposition, oxidation, or depletion of boundary lubricating additives) and are not discernible by morphological examination. These failures are *not* classified in this Atlas. When they occur, they are merely designated FC 11: Oil failure, and likewise for the other lubricant classes.

Lubricants, unlike all other parts of the Hertz contact machine elements, are routinely replenished or replaced in service. A unique ''failure'' process resulting from these practices is introduction of the wrong lubricant (a lubricant other than the one specified). This can lead to failure through two processes:

1. Use of a lubricant with the wrong *rheology* or *chemistry*, or use of an improper *quantity* of lubricant may result in any of the failure modes hereafter described.
2. Admixture of a *different class* of lubricant to a supply already present may result in chemical or physical reaction producing an unserviceable mixture.

18.1 OIL FAILURE FAILURE CODE: 11

18.1.1 Definition

Any defect of, or damage to, the selection, quality, or quantity of the oil lubricant to a Hertz contact machine element is designated an oil failure in this Atlas.

18.1.2 Nomenclature

All failure designations are conventional except ''friction polymer,'' which designates a (colored) hard coating formed from the lubricant on the contact path of a component. This deposit is also called ''deposit,'' ''lacquer,'' ''surface discoloration'' or other non-specific designations.

18.1.3 Failure Process

Two major processes of oil lubrication failure in Hertz contact machine elements are distinguished:

1. *Contact lubrication failure*. The quantity, viscosity or boundary lubricating ability of the lubricant in the contact interface is not adequate, resulting in one or more of the following:

- *Friction* is excessive.
- *Wear, galling,* or *contact fatigue* failures occur prematurely.
- *Contaminant* in the lubricant produces dents and three-body wear.
- Water or aggressive decomposition products of the oil cause *corrosion.*

2. *Cooling failure.* The heat removal through impingement of bulk oil on working surfaces is insufficient and overheating results. This may in turn bring about contact lubrication failure or directly lead to heat imbalance failure.

   The *system* providing oil lubrication strongly influences the role lubrication plays in cooling the Hertz machine element. Lubrication by drip feed or by an impregnated lubricant reservoir (instrument bearings) provides little cooling capacity. Mist lubrication provides cooling by the entraining gas stream, which is effective in steady-state conditions but has little on-site heat capacity to quench (counteract) heat excursions (such as in galling). Bulk oil lubricating systems are effective cooling means. Their capability increases in the order: sump, splash, circulating and jet (or in-race) lubrication.

The following sections describe changes in the oil lubricant which are diagnostic of, and conducive to, failure of the machine element through inadequate lubricant performance.

18.1.4 Friction Polymer — Failure Code: 11.1

18.1.4.1 Definition

A *friction polymer* is a thin, solid, adherent coating deposited from the lubricant onto a contact surface. It is insoluble in commonly used solvents.

18.1.4.2 Failure Process

Under conditions of elevated temperature (and perhaps, sliding), contact surfaces may, after substantial running time, become coated with a translucent film of organic material deposited out of the lubricant. The literature suggests that these coatings are polymers formed from the lubricant in the high-pressure, high shear environment of the Hertzian contact (hence "friction polymers"). The steel contact surface material is believed to act as a catalyst and to contribute iron to the compounds formed.

18.1.4.3 Distinctive Appearance

The friction polymer appears as a colored coating on the contact surfaces *only.* (Temper color (FC 00.19) is not limited to contact surfaces.) The friction polymer is generally transparent or translucent: finishing marks can be seen through it. It often forms circumferential bands separated by gaps which are of metal color. Due to heavy sliding, the friction polymer is generally worn away from flange contacts but may persist in rolling contacts.

When thin, the friction polymer is light yellow in color; thicker coatings can be brown, reddish or greenish.

A friction polymer is distinguished from *temper color* (FC 00.19) by two characteristics:

1. It is limited to contact areas.
2. When quickly wiped with a cotton swab dipped in dilute (1:10) HCl (hydrochloric acid) in water, it remains unaffected. Temper color is dissolved, leaving bare metal.

A friction polymer is distinguished from *dried-on grease* by being insoluble in the commonly used solvents. Dried-on grease usually can be removed (although often with difficulty) by suitable solvents and/or detergents.

A friction polymer is distinguished from *rust* by color (usually lighter) and by its placement in circumferential bands in the contact area only. Contact corrosion is in patches (often at rolling element spacing); general corrosion is not confined to contact surfaces.

18.1.4.4 Causes

Friction polymer formation is promoted by high contact temperature and (probably) by high contact pressures and shear rates. Roughness of the contact surfaces, the presence of yellow-metal bearing separators and the chemistry of the lubricant have all been suspected of having an influence on friction polymer formation.

There is little data concerning specific lubricant chemistry influences on friction polymer formation. Hydrocarbon and polyester oils, the most commonly used, are known to form friction polymers.

18.1.4.5 Effects of Friction Polymer

A friction polymer is usually not detrimental to functioning (with the exception of instrument bearings in which it depletes an already minimal lubricant supply), but has been used as an indicator of severe operating conditions, especially overheating.

18.1.5 Water in Oil — Failure Code: 11.2

18.1.5.1 Definition

Water in Oil is the presence of liquid water in a (non-water-miscible) oil.

18.1.5.2 Failure Process

Conventional lubricating oils do not freely mix with water. However, small quantities of water can be absorbed from humid atmosphere or directly mixed into the oil, where they are emulsified. Larger quantities may be present as droplets or as free (separated) water.

Water-based hydraulic fluids are used as lubricants for some Hertz contact machine elements. This failure mode does not apply to them.

18.1.5.3 Distinctive Appearance

1. Small quantities of water are *not visible* in oil. Laboratory evaluation is necessary.
2. Somewhat larger quantities of water can give the oil a *cloudy* or *milky* (non-transparent) appearance.
3. Even larger quantities of water may appear as suspended *droplets* visible in transmitted light.
4. Large volumes of water separate from most oils and form a distinct *layer* if the fluid is allowed to stand.

18.1.5.4 Causes

1. Oil contaminated with water as supplied to the chamber.
2. Water ingress past the chamber seal due to
   - cleaning of machinery;
   - environmental exposure (condensation, rain, snow, flooding);
   - process water.
3. Leakage of water into (circulating) oil in an oil/water heat exchanger.

18.1.5.5 Effects of Water in Oil

- Water in most oils is detrimental to *boundary lubricating* ability.
- Water in oil is highly *corrosive* (contact corrosion).

Note: Anti-oxidant additives in oil may mitigate the corrosivity of small percentages of water.

- A direct detrimental effect of water in oil on *spalling* crack formation has been demonstrated.
- Water in droplets and free water entrained with the oil impairs *EHD film* forming ability. Since water does not increase viscosity with pressure as oils do, a water drop passing through a Hertz contact can cause local film collapse.

18.1.6 Solid Contaminant in Oil — Failure Code: 11.3

18.1.6.1 Definition

Solid contaminant in oil is the suspension of *unintended* solid particulates in oil.

Some oils contain finely divided graphite, molybdenum disulphide or other solid lubricants as deliberate additives.

18.1.6.2 Failure Process

The failure process causing oil contamination by solids occurs when the oil comes into contact with the contaminant and mixes with it.

Almost any finely divided solid can become suspended in oil where it is abrasive to varying degrees and may also act to degrade the oil chemistry. Common types of contaminant are ceramic particles (dust, sand, abrasive), metal particles (from machining, wear, spalling) and organic particles (fibers, dust). For purposes of diagnosing their origin, solid containinants are usually classified into the following categories:

1. Non-metal abrasives (sand, dust, or grinding grit).
2. Metal particles:
   - Steel particles: steel machining chips and shavings; steel wear particles; steel spalling debris.
   - Non-ferrous metal particles.
3. Organic particles.

18.1.6.3 Distinctive Appearance

Solid contaminant in oil may be observed by these simple methods:

- Viewing by unaided eye.
- Touch.
- Viewing under low magnification on a glass slide.
- Examination of a filter or a magnetic drainplug.

Note: Numerous laboratory methods exist for more detailed examination of contamination in oil, including spectrography, SEM examination, classification of magnetic debris by ferrograph, optical particle counting methods, etc.

Viewing by Unaided Eye. Contaminated oil appears cloudy when viewed in transmitted light. Metallic contaminants may produce a metallic glitter in reflected light.

Examination by Touch. Solid contaminants of hard materials may cause the oil to feel *gritty* when rubbed between the fingertips. This occurs if the particles are not too fine and the contamination is distributed throughout the oil.

Viewing Under Low Magnification. Under 10–30 power magnification of oil placed on a glass slide, larger solid contaminant particles are individually visible.

- *Metal particles* usually glitter in reflected light.
- *Machining chips* or shavings may be distinguished from thin laminar *wear* particles by shape.
- *Spalling* debris are blocky and have fracture surfaces (unless extensively rolled over).

Steel particles often appear silvery, while *brass* and *bronze* particles appear golden. However, interference colors or viewing through a layer of colored oil can change the hues.

Accurately spherical particles have been detected in spalling failure by scanning electron microscopy.

Ceramic (abrasive) particles usually do not glitter and have sharp fracture edges. Fiberglass particles (from reinforced rolling bearing separators) are fibers with fractured ends.

Organic particles may be fibers (textile) or wear debris (from plastic or elastomer components).

Examination of Filter or Magnetic Drainplug. Oil circulations are often equipped with filters; oil sumps may feature magnetic drainplugs. A filter collects solid contaminants in excess of its pore size. Filter residue or the mass adhering to a magnetic drainplug can be washed and examined under magnification. Criteria are similar to those for oil examination.

18.1.6.4 Causes

- *Chamber contamination* left behind from manufacture or assembly. The contaminant can be common dust, casting sand, polishing compound, paint residue or chips of any of the materials used in the assembly.
- *Oil contamination* present in the oil as supplied to the chamber. This contamination can vary greatly, coming from improperly cleaned containers, workplace dirt, admixture of old lubricant, a contaminated oil circulating system, etc. Any metal or ceramic particle may be found. Organic fibers (from wipers) are also common.
- *Wear particles* or *spalling debris* from any of the working components. This is most often steel from the Hertz contact components. In the case of bearings, separator material may provide debris. Lubrication systems common to several machine elements (example: bearings and gears or pistons) carry debris between the elements.
- *Process material particles* in any machinery processing dusty material or slurries or making chips. The particles can be metal, ceramic or organic.
- *Atmospheric dust* carried directly into the chamber past the seals. This dust is generally ceramic (sand or clay).
- *Combustion products (soot)* in the circulating oil of internal combustion engines.

18.1.6.5 Effects of Solid Contaminant in Oil

Hard contaminants, down to micrometer particle size, are abrasive to the working components. See FC 00.12 for wear of contact components, FC 01.13 for separator wear, FC 01.24 for guidering wear and FC 02.22 for seal wear.

Solid contaminants (whether hard or soft) may produce dents in Hertz components. See FC 00.18. Dents are major spalling causes.

Contaminant in the oil may cause noise and vibration in the machine element.

In circulating lubrication, solid contamination may clog filters and jets and may interfere with heat transfer by encrusting heat exchangers.

18.1.7 Discolored Oil — Failure Code: 11.4

18.1.7.1 Definition

Discolored oil is oil of a color different from the unused oil of the same type (especially when viewed in transmitted light).

18.1.7.2 Failure Process

Chemical changes in the oil may cause it to discolor. Oil discoloration may also be caused by water or solid contamination. This failure mode is defined to cover *chemical* discoloration or discoloration by an unknown source.

In replenishing or replacing the oil supply in the machine, inadvertent selection of the *wrong oil* may occur.

The *admixture* of oil of a different type to an existing supply may create a blend of unexpected properties. If the classes are *incompatible*, a chemical reaction may occur, producing an unserviceable fluid. *Replacement* of the oil supply with one of different specification may produce any of the failure modes hereafter listed.

18.1.7.3 Distinctive Appearance

Chemically *decomposed* oil may differ in color or translucency from unused oil in virtually any way (including none). Comparison with unused oil and knowledge of the appearance of decomposition (oxidation) products of the oil in use are necessary for diagnosis.

- A common discoloration in mineral oils is *darkening.*
- Oil containing small amounts of finely dispersed water is *milky.* See FC 11.2.
- Solid contaminated oil is often *opaque* and/or darkened. See FC 11.3.

The *wrong oil* or a mixture of two different oils may produce unexpected appearance (color, viscosity, odor, etc.).

18.1.7.4 Causes

Causes of chemical decomposition:

- *Overheating.* Many oils oxidize at elevated temperature.

Note: Antioxidant additives are commonly provided to retard oil oxidation.

- *Ingress of reactive chemicals.*
- *Exposure to incompatible metals.* Certain synthetic oil formulations react with yellow-metal components.

Causes of contamination are listed under FC 11.2 and FC 11.3.

18.1.7.5 Effects of Discolored Oil

Chemical discoloration of oil is used as a warning symptom of chemical change. Its potential for harmful effects can be identified by chemical analysis only.

18.2 GREASE FAILURE — FAILURE CODE: 12

General Description

To most Hertz contact machine elements, grease is supplied in the form of a *pack*. The grease may be packed into the machine element (rolling bearing with integral closures) or into the chamber at assembly. It may be injected periodically through a channel, during service. The grease supplied by any of these methods is generally intended to be *channeled* by the moving parts of the machine element, so that the bulk grease is formed into a pack surrounding the machine element, but the volume swept out by the moving parts is just left free of bulk grease. A thin layer of oil containing some proportion of thickener covers the contact surfaces and is replenished by the moving parts wiping fresh grease from the pack's "working" walls which they contact during operation. It is believed that the grease wiped off by a moving part is richer in oil than the bulk grease, and that the thickener structure is partially broken down. In a normal grease pack, oil is replenished at the working wall by capillary action from the bulk of the pack.

18.2.1 Definition

Any defect of, or damage to, the selection, quality or quantity of the grease lubricant to a Hertz contact machine element is designated a grease failure in this Atlas.

18.2.2 Nomenclature

All failure designations are conventional except "*friction polymer*," which designates a (colored) hard coating formed from the lubricant on the contact path of a component. This deposit is also called "deposit," "lacquer," "surface discoloration" or other nonspecific designations.

18.2.3 Failure Process

Contact components lubricated with grease fail—as do those lubricated with oil—through inadequate contact lubrication or imbalance between heat generation and heat removal. Compared with oil lubrication, especially one using substantial volumes of oil to wash the components, a grease pack removes minimal heat. Accordingly, heat imbalance failures due to grease lubricant malfunction are the result of excess heat generation, not of reduced heat removal by the grease.

In the following sections, deficiencies in the grease pack of the Hertz contact machine element are described. Through these deficiencies, the machine element's lubrication is impaired and eventually the machine element fails. In the present section, these modes of lubrication failure are enumerated.

Grease lubrication may fail under the following conditions:

- The oil supply to the contacts becomes insufficient as a result of *depletion of oil* at the working wall of the grease pack.
- *Contamination* increases friction losses and impedes capillary oil movement in the grease.
- *Poor channeling* of the grease causes its free surface to recede out of contact with the moving parts.
- Excessive chamber *temperature* reduces oil viscosity.
- Severity of *contact conditions* (such as local temperature, or shear rate) damages the grease.

18.2.4 Effects of Grease Failure

The failure of a Hertz contact machine element may take place by one of the grease failure processes described below.

Ineffective lubrication, which fails to provide oil in the quantity required, but is stable over the short term, may cause one or more of the following failures of the working components:

- *Wear* of contact component (FC 00.12), guiding-component (FC 01.13 or FC 01.23) or seal (FC 02.12).
- *Spalling* (FC 00.16).
- *Galling* of contact component (FC 00.13), or guiding component (FC 01.14 or FC 01.24).

Cyclic grease failure arises if the oil on the contact surfaces is depleted or contaminated under operating conditions that are marginally too severe for the grease. A skin of grease immediately adjacent to the working wall dries out and fails to provide sufficient oil replenishment. The lubrication effectiveness is impaired. The temperature of the machine element rises, causing the grease pack to soften and slump. This injects new grease among the moving parts. The excess slumped grease is expelled by the moving parts and a fresh, not oil-depleted working surface is reestablished, providing sufficient oil replenishment until the cycle repeats. The repeated cycles of grease damage and impaired lubrication eventually damage enough grease to prevent restoration of normal lubrication before heat imbalance failure sets in. The machine element fails by irreversible grease failure (see below).

Irreversible failure of lubrication arises from an unstable increase of operating temperature and heat imbalance failure. This process takes place if the operating conditions are too severe for the recovery of the grease pack described in the preceding paragraph. The failure mode characteristic of this process is *heat imbalance failure* (FC 00.19).

If the grease failure is very gradual, failure modes listed under "Ineffective lubrication" may arise first and terminate serviceability of the machine element.

18.2.5 Grease Quantity Defect — Failure Code: 12.0

18.2.5.1 Definition

A grease quantity defect is defined as an excess or shortfall of grease charge in the chamber (or sealed bearing).

It is common practice to specify a percentage range of the chamber (or bearing) volume as the required grease charge.

18.2.5.2 Nomenclature

The designation "grease quantity defect" is uncommon. Specific deviations are called "overgreasing" or "excess grease" and "undergreasing" or "insufficient grease."

The terms "slumped grease pack" and "channeled grease pack" are commonly used to describe the condition of a grease pack in which the grease has or has not softened.

18.2.5.3 Failure Process

A stable channeled grease pack is contingent upon the right volume of grease in the chamber. If the grease charge is in error, one of the consequences described below may ensue.

Excessive grease tends to slump back into the volume swept out by moving parts, is thrown clear time and time again (churned), until eventually it is purged from the vicinity, or softened. Softening accelerates the churning and eventually leads to *liquefaction,* at which point the pack collapses and is often expelled from the chamber, leaving a shortfall of grease.

Insufficient grease does not last as long in service as the specified pack and when exhausted can lead to failure. Severe insufficiency may prevent proper channeling from the outset; the grease is thrown clear of the moving parts and remains too remote to resupply the contact surfaces with lubricant.

18.2.5.4 Distinctive Appearance

If the chamber is accessible, then the grease remaining at the time of examination can be estimated or weighed.

Note: Excessive grease tends to purge. The amount found upon opening the chamber may be low, though the failure was initiated by excessive grease.

Excessive grease may be identified as follows:

- Grease may be softened, liquefied.
- Grease may have *slumped* into the path of moving components.
- Grease may be *discolored* from overheating.

Insufficient grease appears as follows:

- Grease pack may be *out of contact* with moving parts.
- Grease may be *discolored* from overheating.

