

CASTING COPPER-BASE ALLOYS

3rd Edition

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PREFACE

The second edition of the *Casting Copper-Base Alloys* handbook was published in 2007, after seven years of intense work by the AFS Technical Committee, Copper Alloy Division. Previous to that, the first edition was published in 1984. It was noted in the preface of the second edition that much had transpired in the twenty-plus years between the publications of each edition. Eight years later, the book has been updated again. Significant changes to several chapters, along with a brand new chapter, warranted a new edition designation for *Casting Copper-Base Alloys*.

We have also included more color images throughout the book, updated the look of the interior and corrected the errors that were in the previous edition.

On behalf of those who contributed to this revised edition, thank you for your interest in this book.

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STANDARD DESIGNATIONS FOR COPPER AND COPPER ALLOYS

INTRODUCTION

In the past, cast copper alloys were classified by a variety of systems including the ASTM letter-number designation based on nominal composition, by trade names, and by descriptive terms such as “ounce metal,” “Navy M,” and so forth. However, with technological developments, new alloys were produced and existing alloys modified, making the old designation systems inadequate and misleading. The Unified Numbering System (UNS) was developed during the 1970s based on a precise description of the composition range for each alloy, which is now the accepted alloy designation system used in North America for cast copper and copper alloy products. Originally developed as a three-digit system by the copper and brass industry, the designations have been expanded to five digits that follow a prefix letter “C.” The Unified Numbering System is managed jointly by the American Society for Testing and Materials (ASTM) and the Society of Automotive Engineers (SAE). The registration and compilation of UNS alloy numbers and their specific copper and copper alloy compositions are administered by the Copper Development Association (CDA).

New designations are assigned as new coppers and copper alloys come into commercial use and designations are discontinued when an alloy ceases to be used commercially. Anyone may submit requests for changes in the list. New designations are assigned if a copper or copper alloy meets three criteria as follows:

1. The complete chemical composition is disclosed.
2. The copper or copper alloy is in commercial use or is proposed for commercial use.
3. The composition does not fall within the limits of an already designated composition in the list. (Exceptions may be made for standard alloys for countries outside North America.)

With this system, cast alloys are numbered from C80000 through C99999. The compositions are grouped into the following families of coppers and copper alloys:

Coppers—metals that have a designated minimum copper content of 99.3% or higher.

High-Copper Alloys—the cast high-copper alloys have designated copper contents in excess of 94%, to which silver may be added for special properties.

Brasses—these alloys contain zinc as the principal alloying element, with or without other designated alloying elements present such as iron, aluminum, nickel, and silicon. The cast alloys comprise four major families of brasses: copper-tin-zinc alloys (red, semi-red, and yellow brasses); manganese bronze alloys (high-strength yellow brasses); leaded manganese bronze alloys (leaded, high-strength yellow brasses); and copper-zinc-silicon alloys (silicon brasses and bronzes). As noted, the designations are based on precise compositional limits; however, the ingot analysis may differ slightly from the composition shown (which is for the final casting). This is to allow for the loss of elements by oxidation or volatilization, or the possible pickup of impurities when the ingot is remelted to make the casting.

Bronzes—broadly speaking, bronzes are copper alloys in which the major alloying element is not zinc or nickel. Originally, “bronze” described alloys with tin as the only or principal alloying element. Today the term is generally not used by itself but with a modifying adjective. The cast alloys include four main families of bronzes: copper-tin alloys (tin bronzes); copper-tin-lead alloys (leaded and high-leaded tin bronzes); copper-tin-nickel alloys (nickel-tin bronzes); and copper-aluminum alloys (aluminum bronzes). The family of alloys known as manganese bronzes, in which zinc is the major alloying element, is included in the brasses category above.

Copper-Nickels—these are alloys with nickel as the principal alloying element, with or without other designated alloying elements present.

Copper-Nickel-Zinc Alloys—known commonly as “nickel silvers,” these are alloys which contain zinc and nickel as the principal and secondary alloying elements, with or without the presence of other designated elements.

Leaded Coppers—these alloys comprise a series of cast alloys of copper with 20% or more lead, usually with a small amount of silver present but without tin or zinc.

Special Alloys—alloys whose chemical compositions do not fall into any of the above categories are categorized as “special alloys.”

The use of these standard designations is optional. They do not preclude the manufacture or supply of products that do not conform to them.

The designated compositional limits do not preclude the possible presence of other unspecified elements. By agreement between supplier and consumer, an analysis may be required, and limits may be established for elements not cited. Percentage contents of elements shown as “remainder” are normally calculated by difference.

DESIGNATION NUMBER AND CHEMICAL COMPOSITION

The designation numbers and chemical compositions currently assigned to various alloys are listed in following pages. It will be noted that, with the exception of numbers in the C81000 and C94000 series where there is some overlap, each alloy family is limited to a specific series of numbers. For example, the yellow and leaded yellow brasses are all confined to numbers in the C85000 series, the nickel silvers to those in the C97000 series, and so on.

MECHANICAL PROPERTIES

Mechanical properties are not considered in this designation system, which is based solely on chemical composition. The mechanical properties are a function of the manufacturing method as well as of composition, as shown in Table 1-1.

The example above emphasizes the fact that the designation system is not a specification to which products are manufactured. Thus, before manufacturing begins, reference must be made to the current relevant specifications. For more detailed information on the designation system, composition, foundry, and physical and mechanical properties, etc., the reader is referred to “<http://www.copper.org>” www.copper.org (the Official Website of the Copper Development Association, Inc.) and specifically to <http://www.copper.org/resources/standards/uns-standard-designations.html> for an explanation of alloy designations and to <http://www.copper.org/resources/properties/db/basic-search.php> for alloy information concerning casting alloys in detail.

Table 1-1. Mechanical Properties as a Function of Manufacturing Method and Composition

Alloy No.:	C83600		C92200		C93700	
	Casting Method:	Sand or Centrifugal*	Continuous**	Sand or Centrifugal*	Continuous**	Sand or Centrifugal*
Tensile Strength (ksi)		30	36	34	38	30
0.5 Yield Strength (ksi)		14	19	16	19	12
Elongation (% in 2 in)		20	15	24	18	15

* ASTM B584, ASTM B271; ** ASTM B505

COPPERS

Table 1-2 Designation Number and Chemical Composition of Cast Copper Alloys

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper No.	Cu (min.) (incl. Ag)
C80100	99.95
C81100	99.70

HIGH-COPPER ALLOYS

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ¹²	Be	Co	Si	Ni	Fe	Al	Sn	Pb	Zn	Cr	Other Named Elements
C81200	99.9 ²⁸	-	-	-	-	-	-	-	-	-	-	P 0.045-0.065
C81400	Rem	0.02-0.10	-	-	-	-	-	-	-	-	0.6-1.0	
C81500	Rem.	-	-	0.15	-	0.10	0.10	0.10	0.02	0.10	0.40-1.5	
C81540	95.1 min. ¹	-	-	.40 - .80	2.0-3.0 ²	0.15	0.10	0.10	0.02	0.10	0.10-6	
C82000	Rem.	.45-8	2.4-2.7 ²	0.15	0.20	0.10	0.10	0.10	0.02	0.10	0.09	
C82200	Rem.	.35-8	-	-	1.0-2.0	-	-	-	-	-	-	
C82400	Rem.	1.65-1.75	0.30-0.65	-	0.20	0.20	0.15	0.10	0.02	0.10	0.09	
C82500	Rem.	1.90-2.25	0.35-0.70 ²	0.20-35	0.20	0.25	0.15	0.10	0.02	0.10	0.09	
C82510	Rem.	1.90-2.15	1.0-1.2	0.20-35	0.20	0.25	0.15	0.10	0.02	0.10	0.09	
C82600	Rem.	2.25-2.55	0.35-0.65	0.20-35	0.20	0.25	0.15	0.10	0.02	0.10	0.09	
C82700	Rem.	2.35-2.55	-	0.15	1.0-1.5	0.25	0.15	0.10	0.02	0.10	0.09	
C82800	Rem.	2.50-2.85	0.35-0.70 ²	0.20-35	0.20	0.25	0.15	0.10	0.02	0.10	0.09	

COPPER-TIN-ZINC AND COPPER-TIN-ZINC-LEAD ALLOYS

Red Brasses and Lead Red Brasses

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ⁴	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co)	S	P	Al	Si
C83300	92.0-94.0 ¹³	1.0-2.0	1.0-2.0	2.0-6.0							
C83400	88.0-92.0 ¹³	0.2	0.5	8.0-12.0	0.25	0.25	1.0	0.08	0.03 ³	0.005	0.005
C83450	87.0-89.0 ¹³	2.0-3.5	1.5-3.0	5.5-7.5		5	.8-2.0	0.08	0.03 ³	0.005	0.005
C83460	Rem ¹²	2.5-4.5	0.09	4.0-6.0	0.50-1.0	0.25	1.0	0.15-0.6	0.05-0.10	0.005	0.005
C83470	90.0-96.0 ¹³	3.0-5.0	0.09	1.0-3.0	0.50	0.20	1.0	0.20-0.6	0.01 ²⁹	0.01	0.01
C83500	86.0-88.0 ¹³	5.5-6.5	3.5-5.5	1.0-2.5	0.25	.5	0.50-1.0	0.08	0.03 ³	0.005	0.005
C83600	84.0-86.0 ¹³	4.0-6.0	4.0-6.0	4.0-6.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005
C83800	82.0-83.8 ¹³	3.3-4.2	5.0-7.0	5.0-8.0	0.30	0.25	1.0	0.08	0.03	0.005	0.005
C83810 ⁵	Rem. ¹³	2.0-3.5	4.0-6.0	7.5-9.5	0.50		2.0		-	0.005	0.10

SEMI-RED BRASSES AND LEADED SEMI-RED BRASSES

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ^{4, 13}	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co)	P	Al	Si	Bi
C84000	82.0-89.0 ¹³	2.0-4.0	0.09	5.0-14.0	0.04	0.20	0.50-2.0	0.05	0.005	0.005	
C84010	82.0-89.0 ¹³	2.0-4.0	0.09	5.0-14.0	0.04	0.20	0.50-2.0	0.05	0.005	0.005	
C84020	82.0-89.0 ¹³	2.0-4.0	0.09	5.0-14.0	0.04	0.20	0.50-2.0	0.05			
C84030	82.0-89.0 ¹³	2.0-4.0	0.09	5.0-14.0	0.04	0.10-1.5	0.50-2.0	0.05			
C84200	78.0-82.0 ^{4,13}	4.0-6.0	2.0-3.0	10.0-16.0	0.40	0.25	0.8 ²	0.05 ³	0.005	0.005	-
C84400	78.0-82.0 ^{4,13}	2.3-3.5	6.0-8.0	7.0-10.0	0.40	0.25	1.0 ²	0.02 ³	0.005	0.005	-
C84410 ³⁰	Rem. ^{4,13}	3.0 - 4.5	7.0-9.0	7.0-11.0			1.0 ²	-	0.01	0.2	0.05
C84500	77.0-79.0	2.0-4.0	6.0-7.5	10.0-14.0	0.4	0.25	1.0 ²	0.02 ³	0.005	0.005	-
C84800	75.0-77.0	2.0-3.0	5.5-7.0	13.0-17.0	0.4	0.25	1.0 ²	0.02 ³	0.005	0.005	-

Copper Alloy No.	Other Named Elements
C84000	Mn 0.01, S 0.10-0.65, B 0.10, Zr 0.10
C84010	Mn 0.01-0.20, S 0.10-0.65, B 0.10, Zr 0.10
C84020	Mn 0.20, S 0.10-0.65, B 0.10, Zr 0.10, C 0.10, Ti 0.10
C84030	Mn 0.20, S 0.10-0.65, B 0.10, Zr 0.10, C 0.10, Ti 0.10
C84200	S 0.08
C84400	S 0.08
C84410	
C84500	S 0.08
C84800	S 0.08

YELLOW BRASSES AND LEADED YELLOW BRASSES

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ⁴	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co)	Mn	As	S	P	Si
C85200	70.0-74.0 ¹⁴	0.7-2.0	1.5-3.8	20.0-27.0	0.6	0.20	1.0			0.05	0.02	0.05
C85400	65.0-70.0 ¹⁵	0.50-1.5	1.5-3.8	24.0-32.0	0.7		1.0 ²					0.05
C85450	60.0-64.0 ¹²	0.50-1.5	0.09	Rem.	0.30-1.0		1.0 ²	0.6				
C85470	60.0-65.0	1.0-4.0	0.09	Rem	0.20						0.02-0.25	
C85500	59.0-63.0 ^{3,14}	0.20	0.20	Rem.	0.20		0.20 ²	0.20				
C85550	59.0-64.0 ¹²	0.30	0.09	Rem	0.15		0.20 ²					0.30-1.0
C85560	60.0-64.0 ^{12,28}	0.20-0.50	0.10-0.25	Rem ³¹	0.15		0.20		0.05-0.20 ³²			
C85700	58.0-64.0 ¹⁶	0.50-1.5	0.8-1.5	32.0-40.0	0.7		1.0					0.05
C85800	57.0min. ¹⁶	1.5	1.5	31.0-41.0	0.50	0.05	0.50 ²	0.25	0.05	0.05	0.01	0.25
C85900	58.0-62.0	1.5	0.09	31.0-41.0	0.05	0.20	1.5	0.01		0.10-0.65	0.01	0.25
C85910	58.0-62.0	1.5	0.09	31.0-41.0	0.05	0.20	1.5	0.01-0.20		0.10-0.65	0.01	0.25
C85920	58.0-62.0	1.5	0.09	31.0-41.0	0.05	0.20	1.5			0.10-0.65		0.25
C85930	58.0-62.0	1.5	0.09	31.0-41.0	0.05	0.10-1.5	1.5			0.10-0.65		0.25

Copper Alloy No.	Other Named Elements
C85200	Al 0.005
C85400	Al 0.35
C85450	Al 1.0
C85470	Al 0.10-1.0
C85500	
C85550	Al 0.30
C85560	Bi 0.60-0.90
C85700	Al 0.8
C85800	Al 0.55
C85900	Al 0.10-0.6, B 0.20, Zr 0.20
C85910	Al 0.10-0.6, B 0.20, Zr 0.20
C85920	Al 0.10-0.6, B 0.20, Zr 0.20, C 0.10, Ti 0.30
C85930	Al 0.10-0.6, B 0.20, Zr 0.20, C 0.10, Ti 0.30

MANGANESE AND LEADED MANGANESE BRONZE ALLOYS

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ^{4,17}	Sn	Pb	Zn	Fe	Ni (incl. Co)	Al	Mn	Si	Other Named Elements
C86100	66.0-68.0	0.20	0.20	Rem.	2.0-4.0	-	4.5-5.5	2.5-5.0		
C86200	60.0-66.0	0.20	0.20	22.0-28.0	2.0-4.0	1.0	3.0-4.9	2.5-5.0		
C86300	60.0-66.0	0.20	0.20	22.0-28.0	2.0-4.0	1.0	5.0-7.5	2.5-5.0		
C86350	60.0-64.0	0.8	0.09	Rem	1.0	0.50	0.30-1.1	2.0-5.0		Mg 0.10
C86400	56.0-62.0	0.50-1.5	0.50-1.5	34.0-42.0	0.40-2.0	1.0	0.50-1.5	0.10-1.0		
C86500	55.0-60.0	1.0	0.40	36.0-42.0	0.40-2.0	1.0	0.50-1.5	0.10-1.5		
C86550	57.0 min.	1.0	0.50	Rem.	0.7-2.0	1.0	0.50-2.5	0.10 - 0.30	0.10	
C86700	55.0-60.0	1.5	0.5-1.5	30.0-38.0	1.0-3.0	1.0	1.0-3.0	1.0-3.5		
C86800	53.5-57.0	1.0	0.20	Rem.	1.0-2.5	2.5-4.0	2.0	2.5-4.0		

COPPER-SILICON ALLOYS (Silicon Bronzes and Silicon Brasses)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Zn	Fe	Al	Si	Mn	Mg	Ni (incl. Co)	S
C87200	89.0				2.5						
C87300	94.0min ¹²		0.09	0.25	0.20		3.5-4.5	.8-1.5			
C87400	79.0min. ¹⁸		1.0	12.0-16.0		0.8	2.5-4.0				
C87500	79.0min. ¹²		0.09	12.0-16.0		0.50	3.0-5.0				
C87600	88.0min.		0.09	4.0-7.0	0.20		3.5-5.5	0.25			
C87610	90.0 min. ¹²		0.09	3.0-5.0	0.20		3.0-5.0	0.25			
C87700	87.5 min. ¹⁸									0.25	
C87710	87.5 min. ¹⁸									0.25	
C87800	80.0 min. ¹²	0.25	0.15	12.0-16.0	0.15	0.15	3.8-4.2	0.15	0.01	0.20 ²	0.05
C87845	75.0-78.0 ¹²	0.10	0.02	Rem	0.10	0.09	2.5-2.9	0.10		0.20 ²	
C87850	74.0-78.0 ¹²	0.30	0.09	Rem	0.10	0.09	2.7-3.4	0.10		0.20 ²	
C87860	75.0-79.0 ¹²	0.30	0.09	Rem	0.10		2.7-3.5	0.10		0.20 ²	
C87870	75.0-79.0 ¹²	0.30-0.7	0.09	16.0-23.0	0.10		2.7-3.5	0.10		0.20 ²	

Copper Alloy No.	Other named elements
C87200	
C87300	
C87400	-
C87500	-
C87600	-
C87610	
C87700	
C87710	
C87800	P 0.01 P, As 0.05, Sb 0.05
C87845	P 0.03-0.06, As 0.015, Sb 0.015
C87850	Sb 0.10
C87860	Zr 0.002-0.030
C87870	Zr 0.030

COPPER-BISMUTH AND COPPER-BISMUTH-SELENIUM ALLOYS

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co)	S	P	Al	Si	Bi	Se	Other named elements
C89320	87.0-91.0 ¹²	5.0-7.0	0.09	1.0	0.20	0.35	1.0	0.08	0.30	0.005	0.005	4.0-6.0	-	
C89325	84.0-88.0 ^{17,28}	9.0-11.0	0.10	1.0	0.15	0.50	1.0	0.08	0.10	0.005	0.005	2.7-3.7	-	
C89510	86.0-88.0 ¹²	4.0-6.0	0.09	4.0-6.0	0.20	0.25	1.0	0.08	0.05	0.005	0.005	0.50-1.5 ³⁴	0.35-75 ³⁴	
C89520	85.0-87.0 ¹²	5.0-6.0	0.09	4.0-6.0	0.20	0.25	1.0	0.10-0.65		0.005		1.5-2.2 ³⁴	0.8-1.2 ³⁴	
C89530	84.0-89.0 ¹²	3.5-6.0	0.20	7.0-9.0	0.30	0.20	1.0		0.05	0.01	0.01	1.0-2.0	0.10-0.30	
C89535	84.0-89.0 ¹²	2.5-5.5	0.25	5.0-9.0	0.30	0.20	0.30-1.0		0.04	0.01	0.01	0.8-2.0	0.50	
C89537	84.0-86.0 ¹²	3.0-6.0	0.09	5.0-13.0	0.50							0.6-1.2	0.50-3.0	Mg 0.01-0.10, B 0.0005-0.0020
C89540	58.0-64.0 ¹²	1.2	0.10	32.0-38.0	0.50		1.0			0.10-0.60		0.6-1.2	0.10	
C89550	58.0-64.0 ¹²	1.2	0.09	32.0-40.0	0.50	0.05	1.0	0.05	0.01	0.10-0.6	0.25	0.6-1.2	0.01-0.10	-
C89560	58.0-61.0 ¹⁴	0.25	0.09	Rem	0.12					0.30-0.8		1.0-2.4		B 0.0003-0.0015, Cd 0.001
C89580	74.0-78.0 ¹²	0.50	0.09	Rem	0.10		0.30	0.30		0.10-1.2		0.10-1.0		
C89720	63.0 ¹²	0.6-1.5	0.09	26.0-32.0	0.10	0.02-0.20	0.10	0.10	0.02	0.35-1.5	0.40-1.0	0.50-2.0		Mn 0.10, Bi 0.0005-0.01
C89831	87.0-91.0 ^{17,28}	2.7-3.7	0.10	2.0-4.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005	2.7-3.7	-	
C89833	86.0-91.0 ¹³	4.0-6.0	0.09	2.0-4.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005	1.7-2.7	-	
C89835	85.0-89.0 ^{17,28}	6.0-7.5	0.09	2.0-4.0	0.20	0.35	1.0	0.08	0.10	0.005	0.005	1.7-2.7	-	
C89836	87.0-91.0 ¹²	4.0-7.0	0.25	2.0-4.0	0.35	0.25	0.90	0.08	0.06	0.005	0.005	1.5-3.5		
C89837	84.0-88.0 ^{17,28}	3.0-4.0	0.10	6.0-10.0	0.30	0.25	1.0	0.08	0.050	0.005	0.005	0.7-1.2	-	
C89841 ¹⁵	73.0-77.0 ¹²	0.30		18.0-23.0	0.10	0.10	0.20			0.01	2.8-3.4	0.50-1.0		Mn 0.10
C89842	78.0-82.0 ¹²	2.0-3.0	0.09	Rem	0.30	0.05	0.10-0.50		0.005-0.02	0.01	0.005	1.5-2.5		
C89844	83.0-86.0 ¹³	3.0-5.0	0.20	7.0-10.0	0.30	0.25	1.0	0.08	0.05	0.005	0.005	2.0-4.0	-	-
C89845	82.5-87.5 ¹²	3.0-5.0	0.09	6.0-9.0	0.30	0.25	1.5-2.5			0.01	0.01	1.0-2.0		
C89940	64.0-68.0 ¹²	3.0-5.0	0.01	3.0-5.0	0.7-2.0	0.10	20.0-23.0	0.05	0.10-0.15	0.005	0.15	4.0-5.5	-	20Mn