18.2.5.5 Causes

Excessive grease may be the result of the following causes:

- Initial overgreasing.
- Regreasing with more grease or more frequently than specified.
- Leakage of oil into the grease, from an adjacent, inadequately sealed chamber.

Note: If oil leaks into the grease pack, it will both increase the total grease volume and soften the grease (see FC 12.1).

Insufficient grease may result from the following causes:

- Initial undergreasing.
- Regreasing with less grease or less frequently than specified.
- Loss of grease by leakage from the chamber.

18.2.5.6 Effects of Grease Quantity Defect

Excess grease may cause:

- Excessive frictional losses.
- Overheating and heat imbalance failure (FC 00.19).
- Softening or liquefaction of the grease with subsequent loss of grease.

Insufficient grease may cause:

- Inadequate lubrication with wear (FC 00.12), galling (FC 00.13), or heat imbalance failure (FC 00.19).
- Drying out, discoloration and decomposition of grease.

18.2.6 Softened or Liquefied Grease — Failure Code: 12.1

18.2.6.1 Definition

Grease with a consistency that is moderately lower than when unused is defined as *softened.* Grease of consistency so low as to be a thick fluid is defined as *liquefied.*

18.2.6.2 Failure Process

Consistency changes may be due to *shearing.*

- Conventional greases, especially those with a soap thickener tend to *soften* when severely sheared (some greases harden when sheared within certain limits). The softening is attributed to changes in the filamentary structure of the thickener. Filaments tend to fragment if sheared excessively and softening results.
- Extreme shearing may destroy the thickening effect to the degree that the grease turns into a thick fluid incapable of channeling, that is, the grease *liquefies.*

Note: In most cases softening and liquefaction due to shearing are not reversible.

Consistency defects may be due to *dilution* or mis-selection.

- *Leakage* of oil from an adjacent and ineffectively sealed chamber may add oil to the grease pack and thereby soften its consistency.
- Use of the *wrong grease,* for example, during relubrication, may introduce grease of the wrong consistency.
- Change in consistency due to dilution or mis-selection is irreversible unless the grease pack is replaced.

Consistency changes may be due to *heating.*

- Reversible softening can occur when the grease is *moderately* heated.
- *Excessive* heating leads to liquefaction and the original grease consistency is not restored upon subsequent cooling, although the grease will become somewhat thicker.

18.2.6.3 Distinctive Appearance

Softening of grease may be detectable without laboratory testing by observing its tendency to slump when packed with a vertical free surface. Reliable determination of softening is made by penetration measurement.

A grease, when *liquefied,* cannot be packed, behaves as a thick fluid, and has no reproducible penetration depth when measured.

18.2.6.4 Causes

- *Overgreasing.* An overgreased chamber may force grease into the volume swept by moving parts and thus expose it to indefinite churning.
- *Grease with too low consistency.* Inappropriate grease selection may result in slumping of the grease during normal operation, exposing it to churning.
- *Excessive vibration.* Greases differ in their ability to withstand a vibratory environment without slumping.
- *Use in a rolling bearing with outerring rotation.* In an application where the stationary part is the shaft and innerring, grease is expelled by the rolling elements, thrown against the separator which rotates and flings it against the faster rotating outerring. Some grease may be retained in the outerring groove, but most is centrifuged out to the sides and pumped back toward the rolling elements and cage, where the cycle is repeated. This continuing churning is a severe hazard to the consistency of the grease.

Note: A similar failure may occur in gearing comprising a rotating internal gear.

- *Elevated operating temperature* softens grease and may precipitate liquefaction directly or via churning.
- *Excess operating speed.* Grease lubricated applications have strict speed limits. Exceeding the speed acceptable for a given grease places greater mechanical and thermal stresses on the grease than it can readily support; these stresses tend to soften the grease.

18.2.6.5 Effects of Grease Softening and Liquefaction

Softening of the grease pack, unless reversed upon cooling, is a self-aggravating failure, leading to grease loss. Machine element failure can be avoided by purging and replacement of the damaged grease, only if the contact surfaces are not yet damaged and if the operating conditions causing the grease softening have been remedied.

Liquefaction of grease generally produces inadequate lubrication in short order, leading to machine element failure.

18.2.7 Carbonized Grease — Failure Code: 12.2

18.2.7.1 Definition

Carbonized grease is grease containing solid carbon particles arising from grease decomposition.

18.2.7.2 Failure Process

Extreme overheating of common greases (especially those with soap thickeners) decomposes grease constituents to the point where free carbon particles form. They may be finely distributed, but generally are large enough to be gritty to the touch. They generally become mixed with remaining grease.

Carbonized grease may retain some lubricating ability from the remaining un-decomposed material, but is generally unsuitable for service.

Note: Greases with clay (bentonite) thickeners exist. Bentonite does not carbonize, but the organic oil content may. Bentonite grease, when exposed to the high temperatures causing carbonization of the oil, may produce clumped clay particles which can be abrasive.

18.2.7.3 Distinctive Appearance

Carbonized grease contains black particles of carbon. The entire grease pack may be darkened by distributed carbon particles. However, it is more common to find carbonized grease adhering to surfaces of the working parts, or in the "skin" of overheated grease that may form along the working wall of the grease pack. If the carbon is finely distributed, it gives the grease a blackish hue, compared to its color when unused.

Note: Grease may show dark discoloration from causes other than carbonization.

If the thickener in a carbonized grease can be dissolved, then filtration may leave black carbon dust on the filter paper. However, dark residues may arise from other sources and laboratory methods may be needed to differentiate between them.

If agglomerated carbon grains are present, then distinct black granules can be seen in the grease on a glass slide, under the microscope. Grittiness can also be felt when rubbing the grease between the fingertips.

Carbon grains are of rounded shape and tend to agglomerate. This may aid in distinguishing them from solid contaminant particles covered with blackish oil residue, which are more likely to be angular, and agglomerate less.

18.2.7.4 Causes

- Rapid, extreme *overheating* of grease in the process of a heat imbalance failure.
- Severe *depletion* of grease pack. Remaining grease quantities adhering to working contact components are insufficient for lubrication; heat imbalance results and the grease carbonizes.

18.2.7.5 Effects of Carbonized Grease

Carbonized grease has marginal lubricating ability (the oil release ability is impaired), and its consistency is stiffer than in the unused grease. It is unlikely to permit normal machine element performance.

18.2.8 Friction Polymer — Failure Code: 12.3

18.2.8.1 Definition

Same as under FC 11.1: Friction polymer in oil lubrication.

18.2.8.2 Failure Process

Formation of friction polymer from grease proceeds as from oil (see FC 11.1). The friction polymer and any dried-on grease residue may both form coatings on the same surfaces. Generally, dried-on grease can be washed off with suitable solvents and detergents, whereas friction polymer is insoluble in common solvents.

18.2.8.3 Distinctive Appearance

Same as under FC 11.1: Friction polymer in oil lubrication.

18.2.8.4 Causes

Same as under FC 11.1: Friction polymer in oil lubrication.

18.2.8.5 Effects of Friction Polymer

Same as under FC 11.1: Friction polymer in oil lubrication.

18.2.9 Water in Grease — Failure Code: 12.4

18.2.9.1 Definition

Same as under FC 11.2: Water in oil.

18.2.9.2 Failure Process

Water can be incorporated into grease from the same sources as into oil (see FC 11.2). Due to pack formation, grease can entrap substantial quantities of water, either thoroughly blended with the grease, held as drops or in sizeable pockets.

Water in grease has the same detrimental effects as in oil. Additionally, some greases are washed out of the chamber by sufficient water.

Note: Water-tolerant grease formulations exist that resist washing out and help to protect corrodible parts from small amounts of water. However, large amounts of water are detrimental with any grease.

18.2.9.3 Distinctive Appearance

Minimal amounts of water in grease are invisible and require laboratory testing.

Modest amounts of water can be present in two conditions:

- Blended into the grease, which gives the grease a whitish appearance (compared to the color of unused grease).
- Present as *droplets,* which may be visible if a smear of grease is placed on a glass slide or a small quantity of grease is squeezed flat in a transparent plastic bag.

A *large concentration* of water is present as a free phase in pockets of the grease pack or loose in the chamber.

18.2.9.4 Causes

Same as for water in oil. See FC 11.2.

18.2.9.5 Effects of Water in Grease

- The same effects arise as for water in oil (see FC 11.2).
- Grease may be *softened,* with resulting slumping, liquefaction and loss of grease.
- Grease may be *washed out* of the chamber with resulting loss of lubrication.

18.2.10 Solid Contaminant in Grease — Failure Code: 12.5

18.2.10.1 Definition

Grease contamination is solid particulate matter blended into, or present along with, grease in the chamber. Because grease can pack, contamination can be limited to layers, or isolated volumes, or may extend through the entire grease quantity in the chamber.

18.2.10.2 Failure Process

The sources of solid contaminant in grease are the same as in oil (see FC 11.3).

Notes:

1. Improperly prepared grease thickener may be a source of granules, which may produce noise (less often nicks). Examples follow.
2. Bentonite thickener may contain, or agglomerate into, larger grains.
3. Nitrite anti-oxidants added to some greases may form crystallites larger than acceptable for quiet running applications in bearings.

18.2.10.3 Distinctive Appearance

Observation of contaminant in grease is performed by means similar to that of contaminant in oil (see FC 11.3). Because grease forms *packs,* examination of specific layers is diagnostic:

1. Contaminant in the layers immediately *adjacent* to a moving component suggests particle removal (wear, spalling) from that component. Identification of particle material and comparison with component material is diagnostic.
2. Contaminant in the *outermost layers* of the grease pack (facing seals) is indicative of contamination ingress into the chamber.
3. *Widely distributed* contaminant may result from either of the above conditions after long running, or indicate initial contamination of chamber or grease supply.

18.2.10.4 Causes

Causes of grease contamination are similar to those of oil contamination. See FC 11.3.

18.2.10.5 Effects of Solid Contamination of Grease

A grease pack can interact with contamination in two different and opposing ways.

Protective effects of grease against component damage by contaminant.

Contaminant formed at the working surfaces, for example, by wear, can be expelled into the grease pack and held there, reducing the damage it causes to the working surfaces.

If the contaminant enters the chamber through a seal, that is, if it encounters the outside of the grease pack, then the pack acts as a barrier and can absorb substantial contamination without permitting it to reach the working surfaces.

Labyrinth seals are often filled with grease for the purpose of trapping contaminant before it enters the chamber proper.

Damaging effects of grease/contaminant combination.

If too much contaminant is incorporated into the grease, then it will be continually presented to the moving components and act as an abrasive, cause noise, wear and nicks, and, if the contamination is sufficiently severe, ultimate failure.

Hard contaminants, down to micrometer particle size, are abrasive to the working components. See FC 00.12 for wear of contact components, FC 01.13 for separator wear, FC 01.24 for guidering wear and FC 02.22 for seal wear.

Solid contaminants (whether hard or soft) may produce dents in contact components. See FC 00.18. Dents are major spalling causes. Contaminant fed onto the working surfaces from the grease may cause noise and vibration in the machine element.

18.2.11 Grease Dried Out or Discolored — Failure Code: 12.6

18.2.11.1 Dried-out Grease — Failure Code: 12.6.1

18.2.11.1.1 Definition

Grease that has lost some of its unused oil content and thereby acquired a harder consistency than when unused is defined as *dried out.*

- *Grease dried out in bulk* has lost oil throughout the volume of the grease pack.

- *Grease with dried skin* shows a dried-out layer adjacent to a free surface (mostly the surface swept by a moving part).

18.2.11.1.2 Failure Process

Grease may lose some of its oil content (dry out) through the processes described below.

Bleeding

To be effective as a lubricant, grease must release oil to the moving surfaces. This is known as "bleeding." The rate of bleeding depends on grease composition, operating temperature and mechanical factors, such as vibration and the shape, size, surface finish and speed of parts moving through it. Bleeding is an inevitable source of oil loss from grease, but may be sufficiently low to permit very long grease life.

The free surface of the grease pack swept by a moving part is especially prone to drying out, and thus to developing a *dried-out skin*. The moving part wipes oil (and some thickener) from the working walls of the grease pack. If the depletion of oil is large and replenishment from the bulk pack slow, a permanently dried-out skin can form. In such a skin, capillary replenishment of oil is slowed down, further aggravating the drying out.

If the grease and operating conditions are well matched, capillary replenishment of the oil prevents formation of a dried-out skin. The bulk of the pack may eventually dry out if oil depletion is severe.

Evaporation

Evaporation, especially at higher temperatures or in vacuum, attacks all free surfaces. If rapid, it may lead to dried-out skins on these surfaces; if slower, or if the pack is churned, the entire bulk of the pack may dry out.

18.2.11.1.3 Distinctive Appearance

Dried-out *bulk* grease may appear darker than normal and feel stiffer to the touch. Moderate degrees of oil loss may not be detected by these methods and require laboratory measurement of penetration or oil content.

Dried-out *skin* on grease, if pronounced, may be visible as a layer of changed color and felt with a probe, as a harder surface. If moderate, micro-penetrometer measurement or oil content determination on a local sample may be required for diagnosis.

18.2.11.1.4 Causes

Capillary oil loss can lead to dried-out grease under these conditions:

- *Overheating,* causing reduced oil viscosity and faster capillary movement.
- *High speed* of moving surfaces that increase the wiping effect. This may lead to dried-out skin if replenishment of oil from the bulk pack fails to keep pace.
- Excessive *age* of grease pack without replacement.
- *Instability* of grease. Some greases spontaneously bleed oil under gravity; others do so in vibratory environment.

Evaporation of oil is enhanced by these effects:

- *Volatile* components in the oil.
- Elevated *temperature* over extended time.
- *Vacuum* environment.

Contamination by fine particles may increase the volume of solid matter in the grease, thus reducing the percentage of oil. This may lead to both the appearance and performance of dried out grease, even though no oil is lost.

18.2.11.1.5 Effects of Dried-out Grease

Dried out grease is often the first symptom of the generic grease failure processes described under Section 18.2.3.

18.2.11.2 Discolored Grease — Failure Code: 12.6.2

18.2.11.2.1 Definition

Grease is discolored if its color differs from that of the unused grease.

18.2.11.2.2 Failure Process

Grease is a complex system and many causes of discoloration affect it, among which are the following:

- Change in *oil content.*
- *Water* ingestion (at low levels).
- Solid *contamination* by fine particles.
- *Chemical change* in oil or thickener.

In replenishing or replacing the grease supply in the machine, inadvertent selection of the *wrong grease* may occur.

The *admixture* of grease of a different type to an existing pack may create a blend of unexpected properties. If the classes are *incompatible,* a chemical or physical reaction may occur between base oils or thickeners, producing an unserviceable grease.

The *replacement* of the grease pack with one of different specification may produce any of the failure modes herein listed.

18.2.11.2.3 Distinctive Appearance

Chemically *decomposed* grease may differ in color or translucency from unused grease in virtually any way (including none). Comparison with unused grease and knowledge of the appearance of decomposition (oxidation) products of the grease in use, are necessary for diagnosis.

A common discoloration in greases is *darkening,* or dulling of the (artificial) color added to unused grease.

Grease containing small amounts of finely dispersed *water* is milky (see FC 12.4).

Solid *contaminated* grease is often darkened, gray or brown (see FC 12.5).

The *wrong grease* or a mixture of two different greases may produce unexpected appearance (color, consistency, odor, etc.).

18.2.11.2.4 Causes

The causes of grease discoloration are those of the processes of which it is a symptom. Examples follow.

Dried-out grease as described above.

Water contamination. See FC 12.4.

Solid contamination. See FC 12.5.

Chemical changes in oil or thickener brought about by one of the following causes:

- *Overheating.* Many greases oxidize at elevated temperature.

Note: Antioxidant additives are commonly provided to retard grease oxidation.

- *Ingress of reactive chemicals.*
- *Exposure to incompatible metals.* Certain synthetic grease formulations react with yellow metal components.
- *Long-term instability of formulation.* Greases are complex materials. Stability over the extreme periods (at times many years) during which a greased and sealed Hertz contact machine element (bearing) is expected to function may be difficult to achieve, especially if the operating conditions are severe.

Admixture or substitution of *the wrong grease.* A common source of inadvertent mixing is regreasing during service using a grease dispenser charged with the wrong grease.

18.2.11.2.5 Effect of Grease Discoloration

Discoloration is used as a warning symptom for grease failure by contamination, chemical decomposition or oil loss.

18.2.12 Electric Current Damage to Grease — Failure Code: 12.7

18.2.12.1 Definition

Electric current damage to grease is defined as the damage to grease in a Hertzian contact caused by the passage of electric current (spark).

18.2.12.2 Nomenclature

Alternative designations to electric current damage are given in the Nomenclature to FC 00.21.

18.2.12.3 Failure Process

Passage of electric current between the surfaces of a grease-lubricated Hertzian contact (see FC 00.21) produces chemical damage to the grease, similar in nature to that caused by severe overheating. Because a spark affects only a small quantity of grease at a time, electric current damage to grease tends to be localized. Small volumes of severely damaged grease are found in undamaged bulk grease, where they are eventually dispersed by movement within the grease pack.

Note: Grease damage from overheating by other causes may be generalized, if the temperature of an entire machine element becomes excessive; it may be localized if it is due to galling event.

18.2.12.4 Distinctive Appearance

Localized volumes of discolored (FC 12.6) or carbonized (FC 12.5) grease dispersed in the grease pack near the contact path.

Electric current damage to contact components (FC 00.21) is expected to be observed along with the grease damage.

18.2.12.5 Causes

High local temperatures caused by passage of current (spark). Possible electrolytic effects in some greases.

18.2.12.6 Effects of Electric Current Damage to Grease

The effects are the same as for decomposed (FC 12.6) or carbonized (FC 12.5) grease.

18.3 Failure of Other Lubricants — Failure Code: 13

18.3.1 Definition

All lubricants not defined as oil or grease are included in the definition of 'other lubricants'. They include the classes listed below.

1. Solid lubricants:
   - Lubricant *coatings.*
   - Lubricant *compounds,* including,
     solid compounds and
     hard organic gels which contain entrapped oil.
   - *Sacrificial* components with lubricating ability.
   - *Composites* of which one element is a lubricant.
   - *Powder* and *smoke* lubricants.
2. *Vapor phase lubricants* which deposit lubricating layers in situ.
3. *Liquids* other than organic oils (water, cryo-fluids, process fluids).

This section covers the failures of these numerous lubricant classes.