COPPER-TIN ALLOYS (Tin Bronzes)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co)	S	P	Al	Si	Mn
C90200	91,0-94,0 ^{4,19}	6,0-8,0	0,30	0,50	0,20	0,20	0,50	0,05	0,05 ³	0,005	0,005	
C90280	87,0-90,0 ¹²	9,0-11,0	0,09		0,30-0,6			0,30-0,6	0,05			
C90300	86,0-89,04 ^{4,19}	7,5-9,0	0,30	3,0-5,0	0,20	0,20	1,05	0,05	0,05	0,005	0,005	
C90400	86,0-89,0 ¹³	7,5-8,5	0,09	1,0-5,0	0,40	0,02	1,0	0,10-0,65	0,05	0,005	0,005	0,01
C90410	86,0-89,0 ¹³	7,5-8,5	0,09	1,0-5,0	0,40	0,02	1,0	0,10-0,65	0,05	0,005	0,005	0,01-0,20
C90420	86,0-89,0 ¹³	7,5-8,5	0,09	1,0-5,0	0,40	0,02	1,0	0,10-0,65	0,05	0,005	0,005	0,20
C90430	86,0-89,0 ¹³	7,5-8,5	0,09	1,0-5,0	0,40	0,10-1,5	1,0	0,10-0,65	0,05	0,005	0,005	0,20
C90500	86,0-89,0 ^{4,22}	9,0-11,0	0,30	1,0-3,0	0,20	0,20	1,0	0,05	0,05 ³	0,005	0,005	
C90700	88,0-90,0 ^{4,19}	10,0-12,0	0,50	0,50	0,15	0,20	0,50	0,05	0,30 ³	0,005	0,005	
C90710	Rem. ^{4,19}	10,0-12,0	0,25	0,05	0,10	0,20	0,10	0,05	0,05-1,2 ³	0,005	0,005	
C90800	85,0-89,0 ^{4,19}	11,0-13,0	0,25	0,25	0,15	0,20	0,50	0,05	0,30 ³	0,005	0,005	
C90810	Rem. ^{4,19}	11,0-13,0	0,25	0,30	0,15	0,20	0,50	0,05	0,15-0,8 ³	0,005	0,005	
C90900	86,0-89,0 ^{4,19}	12,0-14,0	0,25	0,25	0,15	0,20	0,50	0,05	0,05 ³	0,005	0,005	
C91000	84,0-86,0 ^{4,19}	14,0-16,0	0,20	1,50	0,10	0,20	0,8	0,05	0,05 ³	0,005	0,005	
C91100	82,0-85,0 ^{4,19}	15,0-17,0	0,25	0,25	0,25	0,20	0,50	0,05	1,0 ³	0,005	0,005	
C91300	79,0-82,0 ^{4,19}	18,0-20,0	0,25	0,25	0,25	0,20	0,50	0,05	1,0 ³	0,005	0,005	
C91600	86,0-89,0 ^{4,19}	9,7-10,8	0,25	0,25	0,20	0,20	1,2-2,0	0,05	0,30 ³	0,005	0,005	
C91700	84,0-87,0 ^{4,19}	11,3-12,5	0,25	0,25	0,20	0,20	1,2-2,0	0,05	0,30 ³	0,005	0,005	

Copper Alloy No.	Other Named Elements
C90200	
C90280	
C90300	
C90400	B 0,10, Zr 0,10
C90410	B 0,10, Zr 0,10
C90420	B 0,10, C 0,10, Ti 0,10Zr 0,10
C90430	B 0,10, C 0,10, Ti 0,10Zr 0,10
C90500	
C90700	
C90710	
C90800	
C90810	
C90900	
C91000	
C91100	
C91300	
C91600	
C91700	

COPPER-TIN-LEAD ALLOYS

Leaded Tin Bronzes

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ^{4,13}	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co)	S	P ³	Al	Si	Mn
C92200	86,0-90,0	5,5-6,5	1,0-2,0	3,0-5,0	0,25	0,25	1,0	0,05	0,05	0,005	0,005	
C92210	86,0-89,0	4,5-5,5	1,7-2,5	3,0-4,5	0,25	0,20	0,7-1,0	0,05	0,03	0,005	0,005	
C92220	86,0-88,0	5,0-6,0	1,5-2,5	3,0-5,5	0,25	-	0,50-1,0	-	0,05	-	-	
C92300	85,0-89,0	7,5-9,0	0,30-1,0	2,5-5,0	0,25	0,25	1,0	0,05	0,05	0,005	0,005	
C92310	Rem.	7,5-8,5	0,30-1,5	3,5-4,5	-	-	1,0		-	0,005	0,005	0,03
C92400	86,0-89,0	9,0-11,0	1,0-2,5	1,0-3,0	0,25	0,25	1,0	0,05	0,05	0,005	0,005	-
C92410	Rem.	6,0-8,0	2,5-3,5	1,5-3,0	0,20	0,25	0,20	-	-	0,005	0,005	0,05
C92500	85,0-88,0	10,0-12,0	1,0-1,5	0,50	0,30	0,25	0,8-1,5	0,05	0,03	0,005	0,005	-
C92600	86,0-88,5	9,3-10,5	0,8-1,5	1,3-2,5	0,20	0,25	0,7	0,05	0,03	0,005	0,005	
C92610	Rem.	9,5-10,5	0,30-1,5	1,7-2,8	0,15		1,0		-	0,005	0,005	0,03
C92700	86,0-89,0	9,0-11,0	1,0-2,5	0,7	0,20	0,25	1,0	0,05	0,25	0,005	0,005	
C92710	Rem.	9,0-11,0	4,0-6,0	1,0	0,20	0,25	2,0	0,05	0,10	0,005	0,005	
C92800	78,0-82,0	15,0-17,0	4,0-6,0	0,8	0,20	0,25	0,8	0,05	0,05	0,005	0,005	
C92810	78,0-82,0	12,0-14,0	4,0-6,0	0,50	0,50	0,25	0,8-1,2	0,05	0,05	0,005	0,005	
C92900	82,0-86,0	9,0-11,0	2,0-3,2	0,25	0,20	0,25	2,8-4,0	0,05	0,05	0,005	0,005	

High-Leaded Tin Bronzes

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co.)	S	P ³	Al	Si
C93100	Rem. ^{4,13}	6.5-8.5	2.0-5.0	2.0	0.25	0.25	1.0	0.05	0.30	0.005	0.005
C93200	81.0-85.0 ^{4,17}	6.3-7.5	6.0-8.0	1.0-4.0	0.20	0.35	1.0	0.08	0.15	0.005	0.005
C93400	82.0-85.0 ^{4,17}	7.0-9.0	7.0-9.0	0.8	0.20	0.50	1.0	0.08	0.50	0.005	0.005
C93500	83.0-86.0 ^{4,17}	4.3-6.0	8.0-10.0	2.0	0.20	0.30	1.0	0.08	0.05	0.005	0.005
C93600	79.0-83.0 ¹³	6.0-8.0	11.0-13.0	1.0	0.20	0.55	1.0	0.08	0.15	0.005	0.005
C93700 ⁷	78.0-82.0 ¹⁷	9.0-11.0	8.0-11.0	0.8	0.7 ³⁵	0.50	0.50	0.08	0.10	0.005	0.005
C93720	83.0 min ¹⁷	3.5-4.5	7.0-9.0	4.0	0.7	0.50	0.50	-	0.10	-	-
C93800	75.0-79.0 ¹⁷	6.3-7.5	13.0-16.0	0.8	0.15	0.8	1.0	0.08	0.05	0.005	0.005
C93900	76.5-79.5 ¹⁵	5.0-7.0	14.0-18.0	1.5	0.40	0.50	0.8	0.08	1.5	0.005	0.005
C94000 ⁵	69.0-72.0 ¹⁶	12.0-14.0	14.0-16.0	0.50	0.25	0.50	0.50-1.0	0.088	0.05	0.005	0.005
C94100 ⁸	72.0-79.0 ¹⁶	4.5-6.5	18.0-22.0	1.0	0.25	0.8	1.0	0.088	0.50	0.005	0.005
C94300 ⁸	67.0-72.0 ¹⁷	4.5-6.0	23.0-27.0	0.8	0.15	0.8	1.0	0.088	0.08	0.005	0.005
C94310	Rem. ¹⁷	1.5-3.0	27.0-34.0	0.50	0.50	0.50	0.25-1.0	-	0.05	-	-
C94320	Rem. ¹⁷	4.0-7.0	24.0-32.0	-	0.35	-	-	-	-	-	-
C94330	68.5-75.5 ¹⁷	3.0-4.0	21.0-25.0	3.0	0.7	0.50	0.50	-	0.10	-	-
C94400	Rem. ¹⁷	7.0-9.0	9.0-12.0	0.8	0.15	0.8	1.0	0.08	0.50	0.005	0.005
C94500	Rem. ¹⁷	6.0-8.0	16.0-22.0	1.2	0.15	0.8	1.0	0.08	0.05	0.005	0.005

COPPER-TIN-NICKEL ALLOYS (Nickel-Tin Bronzes)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co.)	Mn	S	P	Al	Si
C94700 ⁹	85.0-90.0 ¹⁶	4.5-6.0	1.0-2.5	1.0-2.5	0.25	0.15	4.5-6.0	0.20	0.05	0.05	0.005	0.005
C94800	84.0-89.0 ¹⁶	4.5-6.0	1.0-2.5	1.0-2.5	0.25	0.15	4.5-6.0	0.20	0.05	0.05	0.005	0.005
C94900	79.0-81.0 ¹⁹	4.0-6.0	4.0-6.0	4.0-6.0	0.30	0.25	4.0-6.0	0.10	0.08	0.05	0.005	0.005

COPPER-ALUMINUM-IRON AND COPPER-ALUMINUM-IRON-NICKEL ALLOYS (Aluminum Bronzes)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Pb	Fe	Ni (incl. Co.)	Al	Mn	Mg	Si	Zn	P	Other name elements
C95200	86.0 min. ¹⁷		2.5-4.0		8.5-9.5						
C95210	86.0 min. ¹⁷	0.05	2.5-4.0	1.0	8.5-9.5	1	0.05	0.25	0.50		Sn 0.10
C95220	Rem. ¹²	-	2.5-4.0	2.5	9.5-10.5	0.50	-	-	-		
C95300	86.0 min. ¹⁷		0.8-1.5		9.0-11.0						
C95400	83.0 min. ¹²		3.0-5.0	1.5	10.0-11.5	0.50					
C95410	83.0 min. ¹²		3.0-5.0	1.5-2.5	10.0-11.5	0.50					
C95420	83.5min. ¹²	-	3.0-4.3	0.50	10.5-12.0	0.50	-	-	-		
C95500	78.0 min. ¹²		3.0-5.0	3.0-5.5	10.0-11.5	3.5					
C95510	78.0min. ³³	-	2.0-3.5	4.5-5.5	9.7-10.9	1.5	-	-	0.30		.20Sn
C95520	74.5min. ¹²	0.03	4.0-5.5	4.2-6.0	10.5-11.5	1.5	-	0.15	0.30		.25Sn - .20Co - .05Cr
C95600	88.0 min. ¹⁷			0.25	6.0-8.0			1.8-3.2			
C95700	71.0 min. ¹²		2.0-4.0	1.5-3.0	7.0-8.5	11.0-14.0		0.10			
C95710	71.0 min. ¹²	0.05	2.0-4.0	1.5-3.0	7.0-8.5	11.0-14.0		0.15	0.50	0.05	Sn 1.0
C95720	73.0min ¹²	0.03	1.5-3.5	3.0-6.0	6.0-8.0	12.0-15.0	-	0.10	0.10		.10Sn - .20Cr
C95800 ²⁰	79.0 min. ¹²	0.03	3.5-4.5 ²⁰	4.0-5.0	8.5-9.5	0.8-1.5		0.10		-	
C95810 ²⁰	79.0 min. ¹²	0.09	3.5-4.5 ²⁰	4.0-5.0	8.5-9.5	0.8-1.5		0.10	0.05	-	
C95820	77.5min. ¹⁸	0.02	4.0-5.0	4.5-5.8	9.0-10.0	1.5	-	0.10	0.20		.20Sn
C95900	Rem. ¹²	-	3.0-5.0	0.50	12.0-13.5	1.5	-	-	-		

COPPER-NICKEL-IRON ALLOYS (Copper-Nickels)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu ¹²	Pb ¹⁰	Fe	Ni (incl. Co.)	Mn	Si	Nb	C	Be	Other named elements
C96200 ²¹	Rem.	0.01	1.0-1.8	9.0-11.0	1.5	0.50	1.0 ²¹	0.10		P 0.02, S 0.02
C96300	Rem.	0.01	0.50-1.0	18.0-22.0	0.25-1.5	0.50	0.50 – 1.5	0.15		P 0.02, S 0.02
C96400	Rem.	0.01	0.25-1.5	28.0-32.0	1.5	0.50	0.50 - 1.5	0.15	-	P 0.02, S 0.02
C96600	Rem.	0.01	0.80 - 1.1	29.0-33.0	1.0	0.15		-	0.40-7	-
C96700	Rem.	0.01	0.40-1.0	29.0-33.0	0.40 – 1.0	0.15		-	1.1-1.2	Ti 0.15-0.35, Zr 0.15-0.35
C96800	Rem. ¹¹	0.005	0.50	9.5-10.5	0.05 - .30	0.05	0.10 - .30			Sn 7.5-8.5, Mg 0.025, 0.15, Zn 1.0
C96900	Rem.	0.02	0.50	14.5-15.5	0.05 - .30	-	0.10	-	-	Sn 7.5-8.5, Mg 0.15, Zn 0.50
C96950	Rem.	0.02	0.50	11.0-15.5	0.05 - 0.40	0.30	0.10	-	-	Sn 5.8-8.5, Mg 0.15
C96970	Rem.	0.02	0.50	8.5-9.5	0.30		0.10			Sn 5.5-6.5, Mg 0.15, Zn 0.50

COPPER-NICKEL-ZINC ALLOYS (Nickel Silvers)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Zn	Fe	Sb	Ni (incl. Co.)	S	P	Al	Other named elements
C97300	53.0-58.0 ¹⁷	1.5-3.0	8.0-11.0	17.0-25.0	1.5	0.35	11.0-14.0	0.08	0.05	0.005	Si 0.15, Mn 0.50
C97400	58.0-61.0 ¹⁷	25-3.5	4.5-5.5	Rem.	1.5		15.5-17.0				Mn 0.50
C97600	63.0-67.0 ²²	3.5-4.5	3.0-5.0	3.0-9.0	1.5	0.25	19.0-21.5	0.05	0.05	0.005	Si 0.15, Mn 1.0
C97800	64.0-67.0 ²³	4.0-5.5	1.0-2.5	1.0-4.0	1.5		24.0-27.0	0.05	0.05	0.005	Si 0.15, Mn 1.0

COPPER-LEAD ALLOYS (Leaded Coppers)

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Cu	Sn	Pb	Ag	Zn	P	Fe	Ni	Sb
C98200	Rem. ¹²	0.6-2.0	21.0-27.0	-	0.50	0.10	0.7	0.50	0.50
C98400	Rem. ¹²	0.50	26.0-33.0	1.5	0.50	0.10	0.7	0.50	0.50
C98600	60.0-70.0	0.50	30.0-40.0	1.5	-	-	0.35		
C98800	56.5-62.5 ^{1,28}	0.25	37.5-42.5 ²⁴	5.5 ²⁴	0.10	0.02	0.35		
C98820	56.5-62.5 ¹	1.0-5.0	40.0-44.0				0.35		
C98840	Rem.	1.0-5.0	44.0-58.0				0.35		

SPECIAL ALLOYS

Composition, Percent Maximum (Unless shown as a range or a minimum)

Copper Alloy No.	Other designation	Cu ²²	Sn	Pb	Ni	Fe	Al	Zn	Si	Mn	Other named elements
C99300	Incramet800	Rem.	0.05	0.02	13.5-16.5	0.40-1.0	10.7-11.5		0.02		1.0-2.0 Co
C99350		Rem.		0.15	14.5-16.0 ²	1.0	9.5-10.5	7.5-9.5		0.25	
C99400		Rem.		0.25	1.0-3.5	1.0-3.0	.50-2.0	.50-5.0	.50-2.0	0.50	
C99500		Rem.		0.25	3.5-5.5	3.0-5.0	.50-2.0	.50-2.0	.50-2.0	0.50	
C99600	Incramute 1	Rem.	0.10	0.02	0.20	0.20	1.0-2.8	0.20	0.10	39.0-45.0	0.20 Co, 0.05 C
C99700	White Tombasil	54.0 min.	1.0	2.0	4.0-6.0	1.0	0.50-3.0	19.0-25.0		11.0-15.0	
C99710	White Tombasil	60.0 min.	1.0	0.09	4.0-6.0	1.0	1.0	19.0-25.0		11.0-15.0	
C99720	White Tombasil	54.0-59.0 ³³	1.5-2.0	0.05	5.0-6.0	0.6-1.0	1.0-1.4	18.0-24.0	0.05	11.0-14.0	Bi 2.0-3.0, P 0.05
C99740	White Tombasil	55.0-60.0 ³³	1.5-2.0	0.05	5.0-6.0	0.6-1.0	1.0-1.4	17.0-23.0	0.05	11.0-14.0	P 0.1, Bi 4.0
C99750	White Tombasil	55.0-61.0		0.50-2.5	5.0	1.0	0.25-3.0	17.0-23.0		17.0-23.0	
C99760	White alloys	61.0-67.0 ¹³	0.20-1.0	0.09	8.0-12.0 ²	0.6	0.6	8.0-14.0	0.05	10.0-16.0	Sb 0.10-1.0, P 0.05, C 0.10, S 0.25
C99761	White alloys	58.0-64.0 ¹³	0.20-1.5	0.09	8.0-10.0 ²	0.6	0.10-2.0	16.0-21.0	0.05	8.0-12.0	Sb 0.10-1.0, P 0.05, C 0.10, S 0.25
C99770	White alloys	66.0-70.0 ¹³	0.20-1.0	0.09	3.0-6.0 ²	0.6	0.6	8.0-14.0	0.05	10.0-16.0	Sb 0.10-1.0, P 0.05, C 0.10, S 0.25
C99771	White alloys	62.0-70.0 ¹³	0.20-1.5	0.09	2.0-4.0 ²	0.6	0.10-2.0	16.0-21.0	0.05	8.0-12.0	Sb 0.10-1.0, P 0.05, C 0.10, S 0.25
C99780	White alloys	62.0-66.0 ³³	0.50-2.0	0.05	4.0-6.0	0.50	0.30-1.0	16.0-20.0	0.05	12.0-15.0	P 0.05, Bi 2.0

NOTES

1. Includes Ag.
2. Ni + Co.
3. For continuous castings, phosphorus shall be 1.5% maximum.
4. In determining copper minimum, copper may be calculated as Cu + Ni.
5. C83810
6. By agreement between supplier and consumer.
7. C93700
8. C94000, C94100, C94300
9. C94700
10. For welding grades, Pb may not exceed .01 %, for copper-nickel alloys.
11. The following additional impurity limits shall apply:
Al, .10 max; B, .001 max; Bi, .001 max; Mg, .005-15; P, .005 max; S, .0025 max; Sb, .02 max; Sn, 7.5-8.5; Ti, .01 max; Zn, 1.0 max.
12. Cu + sum of named elements, 99.5% min.
13. Cu + sum of named elements, 99.3% min.
14. Cu + sum of named elements, 99.1% min.
15. Cu + sum of named elements, 98.9% min.
16. Cu + sum of named elements, 98.7% min.
17. Cu + sum of named elements, 99.0% min.
18. Cu + sum of named elements, 99.2% min.
19. Cu + sum of named elements, 99.4% min.
20. C95800, C95810
21. C96200
22. Cu + sum of named elements, 99.7% min.
23. Cu + sum of named elements, 99.6% min.
24. Pb and Ag may be adjusted to modify the alloy hardness.
25. C89841
26. .01 – 2.0% as any single or combination of Ce, La or any other rare earth* elements, as agreed upon.
27. Removed from this edition.
28. Cu value includes Ag.
29. For continuous castings, P shall be 1.0% max.
30. C84410
31. For optimum dezincification resistance (DZR) properties, Zn should not exceed 38%.
32. P may be substituted for As.
33. Cu + Sum of Named Elements, 99.8% min.
34. Bi:Se . = 2:1
35. Fe shall be 0.35% max. when used for steel backed bearings.

* ASM International definition: One of the group of chemically similar metals with atomic numbers 57 through 71, commonly referred to as lanthanides.

CHAPTER 2

CONFORMING SPECIFICATIONS FOR COPPER-BASE ALLOYS

Today, there is a confusing array of specification requirements confronting the metalcaster. The purpose of this chapter is to provide guidance as to where definitions of such specifications can be found, and to explain the relationships between the various sets of specifications. These relationships are based on the alloy numbers, which are listed on the following pages in numerical order, together with the relevant specification numbers for different products. This list covers only data from the major national standards-writing bodies and does not include the many individual specifications issued by private companies and public utilities to meet their own special requirements. For further information the reader is referred to the Copper Development Association (www.copper.org). Contact information is available at the end of this chapter.

Copies of specifications may be obtained from the sources listed at the end of this section. It must be emphasized that although different specifications may be listed under an alloy number, this does not mean that the requirements of the specification are identical; it is necessary to refer to the particular specification quoted on the foundry order before manufacture is commenced. As an example, 33 alloys are covered in ASTM B584 but only three alloys are permissible in the related ASME Boiler and Pressure Vessel Code specification SB584.