18.3.2 Nomenclature

Due to the multitude of "other" lubricant types, many descriptive terms are used for their failure. For *solid lubricant* compacts, including the hard gels, failure modes such as fracture, cracking, wear, and melting are recognized. Powder, vapor and cryo-fluid lubricants require unique terminology depending on their specific type.

18.3.3 Failure Process

18.3.3.1 Failure of Solid Compacts, Coatings, or Sacrificial Components

Failure of solid lubricant compacts or coatings may occur by many modes, such as:

1. Cracking, fracture or separation.
2. Wear.
3. Chemical decomposition of the solid lubricant.
4. Inability of the lubricant to provide required lubrication, due to one of the following causes:
   - Excessive load or speed.
   - Off-specification operating temperature.
   - Contamination.
   - Dimensional change of lubricant compact.

18.3.3.2 Failure of Vapor Phase Lubricants

Vapor phase lubricants function by interacting with the lubricated surfaces in a way that creates a continuously replenished layer of lubricating solid or liquid. This lubrication method can operate by two distinct processes:

(a) *Vapor phase deposition* where the vapor reacts with the lubricated surface to form a solid deposit layer.

(b) *Vapor phase condensation* where a liquid lubricant film condenses from the vapor on the lubricated surface.

Corresponding to these processes, vapor phase lubrication may fail by the following modes:

1. The lubricating vapor does not reach the working surfaces at a sufficient rate. This may result in failure of either process (a) or (b).
2. The reaction with the lubricated surface required in process (a) fails to produce the required lubricating layer at the required rate or with the required properties.
3. Interference by an external agent, such as excess heat, solid, liquid or gaseous contaminant obstructs creation or functioning of the solid lubricating layer (a) or liquid film (b).
4. The operating conditions are too severe for the lubricating layer (a) or film (b) to prevent failure.

If any of these lubrication failures occurs, the lubricated surfaces may undergo one or more of the types of damage listed under "*Contact lubrication failure*" in 18.1.3. Mild wear of the contact surface (FC 00.12.3.2), surface distress (FC 00.17.1) or galling (FC 00.13.2) are likely on the contact surfaces, as is separator wear (FC 01.13), galling (FC 01.14) or fracture (FC 01.11.2). Heat imbalance failure of the bearing (FC 00.19) may occur.

18.3.3.3 Failure of Lubricant Types Not Listed Above

Failures of lubricant types not listed above (powder, gas, cryo-fluid, or transfer films) are dependent on the specific type and mode of functioning of these lubricants.

18.3.4 Distinctive Appearance

Distinctive appearance of the failures is described on the individual Plates.

18.3.5 Causes

Causes of the failures are described on the individual Plates.

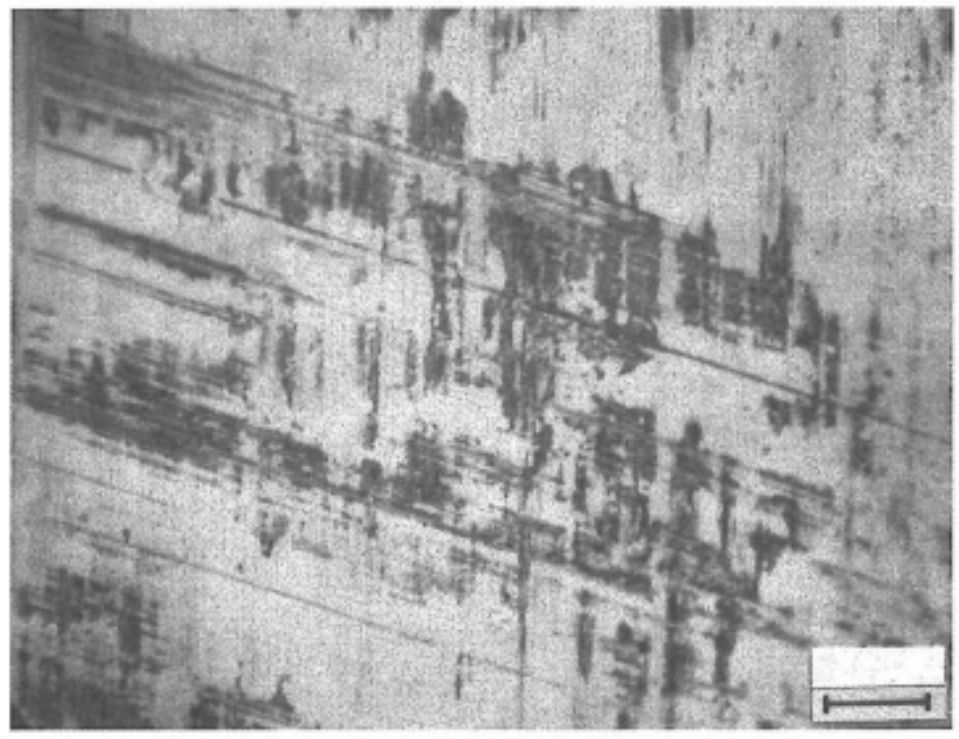
18.3.6 Effects of Non-oil, Non-grease Lubricant Failure

Effects of the failures are described on the individual Plates.

Cross-Index of Secondary Failure Codes

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PLATES



DATA

Plate No: 18.1
Archive No: 006-15
Image type: light microgram
Scalebar = 100 μm (micros: ±20%, others: +100%, −50%)
Component: 0 (solid lube film); G, run
Speed:
Load:
Lubrication: mineral oil based gear oil, ? °C
Failure Code 1: 11.1 Friction polymer, oil lubrication
Failure Code 2: 00.12.3.2.2 Scratch marks, kinematic wear marks in rolling surface
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: A gear tooth operated in oil with an anti-wear additive which forms visible patchy surface deposits. Scratchmarks pass through the deposit patches. The film persists in some scratches, and metal is exposed elsewhere. The gear is operable; the patchiness of the deposit may limit the ability of the additive to provide uniform anti-wear action.
Image Description: The gray background is gear surface material, showing N–S running finishing lines. Patches of black deposit film are oriented along these finishing lines. NW–SE running sharp scratchmarks (mostly black) are due to wear. The deposit is interrupted by the scratches. The black film may be pressed into the scratch while worn away outside; elsewhere the scratch has removed the film, forming a gray line on black background.
Suspected Causes: "Anti-wear" additives of many compositions are used in lubricating contact surfaces. Such additives may be helpful in running-in, and in mitigating the consequences of sliding in the contact, such as in gears. Most additives do not form films visible under low magnification, but some (such as those containing graphite or molybdenum disulfide) may. Incompleteness of protective films exposes the surfaces to wear or galling.

DATA

Plate No: 18.2
Archive No: 103-004&005
Image type: a, b: color microgram [SEE IMAGE IN APPENDIX.]
Scalebar = a,b: 40 μm (micros: ±20%, others: +100%, −50%)
Component: ACBB; OR, run
Speed:
Load:
Lubrication: synthetic hydrocarbon impregnated separated, 25°C
Failure Code 1: 11.1 Friction polymer, oil lubrication
Failure Code 2: 00.17.1.2 Microspalling (advanced surface distress)
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: (a): Friction polymer formation out of the thin oil layer deposited at mounting on the ball paths of a separator-less ACBB. There is no replenishment of oil. In 'parched' EHD lubrication, the film progressively thins. The friction polymer formation rate increases rapidly with decreasing EHD film. No surface damage has occurred yet. (b): Similar events occurred as in (a), but all fluid is lost, and surface distress started. In high speed BB, (a) can change to (b) very rapidly.
Image Description: (a): Micrographic view on OR ball groove; contact track and adjacent bands are in focus. Crossing the track from image E to W: (1) Narrow multicolored band (interference colors) of friction polymer, (2) metallic color in contact track, (3) wide multicolored band of friction polymer. (b): Image as in (a): (1) Contact band is gray with black microspall craters; (2) uniform darker gray friction polymer band is to the W; (3) thinner band, out of focus, is to the E.
Suspected Causes: Lubricant polymerization occurs gradually under contact stresses, and accelerates greatly when EHD film becomes very thin, causing very high film shearing rates. Friction polymer is swept out of contact by ball spin and deposited in the adjacent band (one side is favored by spin direction). Further EHD film thinning causes surface distress.

DATA

Plate No: 18.3
Archive No: 006-39&40
Image type: a: light macro, b: light microgram
Scalebar = a: 20, b: 12 mm (micros: ±20%, others: +100%, −50%)
Component: 0; lubricant contaminant from TRB, run
Speed:
Load:
Lubrication: mineral oil, ? °C
Failure Code 1: 11.3.02 Severe oil contamination
Failure Code 2: 11.5 Carbonized oil deposit
Failure Code 3: 11.3.3 Abrasive contaminant in oil
Failure Code 4: 11.3.1 Steel contaminant in oil

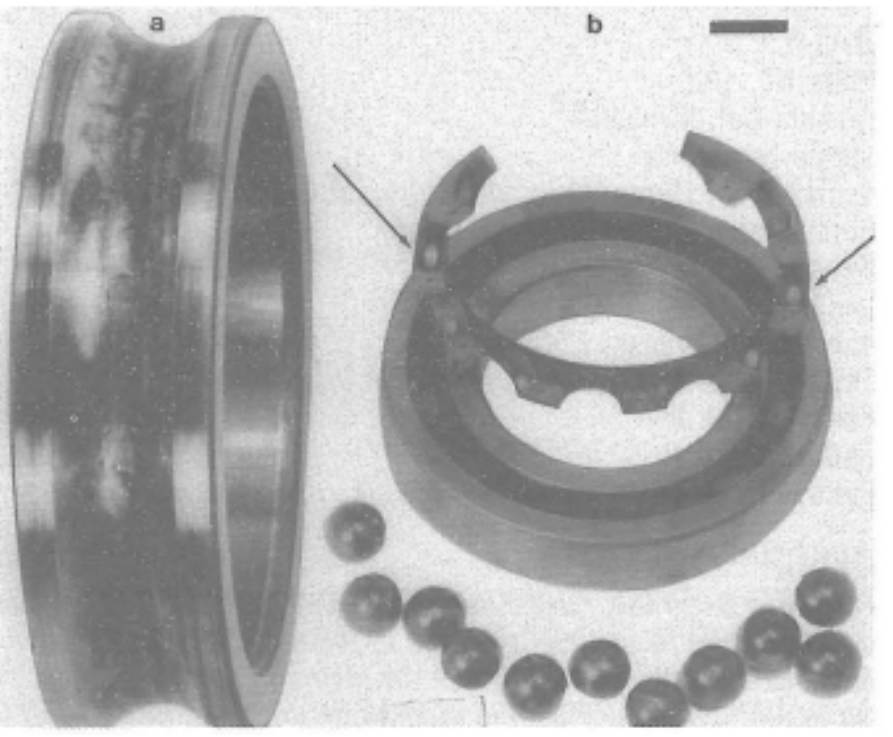
DESCRIPTIONS

a b

Failure Description: Filtrate is shown from ultrasonic cleaning solvent used on a TRB. Black flakes are visible (possibly carbonized lubricant), some iron and other metal and abrasives were identified. Contamination of this magnitude causes denting and may cause premature wear.
Image Description: (a): Black flakes and powder contaminant of TRB collected from ultrasonic cleaning solvent used in examination is shown on gray background. White patches are light reflections. (b): Same debris is shown magnified. Black flakes appear to be detached carbonized oil deposits. The mottled gray mass at image NW is some other contaminant, not identifiable from this image.
Suspected Causes: Carbonized oil indicates high temperature at some point in the lubricated chamber (not necessarily in this bearing). Iron-containing particles found are probably wear. Extraneous abrasive contamination has gained access to the chamber.

DATA

Plate No: 18.4
Archive No: 087-040
Image type: view
Scalebar = a: 20, b: 10 mm (micros: ±20%, others: +100%, −50%)
Component: ACBB; a: IR; b: assembly & B & G (separator), run
Speed: 700 KdN
Load:
Lubrication: oil, ? °C
Failure Code 1: 11.5 Carbonized oil deposite
Failure Code 2: 00.19.2.1 Hot plastic flow without welding (rollout)
Failure Code 3: 00.18.3 brinnelling
Failure Code 4: 01.11.2 Separator fracture, cracking



DESCRIPTIONS

Failure Description: Visible are heat imbalance, oil carbonization, battered and brinnelled IR ball path and balls, fractured separator, separator wear (FC 01.13.1.2); all from observed misaligned mounting and operation at high speed and acceleration. This is a gross failure.
Image Description: (a): IR is viewed on OD. There is an irregular circumferential black band in the ball path bottom. The ball path is plastically deformed (battered). brinnell marks, at ball spacing, arise from bearing seizure. (b): Image N: broken separator half (machined metal) shows wear in the pockets (arrows). Next S: an assembled bearing with the separator half removed. Far S: balls, with carbonized black deposits and plastic deformation.
Suspected Causes: Observed mounting misalignment caused severe moment loading of the bearing, resulting in high separator forces, wear and fracture. The bearing overheated and the oil carbonized. Eventually, bearing seizure, brinnelling and plastic flow resulted.

DATA

Plate No: 18.5
Archive No: 027-129&130
Image type: a, b: color view [SEE IMAGE IN APPENDIX.]
Scalebar = a, b: 20 mm (micros: ±20%, others: +100%, −50%)
Component: 0; grease & DGBB, unrun
Speed:
Load:
Lubrication: mineral oil based grease
Failure Code 1: 12.00 Grease, as-manufactured
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -
See also PLATES: 18.4 and 18.15

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Samples of as-manufactured greases: (a) in container, (b) in container and charged into DGBB. Many other original grease colors are made; color is no indication of composition. Color and consistency (stiffness) samples of as-manufactured grease are required for comparative evaluation of grease packs modified by service. These are not failures. See PLATES 18.14 and 18.15 for comparison with used grease.
Image Description: (a): Three brand-name greases are packed into shallow containers as color samples. These three greases are equivalent in satisfying a specific user standard. The color of grease charged into a bearing may differ from bulk, due to thin layer, dark background, etc.
Suspected Causes: This Plate illustrates the color baseline needed for grease appearance evaluation. Each grease used requires its own baseline. The quantity of the grease charge must be determined by weighing. The condition of the grease pack after running differs from as-charged, due to channeling, slumping, liquefaction, discoloration, water, solids or carbonization. Color, consistency and pack condition baselines are desirable.

DATA
Plate No: 18.6
Archive No: 087-030
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: 0 (grease) & TRB, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 12.02 Grease pack excessive
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS
Failure Description: Grease was pumped through a TRB from an excessive original grease pack and appeared as a bead at the *small* flange side. This illustrates the churning (working) of an excessive grease pack as it is forced through the moving parts of the bearing. Unless there is open space at the small flange side of this bearing, the grease will be forced back into the moving parts, will liquefy and be lost or fail.
Image Description: TRB viewed on *small* flange sideface. Light colored grease appears in beads around the IR flange OD; most heavily in the SW and NW image quadrants.
Suspected Causes: Bearings may be overgreased at installation or when regreasing a housing equipped with a regreasing fixture. Grease must have space to be channeled out of the volume swept out by the moving bearing parts to form closely conforming walls at each side and supply lubricant by pickup from these walls. Excess grease is repeatedly pumped through the bearing until it liquefies and/or the bearing overheats.

DATA
Plate No: 18.7
Archive No: 064-001
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 200 mm (micros: ±20%, others: +100%, −50%)
Component: 0 (grease) & C (seal), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 12.02 Grease pack excessive
Failure Code 2: 25.1 Labyrinth seal failure
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS
Failure Description: Grease extruded from the regreasable external labyrinth seal on a bearing pillow block. The seal is likely to have been overgreased. This is not a failure, unless grease loss is indicative of overheating in the labyrinth seal grease pack, with resulting liquefaction and runout of the grease pack.
Image Description: At image W is a split pillowblock. An external labyrinth seal housing is mounted on the E face of the block; it is followed eastward by an exposed shaft and then a gearbox. Just S of the seal housing centerline is a regreasing nipple. A bead of extruded gray grease runs along the E contour of the seal housing, on the shaft.
Suspected Causes: Labyrinth seals are generally grease-filled to aid in contaminant exclusion. A regreasing nipple may be provided to replenish the grease charge. If excess grease is pumped in, it will appear as a bead between the seal and the shaft. Overgreasing is usual, to assure purging of contaminated grease from a seal. If fresh grease is purged in operation, then overheating and liquefaction of the grease in the seal may have occurred and sealing is lost.

DATA
Plate No: 18.8
Archive No: 093-k120&k138
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = a, b: 20 mm (micros: ±20%, others: +100%, −50%)
Component: 0 (grease) & SRB (mounted), run
Speed:
Load:
Lubrication: mineral oil based grease, ? °C
Failure Code 1: 12.1 Softened or liquefied grease
Failure Code 2: 12.01 Grease pack low
Failure Code 3: 12.00 Grease, as-manufactured
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS
Failure Description: Spherical roller bearing grease pack after removal of housing end-cover. (a): Normal pack, grease essentially as manufactured. (b): Depleted pack of liquefied grease (the rest of the pack has run out). (b) is likely to fail imminently due to loss of lubrication.
Image Description: (a): Shaft with bearing seat extends from image W into a SRB. The SRB sideface is covered by brick-red, smooth, semi-solid grease. The bearing is in a housing (gray sideface with mounting hole at image E). (b): SRB in housing, viewed on the sideface. The shaft has been removed. The IR bore is at image center. Roller- and ring-sidefaces are thinly covered by brick-red grease. All grease between the rollers has run out. The grease is a thick liquid.
Suspected Causes: Grease liquefies if (1) it is severely overheated and/or (2) worked (kneaded) beyond the tolerance of the grease type. An overheated grease pack softens and slumps into the bearing where it is severely worked by the separator and rollers, causing further liquefaction. Liquefied grease is often expelled from the housing past seals or fit surfaces.

DATA
Plate No: 18.9
Archive No: 093-k135
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 30 mm (micros: +20%, others: +100%, −50%)
Component: 0 (grease) & M (housing), run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 12.1 Softened or liquefied grease
Failure Code 2: 12.02 Grease pack excessive
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS
Failure Description: A flow of grease is extruded past the housing/endcap fit interface and is deposited on the outside face of the endcap. The grease pack is likely to have been excessive, causing heavy pumping action, liquefaction of grease and extrusion through the encap fit gap. The bearing lubrication is impaired, and early failure through heat imbalance is likely.
Image Description: The circular blue/gray housing endcap is held with four hex-head screws. A flip-lid junction box is attached at the endcap center; a coil spring is at image N. A rippled run of dark gray-green grease extends from N endcap edge to the junction box. The grease flow emanates from the endcap fit interface at image N.
Suspected Causes: Over-lubrication of bearing chambers (especially those with relubrication fittings) is a common failure cause. An excessive grease pack cannot be channeled outside the volume swept out by the moving bearing parts and therefore is continuously churned. It progressively liquefies and is then lost through gaps in the housing assembly.

DATA

Plate No: 18.10
Archive No: 093-k134
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: 0 (grease) & SRB, run
Speed:
Load:
Lubrication: mineral oil based grease, ? °C
Failure Code 1: 12.1 Softened or liquefied grease
Failure Code 2: 12.5.3 Abrasive contaminant in grease
Failure Code 3: 12.5.2 Non-steel metal contaminant in grease
Failure Code 4: 12.5.1 Steel contaminant in grease

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Grease was imparted a gray color by solid contaminants. A thin layer of liquefied grease is in the bearing, with the remaining pack lost. Abrasive contaminant has caused wear, creating non-steel metal particles from the separator and/or steel particles from rolling elements. These were mixed into the grease. The bearing is likely to fail early due to (1) loss of lubrication as a result of grease loss, and (2) wear with possible separator fracture.
Image Description: Oblique view of SRB on sideface, in housing and on shaft. Bearing-retaining shaft endplate is removed. Thin smears of grease cover parts of the roller endfaces and intervening spaces. Much of the grease pack was observed to be lost. The remaining grease is semi-liquid, medium gray and gritty to the fingertip test. A sprinkling of reddish abrasive dust not yet mixed into the grease is at image SE on the housing surface. Isolated particles are on the bearing sideface.
Suspected Causes: This bearing operated in an abrasive dust laden environment (shaker screen), which penetrated past the seal, was mixed with the grease, and abraded the sliding (and possibly the rolling) bearing surfaces, creating further contamination. Hot running has resulted from the impaired lubrication. Wear is likely on the separator, and possibly on the rolling elements. Abrasive particles and wear debris from the separator (non-steel) and possibly from the rolling elements (steel) are in the grease.

DATA

Plate No: 18.11
Archive No: 027-215&219&218
Image type: a, b, c: color view [SEE IMAGE IN APPENDIX.]
Scalebar = a, b, c: 12 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; IR, run
Speed:
Load:
Lubrication: mineral oil based grease, ? °C
Failure Code 1: 12.3 Friction polymer, grease lubrication
Failure Code 2: 00.15.1.2.0.2 Normal fretting, accurate radial fit, radial load
Failure Code 3: 00.12.3.2.1.2 Wear track off-center in contact
Failure Code 4: 00.12.3.2.1.1 Wear track centered in contact

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Friction polymer formed in contact path of three IRs. (a): Heavy thrust load; (b): moderate load with thrust component; (c): light radial load. Incidental fretting has occurred in the bore of (a). Wear track location, as indicated by friction polymer, is off-center (due to thrust load) in (a) and (b), and is essentially centered (from radial load) in (c). These are not failures, but (a) was very heavily loaded and ran at elevated temperature.
Image Description: Multicolored (brown, gray, purple) friction polymer coatings are visible in circular bands around the IR, indicating the contact path. (a): Half of the groove, lying to image W, is covered with friction polymer. Fretting is visible in the bore. (b): One wide band of friction polymer is visible off center, toward image W. (c): A narrow band of friction polymer is near groove center, flanked by two thin brown lines.
Suspected Causes: Friction polymer develops in Hertz contacts by decomposition of the lubricant to form an adherent, hard coating on the steel surface. It is typically yellow, brown, gray or purple. High temperature, low EHD film thickness and (some) sliding contribute. Higher sliding may wear the polymer off. Friction polymer does not dissolve when dilute hydrochloric acid etchant is briefly applied (temper color does).

DATA

Plate No: 18.12
Archive No: 027-173&174
Image type: a, b: color view [SEE IMAGE IN APPENDIX.]
Scalebar = a, b: 5 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; B, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 12.3 Friction polymer, grease lubrication
Failure Code 2: 00.19.4.1 Friction polymer on rolling track
Failure Code 3: -
Failure Code 4: -
See also PLATES: 10.3, 13.16 and 15.38

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Multicolored lines of a hard organic coating on the ball surfaces have formed as a result of grease polymerization under contact stresses at relatively high temperature. Friction polymer of this magnitude is not a failure but serves as a warning of high temperature in the bearing. See similar friction polymer coatings on Plates 10.3, 13.16 and 15.38.
Image Description: (a): Three balls are at image NW, SW and E. The NW and E balls show multiple families of coaxial circular lines of hard brown, yellow and bluish-black coating; the SW ball shows one family of lines over the entire surface. Steel-colored lines show where the polymer was worn off. (b): Three balls are at W, NE and SE. Finer, brown friction polymer line families appear on each ball. The irregular black dots on all balls are imaging artifacts.
Suspected Causes: Formation of adhering friction polymer on rolling contact surfaces, from mineral oil (and some other organic) lubricants, indicates relatively severe contact conditions, probably with some sliding. The polymer coating is distinguishable from temper color by the momentary application of diluted hydrochloric acid etchant, which removes temper color, but *not* friction polymer.

DATA

Plate No: 18.13
Archive No: 027-204&205&206
Image type: color macro [SEE IMAGE IN APPENDIX.]
Scalebar = a, b, c: 5 mm (micros: ±20%, others: +100%, −50%)
Component: 0; grease, run
Speed:
Load:
Lubrication: mineral oil based grease, ? °C
Failure Code 1: 12.5 Solid contaminant in grease
Failure Code 2: 12.2 Carbonized grease
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Specimens of used grease are spread on a glass slide for visual examination. (a): Shows a small volume of black contaminant particles, and a possible darkening of the grease. (b): Shows severe blackening of the grease (carbonized grease), and particulate contaminant. (c): Distinct dark contaminant particles are visible in otherwise fresh-appearing grease. Color evaluation of grease requires fresh-grease baseline.
Image Description: (a): Unevenly spread brownish grease smear on glass slide. In NW image quadrant, the color is darker brown, as if grease were decomposed. Black powder and granules mixed into the grease represent solid contaminant. (b): As (a), but much heavier black (carbonized) mass is in the grease. (c): Reddish, fibrous grease smear, with a few isolated small black contaminant particles. Fingertip test may feel gritty in (a), more so in (b). No metallic particles are seen.
Suspected Causes: External contaminants and/or bearing wear may produce particulate contamination, which, if very fine, darkens the grease. Discoloration may be due to high temperature, which, if severe, may lead to carbonization.

Failure Code: 12.5.02
Failure Code: 12.6.2

DATA

Plate No: 18.14
Archive No: 027-132
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 8 mm (micros: ±20%, others: +100%, −50%)
Component: 0 (grease); DGBB, run
Speed:
Load:
Lubrication: mineral oil based grease, ? °C
Failure Code 1: 12.5.02 Severe grease contamination
Failure Code 2: 12.5.1 Steel contaminant in grease
Failure Code 3: -
Failure Code 4: -
See also PLATES: 18.5, 18.13 and 18.15

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Darkened (discolored) contaminated grease is in DGBB originally charged with grease No 1. of Plate 18.5 (a). Color turned from red to gray-brown, smooth pasty consistency to gritty. Steel particles are observed in the grease specimen. Separator wear is suspected. The bearing is likely to fail from inadequate lubrication.
Image Description: In a DGBB, grease adheres to the OR land and the separator. The part of the pack located at the OR appears smooth but gray, the part on the separator is gritty and gray. Fingertip feel of a grease specimen is gritty. Steel particles may be visible in the grease on a glass slide, with a magnifier. Upon separator disassembly, wear may be visible.
Suspected Causes: Separator wear, due to geometry error, strongly misaligned load or external contamination, produces fine steel particles which are mixed into the grease. They discolor it and render it gritty. Heavily contaminated grease acts as an abrasive in addition to (or in lieu of) being a lubricant. See Plate 18.5 for fresh grease, and Plates 18.13 and 18.15 for decomposed grease.

DATA

Plate No: 18.15
Archive No: 027-131
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 10 mm (micros: +20%, others: +100%, −50%)
Component: 0 (grease); DGBB, run
Speed:
Load:
Lubrication: mineral oil based grease, ? °C
Failure Code 1: 12.6.2 Grease discolored
Failure Code 2: 12.6.1 Grease dried out
Failure Code 3: -
Failure Code 4: -
See also PLATES: 18.5, 18.13 and 18.14

[See Image in Appendix]

DESCRIPTIONS

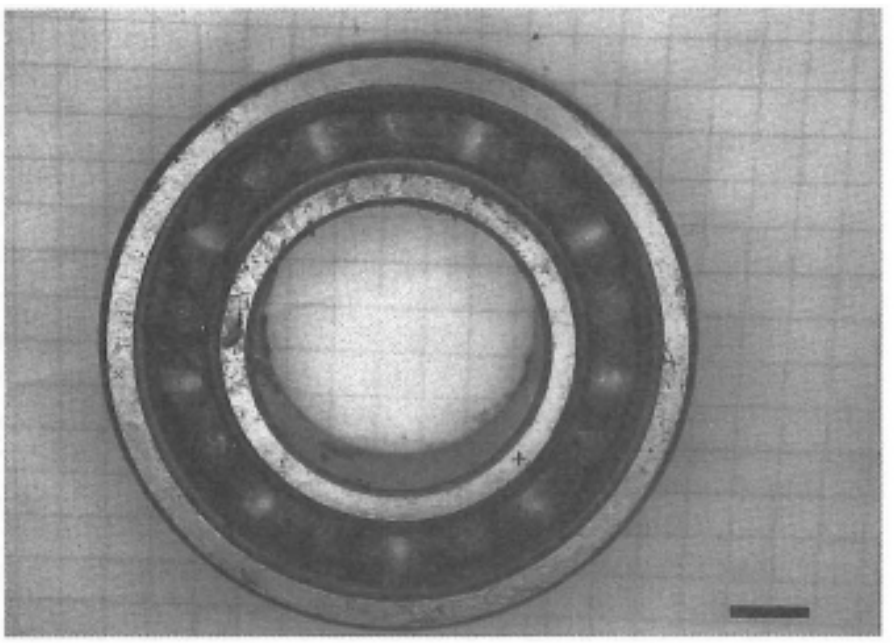
Failure Description: Darkened (discolored) and dried grease in a DGBB originally charged with grease No 1. of Plate 18.5 (a). Color turned from red to reddish-brown, smooth pasty consistency to granular. Remaining grease adheres to the separator. Other parts of the grease charge may have been lost, either in service or at seal removal. The bearing is likely to fail early from inadequate lubrication due to extensive oil loss from dried grease.
Image Description: On the separator of a DGBB, globs of grease adhere to recesses, as between the pocket and the riveted area. Grease adheres to the OR land. The grease is much darkened and appears granular. Fingertip examination of a specimen can be used to verify granularity. Unless substantial grease adheres to the removed seal, the pack appears much depleted.
Suspected Causes: Operation at elevated temperature is the most common cause of grease decomposition and drying out. Undercharging (insufficient grease) or overcharging (grease pack liquefies and runs out of the bearing) are also possible causes. Contamination may simulate grease decomposition by changing the grease color. See Plate 18.5 for fresh grease, and Plates 18.13 and 18.14 for contaminated grease.

DATA

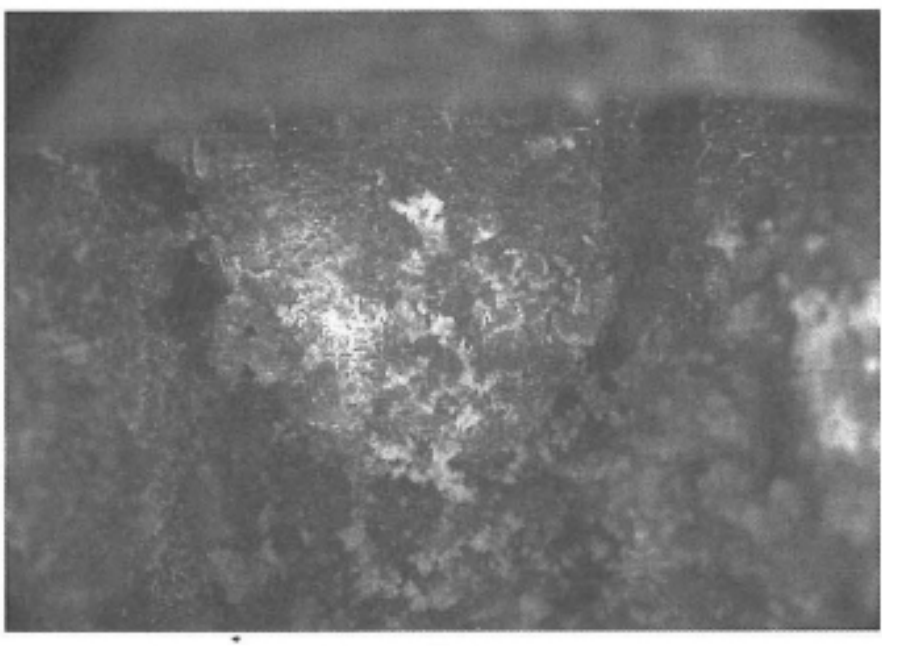
Plate No: 18.16
Archive No: 087-202 through-205
Image type: a, c: view, b, d: light microgram
Scalebar = a, c: 10, b, d: 1 mm
(micros: ±20%, others: +100%, −50%)
Component: 0 (grease) & DGBB, run
Speed:
Load:
Lubrication: grease, ? °C
Failure Code 1: 12.7 Electric current damage to grease
Failure Code 2: 12.6.1 Grease dried out
Failure Code 3: 12.6.2 Grease discolored
Failure Code 4: -

DESCRIPTIONS

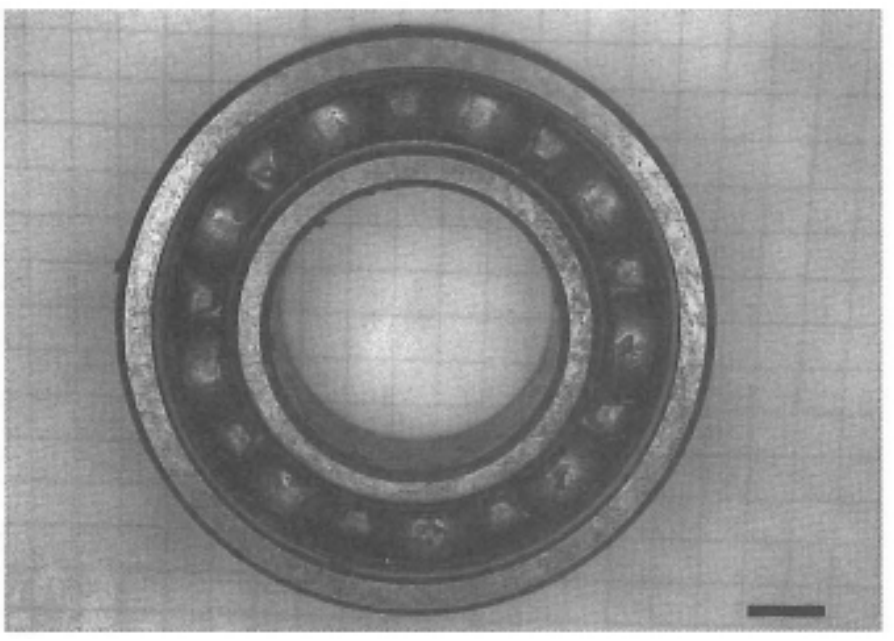
Failure Description: Electric current passage through a greased ball bearing resulted in decomposition, color and consistency change of the grease. Electric erosion may inject contaminants into the grease, but direct damage by current passage through the grease occurs earlier. The grease is deteriorated. The bearing is likely to fail through lubrication failure and/or erosion cratering.
Image Description: (a): Dry-appearing granular grease adheres to the separator of a DGBB with a notch-and-prong fastened ribbon separator. (c): Same configuration; blackened thin grease layer. (b): Microgram of separator prong in (a) (half-oval, light color area near image center) and surrounding separator surface. Grease adheres in dry granules of light and gray color. Dark background is the separator. (d): Microgram of prong in (c), grease adheres in thin smears of gray color.
Suspected Causes: Electric current passage through a bearing can occur when an excessive voltage difference arises across the rolling contacts (often in electrical machinery). The field gradient through the thin lubricant films is very high, sparking results, and the grease decomposes. Damage to metal surfaces (electric erosion) is the end result.



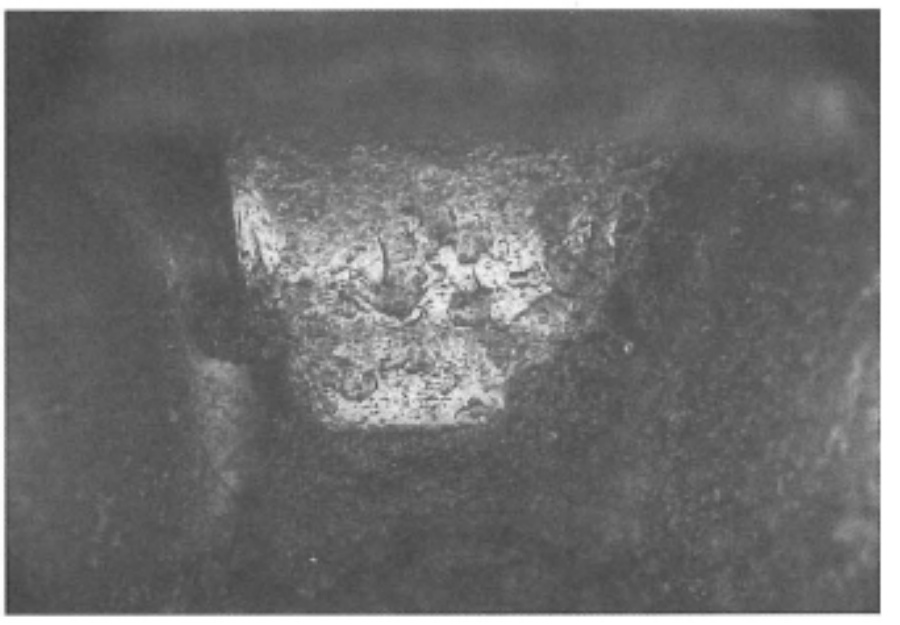
a



b



c



d

DATA

Plate No: 18.17
Archive No: 123-001
Image type: light microgram
Scalebar = 0.92, 0.51 mm marks (micros: ±20%, others: +100%, −50%)
Component: 0, RC test rig rod, T15 tool steel, run against T15 balls
Speed:
Load: 3.34 GPa
Lubrication: Tertiary butyl phenyl phosphate vapor, 371°C
Failure Code 1: 13.1.1 Chemical surface attack by vapor phase lubricant
Failure Code 2: 00.20 Corrosion
Failure Code 3: 00.20.1.3 Contact corrosion
Failure Code 4: 00.12.3.2.1 Smooth rolling surface wear (finish marks removed)
See also PLATE: 18.18

DESCRIPTIONS

Failure Description: The tool steel RC test rig rod was run at high temperature under vapor phase lubrication by an organic phosphate (TBPP) which reacts chemically (corrosively) with the tool steel surface at the high temperature and stress conditions of the test. Under the high stress the contact path widened from 0.51 mm to 0.92 mm during testing, through wear and rolldown. The final contact path was measured to have about 8 mm radius (compared to a ball radius of ~6.2 mm). Two bands of dark corroded deposit have formed along the contact path. The corroded bands appear to follow the pure rolling (Heathcote) bands in the contact path, where sliding does not wear them away. Additionally, one contact corrosion mark has formed while the configuration was stationary.