ALLOY NO. C80100

Ingot	
Federal	QQ-C-521

ALLOY NO. C81400

Ingot	
ASTM	B30
Sand	
ASTM	B770

ALLOY NO. C81500

Centrifugal	
Military	MIL-C-19310
Sand	
Military	MIL-C-19310

ALLOY NO. C82000

Ingot	
ASTM	B30
Sand	
ASTM	B770
Federal	QQ-C-390

ALLOY NO. C82200

Ingot	
ASTM	B30
Sand	
ASTM	B770

ALLOY NO. C82400

Centrifugal	
Federal	QQ-C-390
Ingot	
ASTM	B30
Sand	
ASTM	B770
Federal	QQ-C-390
Valves	
Federal	WW-V-1967

ALLOY NO. C82500

Centrifugal	
Federal	QQ-C-390
Investment	
AMS	4890, 4511
Military	MIL-C-22087
Precision	
Military	MIL-C-11866,
	Composition 17
Sand	
Federal	QQ-C-390
Ingot	
ASTM	B30
Sand	
ASTM	B770

ALLOY NO. C82510

Ingot	
ASTM	B30
Sand	
ASTM	B770

ALLOY NO. C82600

Sand	
Federal	QQ-C-390
Valves	
Federal	WW-V-1967
Ingot	
ASTM	B30
Sand	
ASTM	B770

ALLOY NO. C82700

Sand	
Federal	QQ-C-390
Valves	
Federal	WW-V-1967

ALLOY NO. C82800

Ingot	
ASTM	B30
Sand	
ASTM	B770
Federal	QQ-C-390
Valves	
Federal	WW-V-1967

ALLOY NO. C83300

Ingot
Ingot No. 131

ALLOY NO. C83400

Bands, Projectile Rotating
Military MIL-B-46066

ALLOY NO. C83450

Sand
ASTM B584, B763
Ingot
ASTM B30
Valves
ASTM B763

ALLOY C83470

Continuous
ASTM B505
Ingot
ASTM B30
Sand
ASTM B584

ALLOY NO. C83500

Ingot
Ingot No. 251

ALLOY NO. C83600

Centrifugal
AMS 4855
ASME SB271
ASTM B271
Military MIL-C-15345,
Alloy 1
SAE J461, J462
Continuous
AMS 4855
ASTM B505
SAE J461, J462
Fittings
ANSI B16.15; B16.18;
B16.23; B16.26;
B16.32
ASME SB62, B16.15;
B16.18; B16.23;
B16.26; B16.32
ASTM B62
Federal WW-P-460,
WW-T-725
Flanges
ANSI B16.24
ASME SB62
ASTM B62
Ingot
ASTM B30
Federal QQ-C-525
Ingot No. 115
Investment
AMS 4855
Military MIL-C-22087
SAE J461, J462
Precision
Military MIL-C-11866,
Composition 25
Sand
AMS 4855
ASME SB62
ASTM B62, B584
Federal QQ-C-390
Military MIL-C-22229
SAE J461, J462
Unions
Federal WW-U-516
Valves
Federal WW-V-51,
WW-V-54,
WW-V-1967
Military MIL-V-16720,
MIL-V-18436

ALLOY NO. C83800

Centrifugal
ASTM B271
Federal QQ-C-390
SAE J461, J462
Continuous
ASTM B505
Federal QQ-C-390
SAE J461, J462
Fittings
ASME B16.15, B16.18,
B16.23
ANSI B16.15; B16.18;
B16.23; B16.26;
B16.32
ASTM B584
Federal WW-T-725
Ingot
ASTM B30
Ingot No. 120
Sand
ASTM B584 B763
Federal QQ-C-390
SAE J461, J462
Unions
Federal WW-U-516
Valves
Federal WW-V-1967

ALLOY NO. C84020

Ingot
ASTM B30
Sand
ASTM B584

ALLOY NO. C84030

Ingot
ASTM B30
Sand
ASTM B584

ALLOY NO. C84200

Continuous
ASTM B505
Federal QQ-C-390
Fittings
Federal WW-P-460
Ingot
ASTM B30
Federal QQ-C-525
Ingot No. 101

ALLOY NO. C84400

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Continuous	
ASTM	B505
Federal	QQ-C-390
Fittings	
ASME	B16.15, B16.18, B16.23, B16.26, B16.32
ANSI	B16.15; B16.18; B16.23; B16.26; B16.32
ASTM	B584
Federal	WW-T-725
Ingot	
ASTM	B30
Federal	QQ-C-525
Ingot No.	123
Sand	
ASTM	B584
Federal	QQ-C-390
Unions	
Federal	WW-U-516
Valves	
Federal	WW-V-54
ASTM	B763

ALLOY NO. C84500

Ingot	
Ingot No.	125

ALLOY NO. C84800

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Ingot No.	130
Sand	
ASTM	B584, B763
Federal	QQ-C-390
Valves	
ASTM	B763

ALLOY NO. C85200

Centrifugal	
ASTM	B271
SAE	J461, J462
Continuous	
SAE	J461, J462
Ingot	
ASTM	B30
Ingot No.	400
Sand	
ASTM	B584, B763
Federal	QQ-C-390
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C85400

Centrifugal	
ASTM	B271
SAE	J461, J462
Continuous	
SAE	J461, J462
Ingot	
ASTM	B30
Ingot No.	125, 403
Permanent Mold	
SAE	J461, J462
Sand	
Federal	QQ-C-390
SAE	J461, J462
ASTM	B584, B763
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C85500

Centrifugal	
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 2
Sand	
Federal	QQ-C-390
Valves	
Federal	WW-V-1967

ALLOY NO. C85700

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 3
Continuous	
ASTM	505
Die	
ASTM	B176
Ingot	
ASTM	B30
Ingot No.	405.2
Sand	
ASTM	B584
Federal	QQ-C-390
Valves	
ASTM	B763

ALLOY NO. C85800

Die	
ASTM	B176
Military	MIL-B-15894
SAE	J461, J462
Ingot	
ASTM	B30
Ingot No.	405.1

ALLOY NO. C86100

Centrifugal	
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 5
Ingot	
ASTM	B30
Federal	QQ-C-390
Ingot No.	423
Investment	
Military	MIL-C-22087
Sand	
Federal	QQ-C-390
Military	MIL-C-22229
Valves	
Federal	WW-V-1967

ALLOY NO. C86200

Centrifugal	
AMS	4862
ASTM	B271
Federal	QQ-C-390
SAE	J461, J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Die	
SAE	J461, J462
Ingot	
ASTM	B30
Federal	QQ-C-523
Ingot No.	423
Investment	
SAE	J461, J462
Permanent Mold	
SAE	J461, J462
Precision	
Military	MIL-C-11866, Composition 20
Sand	
AMS	4862
ASTM	B584; B763
Federal	QQ-C-390
Military	MIL-C-22229
SAE	J461, J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C86300

Centrifugal	
AMS	4862
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 6
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Federal	QQ-C-523
Ingot No.	424
Investment	
AMS	4862
Military	MIL-C-22087
SAE	J461, J462
Precision	
Military	MIL-C-11866, Composition 21
Sand	
AMS	4862
ASTM	B22, B584
Federal	QQ-C-390
Military	MIL-C-22229
SAE	J461, J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C86400

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Federal	QQ-C-523
Ingot No.	420
Sand	
ASTM	B584; B763
Federal	QQ-C-390
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C86500

Centrifugal	
AMS	4860
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 4
SAE	J461; J462
Continuous	
ASTM	B505
Die	
ASTM	B176
Ingot	
ASTM	B30
Federal	QQ-C-523
Ingot No.	421
Investment	
AMS	4860
Military	MIL-C-22087
SAE	J461; J462
Permanent Mold	
SAE	J461, J462
Sand	
AMS	4860
ASTM	B584; B763
Federal	QQ-C-390
Military	MIL-C-22229
SAE	J461, J462
Valves	
Federal	WW-V-54, WW-V-1967
ASTM	B763

ALLOY NO. C86700

Centrifugal	
ASTM	B271
Ingot	
ASTM	B30
Ingot No.	422
Sand	
ASTM	B584; B763
Valves	
ASTM	B763

ALLOY NO. C86800

Die	
ASTM	B176
Sand	
Federal	QQ-C-390
Valves	
Federal	WW-V-1967

ALLOY NO. C87300

Centrifugal	
ASTM	B271
SAE	J461, J462
Ingot	
ASTM	B30
Ingot No.	500A
Precision	
Military	MIL-C-11866
Sand	
ASTM	B584, B763
Federal	QQ-C-390
SAE	J461, J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C87400

Centrifugal	
ASTM	B271
SAE	J461; J462
Die	
SAE	J461; J462
Ingot	
Ingot No.	500B
ASTM	B30
Investment	
Military	MIL-C-22087
SAE	J461; J462
Permanent Mold	
SAE	J461; J462
Sand	
ASTM	B584; B763
Federal	QQ-C-390
SAE	J461, J462
Valves	
Federal	WW-V-51; WW-V-1967
ASTM	B763

ALLOY NO. C87500

Centrifugal	
ASTM	B271
SAE	J461, J462
Die	
SAE	J461, J462
Ingot	
ASTM	B30
Ingot No.	500C
Investment	
Military	MIL-C-22087
SAE	J461, J462
Permanent Mold	
SAE	J461, J462
ASTM	B806
Sand	
ASTM	B584; B763
Federal	QQ-C-390
Valves	
ASTM	B763
Federal	WW-V-51; WW-V-54
Military	MIL-V-1187, MIL-V-1202

ALLOY NO. C87600

Centrifugal	
ASTM	B271
Ingot	
ASTM	B30
Ingot No.	500
Sand	
ASTM	B584; B763
Valves	
ASTM	B763
Federal	WW-V-51, WW-V-54
Military	MIL-V-1202

ALLOY NO. C87610

Ingot	
ASTM	B30
Ingot No.	500E
Sand	
ASTM	B584, B763
Valves	
ASTM	B763

ALLOY NO. C87800

Die	
ASTM	B176
Military	MIL-B-15894
SAE	J461, J462
Permanent	
ASTM	B806
Ingot	
ASTM	B30
Ingot No.	500

ALLOY NO. C87850

Ingot	
ASTM	B30
Sand	
ASTM	B584
Permanent Mold	
ASTM	B806

ALLOY NO. C89320

Continuous	
ASTM	B505
Ingot	
ASTM	B30

ALLOY NO. C89520

Ingot	
ASTM	B30
Sand	
ASTM	B584

ALLOY NO. C89535

Ingot	
ASTM	B30
Sand	
ASTM	B584, B763
Valve	
ASTM	B763

ALLOY NO. C89833

Ingot	
ASTM	B30
Sand	
ASTM	B584

ALLOY NO. C89836

Ingot	
ASTM	B30
Sand	
ASTM	B584

ALLOY NO. C89844

Ingot	
ASTM	B30
Sand	
ASTM	B584, B763
Valves	
ASTM	B763

ALLOY NO. C90200

Ingot	
Ingot No.	242

ALLOY NO. C90300

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 8
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
Federal	QQ-C-525
Ingot No.	225
Investment	
Military	MIL-C-22087
SAE	J461; J462
Precision	
Military	MIL-C-11866, Composition 26
SAE	J461; J462
Sand	
ASTM	B584; B763
Federal	QQ-C-390
Military	MIL-C-22229
SAE	J461, J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C90420

Ingot	
ASTM	B30
Sand	
ASTM	B584

ALLOY NO. C90500

Centrifugal	
AMS	4845, 4846
ASTM	B271
Federal	QQ-C-390
SAE	J461; J462
Continuous	
AMS	4845
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	210
Investment	
SAE	J461; J462
Sand	
AMS	4845
ASTM	B22; B763; B584
Federal	QQ-C-390
SAE	J461; J462
Valves	
ASTM	B763

ALLOY NO. C90700

Centrifugal	
ASTM	B427
SAE	J461, J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461, J462
Ingot	
ASTM	B30
Ingot No.	205
Investment	
SAE	J461, J462
Permanent Mold	
SAE	J461, J462
Sand	
ASTM	B427
SAE	J461, J462

ALLOY NO. C90800

Centrifugal	
ASTM	B427
Ingot	
ASTM	B30
Sand	
ASTM	B427

ALLOY NO. C90900

Ingot	
Ingot No.	199

ALLOY NO. C91000

Centrifugal	
Federal	QQ-C-390
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Federal	QQ-C-525
Ingot No.	197
Sand	
Federal	QQ-C-390

ALLOY NO. C91100

Sand	
ASTM	B22
Ingot	
ASTM	B30

ALLOY NO. C91300

Centrifugal	
AMS	7322
Federal	QQ-C-390
Continuous	
AMS	7322
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Federal	QQ-C-525
Ingot No.	194
Sand	
AMS	7322
ASTM	B22
Federal	QQ-C-390

ALLOY NO. C91600

Centrifugal	
ASTM	B427
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 23
Continuous	
Federal	QQ-C-390
Ingot	
ASTM	B30
Ingot No.	205N
Sand	
ASTM	B427

ALLOY NO. C91700

Centrifugal	
ASTM	B427
Ingot	
ASTM	B30
Sand	
ASTM	B427

ALLOY NO. C92200

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 9
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
Military	MIL-B-16541
SAE	J461; J462
Fittings	
Federal	WW-P-460; WW-T-725
Flanges	
ANSI	B16.24
ASME	SB61
ASTM	B61
Federal	WW-P-460, WW-T-725
Ingot	
ASTM	B30
Federal	QQ-C-525
Ingot No.	245
Investment	
SAE	J461, J462
Permanent Mold	
SAE	J461; J462
Sand	
ASME	SB61; SB584
ASTM	B61; B564
Federal	QQ-C-390
Military	MIL-B-16541
SAE	J461; J462
Valves	
ASTM	B61
Federal	WW-V-51; WW-V-54; WW-V-1967
Military	MIL-V-1 187; MIL-V-17547

ALLOY NO. C92210

Ingot	
ASTM	B30
Sand	
ASTM	B584

ALLOY NO. C92300

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 10
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	230
Sand	
ASTM	B584; B763
Federal	QQ-C-390
Military	MIL-C-16540
SAE	J461; J462

ALLOY NO. C92400

Ingot	
Ingot No.	220

ALLOY NO. C92500

Centrifugal	
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	200
Permanent Mold	
SAE	J461; J462
Sand	
SAE	J461; J462
Valves	
Federal	WW-V-1967

ALLOY NO. C92600

Ingot	
ASTM	B763
Ingot No.	215
Sand	
ASTM	B584; B763
Valves	
ASTM	B763

ALLOY NO. C92700

Centrifugal	
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	206
Sand	
SAE	J461; J462

ALLOY NO. C92800

Continuous	
ASTM	B505
AMS	7320
Ingot	
ASTM	B30
Ingot No.	295

ALLOY NO. C92900

Centrifugal	
ASTM	B427
SAE	J461; J462
Continuous	
ASTM	B505
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	206N
Permanent Mold	
SAE	J461, J462
Sand	
ASTM	B427
SAE	J461; J462

ALLOY NO. C93200

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 12
SAE	J461, J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Federal	QQ-C-525
Ingot No.	315
Permanent Mold	
SAE	J461; J462
Sand	
ASTM	B584; B66; B763
Federal	QQ-C-390
SAE	J461; J462
Valves	
ASTM	B763

ALLOY NO. C93400

Centrifugal	
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 11
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Ingot No.	310
Investment	
Military	MIL-C-22087
Sand	
Federal	QQ-C-390
Military	MIL-C-22229
ASTM	B66

ALLOY NO. C93500

Centrifugal	
ASTM	B271
Federal	QQ-C-390
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	326
Sand	
ASTM	B584; B763
Federal	QQ-C-390
SAE	J461; J462
Valves	
ASTM	B763

ALLOY NO. C93600

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
Ingot	
ASTM	B30
Sand	
ASTM	B66

ALLOY NO. C93700

Bearings	
AMS	4827
Centrifugal	
AMS	4842
ASTM	B271
Federal	QQ-C-390
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461
Ingot	
ASTM	B30
Ingot No.	305
Permanent Mold	
SAE	J461; J462
Sand	
AMS	842
ASME	SB584
ASTM	B22; B584; B66; B763
Federal	QQ-C-390
SAE	J461; J462
Valves	
ASTM	B763

ALLOY NO. C93800

Centrifugal	
ASTM	B271
Federal	QQ-C-390
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	319
Permanent Mold	
SAE	J461; J462
Sand	
ASTM	B66; B584; B763
Federal	QQ-C-390
Valves	
ASTM	B763

ALLOY NO. C93900

Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Federal	QQ-C-525

ALLOY NO. C94000

Centrifugal	
Federal	QQ-C-390
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Federal	QQ-C-525
Ingot No.	296
Sand	
Federal	QQ-C-390

ALLOY NO. C94100

Centrifugal	
Federal	QQ-C-390
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Ingot No.	325
Sand	
ASTM	B67
Federal	QQ-C-390

ALLOY NO. C94300

Centrifugal	
AMS	4840
ASTM	B271
Federal	QQ-C-390
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	322
Sand	
AMS	4840
ASTM	B66; B584; B763
Federal	QQ-C-390\
Valves	
ASTM	B763

ALLOY NO. C94400

Ingot	
ASTM	B30
Ingot No.	312
Sand	
ASTM	B66

ALLOY NO. C94500

Ingot	
ASTM	B30
Ingot No.	321
Sand	
ASTM	B66

ALLOY NO. C94700

Centrifugal	
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Investment	
SAE	J461; J462
Permanent Mold	
SAE	J461; J462
Sand	
ASTM	B584; B763
Federal	QQ-C-390
SAE	J461; J462
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C94800

Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Permanent Mold	
SAE	J461; J462
Sand	
ASTM	B584; B763
Federal	QQ-C-390
SAE	J461, J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C94900

Ingot	
ASTM	B30
Sand	
ASTM	B584; B763
Valves	
ASTM	B763

ALLOY NO. C95200

Centrifugal	
ASME	SB271
ASTM	B271
Federal	QQ-C-390
SAE	J461; J462
Continuous	
ASME	SB505
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Flanges	
ANSI	B16.31
ASME	SB148
ASTM	B148
Ingot	
ASTM	B30
Federal	QQ-B-675
Ingot No.	415
Investment	
Military	MIL-C-22087
Permanent Mold	
SAE	J461; J462
Sand	
ASME	SB148
ASTM	B148; B763
Federal	QQ-C-390
Military	MIL-C-22229
SAE	J461; J462
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C95300

Centrifugal	
ASTM	B271
Federal	QQ-C-390
SAE	J461, J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461; J462
Ingot	
ASTM	B30
Federal	QQ-B-67
Ingot No.	415
Permanent Mold	
SAE	J461; J462
ASTM	B806
Precision	
Military	MIL-C-11866,
	Composition 22
SAE	J461; J462
Sand	
ASME	SB148, B-16.24,
	SB271, SB505
ASTM	B148; B763
Federal	QQ-C-390
SAE	J461; J462
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C95400

Centrifugal	
AMS	4870, 4871
ASTM	B271
Federal	QQ C-390
Military	MIL-C-15345,
	Alloy 13
SAE	J461, J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461, J462
Ingot	
ASTM	B30
Federal	QQ-B-675
Ingot No.	415
Permanent Mold	
ASTM	B806
SAE	J461, J462
Precision	
Military	MIL-C-11866,
	Composition 23
Sand	
AMS	4872; 4873
ASME	SB148, SB-271
ASTM	B148; B66; B763
Federal	QQ-C-390
SAE	J461, J462
Valves	
Federal	WW-V-1967
ASTM	B763

ALLOY NO. C95410

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
Ingots	
Ingots No.	415C+D
ASTM	B30
Permanent Mold	
ASTM	B806
Sand	
ASTM	B148
ASTM	B763
Valves	
ASTM	B763

ALLOY NO. C95420

Centrifugal	
AMS	4870, 4871, 4872, 4873
Federal	QQ-C-390
SAE	J461, J462
Sand	
AMS	4870, 4871, 4873
Federal	QQ-C-390
SAE	J461, J462
Valves	
ASTM	B763

ALLOY NO. C95500

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 14
SAE	J461; J462
Continuous	
ASTM	B505
Federal	QQ-C-390
SAE	J461, J462
Ingots	
ASTM	B30
Federal	QQ-B-675
Ingots No.	415
Investment	
Military	MIL-C-22087
Permanent Mold	
SAE	J461; J462
ASTM	B806
Sand	
ASTM	B148; B763
Federal	QQ-C-390
Military	MIL-B-21230; MIL-C-22229
SAE	J461; J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C95510

Centrifugal	
AMS	4880
ASTM	B271
Federal	QQ-C-390
SAE	J461, J462
Continuous	
AMS	4880

ALLOY NO. C95520

Centrifugal	
AMS	4881
ASTM	B271
Federal	QQ-C-390
SAE	J461, J462
Continuous	
ASTM	B505
AMS	4881
Sand	
AMS	4881
ASTM	B148
Federal	QQ-C-390
SAE	J461, J462
Ingots	
ASTM	B30

ALLOY NO. C95600

Ingots	
Ingots No.	415D
ASTM	B30
Federal	QQ-B-675
Sand	
ASTM	B148; B763
Valves	
Federal	WW-V-51, WW-V-54
Military	MIL-V-1187, MIL-V-1202
ASTM	B763

ALLOY NO. C95700

Centrifugal	
Federal	QQ-C-390
Continuous	
ASTM	B505
Ingots	
ASTM	B30
Federal	QQ-B-675
Ingots No.	415D
Sand	
ASTM	B148
Federal	QQ-C-390
Military	MIL-B-21230

ALLOY NO. C95800

Centrifugal	
ASTM	B271
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 28
SAE	J461; J462
Continuous	
ASTM	B505
SAE	J461; J462
Ingots	
ASTM	B30
Federal	QQ-B-675
Ingots No.	415D
Permanent Mold	
ASTM	B806
SAE	J461, J462
Sand	
ASTM	B148; B763
Federal	QQ-C-390
Military	MIL-B-22280; MIL-C-22229, B-24480
SAE	J461, J462
Valves	
ASTM	B763
Federal	WW-V-1967

ALLOY NO. C95900

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
Ingots	
ASTM	B30
Sand	
ASTM	B148

ALLOY NO. C96200

Centrifugal	
ASME	SB369
ASTM	B369
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 25, MIL-C-20159, TYPE II
SAE	J461; J462
Ingots	
ASTM	B30
Sand	
ASTM	B369
Federal	QQ-C-390
Military	MIL-C-20159, TYPE II
SAE	J461; J462
Valves	
Military	MIL-V-18436

ALLOY NO. C96400

Centrifugal	
ASTM	B369
Federal	QQ-C-390
Military	MIL-C-15345, Alloy 24, MIL-C-20159, TYPE I
Continuous	
ASTM	B505
Federal	QQ-C-390
Ingot	
ASTM	B30
Sand	
ASTM	B369
Federal	QQ-C-390
Military	MIL-C-20159, TYPE I
Valves	
Federal	WW-V-51; WW-V-1967
Military	MIL-V-1202

ALLOY NO. C96600

Sand	
Military	MIL-C-81519 (AS)

ALLOY NO. C96700

Ingot	
ASTM	B30
Sand	
ASTM	B770

ALLOY NO. C96800

Sand	
ASTM	B584
Ingot	
ASTM	B30

ALLOY NO. C96900

Continuous	
ASTM	B505/505M
Ingot	
ASTM	B584

ALLOY NO. C96970

Continuous	
ASTM	B505/505M

ALLOY NO. C97300

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
SAE	J461, J462
Permanent Mold	
ASTM	176
Ingot	
ASTM	B30
Ingot No.	410
Sand	
ASTM	B584; B763
Valves	
ASTM	B763
Federal	WW-V-51

ALLOY NO. C97400

Ingot	
Ingot No.	411

ALLOY NO. C97600

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
SAE	J461; J462
Ingot	
ASTM	B30
Ingot No.	412
Permanent Mold	
ASTM	B176
Sand	
ASME	SB584
ASTM	B584; B763
Military	MIL-C-17112
Valves	
ASTM	B763
Federal	WW-V-51; WW-V-54
Military	MIL-V-18436

ALLOY NO. C97800

Centrifugal	
ASTM	B271
Continuous	
ASTM	B505
Ingot	
ASTM	B30
Ingot No.	413B
Sand	
ASTM	B584
Permanent	
ASTM	B176; B763
Valves	
ASTM	B763
Federal	WW-V-51; WW-V-54
Military	MIL-V-18436

ALLOY NO. C98200

Bearings	
AMS	4824
SAE	J460

ALLOY NO. C98400

Bearings	
AMS	4820; 4822
SAE	J460

ALLOY NO. C99400

Sand	
ASTM	B763
Valves	
ASTM	B763
Ingot	
ASTM	B30

ALLOY NO. C99500

Continuous	
ASTM	B584
Ingot	
ASTM	B30
Sand	
ASTM	B763
Valves	
ASTM	B763

ALLOY NO. C99700

Ingot	
ASTM	B30
Permanent Mold	
ASTM	B176

ALLOY NO. C99750

Permanent Mold	
ASTM	B176
Ingot	
ASTM	B30

TECHNICAL ASSOCIATIONS AND SPECIFICATION SOURCES

The information listed was current at the time of this edition's publication.