Image Description: The axis of the test rod runs E–W, the contact track N–S. Initial width of 2ao = 0.51 mm and final width of 2af = 0.92 mm are marked. The contact path is concave after running, reflecting light in the central zone but not near the (thin light) edges of the track. Dark, irregularly textured corrosion bands about 0.12 mm wide run N–S about 1/3 image width from the E and W edges. Some corrosion lines extend outward from the W band. Except where corroded, the track appears polished. At the N–S midpoint of the image, a finger-shaped contact corrosion patch is visible in dark outline where a ball rested when the configuration was stationary.

Suspected Causes: Vapor phase deposition provides lubrication to the contact surface by chemical reaction between lubricant vapor and metal surface at elevated operating temperatures (usually in excess of those at which the liquid phase of the lubricant is functional). The resulting lubrication is essentially by sacrificial dry film. The contact surfaces undergo mild wear, as the sacrificial film wears away. Where sliding is minimal, the film may form faster than it wears off and visible film remains. In regions of higher sliding, the film wears as fast as it forms, resulting in metallic surface. The lubricant used is sufficiently aggressive to form contact corrosion around a stationary ball contact.

$$\frac{2af = 0.92mm}{2ao = 0.51mm}$$

DATA

Plate No: 18.18
Archive No: 123-002&003
Image type: a:, b: SEM
Scalebar = a:, b: 10 μm (micros: +20%, others: +100%, −50%)
Component: 0, RC test rig rod, T15 tool steel, run against T15 balls
Speed:
Load: 3.34 GPa
Lubrication: Tertiary butyl phenyl phosphate vapor, 371°C
Failure Code 1: 13.1.1 Chemical surface attack by vapor phase lubricant
Failure Code 2: 00.20.2 Corrosion pitting
Failure Code 3: 00.05.1 Micro-porosity
Failure Code 4: 00.06 Inclusion
See also PLATE: 18.17

DESCRIPTIONS

Failure Description: Corrosion pits formed in rolling surface as a result of attack by chemically active vapor phase lubricant. A small body of material at A containing higher percentages of the tool steel alloying elements and less iron than the parent steel forms an inclusion intersecting the contact surface (origin uncertain). Possible micro-porosity in steel at B.

Image Description: (a) Metallographic section of rolling track. Straight edge from image NW to SE is edge between rolling surface and section. Area to NE of edge is polished cross section. Finely dispersed round carbides of 1–2 μm diameter typical of tool steel are shown as prominent lighter-gray elements in the section. Metal is medium gray. At A, a wide funnel-shaped darker gray zone about 20 μm wide at the opening extends from the contact surface. Carbides are dispersed in this material. Electron probe analysis showed higher Va, Mo and Cr and much lower Fe than the parent steel. A small, deep, jagged "hole" in the section at B, apparently unconnected to the surface, is (possibly) microporosity. The material to SW of section edge is mounting plastic. (b) Higher magnification section of same track, showing corrosion pitted surface. Unpitted area at extreme image NW. Elsewhere along edge (image center), corrosion pitting has penetrated about 2 μm deep, detaching metal and loosening carbides.

a

b

Suspected Causes: Vapor phase deposition provides lubrication to the contact surface by chemical reaction between lubricant vapor and metal surface at operating temperatures in excess of those at which the liquid phase of the lubricant is operational. The lubricant used is sufficiently aggressive to form corrosion pits in the rolling surface.

DATA

Plate No: 18.19
Archive No: 123-004
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 1 inch = 25.4 mm (micros: +20%, others: +100%, −50%)
Component: DGBB, tool steel, silverplated steel cage; run
Speed: 620 KdN
Load: unknown
Lubrication: Tertiary butyl phenyl phosphate vapor, 288°C
Failure Code 1: 13.1.2 Solid lubricant deposit from vapor phase lubricant
Failure Code 2: 01.14.2 Land guided separator, guide surface galled
Failure Code 3: 01.13.2.2 Land guided separator, guide surface worn, local
Failure Code 4: 01.13.1.2 Separator crossbar worn, both pocket sides
See also PLATE: 18.20

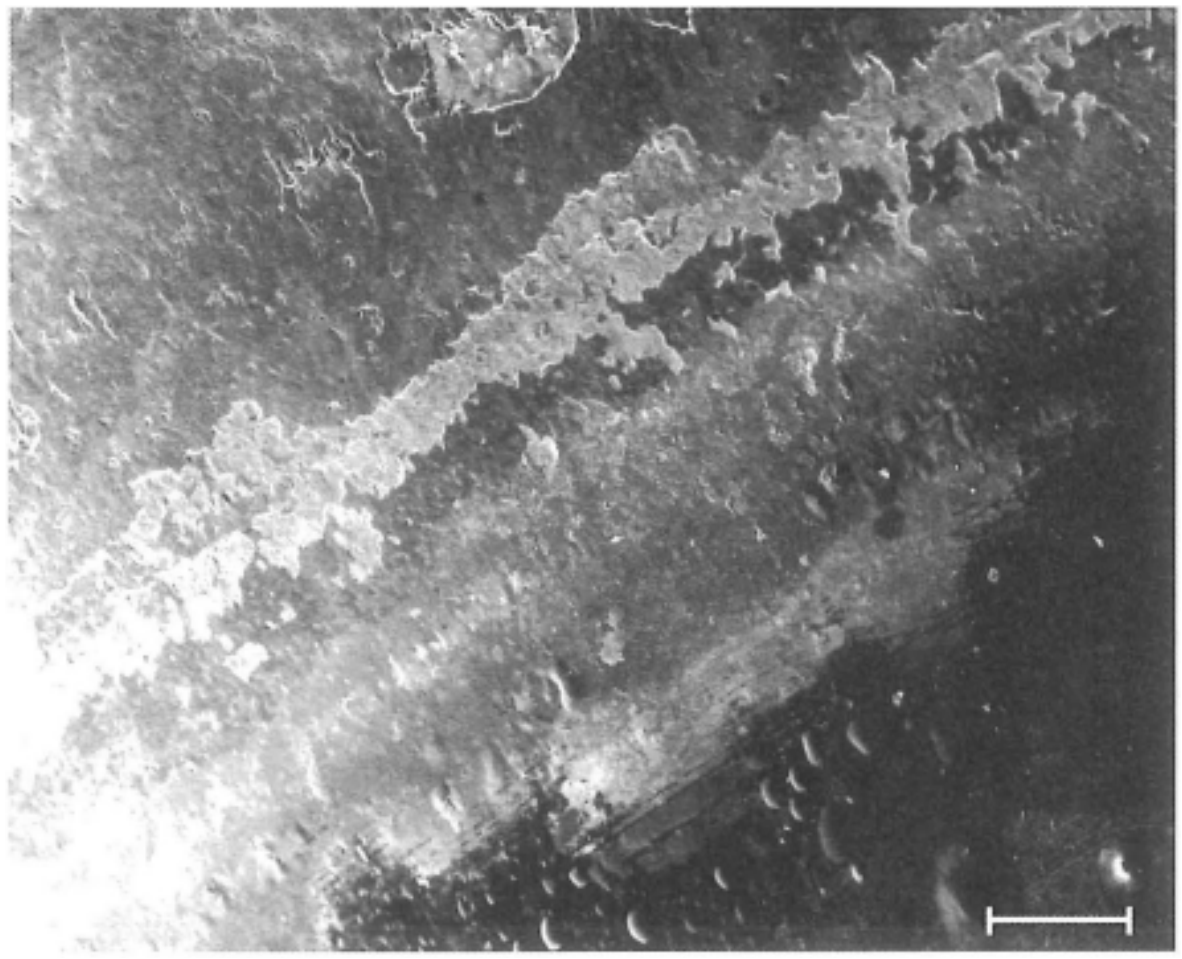
[See Image in Appendix]

DESCRIPTIONS

Failure Description: Test bearing after 1 hour run in aircraft gas turbine engine. Rings and balls covered with solid lubricant deposit generated by vapor phase lubricant supplied as mist. Separator silver plating worn through in pockets and along both rails in contact with OR lands. Some lubricant deposit on cage where steel is exposed, but not on silver. Minor galling of exposed steel. The bearing has not failed, but land guided cage is at risk of galling failure.
Image Description: Disassembled deep-groove ball bearing with one-piece, outerring land guided silver plated steel cage. One ball, both rings and cage shown. Rings and ball surfaces uniformly covered with matte reddish black deposit. The deposit shows burnishing from overrolling in contact tracks. Whitish silver plate on cage worn through to darker steel in pockets and along both rails. "Smeared" appearing lighter galling streaks on darker steel surface of E rail.
Suspected Causes: Vapor phase deposition provides lubrication to the contact surface by chemical reaction between lubricant vapor and metal surface at operating temperatures in excess of those at which the liquid phase of the lubricant is operational. Lubrication occurs by way of the sacrificial surface deposit formed between lubricant and tool steel contact material. At the operating temperature of this test, the lubricant formed a hard, strongly adhering coating on the uncoated rings and balls which tolerates overrolling. The lubrication was effective in the rolling contacts and the bearing operated without functional failure through the test. Note that lubricant does not appear to react with silver plate on cage, and forms no coherent film where cage steel is exposed. Solid lubrication of sliding contacts on separator appears ineffective to prevent wearing off of the silver, and subsequent galling of the steel substrate.

DATA

Plate No: 18.20
Archive No: 123-005
Image type: SEM
Scalebar = 250 μm (micros: ±20%, others: +100%, −50%)
Component: DGBB IR, tool steel, run
Speed: 1 MdN
Load:
Lubrication: Tertiary butyl phenyl phosphate vapor, 480°C
Failure Code 1: 13.1.3 Peeling deposit from vapor phase lubricant
Failure Code 2: 00.12.3.2 Wear in rolling surface
Failure Code 3: -
Failure Code 4: -
See also PLATE: 18.19



DESCRIPTIONS

Failure Description: Test bearing ball path shown after 19 hours of running in aircraft gas turbine engine. Ball groove was initially covered with solid lubricant deposit from vapor phase lubricant supplied as mist. The deposit is flaking off in streaks along the ball track. Rough running and increasing torque occurred shortly before test termination. The bearing is failing from unbalanced formation and wear of solid lubricant deposit at the test temperature. Since the deposit forms by interaction of the lubricant with the surface material, removal of metal is taking place with wear of the deposit.
Image Description: Low-magnification SEM shows IR ball track. Rolling track runs SW–NE. Darker, mottled appearing gray surface is solid lubricant deposit as formed. Bands of lighter gray are zones where the deposit is worn. One uninterrupted light gray band with sharp jagged edges running along the rolling track appears worn down to bare metal. Drop-shaped oval objects in SE corner may be agglomerations of lubricant deposit.
Suspected Causes: Vapor phase deposition provides lubrication to the contact surface by chemical reaction between lubricant vapor and metal surface at high operating temperatures (usually in excess of those at which the liquid phase of the lubricant is functional). Lubrication occurs by way of the sacrificial surface deposit formed between lubricant and tool steel contact material. At the operating temperature of this test, the equilibrium between lubricant deposit formation and wear broke down after 19 hours of running, wear tracks developed and the friction torque underwent a step increase.

MOUNTING COMPONENT FAILURE 19

Failure Code: 20–26

General Description

Neither the definition of mounting components, nor the enumeration of their failures aims for completeness in this Atlas. Many mounting components have functions unrelated to the Hertz contact machine element; many are specialized designs for one machine type. Many failures of these components arise from causes, and have effects, not directly related to the Hertz contact machine element. Detailed information on failures of some general-purpose mounting components such as shafts, is found in [10] and, for gear mounting components, in [9].

19.1 Definition

Mounting components for Hertz contact machine elements include:

- *Fitting components,* having fit interfaces with the Hertz contact machine element. These include, among others: shafts, housings, spacing rings, mounting sleeves, locknuts and lockwashers.
- *Lubrication components,* participating in the lubrication system of the machine elements. These include, among others: external seals and lubricant supply parts.
- For a gear or cam with integral shaft, a *support bearing* is a mounting component.

Failures of *fitting components* fall into four broad classes:

- *Interface failures,* where the fit surface with the Hertz contact machine element fails by wear, galling, fretting, corrosion or nicks.
- *Bulk failures* of cracking, fracture, or permanent deformation.
- *Mounting failures,* where the mounting component is improperly mounted into the machine or the Hertz contact component is improperly mounted in (on) the mounting component.
- *Unrelated failures,* that is, failures unrelated to the function of the part as a mounting component. This is a broad class that may include some failures similar in mode to those listed above.

Failures of *lubrication components* fall into two broad classes:

- *Seal failures,* similar in their effect to those enumerated under FC 02 for integral bearing seals, but comprising a greater variety of failure mechanisms as a result of the greater variety of external seal types.
- *Lubricant supply part failures,* including, among others, defects in lubricant flow control elements, such as oil jet rings, grease valves and oil mist nozzles.

Failures of *support bearings* (if rolling bearings) are covered in the preceding chapters of this Atlas.

19.2 Nomenclature

The designations for failures of mounting components follow those of Hertz contact machine elements where applicable. For failure modes unique to a mounting component, this Atlas does not define nomenclature.

19.3 Failure Process

Due to the multiplicity of component and failure combinations possible for mounting components, only the following brief comments are provided to amplify the list of mounting component failure codes in Chapter 2.

19.3.1 Corresponding Failure Modes

Table 19.1 lists major failure modes and failure codes of mounting components covered in this Atlas for which a corresponding failure mode exists in Hertz contact machine elements.

Any of the mounting component failure modes listed in one block of Table 19.1 corresponds to the Hertz contact machine element failure listed in the same block. Failure coding of mounting sleeves, nuts, lockwashers (FC 24) is insufficiently detailed to tabulate corresponding failure codes. These elements may suffer cracking, fracture, fretting, wear, galling, corrosion and mismounting failures. The corresponding failure codes in Hertz contact machine elements are FC 00.22, FC 00.15, FC 00.12, FC 00.13, FC 00.20 and FC 00.09, in the order listed.

Table 19.1 MOUNTING COMPONENTS. CORRESPONDENCE OF FAILURE CODES.

Mounting component failure code	Mounting component failure designation	Corresponding Hertz element failure code
21.1 22.1	Housing cracked or fractured Shaft cracked or fractured	00.22
21.2 22.2	Housing fretted Shaft fretted	00.15
23.1 21.3 22.3	Spacer, shoulder fretted Housing galled Shaft galled	00.13
21.4 22.4	Housing worn Shaft worn	00.12
21.6 22.5	Housing deformed Shaft deformed	00.23
21.7 21.9 22.6 22.9	Mismounted housing Geometry or assembly defect in housing Mismounted shaft Geometry or assembly defect in shaft	00.09
21.8	Housing corroded	00.20
25	External seal failure	02

19.3.2 Non-corresponding Failure Modes

Mounted Looseness Off-specification (FC 20.03)

Erroneous fit dimensions in shaft or housing, or incorrect tightening of tapered mounting sleeves may result in off-specification mounted radial or axial looseness of bearings. Incorrect spacing of shafts may result in off-specification backlash in gears.

Lubricant Leak from Housing or Covers (FC 21.5)

Imprecise fit, inadequate gasketing, cracks in the housing or covers, etc. may permit lubricant to escape from the chamber.

Seal Failures (FC 25)

Several failure modes are unique to external seals. They differ depending on seal type, as enumerated below.

Labyrinth seals may fail due to misalignment, unintended contact causing rubbing of parts or excessively large gaps. Lack of grease in certain labyrinth seals causes leakage.

Face seals, being complex assemblies, have many unique failure modes: misalignment, warpage of rider, chipping of carbon, leakage of piston ring (if any), fracture of bellows, etc.

Garter lip seals may, in addition to the failures listed in FC 02, fail due to breakage of the garter spring or deformation of the sheet metal casing.

Note: Illustrations of some external lip seal failures may serve to augment the scarce image material available for integral rubbing seals (FC 02).

Failure of Specialized Mounting Components (FC 20)

This Atlas does not cover specialized mounting components, for example, *dampers* for ultra-high speed turbine bearings, *pins* and *bushings* for cam followers or any of the special assembly elements of friction drives.

19.4 Distinctive Appearance

Corresponding failure modes (see Section 19.3.1) of mounting components are similar in appearance to the respective failure modes of Hertz contact machine elements, allowing for the fact that housings and shafts are generally made of different (softer) material and with greater surface roughness than contact components.

In the interface with a hard steel ring, a turned, softer steel shaft is likely to suffer more *wear*, *galling* and *fretting* damage than the hard ring. Conversely it is less likely to *crack*.

Cast iron housings resist *fretting* and *galling* better than steel but *wear* readily.

Aluminum housings *wear* and suffer *plastic rolldown*. Their *thermal expansion* coefficient exceeds that of steel, which may cause loosening of fits.

The appearance of *non-corresponding* failure modes is described in the Plates, to the (limited) extent they are illustrated. Reference to [10] and, for gears, [9], or other literature covering the failed components is required for detail.

19.5 Causes

Many failures of mounting components have causes unrelated to the Hertzian machine element. These are not covered in this Atlas.

The Hertz contact machine element may cause failure in the mounting component by the transmission of forces, heat and relative motion. Details follow.

19.5.1. Fitting Components

Loaded fitting components transmit the forces between contact component and machine and may suffer permanent deformation, cracking or fracture from overload in bending and shear, and (for gear shafts) in torsion.

Fitting components supporting contact components across interfaces may undergo relative motion in the interface and suffer wear, galling or fretting.

Misplaced mounting components (mismounted in assembly or deformed or displaced in service) may unintentionally contact moving parts, causing fouling of a surface, with wear, galling, heat imbalance failure or rubbing cracks.

19.5.2 Lubrication Components

External seals may fail as a result of misalignment of the shaft support bearing, or suffer contamination from debris generated in contact (or guiding) component failure.

Heat imbalance of a contact component may overheat and fail (elastomeric) seal.

Fouling by misplaced contact components may fail a seal or other lubrication component.

19.6 Effects of Mounting Component Failure

Table 19.2 correlates mounting component failures with failure modes resulting from them in the Hertz contact machine elements. Any of the mounting component failure modes listed in one block may cause any of the Hertz contact component failures listed in the same block.

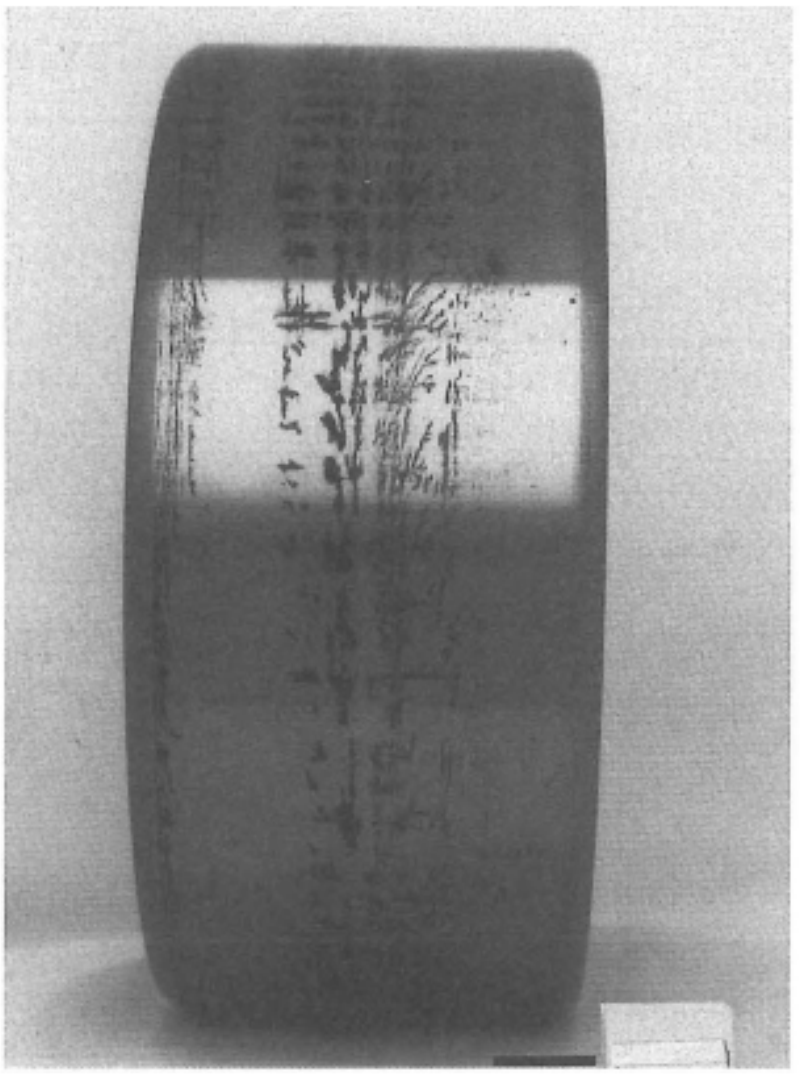
Table 19.2 HERTZ MACHINE ELEMENT FAILURES CAUSED BY FAILURE OF MOUNTING COMPONENTS

Mounting component failure class	Mounting component failure designation	Contact component failure class	Hertz contact machine element failure designation (in order of likelihood)
20	Failure of specialized mounting components		Not covered
20.03	Mounted looseness off-specification	01.1 00.16 00.19	Separator failure Spalling Heat imbalance failure
21.1 22.1	Housing cracked or fractured Shaft cracked or fractured	00.22 00.13 00.16 00.12	Bulk cracking or fracture Galling (fit surface) Spalling Wear (fit surface)
21.2 22.2 23.1	Housing fretted Shaft fretted Spacer, shoulder fretted	00.15 00.12 00.13 00.16 00.22	Fretting (fit surface) Wear (fit surface) Galling (fit surface) Spalling Bulk cracking or fracture
21.3 22.3	Housing galled Shaft galled	00.13 00.16 00.12 00.22	Galling (fit surface) Spalling Wear (fit surface) Bulk cracking or fracture
21.4 22.4	Housing worn Shaft worn	00.13 00.15 00.16 00.12 00.22	Galling (fit surface) Fretting Spalling Wear (fit surface) Bulk cracking or fracture
21.6 22.5	Housing deformed Shaft deformed	00.23 00.22	Permanent deformation Bulk cracking, fracture
21.7 21.9	Mismounted housing Geometry or assembly defect in housing	00.09 00.22 00.19	Mounting error Rubbing cracks Heat imbalance failure
22.6 22.9	Mismounted shaft Geometry or assembly defect in shaft	00.22 00.12 00.16	Bulk cracking or fracture Wear from fouling Spalling
21.5	Lubricant leak from housing or covers	11 12	Oil lubrication failure Grease lubrication failure
21.8	Housing corroded	00.20 00.22	Corrosion Bulk cracking or fracture
25	External seal failure	11 12	Oil lubrication failure Grease lubrication failure

Cross-Index of Secondary Failure Codes

Failure Code	Plate No.
20.01.2.1	16.29
20.01.2.2	19.2
20.02	19.6
21.4	15.26
21.6	7.7
21.7	15.37
21.9	4.2 16.13
22.1	19.7
22.2	19.9
22.3	19.8 19.9
22.4	19.8
22.5	15.1
22.9	15.35 15.36
25.1	18.7
26	13.17 15.21

PLATES

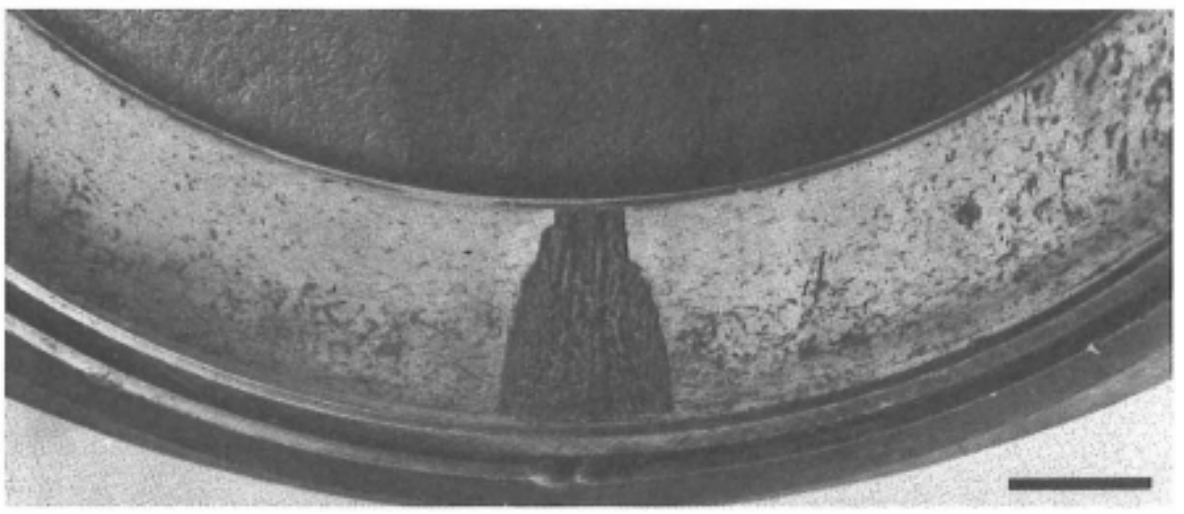


DATA

Plate No: 19.1
Archive No: 027-268
Image type: view
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: DGBB; OR, run
Speed: 125 KdN
Load: 2.4 GPa
Lubrication: grease, 50°C
Failure Code 1: 21.6 Housing deformed
Failure Code 2: 00.15.1.2 Localized fretting, radial fit surface
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Fretting corrosion has formed in a periodic circumferential pattern on the OD of this OR, indicating that support in the housing is uneven, that is, the housing bore has circumferential waviness. The interrupted load support may lead to OR bending fatigue with cross-section cracking.
Image Description: Several circumferential bands of fretting corrosion on the OR OD show a periodic pattern of feathery dark markings. These decorate the high points at which contact with the chattered bore of the housing was most intimate.
Suspected Causes: Waviness in the housing bore may result from vibrations in the boring tool during housing bore machining. Grinding chatter on the OR OD is another possible source of periodic fretting marks. Differentiation requires contour tracing.



DATA

Plate No: 19.2
Archive No: 014-56
Image type: light macro
Scalebar = 10 mm (micros: ±20%, others: +100%, −50%)
Component: TRB; M & OR, run
Speed:
Load:
Lubrication:
Failure Code 1: 21.6 Housing deformed
Failure Code 2: 20.01.2.2 Mounting part nicked or gouged
Failure Code 3: 00.16.01.2.2 Spalling at contact edge, from geometry error
Failure Code 4: 00.18.02.2 Severe or advanced denting

DESCRIPTIONS

Failure Description: The housing has a large nick at the bearing seat, leading to uneven ring support, local overload and a large spall across the entire roller path including the edges. The OR (cup) roller path is covered with large secondary dents from spall debris. Corrosion spots (FC 00.20) may also be present on the roller path. Gross failure through bearing seizure is likely as the spall progresses.
Image Description: Oblique view into the roller path of a TRB OR ('cup'), which is mounted in a housing. At image S, center, the housing edge has two deep nicks with a raised edge between them. Directly N of the nicks, the roller path is spalled across its full width (wide, shallow spall). The remainder of the roller path shows many dents (and what appear to be corrosion spots).
Suspected Causes: The housing is gouged (with a raised edge) across the OR support surface, as the result of severe abuse in mounting, by impact with a sharp tool. The OR mounted in the deformed housing is deflected, causing local stress concentration and early spalling. A cross-section fracture may follow.

DATA

Plate No: 19.3
Archive No: 064-002
Image type: color view [SEE IMAGE IN APPENDIX.]
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: B; M (housing), run
Speed:
Load:
Lubrication:
Failure Code 1: 21.8 Housing corroded
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

[See Image in Appendix]

DESCRIPTIONS

Failure Description: Severe damage to the bearing seat in the boss on a gearbox. This boss receives the bearing OR. The entire boss is covered with corrosion stain. The bearing and endcap fit surfaces are deeply pitted. The bearing fit surface is unsuited for the mounting of a bearing, as poor OD support will cause bulk cracking and/or galling.
Image Description: Oblique view from inside a gearbox, onto the endface of a cylindrical boss (bearing housing) in the gearbox wall (half of a second boss is visible at image N). All elements shown are stained reddish brown by corrosion. One narrow and two wide cylindrical ID surfaces are machined into the boss. Traversing the bore image from front to back, one sees the locating flange, bearing seat and retaining cap seat. The bearing and retaining cap seats are deeply pitted.
Suspected Causes: The gearbox was exposed to a severe, long term corrosive environment while open. The free surfaces, protected by paint, corroded lightly. The unprotected fit surfaces are corroded to uselessness.

DATA

Plate No: 19.4
Archive No: 099-145
Image type: view
Scalebar = 30 mm (micros: ±20%, others: +100%, −50%)
Component: G; M (shaft), run
Speed:
Load:
Lubrication:
Failure Code 1: 22.1 Shaft cracked or broken
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Example of bending fatigue fracture of an integral gear shaft, with the fatigue crack initiated near the surface and expanding through concentric striations. The crack surface is a cross section of the shaft. This is a gross failure.
Image Description: View of cross-section fracture of a shaft. At image E is the fracture initiation. Concentric fatigue striations extend from this point through ⅔ of the shaft diameter. Sudden overstress fracture broke the remaining cross section, forming radial steps as the shaft separated.
Suspected Causes: Overload on the shaft may create bending fatigue. Defects in the shaft material are likely contributors.

DATA

Plate No: 19.5
Archive No: 099-146
Image type: view
Scalebar = 3 in. = 76 mm (micros: ±20%, others: +100%, −50%)
Component: G; M (shaft), run
Speed:
Load:
Lubrication:
Failure Code 1: 22.1 Shaft cracked or broken
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

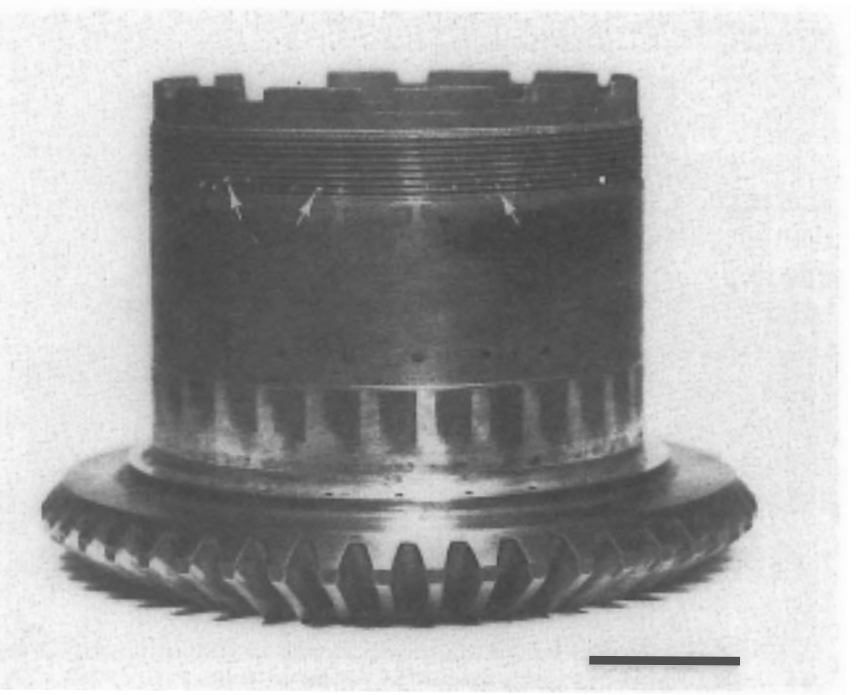
Failure Description: Example of torsional fatigue failure in an integral gear shaft. The fracture surface is twisted and makes an approximate 45° angle with the axis. This is a gross failure.
Image Description: Oblique view of the fracture surface of a gear shaft. The fracture surface at image W is a twisted surface, at approximately 45° with the shaft axis. The fatigue initiation is near the W image edge, and the striations are concentric around the step at that location.
Suspected Causes: Excessive transmitted torque, in possible combination with a defect in the shaft, may initiate torsional fatigue failure. Propagation may be accelerated by torsional vibrations in the system.

DATA

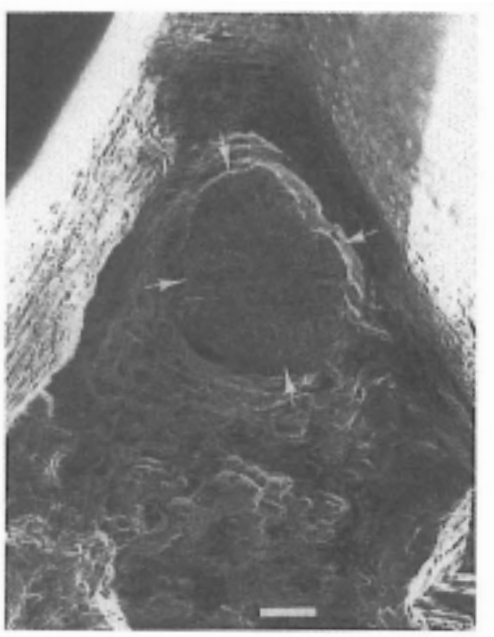
Plate No: 19.6
Archive No: 002-003a&f
Image type: a: view, b: SEM
Scalebar = a: 30 mm, b: 200 μm (micros: ±20%, others: +100%, −50%)
Component: BG; W & M, run
Speed: 91 m/sec
Load: 0.6 GPa
Lubrication: synthetic polyester oil, 176°C
Failure Code 1: 22.1 Shaft cracked or broken
Failure Code 2: 00.08.4 Hydrogen embrittlement cracking or flaking
Failure Code 3: 20.02 Corrosion of mounting part
Failure Code 4: -

DESCRIPTIONS

Failure Description: The integral hollow shaft of a bevel gear shows numerous axial cracks across the screw threads. Hydrogen embrittlement resulting from a plating operation initiated the cracks. Corrosion of the surfaces near and at the threads, from an aggressive environment, may contribute to the cracking. Gross failure is likely from cross section cracking of the shaft.
Image Description: (a): Side view of bevel gear with integral hollow shaft. There is a screw thread at the end remote from the gear. Small axial cracks appear across the threads (white fluorescent dye-penetrant points, arrows). Corrosion pits are on the surface N of the threads. (b): SEM of fracture surface along the axial crack shows the triangular thread cross section in ductile, 'dimpled' fracture. Four arrows show hydrogen embrittlement 'fisheye.'
Suspected Causes: A repair operation involving electroplating is known to have been performed. If properly done, hydrogen embrittlement can result which produces cracks during running. Corrosion pitting indicates chemically aggressive environment, which may have contributed to the cracking.



a



b

DATA

Plate No: 19.7
Archive No: 049-002
Image type: light macro
Scalebar = 20 mm (micros: ±20%, others: +100%, −50%)
Component: SRB; M (journal), run
Speed:
Load:
Lubrication:
Failure Code 1: 22.2 Shaft fretted
Failure Code 2: 22.1 Shaft cracked or broken
Failure Code 3: -
Failure Code 4: -