American National Standards Institute (ANSI)

New York City Office (Operations)

25 West 43rd St.
4th Floor
New York, NY 10036
Phone: 212-642-4900
Fax: 212-398-0023
www.ansi.org

American Society of Mechanical Engineers (ASME)

Headquarters

Two Park Avenue
New York, NY 10016-5990
Phone: 800-843-2763 (US/Canada)
Phone: 001-800-843-2763 (Mexico)
Phone: 973-882-1170 (outside North America)
Fax: 973-882-1717 (New Jersey Service Center)
Email: CustomerCare@asme.org
www.asme.org

American Society for Quality (ASQ)

PO Box 3005
600 N Plankinton Ave.
Milwaukee, WI 53203
Phone: 800-248-1946 (United States and Canada)
Phone: 001-877-442-8726 (Mexico)
Phone: +1-414-272-8575 (All other locations)
Fax: 414-272-1734
www.asq.org

American Society for Testing and Materials (ASTM)

100 Barr Harbor Drive
West Conshohocken, PA 19428-2951
Phone: 610-832-9585
www.astm.org

ASM International

9639 Kinsman Road
Materials Park, OH 44073-0001
Phone: 440-338-5151 or 800-336-5152 (U.S. & Canada)
Phone: 800-368-9800 (Europe)
Fax: 440-338-4634
www.asminternational.org

Copper Development Association, Inc. (CDA)

260 West Madison, 16th Floor
New York, New York 10016-2401
Phone: 212-251-7224
Fax: 212-251-7234
www.copper.org

International Organization for Standardization

ISO Central Secretariat

BIBC II
Chemin de Blandonnet 8
CP 401
1214 Vernier, Geneva
Switzerland
E-mail: central@iso.org
Tel.: +41 22 749 01 11
www.iso.org

National Association of Manufacturers (NAM)

Headquarters

733 10th Street NW
Suite 700
Washington, DC 20001
Toll Free: 800-814-8468
Phone: 202-637-3000
Fax: 202-637-3182
Email: manufacturing@nam.org
www.nam.org

National Institute of Standards & Technology (NIST)

Public Inquiries Unit

100 Bureau Drive
Stop 1070
Gaithersburg, MD 20899-1070
Phone: 301-975-NIST (6478)
Federal Relay Service (800) 877-8339
www.nist.gov

Society of Automotive Engineers (SAE)

USA Headquarters

400 Commonwealth Drive
Warrendale, PA, 15096-0001
Phone: 724-776-4841
Fax: 724-776-0790
www.sae.org

Society of Manufacturing Engineers (SME)

US Office

One SME Drive
Dearborn, MI 48128
Phone: 313-425-3000 or 800-733-4763
Fax: 313-425-3400
www.sme.org

United States Department of Defense (DoD)

DLA Document Services

Building 4/D
700 Robbins Ave.
Philadelphia, PA 19111-5094
Phone: 215-697-6396
<http://quicksearch.dla.mil/>

United States Department of Energy (DoE)

1000 Independence Ave. SW
Washington DC 20585
Phone: 202-586-5000
(800-877-8339 for Hearing and/or Speech Impaired)
Fax: 202-586-4403
Email: The.Secretary@hq.doe.gov
www.energy.gov

CASTING PROCESSES AND MATERIALS

INTRODUCTION

Metalcasters have at their disposal many different methods for pouring castings and some are uniquely suited for the production of specific kinds of castings. Although a foundry may utilize more than one casting process, the choice is usually dictated by the class of product to be made and by the relative economies of the various processes. Factors such as casting size, shape, complexity, quantity, surface finish and dimensional accuracy, together with alloy requirements, must all be taken into account in the selection of the most economical casting process. Table 3-1 addresses the details of some of the casting processes that will be covered in this chapter. The higher operating costs for certain processes may, in some cases, be outweighed by their increased accuracy. With increased accuracy, certain finishing or machining operations may possibly be eliminated, thus actually reducing the net cost of the casting. Besides the direct material costs of sand and binder, the variable costs: labor, floor space, downtime, maintenance, utilities, cleaning, casting yield, and overall sand consumption need to be considered.

Until recently, 85% of the annual tonnage of copper-base alloy castings was produced in expendable sand molds. A significant portion of this chapter is therefore devoted to the green sand and chemically-bonded sand molding processes. Vast amounts of information have been published on foundry sands, binders, additives, and related molding and coremaking processes. The material in this chapter is intended primarily to cover the general principles and basic information relating to selection, operation, and control of sand casting processes.

A smaller, but significant tonnage of copper-base alloy castings is produced in reusable metal molds or dies, utilizing either gravity or mechanical forces for introducing molten metal into the mold cavity. Such processes include pressure diecasting, permanent mold casting, centrifugal casting, and continuous casting. While these processes are used in Europe, primarily for plumbing components, their acceptance in North America has been relatively slow. In recent years, a number of publications have documented the applications of these processes for the production of copper-base alloy

Table 3-1. Process Capabilities

Casting Process	Weight Range kg (lb)	Economical Quantity	Thin Section mm (in.)	Cast hole dimensions mm (in.)	Surface finish µm (µin.)	Dimensional accuracy mm (in.)
Green sand	0.1-100 (0.2 to 220)	1 to 100,000	>5 (0.2)	>6 (0.25)	6-25 (250-1000)	-
CO ₂ /silicate	0.1-100,000 (2-220,000)	1 to 1,000	>5 (0.2)	>6 (0.25)	6-25 (250-1000)	-
Cold box	0.1-100,000 (2-220,000)	1 to 1,000	>5 (0.2)	>6 (0.25)	6-25 (250-1000)	-
Shell mold	0.1-50 (0.2 to 110)	1,000+	>2 (0.1)	>3 (0.1)	3-12.5 (125-500)	±0.5-100 (±0.02-4)
Ceramic	0.1-5,000 (0.2-10,000)	50+	>1.5 (0.06)	-	0.8-3.2 (30-125)	±0.4-100 (±0.02-4)
Investment	0.1-50 (0.2 to 110)	1,000+	>1.5 (0.06)	>1 (0.05)	0.8-3.2 (30-125)	±0.5-100 (±0.02-4)
Gravity PM	0.1-100 (0.2 to 220)	1,000+	>5 (0.2)	>6 (0.25)	3-6 (125-250)	±0.25-100 (±0.01-4)
Low pressure PM		1,000+				±0.5-100 (±0.02-4)

castings. These processes are described here in such a manner as to give the reader an overview of their respective applications, capabilities, restrictions, advantages, and disadvantages.

A small percentage of precision castings are made in expendable molds of plaster (gypsum) or ceramic materials. Both aggregates, in the form of self-hardening slurries, may be used either with expendable patterns for investment casting (lost-wax process), or with conventional, reusable patterns for the production of parted molds. The salient features of these processes will also be discussed.

SAND CASTING PROCESSES

The various categories of sand casting processes are often identified according to the type of binder present in the molding sand mixture. On this basis, the principal types of molds used for the production of copper-base alloy sand castings are:

- Green sand
- Dry sand
- Cement-bonded sand
- Waterless (oil/clay-bonded) sand
- Baked (or heat-cured) core sand
- Shell (phenolic resin-bonded) sand
- Chemically-bonded sand

Green Sand Molding

The green sand process utilizes a molding aggregate where sand grains are bonded together with some form of clay which has been plasticized by the addition of controlled amounts of water. It is the presence of this “temper” water in the sand/clay mixture which causes the molding aggregate to be called green sand, as distinct from dry sand (wherein most of the moisture has been removed by heating the mold).

Green sand molding is the most diversified and widespread process used for casting production particularly for small- to medium-size castings. Molding consists of compacting the tempered sand about the pattern (usually inside a flask of some type) by one or more mechanical means such as jolting, squeezing, ramming, vibrating, slinging, or blowing. The plasticity of the bonding clay is sufficient to produce a mold which is rigid enough to hold its shape during pattern removal, core placement, pouring, and solidification. A simplified version of the process is illustrated in Fig. 3-1. A typical casting produced by this process, together with the mold from which it is made, is shown in Fig. 3-2.

The relative ease with which the molding aggregate can be prepared for use (by mulling or mixing), transported, and stored contributes to the economy and versatility of the process. More importantly, the sand mixture can be reused many times before it must be discarded. In recycling the material, however, it is necessary to compensate for chemical,

physical, and thermal changes caused by exposure to the molten metal and to control the effects of contamination by foreign and degraded matter.

The quality of castings made in green sand molds is highly dependent on the properties of the molding aggregate as well as those of the mold. These parameters can easily change from hour to hour or from day to day unless close process controls are maintained.

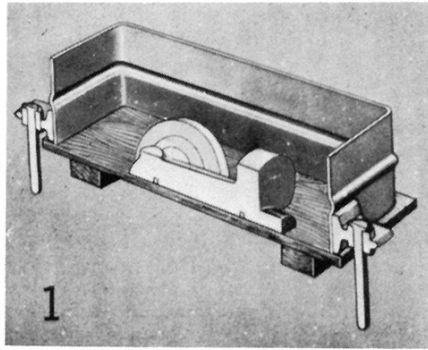
Foundry Sands

Sand can be defined as granular particles resulting from the disintegration or crushing of rocks. Sands are particles of mineral matter ranging in grain size from 0.05 to 2 mm (1/500 to 1/12 in.) in diameter. The most common sand mineral is silica, or quartz, which is silicon dioxide (SiO_2), but other mineral contaminants such as particles of feldspar, mica or metal oxides may be present. Limited amounts of some contaminants may be beneficial in foundry sands, while others, such as sea shells, are not. The term *sand* may also denote several other minerals. Thus, zircon, chromite, olivine, and other refractory materials may be regarded as sands if their grain size falls within the above range.

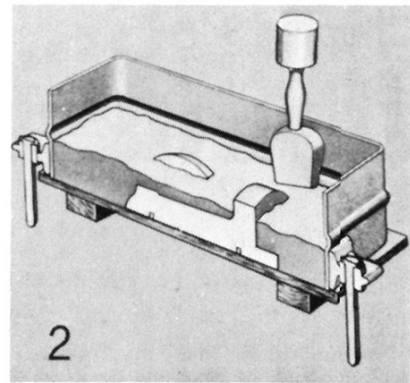
Silica sand is the most widely used base material in brass and bronze foundries for both molding and coremaking and finds application in a wide range of grain sizes, shapes, and distributions, and in different degrees of purity and refractoriness. There are two broad classifications applied to foundry silica sands used for molding; they are *naturally-bonded* or *unbonded sands*.

Naturally-bonded Sands

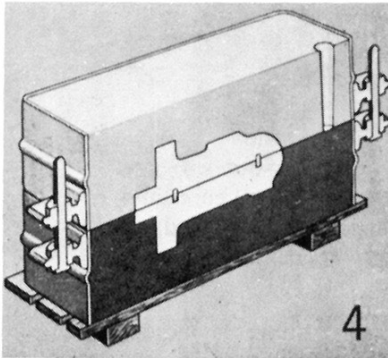
Naturally-bonded sands are found in nature, where sands were deposited from water along with various clay minerals. They exhibit a wide range of grain sizes and clay contents, depending upon their origin and location. Naturally-bonded sands have been used by the foundry industry since the Bronze Age. Early foundry development in North America depended upon the local availability of naturally-bonded sands. The processing of naturally-bonded sands consists primarily of screening to remove oversize particles, roots, and other deleterious material. In some cases it is necessary to partially dry the sand (to approximately 6% moisture) before passing it through mullers, cage mills, or dry pans in order to properly distribute the natural bonding clay. Sands from different deposits, or even from different strata within the same deposit, may have significantly different characteristics. These sands are often blended together, with or without clay additions, to produce sands of particular properties. Areas having extensive deposits of superior, naturally-bonded sands are well-known to both ferrous and nonferrous foundry workers. These sands carry such designations as Albany, New Jersey, McConnellsville, Windsor Lock, Provincetown, Mississippi, Tennessee, etc. The sands contain iron minerals that give them distinctive colors. Naturally-bonded sands are difficult to use in system sands, and cannot be used with chemical



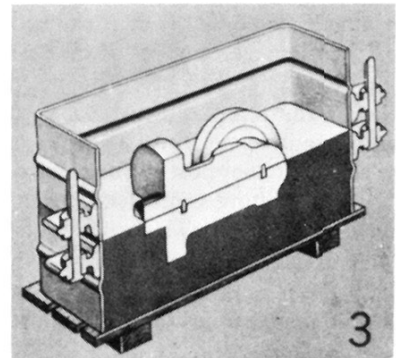
Cross section of the first step in making a green sand mold. Bottom half of the pattern is on the mold board and surrounded by the bottom or drag half of the flask.



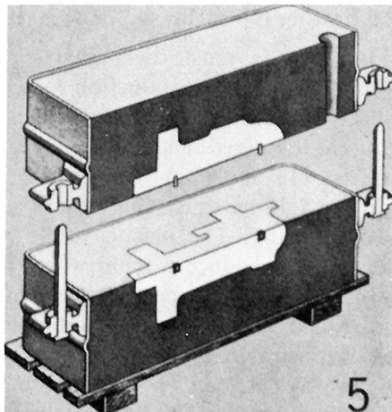
Molding sand is rammed around the pattern in multiple steps to provide uniform density.



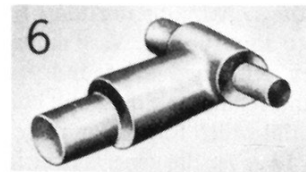
Section through the completed mold with pattern still in place and the sprue hole formed for entrance of molten metal.



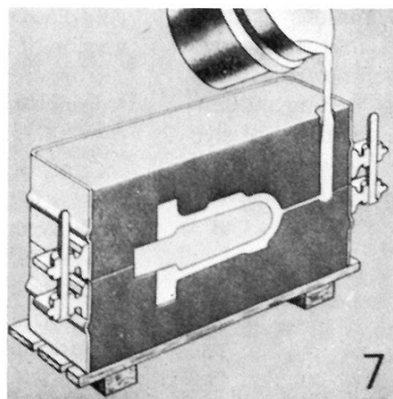
After the bottom half of the mold is filled, it is rolled upright and the top half of the pattern and flask are put in place to complete the mold.



Cope and drag halves of mold are separated in order that the pattern may be removed. The gate channel is then cut from the sprue to the mold cavity.



The core of bonded sand is made separately to form the internal passages of the casting.



After placing core in the mold, it is closed and clamped to resist the pressure exerted by the molten metal when it is poured in the mold.

Fig. 3-1. The process steps in the making of green sand molds are shown. For illustration purposes, the valve body casting is shown without the typical gating and risering which would be necessary to produce this casting as an acceptable product in a copper-base alloy.

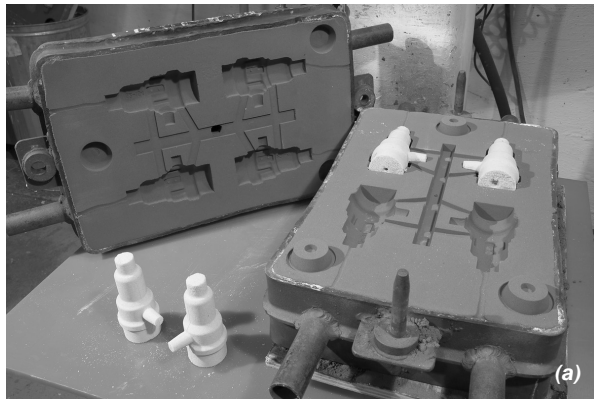


Fig. 3-2. Shown are typical green-sand cope and drag halves of a mold (a), along with the casting produced from the mold (b).

binders. These sands are available cleaned and sized and require expertise in their use for best results.

The problem for users of naturally-bonded sands is the high fines content (~20%) and the occurrence of *clay balling*. This is a common problem with high-clay sands when they are either shipped or processed in a wet condition. The problem is more severe with finer sands than with coarser grades. If the condition is acute, there is very little that can be done to salvage the sand. It should be noted that the three primary factors causing clay balls to form in naturally-bonded molding sands are: 1) excessive water content, 2) excessive clay content, and 3) too much movement of the sand, resulting in a “pelletizing” action. They were generally fluffed up and raked rather than mulled.

The naturally-bonded sands are susceptible to burn-on and expansion-type defects such as buckles, scabs, and rattails. Organic material (usually as some form of cellulose) is often added to these sands to help control such defects. Problems may develop with excessive burn-out of these additives, or when a high level of fines develops in the system sand. If there are excessive amounts of fines in the sand, higher levels of water must be added in order to reach the temper point (adequate sand-bonding strength). These higher moisture levels cause problems by aggravating the formation of wet condensation zones just below the mold surface. The oc-

currence of expansion defects when using naturally-bonded molding sands can be minimized by observing the following:

- Specify sands having the minimum quantity of fines consistent with the attainment of adequate casting surface finish.
- Select highly-refractory sands that resist thermal fracture (and consequent production of fines) during use.
- Remove excessive fines at shakeout with a suitable exhaust/ventilation system.
- Utilize organic additives in amounts adequate to control expansion-related defects without causing excessive gas formation.
- Minimize the level of temper water in the system sand.
- Minimize the rammed density of the mold consistent with required casting finish and dimensional accuracy.

Several trends have resulted in the decreased use of naturally-bonded molding sands: the depletion of satisfactory deposits, inconsistent sand properties, the gradual disappearance of skilled molders, an increase in the use of mechanized molding machines, and greater demands for increased casting quality and surface finish. These trends emphasize the need for more uniform, high-quality sands having properties consistent with the requirements of current molding equipment.

To satisfy this need, unbonded (washed-and-dried) sand has been used as a base aggregate, with controlled amounts of clay, water and other additives to produce molding sand having the desired characteristics. Sands compounded in this manner have been designated as *synthetic sands*. Many find the term “synthetic” objectionable on the basis that the ingredients of the mixtures are virtually all natural mineral substances and not man-made (synthetic) materials. Thus, this second category of sands employed for both molding and coremaking, will be referred to as being *unbonded*, recognizing that the term refers to the form in which they are purchased as opposed to the form in which they are used.

Unbonded Sands

Most unbonded sands used in foundries are predominately silica. Their popularity is a result of their abundance, relatively low cost, good refractory properties, and ease of bonding and reclamation. Silica sands are formed by the weathering of siliceous rock and the geological processes of transport, deposition, and sedimentation by wind and water. The composition, fineness, and grain shape of these deposits depends on the nature of the rock from which they originated and the manner of their deposition.

Silica sand deposits are variously referred to as bank sands, lake sands, dune sands, etc., depending upon whether they were deposited by wind, water, or combinations of both. In most cases the natural deposits are not clean or pure enough to be used as-mined. Consequently, they are almost invari-

ably screened, washed, de-slimed and dried for purposes of removing clay and other contaminants. The screening process often includes classifying the sand to control grain size distribution.

Base sands are frequently designated according to grain shape, as angular, sub-angular, or rounded. Compound-grains also occur in small concentrations, but as this form has low thermal shock resistance, it is generally considered to be inferior or unsuitable for most foundry applications. Most of the naturally-occurring sands have sub-angular grain shapes. The so-called "rounded" sand grains are more nearly spherical, having no doubt undergone a higher degree of erosion by abrasive friction during their formation and deposition. These sands are relatively scarce but are preferred by many metalcasters because of their better flowability and lower binder requirement. Angular sands are not of natural origin but are formed by the crushing and screening of rock.

In spite of their widespread use by foundries, silica sands have the distinct disadvantage of possessing a high coefficient of thermal expansion. The most common mineral comprising these sands, quartz, undergoes a sudden change in crystal form (from alpha to beta quartz) at a temperature of about 1112F (600C), that causes additional expansion. This behavior is shown in Fig. 3-3, which indicates the thermal expansion of quartz to be 1.3% from ambient to normal casting temperatures. This characteristic of quartz causes expansion of mold surfaces when exposed to thermal shock and, unless precautionary measures are taken, can result in casting surface defects such as rattails, buckles, and scabs. Other disadvantages of silica sands are their relatively low chilling power and respiratory problems caused by the insolubility of the particles deposited in the lungs from airborne dusts.

In recent years, metalcasters have increasingly made use of various specialty sands composed of minerals other than silica. These have limited supplies and are much more expensive than silica. Hence, the use of these sands is restricted by economics as well as by availability. The two specialty sands which have been used most frequently in nonferrous foundries are olivine and zircon sand.

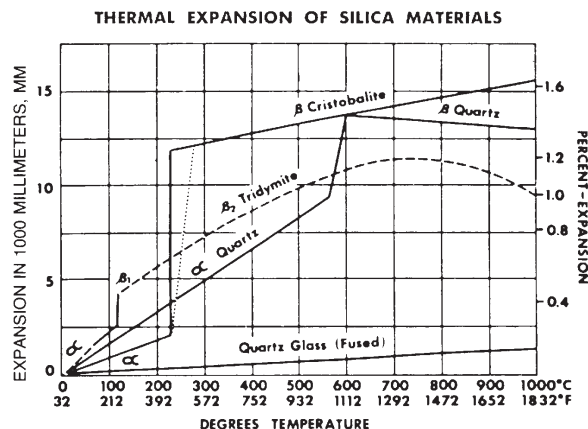


Fig. 3-3. The thermal expansion of silica materials is compared.

Olivine

Olivine contains no free silica, is more refractory than quartz and yet exhibits only about one-third the thermal expansion of quartz (Fig. 3-4). These properties have made olivine attractive as a molding aggregate in a growing number of foundries. Olivine sands exhibit somewhat higher thermal conductivity and can be more chilling than silica (although binders can play a bigger role).

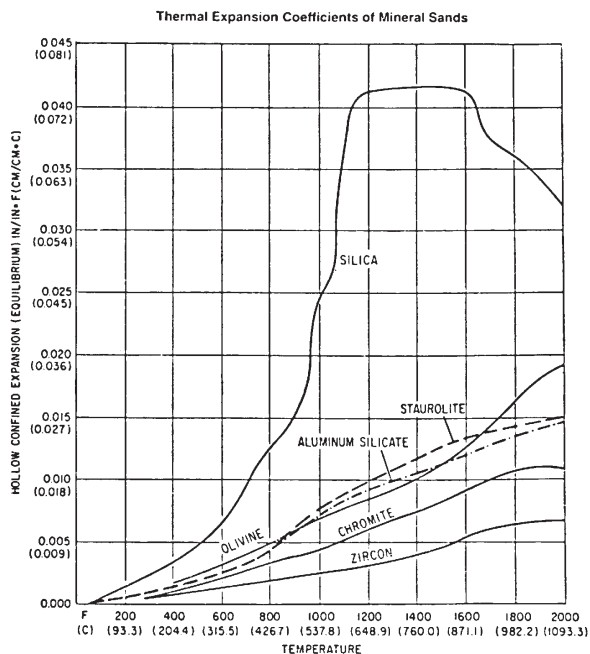


Fig.3-4. Thermal expansion of non-silica aggregates as compared with silica sand.

Olivine is a magnesium-iron orthosilicate, $(\text{Mg, Fe})_2\text{SiO}_4$, which is a continuous solid solution of two minerals forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). Inclusions of other minerals, magnetite, spinels and apatite ($\text{Ca}_5(\text{PO}_4)_3$) are common. The crystal structure can also be transformed to hydrous magnesium silicates (serpentine). Hence physical properties vary with the chemical composition which varies from deposit to deposit. Some jurisdictions may prohibit the use of olivine due to the presence of trace amounts of nickel (even though it is bound and not leachable). Forsterite and fayalite in approximately equal proportions are the primary constituents of a rock called dunite, found principally in the states of Washington and North Carolina. Dunite must be crushed and washed to permit gravity separation of mineral impurities (mainly serpentine and talc), after which it is dried and then screened into different fineness grades of sand. As a crushed material, the grains of olivine sand are angular and somewhat cracked. The forces of mulling and mixing thus result in the rapid production of fines from new sand until the grains have become more rounded, and the breakdown rate stabilizes. This characteristic must be taken into account when selecting the fineness grade of purchased sand. Norway has long been a supplier of olivine foundry sands. The production of olivine foundry sand in the US ceased in 2013.

Unlike silica, olivine is chemically basic. Although it can be readily bonded with clays and most of the inorganic and organic chemical binders, it cannot be used with acid-catalyzed binder systems. Likewise, the refractory characteristics of olivine are damaged if the system sand is allowed to become excessively contaminated by an accumulation of silica (from cores, for example). This can lead to a lowering of the sintering point of the system sand, with attendant problems of defective casting surface finish. Processing and handling costs of olivine sand in the foundry, in terms of energy requirements, are about 25% higher than those for silica, reflecting the difference in density of the two materials.

Zircon

Sands containing zircon (zirconium silicate) are widely distributed in nature; however, commercially-workable deposits depend on the demand for titanium and are largely restricted to Australia, India, South Africa, and northern Florida. The concentration of zircon in Australian deposits is about 15%, whereas Florida deposits are only 1.5–4% and considerably finer. The zircon produced from these deposits is a by-product of separation procedures for the extraction of titanium-bearing minerals. The zircon obtained by the usual but costly method of electrostatic separation is very close to 99.5% purity. From time to time, zircon sands produced by oil-flotation separation methods have appeared on the market. Material produced by this method is of rather high purity, but the oil coating on the grains makes them difficult to coat with binders.

Zircon is the most heat-stable of all available foundry sands and has a thermal expansion coefficient less than one-eighth that of silica (Fig. 3-4). However, it is the combination of high thermal conductivity and density (both of which are nearly twice that of silica) which makes zircon most attractive. The latter two properties give zircon a heat absorption rate nearly four times that of quartz, making it useful as a means for controlling directional solidification when used locally in molds for selective chilling. Whether used as a mold or core aggregate or as an ingredient of a wash coating, zircon is virtually unwetted by most molten metals; this results in excellent casting surface finish. Zircon has the added advantage of chemical stability and is compatible with all known foundry binders, whether inorganic or organic.

Other minerals can be used such, as chromite, mullite and new low-density synthetic refractories.

Clays

Clays are earthy or stony aggregates with innumerable small flat fragments of the order of 1/5000 to 1/50,000 of an inch in diameter. They are composed chiefly of oxides of aluminum and silicon in various ratios, in the form of platelets of hydrous aluminum silicates. Other minerals are also present and play an important role in clay properties and structures. Clays have the unique property of absorbing moisture into their structures in such a manner as to form intermediate

water layers between their platelets, resulting in adhesive, plastic masses. There are numerous types of clay found in nature and these vary significantly in properties, composition, and structure (Table 3-2). From a foundry standpoint, only two groups of clays are of interest: kaolinites and montmorillonites, which can be used to bond sand grains together.

Kaolinite Clays

As a mineral group, kaolinite clays, when uncontaminated, are characterized by being highly refractory. These clays exhibit lower green bonding strengths than the montmorillonite clays. The kaolinite group of clays contains three types, fireclay ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$), ball clay and kaolin (china) clay, of which only fireclay is important to foundries.

Fireclays are the bonding material in naturally-bonded sands, and also occur as free deposits. When a sand/clay mixture is brought to the proper temper by the addition of water and thorough mulling, about 12% by weight of fireclay is required to attain the same green compression strength as would occur if 4.5% montmorillonite clay were used. Similarly, green sands bonded with fireclay require about 5% by weight of water as compared with 3% for sands with montmorillonite clay. Although fireclay properties compare favorably with the montmorillonites, they are seldom used in North America (Table 3-2).

Montmorillonite Clays

Montmorillonite, ($\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 4 \text{ to } 7\text{H}_2\text{O}$), is the primary mineral occurring in bentonite clays. Better commercial grades contain more than 80% montmorillonite. The two important members of this group, *Southern bentonite* and *Western bentonite*, are used extensively for bonding of sands for green sand molding. These two bentonites have significantly different properties, which need to be understood before selecting them. The montmorillonite structure consists of three layers, two silicon-oxygen sheets and one aluminum-hydroxyl sheet between the other two. The central sheet is never fully aluminum hydroxyl, as some of the aluminum ions are substituted by magnesium or iron. Divalent magnesium creates an imbalance which is satisfied by loosely attached ions of sodium, calcium, magnesium or hydrogen.

Southern bentonite contains calcium in its crystalline structure, in the form of bivalent ions (Ca^{++}). For this reason, Southern bentonite is commonly called *calcium bentonite* (also known by the trade name *Panther Creek*). Southern bentonite does not swell appreciably when moistened, and absorbs only slightly more water than does fireclay; it absorbs and loses such water with relative ease. By comparison, Western bentonite contains monovalent sodium ions (Na^+) and is thus commonly referred to as *sodium bentonite* (or *Volclay*). Western bentonite absorbs water slowly, but does so with a high degree of volumetric expansion (swelling) accompanied by the formation of a thixotropic gel.

Table 3-2. Comparison of Bonding Agents and Clay Types

COMPARISON OF VARIOUS BONDING AGENTS			
Leading types of clay bonds	Western Bentonite	Southern Bentonite	Fireclay
Mineral classification	Montmorillonite	Montmorillonite	Kaolinite
Mined location	Wyoming and South Dakota	Mississippi-Alabama	Ohio-Pennsylvania Illinois-Alabama
Mining method	Strip	Strip	Strip, Drift, Shaft
Average grain size	70% finer than 0.2 microns	87% finer than 0.5 microns	70% finer than 20 microns
RELATIVE VALUE OF VARIOUS TYPE OF CLAYS			
	MONTMORILLONITE		Fireclay
	Sodium	Calcium	
Green compression strength	2	1	3
Dry compression strength	1	3	2
Permeability	1	2	3
Least tempering water required	2	1	3
Greatest durability	1	3	2
Highest flowability	3	1	2
Best collapsibility	3	1	2
Sand toughness	1	3	2
Highest hot compression strength at 1650F (900C)	1	3	2
Highest hot compression strength at 1850F (1010C)	1	3	2
Highest hot compression strength at 2000F (1100C)	1	3	2
Least contraction at 2500F (1370C)	3	2	1
Fewest lumps in shakeout sand	3	1	2
Least intensive mixing effort required	2	1	3

1 = best 2 = second best 3 = worst of the three

Both types of bentonite have high sintering temperatures and are about equally effective in developing high green compression strength and permeability when used to bond green sand mixtures. As seen in Table 3-2, however, other characteristics of the two bentonites are significantly different.

Sands bonded with Southern bentonite require less energy to mull, as this clay absorbs water more readily. Such sands are also more flow-able (less stiff), and are thus easier to squeeze and ram into molds. Since these sands possess lower dry and hot strength, they are more collapsible at elevated temperatures. Hence, there is less tendency to form hot tears in castings of wide-freezing-range alloys, and fewer lumps of hot sand are formed at shakeout. Unfortunately, these same characteristics contribute to the possibility of mold erosion during pouring, especially with heavier castings, which usually result in sand inclusions in the castings. Sands bonded with Southern bentonite clay tend to dry out rapidly when left exposed to air. This includes the edges of sand in open molds which are allowed to stand too long before closure. Another disadvantage of Southern bentonite clay is its susceptibility to sand expansion defects. Many authorities ascribe this behavior to the poor wet-tensile strength.

On the other hand, Western bentonite has excellent dry and hot strength. When used as a green-sand bonding clay, it offers the maximum resistance to the formation of sand expansion defects. Conversely, all those factors listed above in favor of Southern bentonite, will be disadvantages for Western bentonite.

The North American preference for Southern and Western bentonite are due to:

- The availability of excellent deposits in the U.S.
- The development of several tests specific to the montmorillonites.
- These two clays (but not fireclay) absorb the methylene blue dye in the MB Clay Test to measure their concentration.
- There have been numerous methods to correlate montmorillonite clay levels to sand properties (strength and moisture level), such as the Wenniger Diagram, which can be used to infer clay content.

No single clay has optimum characteristics in all respects as a bonding material for green sand mixtures. Sand property requirements differ from one foundry to another, depending upon many factors. It is possible to optimize sand properties for given conditions by utilizing the different clays either singly or in combination. Once it is determined that a particular ratio of specific clays best suits foundry requirements for general production conditions, it is often possible to purchase such a blend pre-mixed by the supplier.

There are two common errors which should be avoided by metalcasters. The first is a tendency to select the system sand (and the type of clay used) to conform to equipment limitations in mulling, molding, shakeout, etc., rather than in terms of casting quality. The second error is attempting to over-extend the system sand by exceeding its limitations in the size or thickness of castings produced.

Sand Preparation

In the preparation of green sand molding mixtures, clays must be combined with the proper amounts of moisture and then distributed as uniform coatings around the sand grains. The naturally-bonded sands discussed previously contain fireclays which are already well distributed on the grains. Fireclays absorb moisture much more readily than do the bentonites and thus, simple blade-type or paddle mixers can quickly disperse the moisture throughout naturally-bonded sand. By contrast, much more mechanical energy and time are necessary to plasticize bentonite clays and to distribute them uniformly around the sand grains. This led to the development of mullers utilizing high wheel-pressures and blade-type, high-intensity mixers.

The mulling of green sand mixtures first serves to mix and blend the various ingredients together until they are dispersed homogeneously. Additional mulling and work is required to continue the absorption and distribute the water in the clay, and thereby develop uniform water/clay ratios within the individual grain coatings. This thorough mulling promotes the full development of properties of the mixture. Sands which are insufficiently mulled tend to be both weak and brittle.

System Sands

Molding sands which are cycled for reuse are referred to as *system sands*. The proper selection or design of system sand is no simple matter, since sand property requirements vary from one foundry to another. The problem is further complicated by the partial deterioration of the clays during each cycle, both chemically and physically, from exposure to heat from the molten metal. Additionally, various kinds of debris and contaminants enter the sand, and heat can build up so as to cause serious changes in properties. The aim of the recycling process should be the establishment of "steady-state" conditions, whereby the sand is cleansed each cycle and suitable additions of new material are made to either dilute or replenish materials formed or lost during the casting process. The net objective of recycling is to maintain the characteristics and properties of the system sand within acceptable working limits.

Designing a System Sand

It is good practice to select system sand with a grain fineness number no greater than necessary, because fines form and accumulate in system sands during their recycling due to thermal and mechanical forces. Modern molding machines and especially the high-density, high-pressure type can utilize coarser sands without sacrificing surface finish.

Wherever possible, it is advantageous to choose the same base sand for both molding and coremaking, thus preventing shifts in grain size or distribution as the system sand becomes diluted by core breakdown. The ideal base sand is one having a four-screen grain distribution. Such sands

require the least amounts of clay bond and temper water to develop optimum properties. System sands in brass and bronze foundries are typically 95–100 AFS gfn (grain fineness number). As core sands are typically 70 AFS gfn to limit binder requirements and core blow defects, new sand additions tend to be about 105 AFS gfn. If the system sand is limited to four screens, then new and core sands should be 3 screen sands, otherwise the system sand becomes a 5 screen sand.

The type of clay selected for bonding a washed-and-dried base sand will be determined not only by the size, shape and thickness of the casting to be produced but also by the equipment available for sand preparation, handling, molding, shakeout, and storage. General characteristics required of any system sand include the following:

- Flowability adequate to fill the flask by gravity
- Compactibility suitable for attaining the desired mold hardness and density
- Adequate green compression strength to prevent mold damage
- Dry- and hot-compression strengths sufficient to avoid chronic mold erosion problems
- Freedom from excessive hard sand lumps at shake out
- Ability to consistently produce quality castings

Foundries producing small- or medium-size castings of light section thickness often find it possible to take advantage of the better mulling, ramming, and shakeout properties afforded by the use of a Southern (calcium) bentonite bonding clay. Conversely, producers of large, heavy-section castings tend to select Western (sodium) bentonite because of its superior dry- and hot-strength and its good resistance to sand expansion defects. In general practice, foundries usually bond their system sands with a blend of different clays in order to optimize system sand properties for the range of conditions encountered in production.

System sands containing fireclay or Southern bentonite as the main binders can have improved resistance to sand expansion defects by the addition of small, controlled amounts of organic additives—usually a form of cellulose (wood flour, cob flour, rice hulls, etc.). These materials should be of uniform fineness and low in ash content. They burn out of the sand at low temperatures and, by a process not fully understood or agreed upon by authorities, prevent the cracking and spalling behavior of mold surfaces which are associated with the occurrence of rattails, buckles and scabs. The effectiveness for such cellulose additives are levels of 1 to 2% by weight. It is a common mistake to use heavier additions of these additives to correct persistent sand expansion problems; other corrective means should be explored instead. Excessive cellulose additions require additional temper water to develop proper green compression strength (in fact each additive requires a characteristic amount of water to maintain temper). This factor, plus the gas-forming tendency of cellulose, combines to aggravate the sand expansion problems (by the formation of wet-conden-

sation layers) and cause expansion defects. The high level of cellulose makes the sand friable and brittle, increases the chances of blowholes and, in extreme cases, causes sooty pock-marks on casting surfaces.

It is difficult to monitor the working level of cellulose additives in system sand. While there are tests to evaluate the overall level of organic materials present, such tests cannot distinguish between desirable additives and organics arising from unwanted residual core binders.

Recycling System Sands

The recycling of system sand begins after mold shakeout and removal of the casting preferably with contained cores and some adhering sand, comprising the following basic steps:

- Shakeout sand is transferred to a coarse vibratory or rotary screen for removal of large contaminant particles such as core butts, wire, metal splash and hard sand lumps.
- Sand is transferred to storage adjacent to the mulling station (possibly with air counter flow for partial cooling and fines removal). Discharge into and from storage hoppers should not result in excessive sand segregation.
- Batch re-mulling takes place, with appropriate additions of new clay, new sand, temper water and other additives.
- Sand is discharged from the muller, preferably followed by aeration to break up caked sand.
- Sand is transferred to storage at molding stations.
- Sand is reused in molding (with or without riddling to remove fine sand lumps and metallics. If the latter are thrown on the floor, they should not be put back into the sand system).
- Metallic balls (6–12 mesh) comprise 0.7 to 1.5% of brass foundry system sands (by iodomethane gravity separation). These particles originate from the sparks which are seen running across the mold during pouring. Their numbers tend to increase, unless the dry system sand is screened weekly (20 mesh).

The effectiveness of some of the foregoing operations can be assessed by visual examination of the sand. The screen distribution test offers such an opportunity for evaluating the removal of metallics, lumps of sand (core butts), or other debris. Unfortunately, however, many of the changes taking place in the system sand as it is recycled cannot be readily seen and must be evaluated at intervals by a series of test procedures, either at the muller location or in the laboratory. It is critical to recognize the nature of these changes.

Clay alteration—the natural ability of clay minerals to be plasticized by the absorption of water can be destroyed by their exposure to elevated temperatures. Bentonites, for example, cannot again absorb water once they have been exposed to temperatures above about 1022F (552C). This

thermal alteration effectively renders them inert as bonding material, and clay minerals thus affected become “dead clays” in the sand mixture. During each casting cycle, therefore, some portion of the clay present in the sand is rendered useless; the amount depends upon the depth of the sand layer in contact with the casting, which reaches the limiting temperature. This depends on casting section thickness, pouring temperature, and cooling time before shakeout. The rate at which new, active clay must be added to replenish that which is thermally destroyed can only be determined by tests (Methylene Blue [MB] Clay or combinations of Green Compression Strength [GCS], moisture and compactibility) designed to measure active clay levels in the sand.

Nevertheless, all clays degrade when exposed to the heat from liquid metal in a mold. Although the actual temperature depends on the clay deposit, Southern bentonite degrades at 600–700F (316–371C), Western bentonite at 1180F (638C) and fireclay at 800F (427C). This usually means that all Southern bentonite within 1 inch of a 1 inch thick copper-alloy casting will be destroyed and all Western within 0.5 inch will be dead. For this reason, recycled system sands will need clay additions to replenish heat damaged sands. Sand adhering to castings at shakeout should not be recovered or added to the system sand, as dead clay simply acts as fines requiring moisture but contributing nothing. Although some dead clay can end up as fines in the sand, much of it forms an oolitic layer around the sand grains, which gradually thickens and darkens as metal oxides, etc. combine with the dead clay.

Generation of fines—the grains of base sand are constantly being eroded by mechanical action. They crack, fragment, and corners get knocked off to form smaller particles due to the thermal shock of the molten metal. If allowed to accumulate in the system sand, fines can cause all manner of problems and casting defects. The level of fines can only be measured by periodic screen analysis and trends noted. Unless the level of fines in the system sand can be maintained by balancing sand losses and disposal rates with fresh sand input from cores and muller additions, other steps must be taken. These include installation of a pneumatic system for fines removal or establishment of a schedule for discarding a portion of the system sand and replacing it with new sand. This amounts to controlling the fines by dilution. It is always preferable to avoid sudden, large additions of new sand and clay or wholesale dumping of a large fraction of system sand in order to avoid abrupt swings in sand properties (and casting finish).

Overheated system sand—a basic error made by many foundries is the under-design, or over-utilization of their system sand, necessitating the recycling of sand to the degree that it becomes seriously overheated in the course of a day's production. Sand is a poor conductor of heat, especially when confined in storage hoppers. Hot sand conditions are all too frequent and make control of sand properties impossible. Experienced sand technologists generally agree that the threshold of “hot sand” conditions begins at about 100F (38C). At this temperature, sand properties begin to deteriorate, and these changes become critical at about

160F (71C) (see Fig. 3-5). Hot sand slows the absorption of water by the clay and its stabilization within the layers coating the sand grains. Additional water must be added, seldom in predictable amounts, to counteract the higher evaporation losses between the muller and the molding station. As sand properties are also temperature dependent, the collection, measurement, and predictive value of the results is problematical. Hot sand against a pattern can cause moisture condensation, sticking, and rough mold surfaces when the pattern is extracted. Although system sand temperature can and should be monitored, it is more important that some means be provided for avoiding temperature build-up in the system. The sand storage silo should allow for cooling and be larger than half the day's production needs unless other cooling steps are taken.