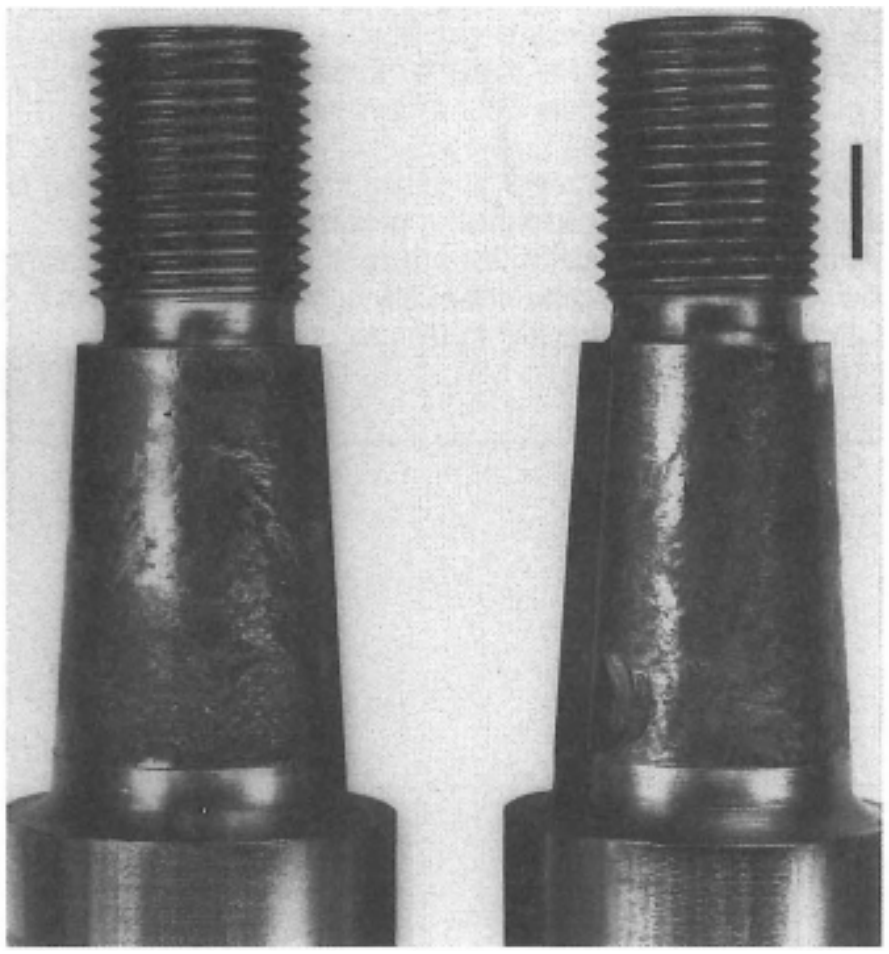


DESCRIPTIONS

Failure Description: Extreme fretting and "chipping" of the bearing seat on the hollow shaft of a paper-machine suction roll. The entire bearing seat surface is covered with corrosion-colored sharp-edged craters, producing a "seashell-fragment" appearance. Dimensions are lost, and the journal is not serviceable.
Image Description: The bearing seat covers most of the image. At image N is the open journal endface with a narrow free OD and undercut, followed, to the S, by the bearing seat, extending at image S to the undercut at the flange. The bearing seat surface is uniformly covered by sharp-edged overlapping craters. The surface is dark colored as from fretting.
Suspected Causes: Low journal wall thickness and low interference existed at the bearing fit. Relative motion caused fretting. During extended operation, the fretted surface developed shallow cracks from bending of the thin shaft. It is conjectured that this process produced the craters which then were covered by fretting corrosion product, producing the dark color. This shaft appearance is very unusual.

DATA

Plate No: 19.8
Archive No: 099-151
Image type: view (2)
Scalebar = 40 mm (micros: ±20%, others: +100%, −50%)
Component: G; M (shaft), run
Speed:
Load:
Lubrication:
Failure Code 1: 22.2 Shaft fretted
Failure Code 2: 22.3 Shaft galled
Failure Code 3: 22.4 Shaft worn
Failure Code 4: -



a b

DESCRIPTIONS

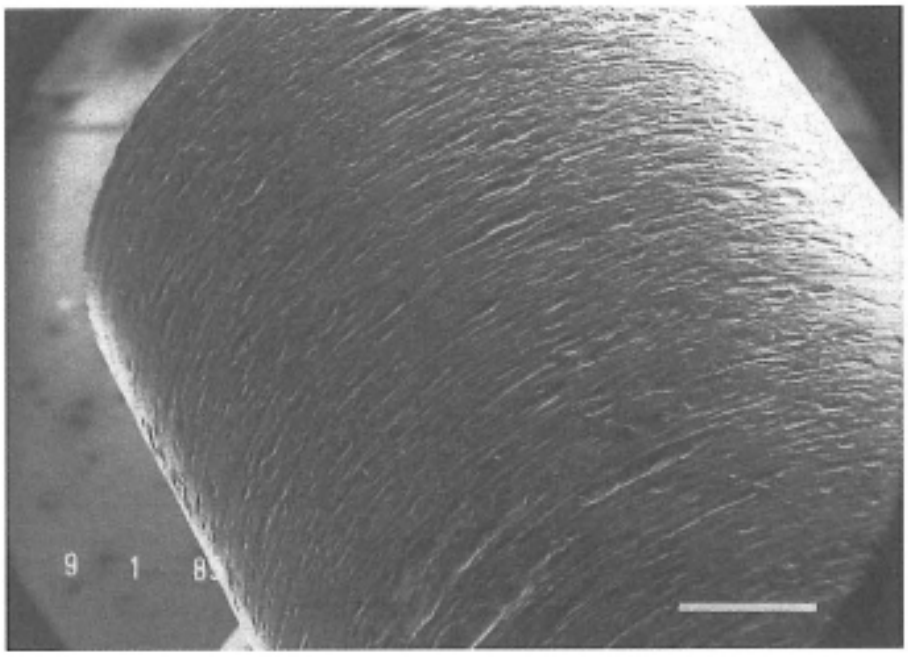
Failure Description: The tapered gear seat is deeply fretted; the original surface is removed. Galling and subsequent wear have occurred. There is an axial elevated line as from a split hub. Gouges are from a removal tool. The gear seat dimension is lost, and the shaft is unserviceable.
Image Description: (a), (b): Views, rotated 180°, of the same tapered gear seat on a shaft with a shoulder (image S) and a thread (image N). The seat surface is completely fretted and galled. The original surface is removed. Fretting corrosion product was largely removed by further wear. The elevated axial line near the W contour of the seat in (b) suggests that there was a split hub in the gear. The circular gouge mark near this line is from a tool used to remove the fretted-on gear.
Suspected Causes: Insufficiently driven-up tapered fit between gear and shaft produces relative motion and fretting, leading to galling and subsequent wear. Judging from the axial line in the seat, the gear has not turned, merely moved microscopically on the shaft.

DATA

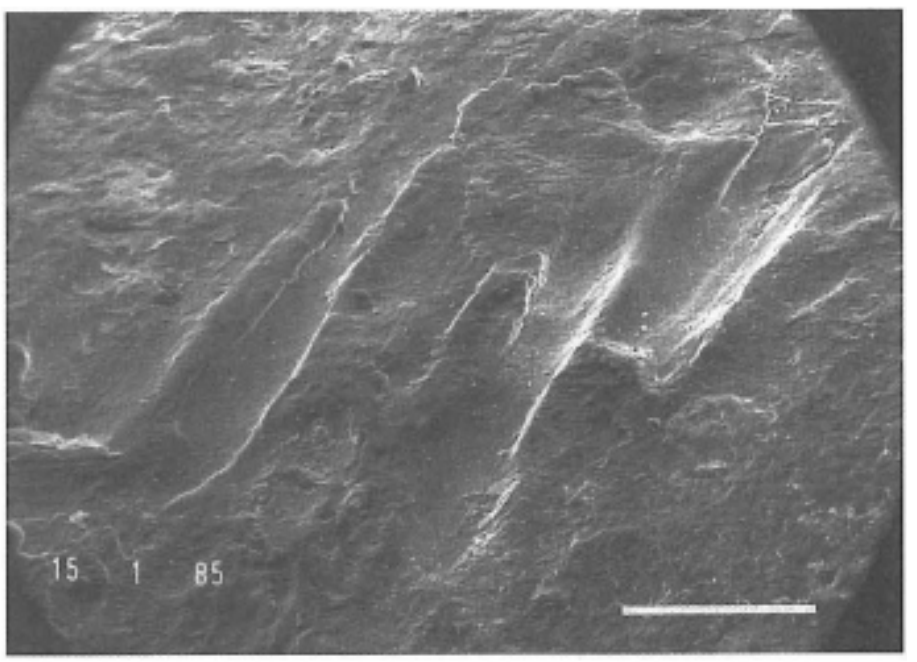
Plate No: 19.9
Archive No: 108-006&002&003
Image type: a, b, c: SEM
Scalebar = a: 900, b: 250, c: 40 μm (micros: ±20%, others: +100%, −50%)
Component: 0 (chain pin), medium hard, run
Speed: 200 cm/s
Load:
Lubrication: none, ? °C
Failure Code 1: 22.4 Shaft worn
Failure Code 2: 22.3 Shaft galled
Failure Code 3: 22.2 Shaft fretted
Failure Code 4: -

DESCRIPTIONS

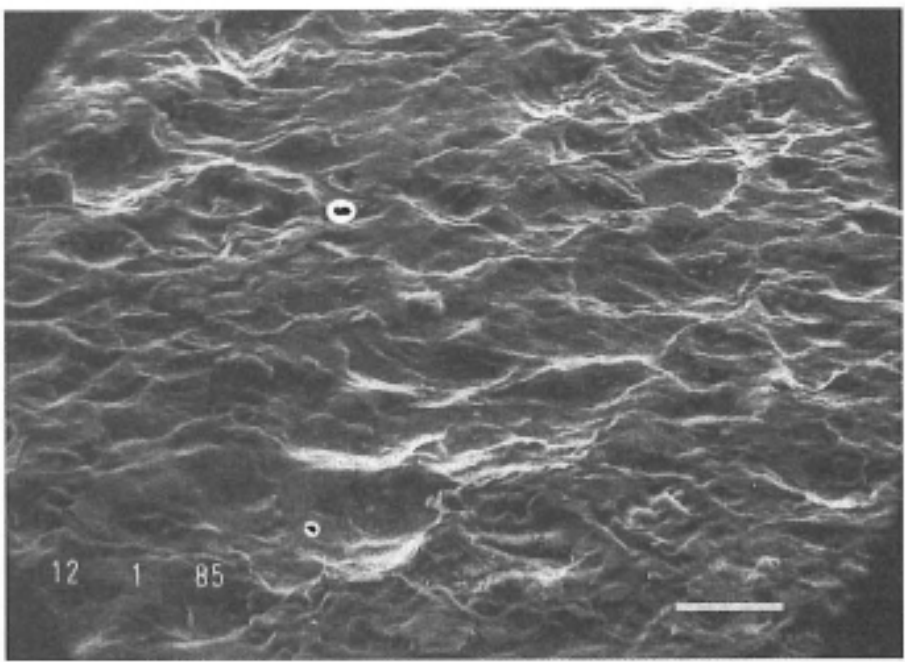
Failure Description: Connecting pin wear, galling and fretting in a roller chain under oscillating motion between pin and bushing during chain articulation. This is an unlubricated chain with hardened bushings and medium hard pins. The entire pin contact surface is severely fretted, and there are circumferential galling and/or wear marks. The chain dimensions are lost, the chain/sprocket articulation becomes faulty and the chain may eventually break.
Image Description: (a): Oblique view of the pin contact surface. Circumferential, interrupted gouge marks from combination of (observed) fretting, wear and galling. (b): Gouges are visible in the SW–NE sliding direction, suggesting plastic flow, and galling, followed by wear. (c): Non-directional depressions and debris from fretting and wear.
Suspected Causes: Roller type drive chains have unlubricated or weakly lubricated sliding contacts between pin and bushing (and between bushing and roller). The former contacts are oscillatory. The surface appearances shown are from unlubricated tests, in which progressive wear and fretting was observed. Macroscopic seizure did not occur, even though the surface appearance suggests repeated galling events. The geometry is lost.



a



b



c

DATA

Plate No: 19.10
Archive No: 001-31
Image type: view
Scalebar = 25 mm (micros: ±20%, others: +100%, −50%)
Component: CRB; IR (with spacer), unrun
Speed:
Load:
Lubrication:
Failure Code 1: 23 Spacer, shoulder damage
Failure Code 2: 00.03 Pit or unfinished area
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Extensive heat treat scale is on the OD surface of the spacer extension to a CRB IR. This OD surface is a free surface and required to be without scale. The presence of scale may contaminate the lubrication system and/or produce stress concentrations which may lead to cracking.
Image Description: Shown is a combination CRB IR and spacer. The roller path is at image S, the spacer extension at image N. The OD surface of the spacer extension is covered with patches of black scale. The arrow points to a scale patch.
Suspected Causes: Inadequate cleanup of surface after heat treatment (as by grinding or grit blasting).

DATA

Plate No: 19.11
Archive No: 099-153
Image type: view
Scalebar = 30 mm (micros: ±20%, others: 100%, −50%)
Component: G; M (garter seal), mounted
Speed:
Load:
Lubrication:
Failure Code 1: 25.2.0 Manufacturing or assembly defect, external contact seal
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Indented and bent sideface of the sheet-metal casing in a garter type (garter-spring loaded) lip seal, due to improper tool use in mounting. The distorted case may prevent the seal from seating properly in the housing or on the shaft and cause leakage.
Image Description: A garter seal assembly is viewed on the sideface. The OD and the outboard part of the visible sideface are the sheet-metal casing. Seal lips are at the ID. The sideface of the casing is indented by radial edges at image E and SE (arrows A), and bruised at image S and W (arrows *B*).
Suspected Causes: Improper mounting tool use caused excessive local force on the sheet metal seal casing, denting and bruising it. Excess interference between the casing OD and the housing bore may prevent smooth assembly and may buckle the casing when it is forced into place.

DATA

Plate No: 19.12
Archive No: 099-152
Image type: light macro
Scalebar = 15 mm (micros: ±20%, others: +100%, −50%)
Component: G; M (garter seal), mounted
Speed:
Load:
Lubrication:
Failure Code 1: 25.2.2 External elastomeric contact seal lip torn
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: The seal lip is cut and folded in a garter-type (garter spring loaded) elastomeric lip seal. The sealing ability is lost. The seal is not serviceable.
Image Description: The metal seal casing is the shaded gray circular band at the seal OD (image S), followed to the N by the double seal lip. At the N–S image centerline, the lips are radially cut and folded toward the viewer. During mounting, these lips were folded under and torn, leaving an unsealed gap.
Suspected Causes: Improper lead chamfer on the shaft or careless handling during mounting may cut a garter seal lip. When pushed onto the shaft, the cut seal lip folds under, and the tear lengthens. The seal becomes unusable.

DATA

Plate No: 19.13
Archive No: 099-154&155&156
Image type: a, b, c: light macro
Scalebar = a, c: 15, b: 30 mm
(micros: ±20%, others: +100%, −50%)
Component: G; M (garter seal), run
Speed:
Load:
Lubrication:
Failure Code 1: 25.2.5 External contact seal chemical/heat damage
Failure Code 2: -
Failure Code 3: -
Failure Code 4: -

DESCRIPTIONS

Failure Description: Three examples of the effects of deterioration of elastomeric seal material by chemical attack or overheat. (a): Multiple radial cracking of the elastomer. (b): Chipping of the seal lip edge. (c): Blistering of the seal lip. Deterioration of the elastomer is irreversible. Sealing ability is lost or impaired, depending on the severity of the damage.

Image Description: (a): Elastomer lip seal is viewed from the *open* side. Traversing the image from S to N one sees casing and two elastomer lips. Multiple dark radial cracks are visible across the elastomer material (arrows). Damage to the N edge of the lip. (Two wire straps are not part of the seal.) (b) and (c): Seals are viewed on *closed* (casing) side. The N-facing edge of the lip is chipped at the arrow in (b), and blistered at the arrows in (c).

Suspected Causes: Excessive operating temperature, unsuitable lubricant/ elastomer combination or aggressive atmosphere may deteriorate the elastomer. It may harden or embrittle and crack or chip. Due to decomposition of the material, the lip may blister.

a

b



c

Appendices

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Failure Code List

Failure code	Failure designation
0	Contact assembly failure
00	Contact part failure
00.0	Manufacturing or assembly defect
00.00	Manufacturing or assembly defect, by location
00.00.01	Defect by location: in fit surface
00.00.02	Defect by location: in contact surface
00.00.02.1	Defect by location: in Hertz contact surface
00.00.02.2	Defect by location: in sliding contact surface
00.00.03	Defect by location: in free surface
00.01	Nick
00.01.1	Local nick
00.01.1.1	Nick with raised edges
00.01.2	Scratch, toolmark, scuffmark
00.01.3	Circular flat nick on ball
00.01.4	Chipped nick in ceramic
00.02	Finishing mark
00.02.1	Grinding, honing, lapping furrow
00.02.2	Wheelhit
00.02.3	Grinding chatter
00.02.4	Machining mark
00.02.4.1	Turning mark
00.02.4.2	Gear hobbing mark
00.02.4.3	Gear shaving mark
00.03	Pit or unfinished area
00.03.1	Surface porosity or pit
00.03.2	Unground area
00.03.3	Unhoned area
00.03.4	Lapping imperfection
00.04	Forming defect
00.04.1	Forming lap
00.04.2	Forming seam
00.04.3	Forming at incorrect temperature
00.04.3.1	Forging at excessive temperature
00.04.3.1.1	Incipient melting from forging at excessive temperature

Failure code	Failure designation
00.05	Casting defect
00.05.1	Micro-porosity
00.05.2	Macro-porosity
00.05.2.1	Pipe or void formed at ingot center
00.05.3	Injection molding defect (in plastic)
00.05.4	Structure defect in ceramic
00.05.4.1	Micro-porosity in ceramic
00.05.4.2	Binder defect in ceramic
00.06	Inclusion
00.06.1	Micro-inclusion
00.06.1.1	Hard micro-inclusion
00.06.1.2	Sulfide inclusion
00.06.1.3	Primary carbide
00.06.2	Inclusion stringer
00.07	Material structure defect pre- or in heat treatment
00.07.1	Soft structure (general or localized)
00.07.1.1	Insufficient bulk hardness
00.07.1.2	Ferritic constituent
00.07.1.3	Upper bainitic constituent
00.07.2	Off-specification martensite platelet size
00.07.3	Defective carbide structure
00.07.3.1	Carbide segregation
00.07.3.2	Lamellar carbide
00.07.4	Visible retained austenite
00.07.5	Forging or heat treat crack
00.07.5.01	Forging crack
00.07.5.02	Heat treat crack
00.07.5.1	Crack with oxidized surface
00.07.5.2	Twisted (baseball) crack
00.07.6	Grain size off-specification
00.07.7	Non-metal structure off-specification
00.08	Material structure damage, post-heat treatment
00.08.1	Grinding temper
00.08.2	Rehardened grinding burn
00.08.3	Grinding crack
00.08.4	Hydrogen embrittlement cracking or flaking
00.08.5	Chemical attack during manufacture
00.08.6	Coating damage
00.08.7	Cold forming damage
00.09	Geometry, assembly or mounting defect
00.09.0	Geometry defect
00.09.1	Scoring from forcible assembly or mounting (no galling)
00.09.2	Galling from forcible assembly or mounting