Green Sand Testing and Control

As stated earlier, the net objective in the control of recycled system sand is to maintain sand characteristics and properties within acceptable working limits. Many metalcasters endorse the practice of sand testing while not attaching any real significance to the actual test results. This is usually because sand property values have not been correlated with casting quality. Both good and bad castings have resulted from "tested" sands on different occasions.

Variations in casting size, shape, and design as well as variations in gating and molding practice impose different demands on sand behavior. Sand technology has not yet reached the point where particular sand property requirements can be analytically predicted. Such information must be determined by observation and test experience. The working limits for any given sand property will always include some degree of compromise, reflecting the range necessary to compensate for variations in product mix. No one property can be optimized without compromising other properties due to the many interrelationships.

The establishment of acceptable working limits for the various properties of a general-purpose system sand requires correlating the results of extensive tests for the entire range of castings produced. A sand system should not be expected to be able to produce too wide a range of casting sizes and section thicknesses with a single sand formulation. Rather than being economical, this practice would seriously compromise production and would result in increased scrap rates.

Today, practical foundry sand technology focuses on six to eight tests that are most important tools for system sand control. These tests are:

- Compactibility
- Moisture content
- Specimen weight
- Permeability
- Green Compression Strength (GCS)
- Methylene Blue (MB) clay

- Sand temperature
- Screen distribution

Compactibility—of tempered sand is measured as the percentage decrease in height of a loosely-packed sample when subjected to a given degree of compaction force. The test is highly sensitive to moisture changes and can be used to supplement or monitor moisture determinations (a change of three units on the compactibility scale is equivalent to ~0.10% variation in sand moisture level). The molder's "feel test," which relates to compactibility, indicates the degree of sand temper (clay/water ratio).

The refinements to the compactibility test enable closer control of sand properties and have made quicker and more accurate testing possible on the production floor. Many foundries install compactibility test equipment on the muller deck for use by the operator as a means of controlling moisture content. In addition to the laboratory rammer-type compactibility tester, automatic units are available that continuously sample and test the sand in the muller, adding the necessary amounts of water at the proper times in order to reach the designated value for compactibility. These systems work for both batch-type and continuous mullers.

Moisture content—not all of the water added to a molding sand is necessarily absorbed by the clay bond; some is absorbed by various inorganic and organic additives or contaminants present in the sand. Whereas the compactibility test is an accurate indicator of sand temper, wide differences in total moisture may be encountered at a constant level of compactibility. For this reason, the moisture test should be performed as a supplement to the compactibility test. When extra moisture is required to reach a given sand temper, it is an indication that there has been a build-up of moisture-absorbing contaminants. Conversely, unusually low values of total moisture may indicate an excess of new, unbonded sand in the system. Unusual fluctuations in total moisture signal the need for additional tests (such as tests for green compression strength [GCS], permeability, and loss-on-ignition [LOI]) in order to evaluate the cause. Several automatic moisture controllers are available to monitor and control moisture levels in system sands.

Specimen weight—a simple and convenient test for evaluating changes in system sand involves the measurement of the weight of sand required to form a standard 2" x 2" AFS rammed specimen. The accumulation of dead clay, fines, and ash (materials on U.S.A. Sieve Nos. 200, 270 and pan) in the sand causes a gradual reduction in sample weight, normally from between 145 and 160 grams. If, however, the specimen weight shows an increasing trend it is an indication that excessive amounts of new or unbonded sand are entering the system.

Permeability—the permeability of a compacted or cured sand specimen is a measure of the ease with which gas can flow through its mass, and is directly related to the venting qualities of the sand when used as a mold or core

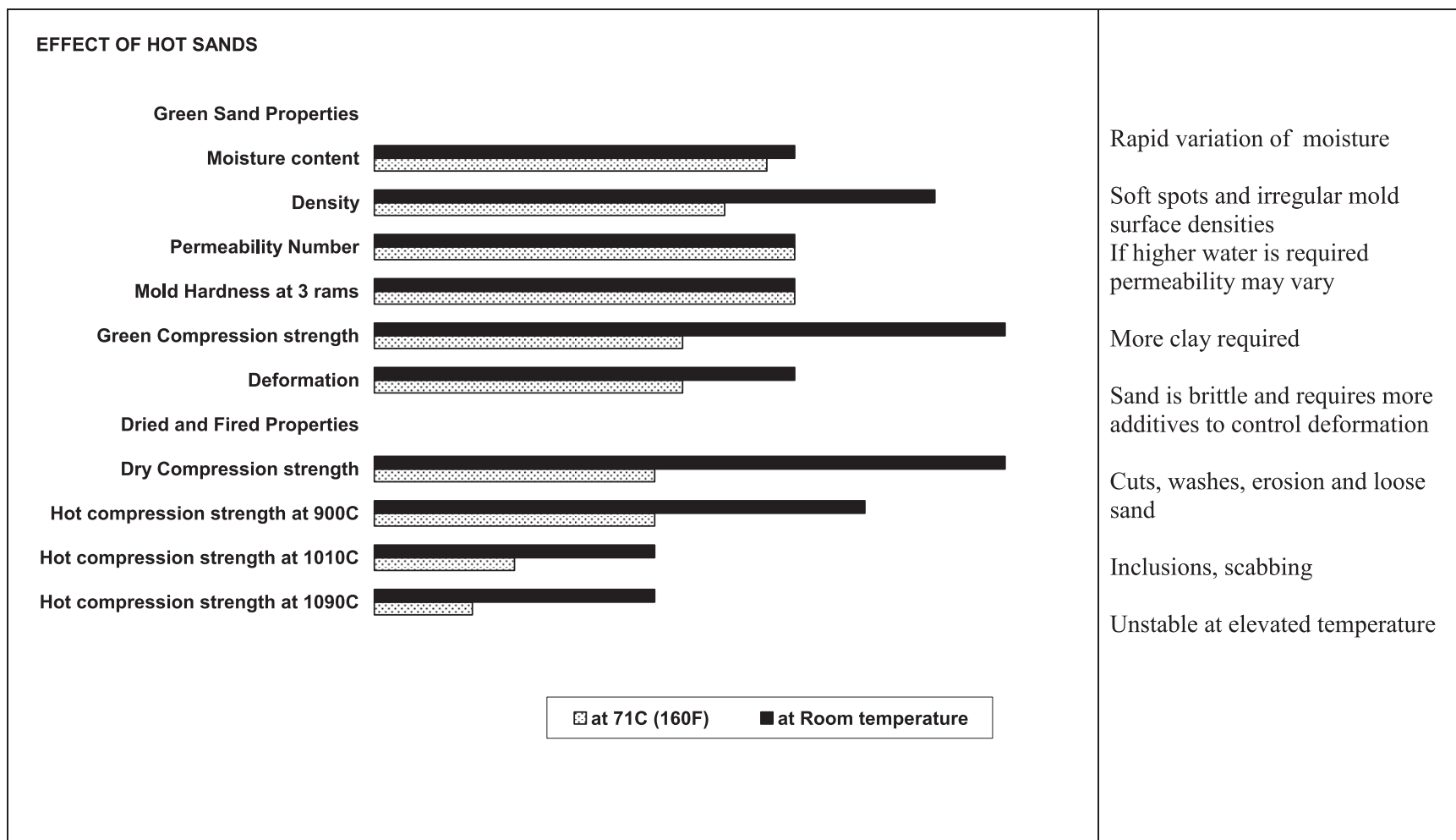


Fig. 3-5. The effect of temperature on sand properties (hot sands) is depicted in the bar chart above.

aggregate. The fineness, shape, and distribution of the sand grains, type and amount of bond material, degree of tempering, moisture level, and density of compaction are all factors influencing permeability. Increased permeability may indicate coarser grain size or lower mold density, factors resulting in rougher casting finish. Reduced permeability reflects conditions which may cause gas-related defects (blowholes, pinholes, etc.). Under conditions of reasonably good control, the permeability of a system sand should not fluctuate widely; however, sustained production of unusually heavy or unusually light castings may cause changes in this permeability. Although the frequency of permeability testing will vary from one foundry to another, hourly testing is good practice. The test is conducted on a 3-ram specimen, which only relates to certain surfaces of a compacted mold. A mold hardness tester is required to estimate sand properties in various parts of the mold, and it is not unusual to find areas with only a fraction of the laboratory properties.

Green Compression Strength (GCS)—the test for green compression strength has been used to determine the effects of the clay bond in system sand, and is often the primary means for establishing the level of clay addition to be made. However, there are several related factors affecting green compression strength. These factors include the degree of mulling, clay content, moisture level, compactibility, and the kind and amount of additives. Hence, the test for green compression strength can be used in conjunction with the compactibility and moisture to evaluate the active clay level and muller efficiency. A comparison with the methylene blue test should be done every two sand cycles.

Methylene Blue (MB) clay—the methylene blue clay test provides a quick and accurate method for determining the level of active clay (montmorillonite) in clay-bonded sand. This measurement involves determining the “base-exchange” capacity of the bentonite present in the sand, and titrating with methylene blue dye to replace the exchangeable ions found only in the structures of active clay materials. The test does not measure the presence of dead burned clay, inert fines, or silt as would be included in the “total clay” value found by use of the older AFS clay-wash/decantation procedure. The methylene blue test is useful for monitoring the active clay level in system sands as well as for checking incoming bentonite shipments to the foundry.

Sand temperature—many problems can be caused by hot molding sands, as has already been discussed. To assist in monitoring sand temperature it is convenient to install thermocouples in batch hoppers.

Screen size—screen size is important for brass foundries, as surface finish quality dramatically affects cleaning, polishing, and plating costs. As mentioned earlier, changes in screen size can be rapid or long-term, and should be avoided and controlled. Factors that should be addressed are: timing and frequency of sand disposal, belts that sling sand into hoppers, etc. and cause loss of fines and sand segregation, maintaining an appropriate mix of light and heavily cored jobs, new sand additions, screen size of new and core sands,

clay additions and clay burn out from heavy section castings and excessive metal splash.

Compaction of Green Sand

No discussion of the green sand casting process would be complete without a consideration of the molding operation itself. Various types of molding equipment have been developed for different applications; however, not all of these are equally efficient in producing quality molds. Although the machines themselves will not be reviewed in detail here, each machine utilizes one or more basic means of mechanical sand compaction. It is important to understand the behavior of green sand as these different compaction forces are applied. With this knowledge, a more intelligent selection can be made in matching a molding system to the type of parts to be cast.

The principal objective of any molding technique should be the production of a mold whose surface will neither wash nor buckle when exposed to sudden contact with hot metal, and a mold rigid enough to retain its shape and dimensions while permitting the rapid escape of gases. This requires the compaction of a suitably formulated sand aggregate so as to produce high, controlled levels of mold density across the entire mold. Two things are necessary when forming a mold with green sand: 1) the sand mass as a whole must move to its final resting place within the flask, and 2) the sand mass must be compacted, or densified, by moving the individual grains closer together. The high frictional forces between the sand and the adjacent surfaces (flask walls and pattern), and between the grains themselves, create a natural resistance against movement or compaction. The response of the sand mass to outside forces depends upon the nature of the force as well as its intensity. Comparisons of the relative effectiveness of ramming, jolting, and squeezing are given in Fig. 3-6.

Ramming, either manually or pneumatically, consists of hammering the sand mass with blows applied to small unit areas. Although sands can be uniformly and densely rammed into small spaces in this manner, the overall level of mold compaction tends to be erratic (Fig. 3-6, a).

Jolting utilizes the inertia of the sand mass itself, causing it to settle and compact against horizontal surfaces of the pattern and parting surface. The upper portions of the sand mass are much less affected (Fig. 3-6, b). Some jolt-type equipment utilizes heavy weights, placed on top of the sand mass, to increase compaction in the upper layers.

Squeezing of the sand in a flask produces a compaction pattern which is the reverse of that produced by jolting. The degree of compaction is greatest in contact with the squeeze head, diminishing as the distance from the squeeze head increases. With relatively high flasks and shallow or flat-backed patterns, squeezing alone may result in relatively soft mold faces even when using high squeeze pressures. With higher patterns, flat squeeze heads create high-density compaction against the upper pattern surfaces and relatively

low compaction against the pattern and flask sidewalls or parting surface (Fig. 3-6, c). The limiting effects of these high-density sand columns can be offset in some measure by use of a profiled squeeze head or by use of multiple pressure feet with hydraulic equalization (as with high-pressure squeeze machines).

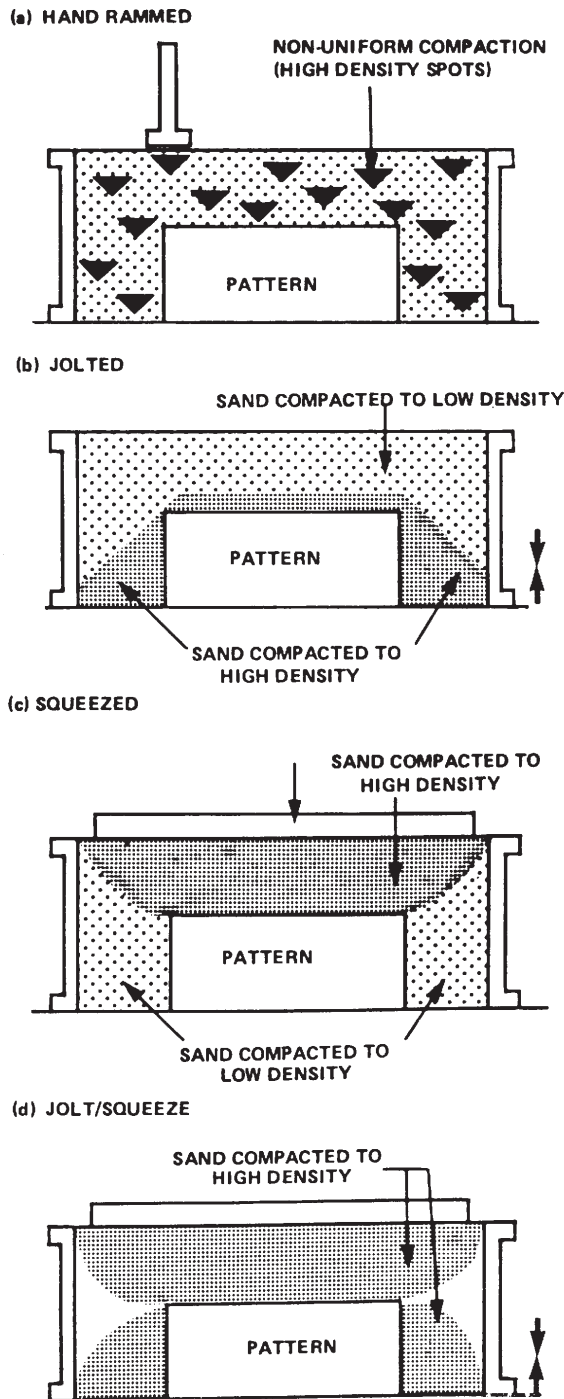


Fig. 3-6. Compaction of molding sands using various molding methods is depicted above.

Jolt/squeeze machines combine the compaction characteristics of both jolting and squeezing (Fig. 3-6, d), thus taking advantage of both forces. Areas adjacent to flask sidewalls still tend to be less dense, however, unless the flask is relatively shallow. Deep pockets of sand inadequately compacted by jolting cannot be markedly improved by the application of subsequent squeeze pressure, however high.

Sand slinging, when properly done, will produce molds of high, uniform density. In this process, small clumps of sand are thrown against the pattern in rapid succession, each slightly overlapping the preceding clump. Compaction is by impact, the degree of which is controlled by the velocity of an impeller which hurls the sand by centrifugal force.

Other miscellaneous compaction techniques have found limited application. One of these is blowing, in which a large mass of sand is initially discharged into the flask by pneumatic pressure, similar to a coremaking operation. The compaction pattern is essentially similar to that of jolting and a subsequent squeezing operation is generally required. One of the more recently developed methods for high-density compaction of green sand utilizes the explosive force of controlled combustion of pressurized gas/air mixtures. To date, such equipment has found only limited application in North America, however its developers claim a uniquely uniform and efficient compaction behavior. This is ascribed both to the uniformity of pressure distribution within the sand mass in promoting movement and to a thixotropic behavior of the clay bonding material, inducing high flowability under the effect of shock pressure.

In summary, the true economy of a green sand molding system depends upon the effectiveness of:

- a well-formulated system sand,
- a well-designed and operated sand recycling system,
- a systematic testing program for monitoring system sand properties and related ingredients, and
- a selection of molding and handling equipment adapted to the foundry's product mix.

WATERLESS SAND MOLDING

In view of the numerous problems associated with the presence of moisture in molding sand and the need for close moisture control in a green sand system in order to maintain good sand properties, waterless binders have been developed. Such binders are plasticized, or tempered by oil as opposed to water. As compared to water, certain oils were found to be especially advantageous, offering the benefits of higher vaporization temperatures, lower rates of gas evolution, and reduced chilling effect. The binder materials, known as bentones, are derived by treating a water-swelling (Western) bentonite with certain organic salts to convert it to an oil-swelling material. Such modified Western bentonites, like the Southern bentonites described earlier, have relatively low dry- and hot-compression strengths. For this reason, these oil/clay-bonded sands are not used for the

production of heavy-section castings. The binders and mixes are available from suppliers, and are used for highly detailed thinner castings, plaques in need of sharp lettering, etc.

Waterless molding sand for copper-base alloy casting production is typically comprised of a washed-and-dried silica sand of AFS gfn 100-180. A bentone binder level of approximately 5%, tempered by a 2% addition of coastal oil (Society of Automotive Engineers-SAE 40) is generally a good formulation. Most foundries using such sands work at green compression strengths of 8-12 psi. Dry compression strengths are usually over 50 psi, and hot compression strengths over 100 psi.

It is important that the waterless sands be mulled, since simple mixing does not coat the grains properly. Proper mulling develops the maximum bond strength and thoroughly distributes the plasticized binder. Although some foundries prefer to first add the oil to the sand, before the binder, the normal procedure is to add the binder to the sand first.

Once the molds have been poured they should be shaken out as soon as solidification occurs. This is to minimize the heat exposure effects on the binder, whereby the oil is partially burned away and the bentone loses its capacity to be replasticized. During recycling, the amount of replacement additives required depends upon the depth of the heat-affected sand layer in the mold. The depth of the heat-affected sand depends on pouring temperature, casting section thickness, and the delay before shakeout. The amount of additives required will also depend on the percentage of unbonded sand entering the system from core breakdown. Premature shakeout, like delayed shakeout, can also cause problems. Excessively hot castings can cause the oil to ignite, accelerating its loss from the sand and creating smoke and fumes in the foundry environment. When using such sands, testing should be done regularly to monitor the level of residual oil in order to make sure that it does not fall below the minimum requirement. Test equipment for this purpose is available from various binder suppliers.

SKIN-DRIED AND DRY SAND MOLDS

As casting size and section thickness become increasingly large, a point is reached beyond which the mechanical and thermal properties of green sand molds are no longer adequate to produce quality castings. One means for extending the application of green sand molds has been to improve their rigidity and heat resistance by the use of supplemental binders, with subsequent drying of the mold. If only the surface of the mold is dried, it is referred to as skin-dried; if the entire mold is dried, it is known as a dry sand mold. Both techniques have fallen into disuse, principally because of the development of new chemical binder systems which do not require prolonged, expensive drying operations and because of the scarcity of molding skills needed for ramming large molds.

Skin-dried (or air-dried) molds are preferred to green sand molds when mold walls free of gas-forming moisture, or

molds exhibiting greater resistance to erosion and thermal shock are desired. Skin-dried molds are first compacted as in green sand molding. Following pattern extraction, special soluble binder materials are applied to the face of the mold, often by spraying. Skin drying is accomplished by means of hot air, torches, radiant heaters or infrared lamps. Mold surfaces are also generally coated with some type of refractory mold wash, either before or after the initial drying, in order to improve erosion resistance and to prevent metal penetration. Molds should be handled, closed, and poured in such a manner as to assure that moisture does not migrate to the dried surface nor condense upon it.

Because the mold interior is green sand, skin-dried molds show good collapsibility and the molding aggregate may be recycled.

Dry sand molds have traditionally been used in the manufacture of heavy castings where even greater mold strength and stability have been required. Such molds are rammed with water/clay/sand mixtures in the same manner as for conventional green sand molds. The molding aggregate contains additional ingredients, however, which are designed to impart high dry-strength. These include materials such as molasses, dextrin, gluten, or other organic substances, added with the temper water together with increased levels of a high dry-strength binder. Following pattern extraction, the mold is then baked throughout at temperatures between 400–600F (204–316C). Baking is accomplished either in a large baking oven or by use of large mold heaters. As in the case of skin-dried molds, surfaces of dry sand molds are coated with refractory washes before use.

Establishment of proper baking time and temperature is essential to the success of the dry sand molding process. The time and energy required for baking, plus the fact that the sand is much more difficult to recycle, make dry sand molding relatively expensive. These factors, plus the molding skills needed for this process, have caused it to be replaced in large measure by processes using sands bonded with self-setting (nobake) resins.

Cement-Bonded Sand Molds

Cement-bonded sand molding is a special method which is used only sparingly in copper-base alloy foundries. It is included here since it is a viable process for the manufacture of large marine propellers (Fig. 3-7). Molds should not collapse prematurely, as risers for a 20 ton propeller may be topped up for 24 hours, and the mold shaken-out a week later. Cement-bonded sand molding is often referred to as the Randupson process.

Air-dried molds of unusual properties are produced by this process, in which such great dry strength is developed that cranes can actually handle portions of the molds without damaging them. Portland cement is the bonding agent. When properly cured and dried, such cement bonded sand molds show little gas-forming tendency. Most cement molds require

drying at higher temperatures but by the same methods commonly used with dry sand molds. Cement molds have the advantage of relatively high chill rates, but must be used with discretion to avoid hot tearing problems. Reclamation of the molding aggregate for reuse is rather expensive.