Failure code	Failure designation
00.09.3	Cracking (fracture) from forcible assembly or mounting
00.1, 00.2	Service failure, contact part
00.12	Wear, mild
00.12.0	Wear, identified by mechanism
00.12.0.1	Adhesive mild wear
00.12.0.2	Abrasive mild wear
00.12.1	Fit surface wear
00.12.1.1	Fit surface polishing
00.12.1.2	Advanced mild wear of fit surface
00.12.3	Bearing contact wear
00.12.3.2	Wear in rolling surface
00.12.3.2.0	Wear track as load type indicator
00.12.3.2.0.1	Wear track when load rotates over innerring
00.12.3.2.0.2	Wear track when load rotates over outerring
00.12.3.2.0.3	Wear track for radial preload
00.12.3.2.0.4	Wear track for out-of-round ring
00.12.3.2.0.5	Wear track for centered axial load
00.12.3.2.0.6	Wear track for combined radial/axial load
00.12.3.2.0.7	Wear track for misaligned outerring
00.12.3.2.0.8	Wear track for misaligned innerring
00.12.3.2.1	Smooth rolling surface wear (finish marks removed)
00.12.3.2.1.1	Wear track centered in contact
00.12.3.2.1.2	Wear track off-center in contact
00.12.3.2.1.3	Wear track shifts in contact
00.12.3.2.1.4	Wear track at contact edge
00.12.3.2.2	Scratch marks, kinematic wear marks in rolling surface
00.12.3.2.3	Step worn in rolling surface or dimension worn off-spec
00.12.3.2.4	Scoring wear (macroscopic gouging without galling)
00.12.3.3	Sliding contact wear
00.12.3.3.1	Wear at edge of sliding contact
00.12.3.3.2	Wear, centered in sliding contact
00.12.3.3.3	Scratch marks in sliding contact
00.12.4	Wear of guiding-component support surface
00.12.5	Gear tooth wear
00.12.5.1	Tooth polishing
00.12.5.2	Smooth tooth wear
00.12.5.3	Destructive tooth wear
00.12.5.3.1	Abrasive (destructive) tooth wear
00.12.5.3.2	Adhesive (destructive, non-galling) tooth wear
00.12.5.3.2.1	Wavy tooth wear
00.12.5.3.2.2	Bumpy tooth wear
00.12.5.3.2.3	Ridging tooth wear
00.12.5.3.2.4	Furrowing tooth wear
00.12.6	Wear at unintended surface contact
00.12.7	Impact wear

Failure code	Failure designation
00.13	Galling (smearing, severe mechanical wear)
00.13.0	Galling, identified by severity
00.13.01	Incipient galling
00.13.02	Extensive galling
00.13.1	Fit surface galling
00.13.1.1	Galling from nick origin, fit surface
00.13.1.2	Galling from rapid motion origin, fit surface
00.13.2	Contact surface galling
00.13.2.1	Rolling surface galling
00.13.2.1.1	Rolling surface galling, no dent or nick visible
00.13.2.1.1.1	Ring galling at load zone entry
00.13.2.1.1.2	Contact galling from high acceleration
00.13.2.1.2	Rolling surface galling, dent or nick visible
00.13.2.2	Galling of sliding contact surface
00.13.2.3	Galling at guiding-part contact surface
00.13.3	Tooth contact galling
00.14	Skid marking (microscopic severe wear)
00.15	Fretting wear
00.15.1	Fretting (fretting corrosion)
00.15.1.1	Generalized fretting, radial fit surface
00.15.1.2	Localized fretting, radial fit surface
00.15.1.2.0	Radial fit surface fretting as mounting diagnostic
00.15.1.2.0.1	Normal fretting, accurate radial fit, thrust load
00.15.1.2.0.2	Normal fretting, accurate radial fit, radial load
00.15.1.2.0.3	Excessive fretting, loose or inaccurate radial fit
00.15.1.2.0.4	Displaced radial fit fretting from high thrust load
00.15.1.2.0.5	Skewed radial fit fretting from misalignment
00.15.1.2.0.6	One-sided radial fit fretting from taper
00.15.1.2.0.7	Irregular fretting in distorted radial fit
00.15.1.2.0.8	Fretting in chatter-marked radial fit
00.15.1.3	Fit sideface fretting
00.15.2	False brinnelling on contact surface
00.16	Spalling (Hertzian contact fatigue)
00.16.01	Spalling, by location
00.16.01.1	Spalling centered in contact
00.16.01.1.1	Centered spalling, normal track width
00.16.01.1.2	Centered spalling, wide track
00.16.01.2	Spalling at contact edge
00.16.01.2.1	Spalling at contact edge, from misalignment
00.16.01.2.2	Spalling at contact edge, from geometry error
00.16.01.2.3	Spalling at contact edge from thrust load
00.16.01.3	Tooth spalling
00.16.01.3.1	Tooth pitchline or dedendum spalling

Failure code	Failure designation
00.16.02	Spalling, identified by progression stage
00.16.02.1	Microplastic deformation indication
00.16.02.1.1	Microplastic deformation bands or 'butterflies'
00.16.02.1.2	Dark-etching microplastic deformation zone
00.16.02.1.3	Micro-sphere spalling debris
00.16.02.2	Contact fatigue cracking
00.16.02.3	Incipient spalling, single spall
00.16.02.4	Incipient spalling, multiple spalls
00.16.02.5	Advanced spalling
00.16.03	Spalling, identified by propagation mode
00.16.03.1	Spall propagating by cracking at spall bottom
00.16.03.2	Spall propagating by re-initiation at surface
00.16.1	Spalling, identified by origin location
00.16.1.1	Subsurface origin spall (high Hertz shear stress)
00.16.1.1.1	Steep entry spall (subsurface origin)
00.16.1.1.2	Spall from subsurface defect
00.16.1.1.3	Subcase-fatigue spall
00.16.1.2	Surface origin spall
00.16.1.2.1	Shallow entry spall from surface point-defect
00.16.1.2.2	Shallow entry spall from surface line-defect
00.16.1.2.3	Shallow entry spall from tensile cracking (ceramic)
00.17	Surface distress (surface fatigue)
00.17.01	Surface distress, no sliding
00.17.02	Surface distress, with sliding
00.17.1	Generalized surface distress
00.17.1.1	Glazing (incipient surface distress)
00.17.1.2	Microspalling (advanced surface distress)
00.17.1.3	Grain pullout (surface distress of ceramic)
00.17.2	Localized surface distress (halo at defect)
00.18	Denting (indentation)
00.18.01	Indentation, identified by location
00.18.01.1	Indentation on (primarily) rolling contact surface
00.18.01.1.1	Denting of rolling surface, no sliding
00.18.01.1.2	Denting of rolling surface, minor sliding
00.18.01.2	Indentation on (primarily) sliding contact surface
00.18.01.3	Indentation on guide-part support surface
00.18.02	Denting, identified by severity
00.18.02.1	Light or incipient denting
00.18.02.2	Severe or advanced denting
00.18.1	Local dent
00.18.1.1	Rounded dent (from soft contaminant)
00.18.1.2	Sharp individual dent(s) from metal debris, asperities
00.18.1.3	Multi-fragment dent (brittle contaminant)
00.18.1.4	Multiple irregular denting from fine, loose hard debris
00.18.2	Rolled-in line in contact
00.18.2.1	Rolled-in line at contact edge

Failure code	Failure designation
00.18.2.1.1	Rolled-in line, one contact edge only
00.18.2.1.2	Rolled-in line, both contact edges
00.18.2.2	Rolled-in line inside contact
00.18.2.2.1	Rolled-in continuous line from opposing edge
00.18.2.2.2	Stippled line(s) or band(s) from rolled-in debris
00.18.3	Brinnelling
00.18.4	Gear tooth, local plastic flow in contact
00.18.4.1	Gear tooth peening (irregular local plastic flow)
00.18.4.2	Gear tooth rippling (transverse wavy plastic flow)
00.18.4.3	Gear tooth ridging (plastic ridges in sliding direction)
00.19	Heat imbalance failure
00.19.1	Heat imbalance, temper colors
00.19.1.1	Generalized temper colors
00.19.1.2	Temper colors in contact surfaces
00.19.1.3	Temper colors on guide-part support surface
00.19.2	Hot plastic flow
00.19.2.1	Hot plastic flow without welding (rollout)
00.19.2.2	Hot plastic flow with bulk welding
00.19.3	Scale formation
00.19.4	Heat discoloration by friction polymer
00.19.4.1	Friction polymer on rolling track
00.19.4.2	Friction polymer on sliding track
00.19.4.3	Friction polymer on guiding part support surface
00.19.5	Local structure damage from frictional heating
00.20	Corrosion
00.20.01	Corrosion, identified by location
00.20.01.1	Generalized corrosion
00.20.1	Corrosion stain
00.20.1.2	Corrosion outside contact only
00.20.1.3	Contact corrosion
00.20.2	Corrosion pitting
00.20.3	Corrosive fingerprint-mark
00.21	Electric erosion
00.21.1	Electric erosion pitting
00.21.2	Electric erosion fluting
00.22	Cracking or fracture, bulk
00.22.01	Fracture classified by location
00.22.01.1	Axial cross section crack in ring
00.22.01.2	Circumferential crack
00.22.01.3	Rolling element (ball, roller) crack
00.22.01.4	Gear tooth crack or fracture
00.22.01.41	Tooth root fracture
00.22.01.42	Tooth corner fracture
00.22.01.43	Mid-tooth fracture
00.22.01.44	Tooth tip chipping

Failure code	Failure designation
00.22.1	Overstress crack
00.22.2	Bulk fatigue crack
00.22.3	Rubbing crack
00.22.4	Chemical origin (stress corrosion, embrittlement) crack
00.23	Permanent deformation, bulk
00.23.1	Plastic rolldown of contact path
00.23.1.1	Contact path rolldown in bearing
00.23.1.2	Gear tooth contact rolldown
00.23.2	Plastic distortion of bulk shape
00.23.3	Dimensional change due to structure transformation
01	Guiding-part failure
01.1	Separator failure
01.10	Separator manufacturing geometry defect
01.11	Separator bulk defect
01.11.1	Separator melting (polymer)
01.11.2	Separator fracture, cracking
01.11.3	Separator weld failure
01.11.4	Separator casting or molding defect
01.11.5	Separator rivet, prong, tang or bolt failure
01.11.6	Separator plating defect
01.12	Separator plastic deformation
01.13	Separator wear
01.13.1	Separator pocket worn
01.13.1.1	Separator crossbar worn, one pocket side
01.13.1.2	Separator crossbar worn, both pocket sides
01.13.1.3	Roller separator, diagonal crossbar wear
01.13.1.4	Roller separator, pocket bottom worn
01.13.2	Land guided separator, guide surface worn
01.13.2.1	Land guided separator, guide surface worn, general
01.13.2.2	Land guided separator, guide surface worn, local
01.13.3	Separator wear from unintended contact
01.14	Separator galling
01.14.1	Separator pocket galled
01.14.2	Land guided separator, guide surface galled
01.15	Separator corrosion
01.16	Separator heat imbalance failure
01.17	Separator contact spalling
01.2	Guidering failure
01.21	Guidering material defect
01.22	Guidering fracture, cracking

Failure code	Failure designation
01.23	Guidering wear
01.24	Guidering galling
02	Seal (integral), failure
02.1	Rubbing seal defect
02.10	Material or manufacturing defect in rubbing seal
02.11	Rubbing seal wear
02.12	Torn rubbing seal lip
02.13	Rubbing seal counterface wear
02.14	Rubbing seal leak
02.15	Chemical attack on rubbing seal
02.19	Geometry or assembly defect in rubbing seal
02.2	Non-rubbing closure defect
1	Lubricant failure
11	Oil failure
11.0	Oil quality defect
11.1	Friction polymer, oil lubrication
11.2	Water in oil
11.3	Solid contaminant in oil
11.3.01	Incipient oil contamination
11.3.02	Severe oil contamination
11.3.1	Steel contaminant in oil
11.3.2	Non-steel metal contaminant in oil
11.3.3	Abrasive contaminant in oil
11.3.4	Soft contaminant in oil
11.4	Discolored oil
11.5	Carbonized oil deposit
12	Grease failure
12.0	Grease quantity defect
12.00	Grease, as-manufactured
12.01	Grease pack low
12.02	Grease pack excessive
12.1	Softened or liquefied grease
12.2	Carbonized grease

Failure code	Failure designation
12.3	Friction polymer, grease lubrication
12.4	Water in grease
12.4.1	Grease discoloration (whitish), from water
12.4.2	Water droplets in grease
12.4.3	Free water in grease
12.4.4	Grease decomposed by chemical agent
12.5	Solid contaminant in grease
12.5.01	Incipient grease contamination
12.5.02	Severe grease contamination
12.5.1	Steel contaminant in grease
12.5.2	Non-steel metal contaminant in grease
12.5.3	Abrasive contaminant in grease
12.5.4	Soft contaminant in grease
12.6	Grease dried out, discolored
12.6.1	Grease dried out
12.6.2	Grease discolored
12.7	Electric current damage to grease
13	Solid or gas lubricant failure
13.1	Vapor phase lubricant failure
13.1.1	Chemical surface attack by vapor phase lubricant
13.1.2	Solid lubricant deposit from vapor phase lubricant
13.1.3	Peeling deposit from vapor phase lubricant
2	Mounting part damage
20.01	Mounting part damage, general description
20.01.1	Generalized mounting part damage
20.01.2	Localized mounting part damage
20.01.2.1	Fouling of mounting part by other moving part
20.01.2.2	Mounting part nicked or gouged
20.01.3	Axial wear or scuffmark on mounting part
20.01.4	Circumferential wear or scuffmark, mounting part
20.02	Corrosion of mounting part
20.03	Mounted looseness (backlash) off-specification
21	Housing damage
21.1	Housing cracked or fractured
21.2	Housing fretted
21.3	Housing galled
21.4	Housing worn

Failure code	Failure designation
21.5	Lubricant leak from housing or cover
21.6	Housing deformed
21.7	Housing mismounted
21.8	Housing corroded
21.9	Geometry or assembly defect in housing
22	Shaft damage
22.1	Shaft cracked or broken
22.2	Shaft fretted
22.3	Shaft galled
22.4	Shaft worn
22.5	Shaft deformed
22.6	Shaft mismounted
22.9	Geometry or assembly defect in shaft
23	Spacer, shoulder damage
23.1	Spacer, shoulder fretted
23.2	Spacer, shoulder corroded
24	Mounting sleeve, nut, lockwasher damage
25	Seal (external) failure
25.1	Labyrinth seal failure
25.1.0	Manufacturing or assembly defect, labyrinth seal
25.1.1	Labyrinth seal wear
25.1.2	Labyrinth seal galling
25.2	External contact seal failure
25.2.0	Manufacturing or assembly defect, external contact seal
25.2.1	External contact seal wear
25.2.2	External elastomeric contact seal lip torn
25.2.3	External face seal carbon chipped
25.2.4	External contact seal conterface worn or galled
25.2.5	External contact seal chemical/heat damage
26	Support bearing damage (of gear, cam)

Failure Mode Index

Failure designation	Failure code
Casting defect	**00.05**
Binder defect in ceramic	00.05.4.2
Injection molding defect (in plastic)	00.05.3
Macro-porosity	00.05.2
Micro-porosity	00.05.1
Micro-porosity in ceramic	00.05.4.1
Pipe or void formed at ingot center	00.05.2.1
Structure defect in ceramic	00.05.4
Contact assembly failure	**0**
Contact assembly failure	0
Contact part failure	**00**
Defect by location: in contact surface	00.00.02
Defect by location: in fit surface	00.00.01
Defect by location: in free surface	00.00.03
Defect by location: in Hertz contact surface	00.00.02.1
Defect by location: in sliding contact surface	00.00.02.2
Manufacturing or assembly defect	00.0
Manufacturing or assembly defect, by location	00.00
Corrosion	**00.20**
Contact corrosion	00.20.1.3
Corrosion outside contact only	00.20.1.2
Corrosion pitting	00.20.2
Corrosion stain	00.20.1
Corrosion, identified by location	00.20.01
Corrosive fingerprint-mark	00.20.3
Generalized corrosion	00.20.01.1
Cracking or fracture, bulk	**00.22**
Axial cross section crack in ring	00.22.01.1
Bulk fatigue crack	00.22.2
Chemical origin (stress corrosion, embrittlement) crack	00.22.4
Circumferential crack	00.22.01.2
Fracture classified by location	00.22.01
Gear tooth crack or fracture	00.22.01.4
Mid-tooth fracture	00.22.01.43
Overstress crack	00.22.1
Rolling element (ball, roller) crack	00.22.01.3
Rubbing crack	00.22.3
Tooth corner fracture	00.22.01.42
Tooth root fracture	00.22.01.41
Tooth tip chipping	00.22.01.44

Failure designation	Failure code
Denting (indentation)	**00.18**
Brinnelling	00.18.3
Denting of rolling surface, minor sliding	00.18.01.1.2
Denting of rolling surface, no sliding	00.18.01.1.1
Denting, identified by severity	00.18.02
Gear tooth peening (irregular local plastic flow)	00.18.4.1
Gear tooth ridging (plastic ridges in sliding direction)	00.18.4.3
Gear tooth rippling (transverse wavy plastic flow)	00.18.4.2
Gear tooth, local plastic flow in contact	00.18.4
Indentation on (primarily) rolling contact surface	00.18.01.1
Indentation on (primarily) sliding contact surface	00.18.01.2
Indentation on guide-part support surface	00.18.01.3
Indentation, identified by location	00.18.01
Light or incipient denting	00.18.02.1
Local dent	00.18.1
Multi-fragment dent (brittle contaminant)	00.18.1.3
Multiple irregular denting from fine, loose hard debris	00.18.1.4
Rolled-in continuous line from opposing edge	00.18.2.2.1
Rolled-in line at contact edge	00.18.2.1
Rolled-in line in contact	00.18.2
Rolled-in line inside contact	00.18.2.2
Rolled-in line, both contact edges	00.18.2.1.2
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