Many favorable claims have been made for the ability to store cement-bonded molds. This is an important advantage in cases where molds require long periods for their assembly, prior to pouring.



Fig. 3-7. A bronze propeller is shown at shakeout, cast in a cement-bonded mold. (Artwork courtesy of Columbian Bronze Corp., Freeport, NY)

CHEMICALLY-BONDED SAND MOLDING & COREMAKING SYSTEMS

Prior to the late 1940s, foundries had relatively little choice in the selection of sand molding or coremaking processes. Small- to medium-size castings were made in green sand molds; larger castings were made in skin-dried green sand, dry sand, or "core molds" (built up of sections bonded with heat-cured core oils). More than 90% of all the cores used in these molds were made with oven-baked, oil-sand mixtures. Following World War II drastic changes occurred with the introduction of heat-cured resin binders and gas-hardened silicate systems. These were followed by more than 20 chemically-cured and gas-hardened resin systems. Consumption of binders that required curing in a hotbox proceeded rapidly in the 1950s and 1960s, but their use declined following the energy crises of 1973 and 1979, to be replaced by nobake and coldbox binders. The usage of the various binders is shown in Fig. 3-8, together with a curve showing the slow, but persistent decline in the use of the more traditional "core oil" binders.

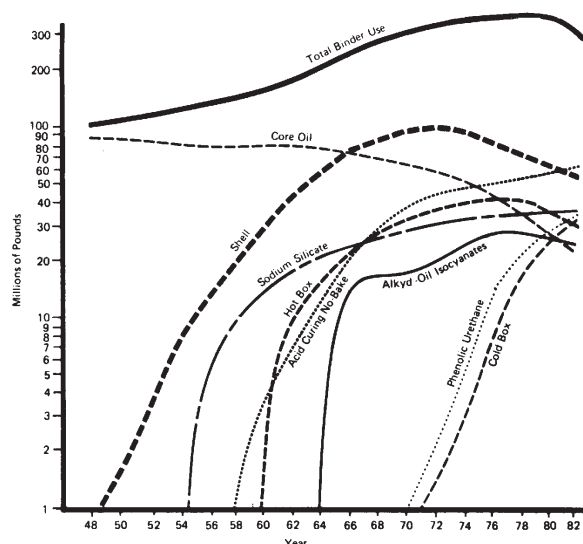


Fig. 3-8. Introduction and growth of chemically bonded sand systems in the United States market is represented above

With the exception of large propellers, most large- to medium-sized copper alloy castings are now produced in chemically bonded nobake molds. Equipment manufacturers have developed automated equipment suitable for the rapid production of molds using coldbox binders that can compete with green sand molding in productivity. Careful decision making with modern financial techniques is required to access the advantages and viability of green sand and nobake molding in any plant expansion. A comparison of sand and binder costs is not sufficient. Factors that may produce significant financial incentives for the use of chemically-bonded sands are:

- The initial cost of equipment and material handling systems is significantly reduced and simplified as greater strengths mean sand to metal ratios can be reduced by half or even a third of those in green sand molding.
- Sand losses will be 10–30% lower (per ton of metal poured) throughout the plant. Labor and dust collection required to contain the losses will be lower.
- Less force is required to handle smaller molds. Utility bills will be lower and fewer air compressors (<23% operating efficiency) will be required to manipulate lighter molds. Maintenance requirements will be lower.
- Greater mold strength means less mold wall movement. Casting yields are improved, and reductions of 10–15% have been reported. Risers will be more effective.
- Flasks and jackets might not be required and their capital and maintenance costs avoided.
- The improved casting quality and tighter tolerances has the potential to reduce cleaning, welding and grinding costs.
- The number of workers, their skills, and training requirements may be lower.
- Floor space and building requirements may be lower.

	Relative tensile strength (1)	Rate of gas evolution (1)	Degree of thermal plasticity (1)	Collapsi- bility speed (1)	Ease of shake- out (2)	Moisture resistance (2)	Curing speed (1)	Strip time (min) (3)	Resistance to overcure (2)	Optimum temperature °C (°F)	Clay & fines resistance (2)	Flow- ability (2)	Air drying rate (1)	Pouring smoke (1)	Metals not recom- mended
ORGANIC															
THERMOSETTING															
SHELL PROCESSES:															
Dry blend	H	M	L	M	F	G	H		G	260 (500)	F	E	N	M	
Warm coat (solvent)	H	M	L	M	F	G	H		G	260 (500)	F	E	N	M	
Hot coat	H	M	L	M	F	G	H		G	260 (500)	F	E	N	M	
HOT BOX PROCESSES															
Furan	H	H	L	H	G	F	H		F	230 (450)	P	G	M	M	(4)
Phenolic	H	H	L	M	G	G	H		F	230 (450)	P	G	M	M	STEEL
OILS															
Core oil	M	M	M	H	G	G	L		P	205 (400)	F	F	H	M	
SELF SETTING															
FURAN NOBAKES															
High nitrogen furan - acid	H	M	L	M	G	G		1-45		27 (80)	P	G	H	M	STEEL
Medium nitrogen furan - acid	H	M	L	M	G	G		1-45		27 (80)	P	G	H	M	
Low nitrogen furan - acid	H	M	L	M	G	G		1-45		27 (80)	P	G	H	M	
PHENOLIC NOBAKES															
Phenolics - acid	M	M	L	M	G	G		2-45		27 (80)	P	G	H	M	
URETHANES															
Alkyd - organometallic	H	M	L	M	F	G		2-45		32 (90)	F	F	H	H	
Phenolic - pyridine	M	H	L	H	G	F		2-20		27 (80)	P	G	H	M	(5)
VAPOR-CURED (COLD BOX)															
Phenolic urethane - amine	M	H	L	H	G	F	H		G	24 (75)	P	G	H	M	(5)
Phenolic/peroxide - SO ₂	M	H	L	M	G	G	H		G	24 (75)	P	G	M	M	-
SOLVENT EVAPORATION -AIR	M	H	-	-	-	G	H		G	- -	-	G	H	-	-
INORGANIC															
THERMOSETTING															
Silicate (WARM BOX)	H	L	L	M	P	F	H		F	120 (250)	P	G	M	M	(4)
SELF-SETTING															
SILICATES:															
Sodium silicate - ester cured	M	L	H	L	P	P		5-60		24 (75)	F	G	M	N	
Sodium silicate - FeSi cured	H	L	L	L	P	P		30		24 (75)	F	G	H	N	
Sodium silicate - 2CaO.SiO ₂ cured	L	L	L	L	P	P		30		24 (75)	F	G	H	N	
CEMENTS:															
Cement - hydraulic cured	M	L	L	L	P	F		45		24 (75)	F	F	L	N	
Cement (fluid sand)	L	L	L	L	P	F		30-60		24 (75)	P	G	L	L	
hydraulic cured															
PHOSPHATES	M	L	L	M	G	P		30-60		32 (90)	F	F	H	N	
Phosphate - oxide cured															
VAPOR CURED															
Sodium silicate - CO ₂	L	L	L	L	P	P	H		P	24 (75)	F	F	H	N	
NOTES: (1) H = High, M = Medium, L = Low, N = None (2) E = Excellent, G = Good, F = Fair, P = Poor (3) Rapid strip times require special mixing equipment (4) Use minimum N ₂ levels for Steel (5) Iron oxide required for Steel										Prepared By AFS Molding Methods and Materials, Division 4 Cured Sand Committees 80 -1 - 1 and 80 - 1 - 2					

Fig 3-9. Comparisons of the properties of various mold and core binder systems are shown above.

The array of binder materials available today to the foundry industry presents a complex combination of chemistries, properties, advantages, limitations, and relative costs. The AFS Molding Methods & Materials Division 4 has classified the binders, as shown in Fig. 3-9, into two major groups: organic and inorganic. Each group, in turn, contains three families characterized by their hardening, or curing mech-

anism; thermosetting, self-setting and vapor-cured. In all cases, curing consists of a chemical reaction which results in the formation of a hard, infusible compound which acts to bond the sand grains together.

Thermosetting reactions are those which require the application of heat in order to cause the ingredients to react. By

contrast, self-setting reactions take place at ambient temperatures and begin as soon as the ingredients are mixed together. The speed of the reaction is often controlled by the addition of some type of catalyst. Vapor-cured binder systems, which also harden at ambient temperatures, consist of at least two ingredients, one of which is a liquid used to coat the sand grains. After the sand mix is compacted to form a mold or core, it is then purged with a gaseous reactant, which is the other ingredient of the system.

The introduction of some of these new binder systems necessitated the design and development of new hardware, including patterns, coreboxes and machines. In some instances, existing hardware was converted and adapted. The selection of any binder usually requires the purchase of mixing, coremaking or molding machines compatible with the binder system and the foundry's mix of casting requirements. Within a few years, foundry management finds it has acquired a process consisting of binder, mold and coremaking machinery, sand reclamation plant, and specialist operators.

All existing core boxes and patterns can be used, although there are some issues. Shellac-based varnishes on wooden boxes or patterns should be avoided as they soften. Some binders leave a gummy deposit which can be difficult to remove with solvents or even scouring. Wood and certain plastics might not maintain their dimensions after such treatments.

The costs and operating characteristics of the various binder systems dictate their versatility in foundry use. Some are best suited to either molding or coremaking alone, while others can be easily adapted to both applications. Core collapsibility is also an issue, as copper-alloys have relatively high pouring temperatures but low heat content. The heat imparted to the cores from thin walled castings, short shakeout times, lack of oxygen from pyrolyzing binders and other mold gases, is often inadequate to decompose the binders. Binder levels for cores should be reduced to a minimum, almost skirting on handling problems to counter-act the cost of removing them. The following discussion is intended to characterize the various systems without necessarily attempting to describe specific applications.

Organic Binders

Thermosetting

The three binders comprising this family are: a) phenol-formaldehyde resin (shell process), b) furan or phenolic resin (hotbox process), and c) oils (core oil).

Phenol-formaldehyde resin is one of the first synthetic resins to find widespread use in the foundry. It is the material utilized as both a mold and core binder in the well-known shell (Croning) process. In the current processes, washed-and-dried silica sand of appropriate grain fineness are first coated with approximately 2% to 4% of a novolac resin, using one of three different mixing techniques: cold, warm, or hot

coating. Novolac is a phenol-formaldehyde resin (thermoplastic) which lacks sufficient formaldehyde to harden, or cure, when heated. The remaining ingredient which is added to the mixture during the coating process is hexamethylene tetramine (hexa). The latter is a reaction product of ammonia and formaldehyde, which supplies the missing formaldehyde for the curing reaction when the coated sand is heated. Temperatures from about 200 to 260°C (400 to 500°F) are required for the sand mix to cure.

The sequence for the foundry process are first, the coated sand is either dumped by gravity or blown from an adjacent storage hopper into contact with a heated pattern plate or core box. The curing reaction takes place from the heated surface inward, and is normally allowed to progress to the point where a crust or shell of desired thickness is formed. At this point, the remaining uncured sand is drained back into the storage hopper usually by inverting the core box and after a sufficient interval in contact with the hot pattern, the cured shell mold or core is stripped or ejected. For best results, the process should be highly instrumented with the liberal use of programmable controllers. A schematic representation of the shell molding process is given in Fig. 3-10. The most authoritative reference on all aspects of the shell process is the AFS publication, *Shell Process Foundry Practice* (1992).

The phenol-formaldehyde shell process has found greater application for coremaking than for molding. Its initial attraction as a molding method lay in its capability to hold closer tolerances than did green sand molds, while providing improved surface finish. From the outset, its disadvantages were lower productivity, expensive pattern equipment, and higher energy costs. The advent of automated, high-density green sand molding served to swing the balance further away from shell molding as a viable economic process.

Shell coremaking has been quite another story. Its initial attraction in the 1950s was due to the fact that it offered a means of eliminating the traditional core blowers, core driers, reinforcing wires, baking ovens and skilled coremaking labor required in the past. The popularity of shell coremaking accelerated rapidly from 1950 onward, peaking in about 1970. Although its use has declined, its popularity has been maintained by new products such as the low-odor-low hexa type. This decline has resulted from at least three factors: 1) the rapid escalation of energy costs beginning in the 1970s, curtailed supplies of natural gas for heating the boxes; 2) environmental regulations dealing with solid waste disposal and the identification of shell sand wastes as sources of free phenol; and 3) the introduction of other fast-cure coremaking binders competitive with the shell process. On the other hand, although cost per ton of coated sand is high, actual consumption per part and sand disposal can be significantly lower, coatings are seldom required, so drying costs and application costs are avoided, finish is excellent so cleaning room costs are lower.

The *hotbox process* utilizes a resin which cures when heat is applied in the presence of an acid catalyst. There are

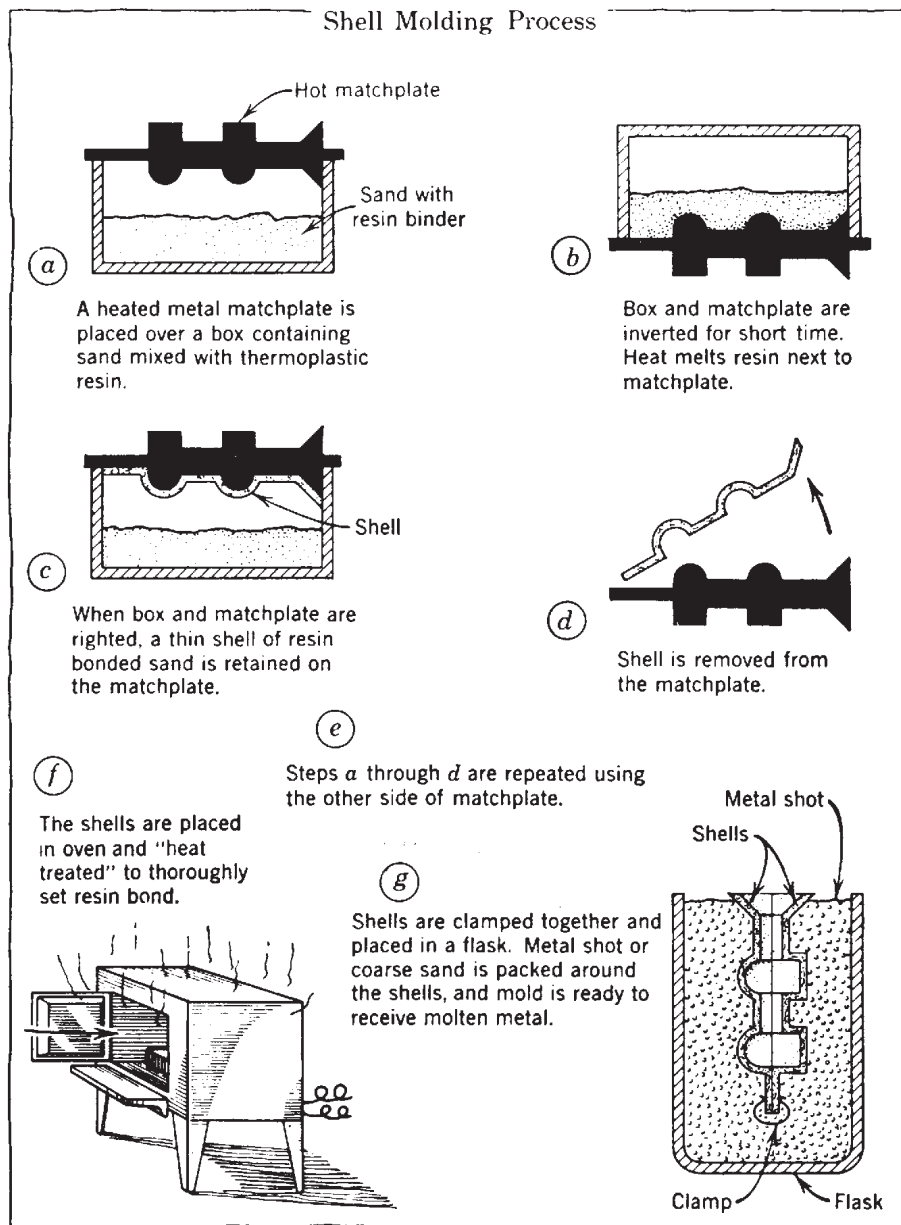


Fig. 3-10. The shell molding process steps are illustrated above.

several hotbox binder systems: the *furan* and *phenolics* and *modified phenolics*. Furan resin cures faster, has superior shake-out, higher productivity, lower odor, and fewer disposal problems, but contains furfuryl alcohol which has supply problems from time to time. New formulations are available that reduce odor and nitrogen problems. For brass foundry applications, both systems provide equivalent results and the choice between the two is largely a matter of the types of sand, mixing equipment, and core blowers which are most economically available.

Mixing procedures are essentially the same when using either binder system. One exception may occur with the phenolic resin system, as the catalyst may be supplied either

in liquid or powdered form. When furnished in the form of powder, the catalyst must first be activated with water according to supplier's instructions. A typical mixture when using a urea-furan binder would be 2% resin (based on sand weight) plus 20% liquid catalyst (based on resin weight). While they can be mixed in a vertical-wheel muller, the bench life is short from loss of moisture. On-demand mixers minimize the amount of coated sand and improve binder distribution. The amounts of catalyst and resin will vary, depending upon foundry needs, sand acid demand value (ADV), humidity, and ambient temperature.

The tensile strength of a hotbox resin sand core will vary directly with binder content, and is affected by core box

temperature and cure time. Cure time depends upon core section thickness for any given temperature and can be significantly changed by the amount of catalyst added. Excessive temperatures or curing rates can result in friable cores, and proper conditions can best be determined by experimentation.

The hotbox process requires the use of cast-iron core boxes preferably with temperature control. Standard mixing equipment is adequate as long as accurate controls exist for making measured batch additions and timing the mixing cycle. The process offers a simple, versatile means for high-production coremaking at a moderate cost. It becomes competitive with the conventional baked oil-sand process for any job requiring 50 or more cores. If water-based coatings are required then driers will be needed. In such cases, the savings in core driers will usually offset the cost of the more expensive core box required for hotbox production.

Post-curing of hotbox cores is desirable, but not always necessary. With all chemically bonded cores, through-curing is essential to ensure casting quality; therefore, it is recommended that hotbox coremaking facilities include a method for post-curing.

The *warmbox* system is a substitute for the hotbox furan in that it uses the same coating equipment, processing procedures and production techniques. The differences are in catalyst and resin chemistry. The resin is 70% furfuryl alcohol with less than 2.5% nitrogen. The catalyst is a copper salt of toluene sulfonic acid and copper chloride dissolved in a mix of water and methanol. Although the resin/sand mix has thermosetting properties, no reaction occurs until the temperature exceeds 150F (66C), and the mix has a 2–3 hour bench life. The warmbox systems use considerably less binder than the hotbox. Blow pressures and operating temperatures are less. As the sand mix changes from light green-yellow to dark green (392F/200C, optimum) and finally burnt (500F/260C), temperature control is relatively simple.

Although the warmbox process has a high cost, it can economically replace solid shell cores. When fully cured, cores are rigid with little or no post-strip distortion or sagging. The warmbox process offers a number of other advantages:

- high reactivity results in a short cycle
- lower tool warpage and extended tool life
- lower pattern temperature means less energy
- lower blowing pressure reduces tool life, cleaner tooling, less down time
- lower free formaldehyde and gas emissions
- spent sands meet EPA standards.

Core oils—in spite of the many new chemical resin binder systems available today, many foundries still make substantial use of the traditional baked oil-cereal-sand mixtures for coremaking. Such mixes actually consist of four basic ingredients; sand, water, core oil, and cereal. Commercial core oils are usually formulated with three basic ingredients:

drying (or oxidizing) oil or resin, a petroleum resin that is partially thermosetting, and a solvent to reduce the viscosity of the liquid. At the usual baking temperatures of 375 to 450F (190 to 232C), such oils oxidize and polymerize to form a strong bond for the sand grains. Other additives (i.e. wetting, release agents) are often used to provide special properties such as collapsibility, hot-compression strength, flowability, ease of blowing, or dimensional stability. Each of the basic ingredients as well as formulation, mixing order, mulling procedure, and drying have an effect on the four principal core properties:

- green compression strength (uncured state)
- baked strength (cured tensile strength)
- baking speed (rate of cure)
- hardness

Simple oil-sand mixtures cannot be used because of their poor green strength, causing the green cores to sag and collapse readily. It is for this reason that small amounts of cereal (corn flour) and water are added to the core mix. The plasticized cereal adds substantial green compression strength to the mixes, although green cores must still be supported by plates or corrugated trays until baked. Cereal also causes marked improvement in baked strength but has relatively little effect on core hardness; it has an adverse effect on the flowability and blowing characteristics of the green mix.

The water addition must be carefully proportioned during mixing and should be introduced to the muller before the core oil is added. During the baking cycle, no appreciable hardening can occur until the water is first evaporated from the cores. For this reason, the higher the water additions, the slower the baking speed. The baking cycle for silica-sand core mixes may vary from one core oil formulation to another, but typically is about one hour per inch of core thickness (the cycle time is doubled when using zircon sand).

Self-Setting Binders

The three members of the self-setting binder family are: a) furan nobake resins, b) phenolic nobake resins, and c) urethanes.

Furan nobake is the generic name of a family of foundry binders based on furfuryl alcohol that cure at room temperature. The binder contains two liquids: the furfuryl alcohol and an acid which causes the furfuryl alcohol to polymerize. Although the main ingredient of Part I is mostly furfuryl alcohol, it is modified with urea, formaldehyde, additives such as phenolic resins or extenders. The urea-modified resins are less costly; however, the urea introduces nitrogen into the system in direct proportion to its concentration. Higher nitrogen levels can cause pinholing problems with many ferrous alloys; however this is not of great significance for copper-base alloys.

Part II is an acid catalyst for the furan nobake system. Furan nobake Part II ingredients are usually proprietary mixtures of acids, solvents, and sometimes a color-coded dye. The two main classes of catalysts are either phosphoric acid (75%, or 85% phosphoric, and perhaps some sulfuric acid in water), or an organic sulfonic acid (a solution of benzenesulfonic acid (BSA); toluene sulfonic acid (TSA), or other sulfonic acids, usually in combination). Solvents for these organic acids are water and methanol. The strength and concentration of the acid affects the speed of the curing reaction. The catalytic effect of Part II depends on its residual activity after neutralizing foreign materials, sand acid demand value (ADV) and even acids and basic oxides from various reclamation procedures. For this reason the acid catalyst should be added to the sand first and thoroughly dispersed. Thus, when Part II is added, there will not be excessive concentrations of acid to accelerate the cure rate in local areas. Mixing Part I and Part II together in the absence of sand will result in an exothermic reaction which can result in an explosion.

Washed-and-dried silica sands (and zircon) are readily used with furan nobake binders; olivine, however, due to its alkaline nature, cannot be recommended. Binder requirements are increased with the fineness or angularity of the sand, as well as by the presence of fines or clays.

Mixing is readily accomplished with all the common types of equipment, however batch mixing is not normally recommended for sand formulations having short working times. Since the hardening process begins as soon as the binder is added to the catalyst-coated sand and is continuous and irreversible, it is important that prepared sand mixtures be used as rapidly as possible. Continuous mixers placed immediately adjacent to the molding station are advisable. The average level of resin binder required is approximately 1% (based on sand weight), and may vary from 0.8 to 1.4% depending on sand characteristics, mixing equipment, and property requirements. Catalyst levels are usually between 15% and 45% of the weight of resin present in the mix, and are varied to control the cure rate. Sand temperature has a significant effect on cure rate and should ideally be held between 70–80F(21–27C). The binder supplier should be consulted if sand temperature control is a problem.

Working time and *strip time* are both measures of the cure rate for self-hardening sand mixtures. Strip time is the duration between mixing and removal of the cured sand from the pattern or core box. Working time is the allowable delay between mixing and utilization of the mixture. Moving or working the sand after this period will break bonds and result in reduced strength. The working time for furan nobakes is usually about fifty-percent of the strip time. Strip time can be anywhere from less than one minute to several hours, depending on the kind and amount of catalyst used and the sand temperature. This system can tolerate the presence of some moisture; curing, in fact, generates small amounts of water within the mold or core. The presence of excessive moisture in the mix will prolong the curing time.

Phenolic nobake (acid-cured) systems are likewise composed of a liquid resin binder and a liquid catalyst. Unlike the furans, the phenolic resins contain water in amounts ranging from about 8% to 25%. Higher water levels result in lower cure rates and lower tensile strength. The principal type of catalyst used with the phenolic nobake system is a mixture of sulfonic acids (BSA, TSA and others). Small amounts of sulfuric acid are sometimes also added to these acid mixtures to accelerate curing. Unlike the furan nobakes, phenolic nobakes should not be catalyzed with phosphoric acid which results in slow curing and low properties.

Typical mixtures with phenolic nobakes consist of about 1.5% resin ($\pm 0.5\%$) and catalyst levels ranging from 20 to 45% of the weight of resin employed. Recommended procedures for mixing and use, as well as control of cure rates and properties are essentially the same as discussed for furan nobakes. In general, the strength of sands bonded with phenolic nobakes is somewhat lower than for the furan nobakes.

Urethane nobake systems are of two different types: alkyd oil urethanes and phenolic urethanes. The former was introduced in 1965 and is the third highest selling binder system.

Alkyd oil urethane binders are available pre-catalyzed for a predetermined work/strip time as a two-component system, or as a three-component system; this provides flexibility through on-site cure speed adjustment by catalyst metering. In either version, the work to strip time ratio is approximately 1:2; that is, a sand mixture with a 25-minute work time can, in most cases, be stripped in 50 to 60 minutes. While product names and designations vary from one supplier to another, the alkyd (oil) component is often referred to as Part A, Part I, or some other primary designation. This first component constitutes the bulk of the resin used, and will be referred to in the further discussion of this system as Part A. The polymeric isocyanate component is, again, variously named, and is normally used at levels of 18–20% (based on Part A). In further references, this isocyanate component will be designated as Part C. The third component (if purchased separately), the catalyst, is used at levels of from 2% to 10% based on Part A, and contains metallic driers that act as urethane catalysts. This component will be referred to as Part B.

When all three component parts are mixed with the sand, two reactions take place. First, the polyisocyanate (Part C) crosslinks with the oil-modified alkyd (Part A) to produce a urethane bond with sufficient strength to permit stripping and handling. This stage does not require oxygen or removal of reaction products such as water. The second stage of the curing reaction requires oxygen for the further polymerization of the alkyd resin. Remaining solvents also evaporate at this stage. As this stage is oxygen-dependent, section size and foundry conditions can affect the curing time. The oil-modified alkyd resin (Part A) contains the hydroxyl groups. The percentage of Part A used in a typical sand mixture is 1.5% (based on the weight of the sand), though this may vary $\pm 0.5\%$ depending on sand type, sand purity, and casting requirements. An increase or decrease in Part A will correlate directly with the ultimate strengths the system will develop,

if Parts B and C are kept in the same relative proportions to Part A. Part B (the catalyst) contains metal salts, called driers, which determine the speed of the reaction as well as the overall curing characteristics of the system. The metallic driers assist the oxygenation reaction as well as the isocyanate reaction, thus controlling the overall cure rate of the alkyd (oil) urethane system. Amines up to 2% are added to the metallic driers when fast strip times are required. An increase in Part B will increase the speed of the reaction, thus decreasing the work time. The faster the alkyd (oil) urethane resin system selected, the higher the early tensile strength.

The use of a metering pump is recommended for controlling the catalyst addition (Part B) especially when low flow rates are required (under 0.8% based on weight of the sand). If a metering pump is used, the catalyst should be pumped into the Part A resin line just before entering the mixing chamber. This allows the catalyst to become dispersed in the alkyd (oil) resin and thus does not result in soft spots in the mold or core. In many instances, Parts A and B are used premixed, thus eliminating pumping problems associated when small amounts of Part B are required. The use of a premix has advantages when sand temperatures can be maintained at a constant temperature. Otherwise, the percentage of Part B in the premix may require frequent adjustments to compensate for varying in-plant temperatures.

Part C is the polyisocyanate component which co-reacts with the resin, Part A, and should not be considered a catalyst because it undergoes a chemical change to form the urethane polymer, and a specific quantity is needed to obtain desirable curing characteristics. If less than this quantity is used, the curing rate as well as the ultimate tensile strength will be impaired. Too large a quantity of Part C containing 10% nitrogen will increase the possibility of gas defects due to unreacted nitrogen complexes. The recommended amount of Part C is between 18% and 20% (based on Part A), to account for mixing deficiencies, moisture in the sand and typical foundry variables. Part C, particularly sensitive to moisture, hardens after prolonged exposure forming a skin at the air contact surface. Tightly closed containers, moisture absorbers, and nitrogen blankets are commonly used to keep moisture out of Part C.

In a typical sand mixture of 1.5% Part A (based on weight of sand), 6% Part B (based on weight of Part A), and 20% Part C (based on weight Part A), the cured core will contain 0.03% nitrogen based on sand weight. Although alkyd (oil) urethanes contain nitrogen, the cured system structure does not evolve decomposition products of nitrogen as readily as do urea-containing binder systems.

Mixing efficiency is extremely important in the development of the optimum cure strength of the binder system. The viscosity of the various liquid components should be closely monitored. Changes in viscosity can affect pump delivery, mixing efficiency, and ultimate core density and core quality. The variables that have a detrimental effect on this binder system's performance are:

- High sand temperatures (heat speeds up the reaction and reduces the bench life of the mixture)
- High humidity (moisture reacts with Part C decreasing the flowability of the mixture)
- High acid-demand value (ADV) of the base sand (alkaline impurities speed up the reaction)
- Aeration of the sand mixture causes solvents to evaporate, decreasing the flowability of the mixture.

Alkyd-oil urethane systems are generally less sensitive to sand types than are other nobake binder systems because of the nature of the curing reaction. Silica sands and specialty sands such as olivine and zircon are compatible with alkyd-oil urethane binders. For optimum performance, the following recommendations are offered for sand selection:

- A rounded grain shape provides the best properties for a given resin level (tensile strength, scratch hardness, flowability and density).
- Sand fineness between 45 and 75 AFS gfn are preferred. Finer sands increase binder requirements and decrease flowability.
- Strongly acidic sands retard cure rate while alkaline sands accelerate the rate.
- The lower the moisture, the faster the cure rate—and vice versa. Water contamination of the binder is significantly more detrimental to initial cure than is water contributed by moist sand.

Other variables that will significantly affect the properties and productivity of the alkyd (oil) urethane systems are:

- Combustibles—Loss-on-ignition (LOI) should be kept below 2% maximum (an issue for mechanical reclamation). Excessive LOI results in higher binder levels, reduced flowability, and may be correlated with casting defects.
- Temperature—the alkyd-oil urethane reaction is exothermic, thus any increase or decrease in sand temperature will affect the cure rate. For rapid cure rates at minimal catalyst levels, select a sand temperature between 81–90F (27–32C) and maintain this temperature within $\pm 3^{\circ}\text{C}$ for reproducible cure rates. Approximately 0.5°C change in temperature increases or decreases the strip time by 1 minute. It is also recommended to maintain pattern temperatures around 86F (30C) and resin temperature at 77F (25C).
- Segregation—segregation of the grain sizes in the sand during handling and storage affect the tensile strength, flowability, and casting quality at a given binder level.
- Additives—for most applications, additions of 1.5% to 2% red or black foundry-grade iron oxide will improve the hot-strength and minimize surface porosity as well as excessive lustrous carbon deposits. Pouring temperature of the metal, gating practice, binder level, pouring time, and base-sand type all influence the formation of lustrous carbon.

- **Effect of Baking**—oven-baking of alkyd-oil urethane bonded core/molds at 300–400F(150–200C) from 2 to 24 hours (depending on casting size) promotes further crosslinking of the binder system resulting in higher tensile strengths, improved erosion and hot-strength properties, while minimizing the volatiles in the sand mixture. Baking at temperatures above 400F (200C) is detrimental and should be avoided.
- **Washes**—almost all washes can be applied. Water-based washes should not be applied until 24 hours after stripping or after baking, and should be dried immediately after application. Alcohol-based washes should be lit-off as soon as possible; but laws against Volatile Organic Compounds (VOC) emissions are reducing sales of these washes. Washes should penetrate the surface by at least two sand grains. As this will reduce the measured permeability of the surface to zero, venting becomes important. Vents should be narrow enough (~1/16 inch) that metal does not penetrate and cause surface sinks.

Phenolic urethane nobake (PUNB) binders were introduced in 1970, and are capable of producing strippable cores or molds within 1 to 15 minutes of filling the pattern or corebox. Phenolic urethane nobakes are three-component binders. Part I is a phenolic resin blended with solvents. Part II is a blend of polymeric methylene diisocyanate (MDI) and solvents. Part III contains the catalysts, which are various blends of pyridine derivatives and solvents, to regulate the reaction between Parts I and II. The unique feature of PUNB's is the curing reaction. Basically, there is a delay in the curing reaction after the three components are mixed with the sand. This is the work time of the mixture. This delay enables the sand mixture to remain free-flowing until the curing reaction begins. Work time can be as high as 75% of the strip time. Once the reaction starts, it is extremely rapid and thorough. Because this crosslinking reaction involves no side products, the curing rate is constant throughout the entire sand mass. The center of the core cures at the same time the edges do, and the same strength is developed in the core and at the edges. There is no prolonged plastic stage during the cure nor are there soft spots after the cure is completed. Two-thirds of the system's ultimate strength is attained after approximately 4 hours, and ultimate strengths are achieved at 6 to 12 hours after stripping. Since the curing reaction occurs so rapidly, high production rates and rapid equipment turnover is possible. The cure speed of a particular sand/resin mixture is dependent on: the percent of catalyst; the catalyst type; and the sand temperature, ADV, and moisture content.

The total binder level for PUNB's is based on the weight of the sand and is usually in the range of 0.8–1.8%. If the castings to be poured are sensitive to gas defects, then the normal Part I to Part II ratio of 50/50 should be shifted to 52.5/47.5 or even 60/40. This should be discussed with the binder supplier, and some loss of tensile strength can be expected. It is generally recommended that equal amounts of Part I and Part II be added to the sand to reach the binder level

desired. Catalyst usage is generally 2–9% of the weight of Part I depending on the strip time desired, the type of base sand, the sand temperature, and the type of catalyst being used. If catalyst usage is outside the 2–9% range, then a catalyst with a different reactivity should be used. Recommendations for obtaining optimum performance properties with PUNB resin systems are:

- **Sand Selection**—round-grain silica sands yield optimum performance properties. Specialty sands including zircon sands and chromite sands are compatible with PUNBs, as are most subangular lake and bank sands. Acid impurities tend to slow the curing, while basic contamination may speed up the cure.
- **Sand Fineness**—an AFS gfn of 50 to 80 is recommended with a minimum of fines (material on the U. S. sieve numbers 200, 270, and PAN). Poor sand reclamation or sand segregation can result in excessive fines and the need for more binder because of the increased sand surface area.
- **Sand Moisture**—less than 0.25% moisture content is recommended. Moisture levels above this will result in slower cure rates, lower strengths and variable sand flow rates.
- **Sand Temperature**—while the ideal sand temperature for PUNB's is 80-90F (27–32C), sand as cool as 60F (16C) or as warm as 100F (38C) is usable. The main concern should be the maintenance of a consistent sand temperature not varying more than $\pm 3^{\circ}\text{C}$. When such a condition exists, cure speeds are consistent and predictable, and the need to adjust catalyst levels during core/mold production will be minimized. If sand heaters and coolers are needed to maintain this temperature range, then they are strongly recommended.
- **Sand Additives**—the use of 1.5 to 2% foundry-grade red or black iron oxide may be required (typically steel) for optimum casting finish from improved hot-compression strength and the elimination or reduction of surface porosity and lustrous carbon casting defects.

The PUNB resin system can be mixed in most foundry batch mullers, auger-type continuous mixers, and the newer generation of high-speed intensive mixers. Part I and the appropriate catalyst are added to the sand first. Because of the small amount of catalyst used, it is recommended that the catalyst be preblended with Part I prior to addition to the sand. This will ensure that the catalyst is efficiently distributed and that the binder system will perform in an optimum manner. Zero-retention continuous mixers are ideal for the PUNB system as are conventional batch mixers, provided that only the amount of mixed sand that can be used before the work time expires is prepared at a given time.

Mixing times for batch mixers are best determined at the point of use. Overmixing of sand and resin may result in lower tensile strengths due to partial curing of the mixture.

Undermixing may result in poor distribution and lower tensile strengths. Properly mixed sand will discharge from a muller as a free-flowing mass that can be distributed and compacted easily since essentially no green strength exists. When continuous mixing is employed, gear pumps accurate to $\pm 1\%$ are recommended to pump the two binder components I and II. The pre-blending of Part I and catalyst is conveniently accomplished by mating the catalyst pump exit hose to the Part I hose immediately upstream from its point of discharge into the sand. Part I and catalyst should be added to the sand prior to Part II. However the mixing is accomplished, calibration and maintenance of the mixing equipment (mixer blades, sand flow controls, pumps) is essential to a smoothly operating nobake system. Weighing and pumping devices should be checked for accuracy at least once per shift. Part I, Part II, catalyst, and sand delivery rates should be calibrated to conform to a predetermined process control plan.

Vapor-Cured Systems

Vapor-cured (coldbox) systems are hybrids since the processes are based on chemistries which are similar to the acid-catalyzed urethane resin system already discussed. When mixed with sand and either rammed or blown into a mold or core box, these binders are cured by introducing into the sand a vaporized liquid or gaseous catalyst at room temperature. No external heat is required. Currently, there are two gas-cured organic binder systems widely in use: the phenolic urethane-amine system and the furan-SO₂ system.

The phenolic urethane-amine system (PUCB) has experienced phenomenal growth since its introduction in 1968. Similar to the phenolic urethane nobake process, the coldbox version consists of a three-part resin system: phenolic resin, isocyanate, and amine catalyst. Total resin based on sand varies from 0.8% for aluminum to 1.5% for cores in ferrous castings. Tertiary amines such as triethylamine (TEA) and dimethylethylamine (DMEA) are used to set the sand. These low-boiling-point amines are vaporized in a carrier gas (6-12% in the carrier gas) and introduced to the sand mixture to achieve an almost instantaneous cure. Since liquid amines are flammable, inert carrier gases such as nitrogen and carbon dioxide are normally used to minimize fire or explosion hazards. Typical cure rate values range from 2 lbs. of sand per second to 10 lbs. per second. The final step in the curing process involves the use of a high-pressure air purge to distribute the amine to all portions of the core box and ultimately flush residual amine vapors from the core cavity. These vapors are collected from the sealed core box and exhausted into an acid-bath chemical scrubber where they are neutralized. Sand chemistry, temperature, and moisture levels have a significant effect on the system's bench life. Basic sands, such as lake sand, bank sand, and olivine contain alkaline impurities that decrease the bench life of the system. On the other hand, when used with neutral sands the bench life should be in excess of three hours. High temperatures cause solvent evaporation, and lower the bench life which may result in friable core surfaces. A usable sand-temperature working range is 50 to 100F (10 to 38C).

High moisture levels in the sand also result in decreased bench life and ultimate strengths. In addition to reacting with the isocyanate, moisture decreases the adhesion between the resin film and the sand grain causing a poor bond. Moisture levels up to 0.2% can be tolerated but should be maintained at minimal values.

Acrylic-epoxy-SO₂ system—an earlier furan-SO₂ system was basically a gas-cured furan system which, instead of using a liquid catalyst, relied on the passage of sulfur dioxide gas through the uncured sand mix in the presence of an oxidizing agent (in this case organic peroxide) to create the acid. This produced an instantly-cured core or mold exhibiting all the characteristics of a conventional furan nobake system. This system has been largely replaced by the Acrylic-epoxy-SO₂ system, although some nonferrous foundries still use the furan system as core shakeout can be critical.

The epoxy-SO₂ process uses a two component system. Part I is an epoxy resin with an organic hydroperoxide. Part II is a mix of acrylic resin, epoxy resin, additives and a solvent. The sand is coated with the two components and exposed to the SO₂ gas which starts a free-radical reaction with the acrylic. The acrylic component cures rapidly which gives the system early handling strength. The epoxy reacts slowly allowing for good pattern release and after 24 hours good hot strength. Resin consumption ranges from 0.5 to 1.5% based on sand and application.

Sulfur dioxide (SO₂) is supplied in cylinders as a liquified gas which has a pressure of 35 lbs. per square inch at 77F (25C). Gas generators are available to provide blends of SO₂ and nitrogen (N₂) for curing. Consumption will normally be less than 4 kg per ton of cured sand. The SO₂/N₂ blends use less SO₂ and leave less SO₂ in the mold or core. The SO₂ must be distributed evenly and finally purged from the sand. Purge air must be free of oil and water, and the best results are obtained by using a heated purge air. Typical temperatures are 95F (35C) and commercial air heaters are available for this purpose. Excess SO₂ is removed from the purge air in a chemical scrubbing unit, typically a packed scrubbing tower where the SO₂ gas is absorbed by reaction with 5% sodium hydroxide solution. The resultant sodium sulfate solution has a pH of 8.5 and can usually be discharged into municipal sewage systems. Due to the toxic nature of sulfur dioxide, the system must be closed to prevent leakage into the working environment.

Sand mixing can be accomplished either in the batch mullers or continuous mixers. The two resins are added to the sand and mixed. At this stage, the mixed sand has a very long bench life and will only cure when the SO₂ gas is introduced. Curing is then instantaneous with very high tensile strengths being obtained. Coated sand is easily handled, does not stick to the sides of hoppers or blow magazines. The long bench life allows coated sand to be left in blow magazines, with easy start-up after production delays or plant shut downs. Losses and cleaning are thus minimized.

As with the other binder systems previously mentioned, the methods used for producing cores or molds are blowing, jolt/squeeze, hand ramming, or mechanical vibration. For high production rates, blowing is commonly practiced with curing taking place within the automatic cycle of the machine. Generally, any machine designed for use with a gas-curing coldbox system can be used. Where manual core blowers are employed, these machines can either be converted to cure the cores within the machine or the filled core boxes can be gassed in a conventional curing chamber. With jolt/squeeze, hand-ramming, or mechanical vibration methods, the filled core or mold is normally placed in a suitably sized chamber for curing. To obtain the most cost-effective operation, it is most important to have good sealing. Correct sealing ensures the optimum curing of the mold/core and also prevents excessive use of the SO₂ gas, thus extending the life of the solution within the scrubbing unit. As with any gas-cured coldbox system, the SO₂ processes are dependent on the ability of the curing gas to reach every area of the core or mold and then be purged clean in as short a time as possible. To produce a positive pressure within the cavity, the combined venting area must be smaller than the gas inlet area.

Although vent areas and pressure drops are important, they can only work if the vent placements within the core or mold cavity are correct. To prevent gas “bypass” and uncured areas within an otherwise well-cured core or mold, vents should be placed in the deepest areas of the core or flask and as far away as possible from the gas inlet, as is true for any gas-cured system.

The acrylic-epoxy-SO₂ system offers a number of advantages for the foundries: specifically no formaldehyde, or isocyanates in the decomposition products, excellent shakeout properties, reduced hot tearing and veining defects, higher productivity from reduced cleaning and start-up costs, and consistent properties due to the long bench life.

Mixing and Foundry Use of Nobake Sands

There are several types of mixers used with nobake binder systems. The best mixer to use for a particular operation depends on the binder system and the sand volume required. The batch mixer, used by the foundry industry for many years, is normally used to mix sand with binders that have long working times or are slow curing. The auger or screw-type continuous mixer is another commonly used piece of equipment. With this type of mixer, catalyst and binder are added to the sand as it is screwed along the trough and mixed together. However, continuous mixers of this type have a tendency to waste a considerable amount of coated and raw sand since, unless it is used within a reasonable length of time, the sand in the mixing trough must be discarded. Another type of mixer is the high-speed continuous and/or batch mixer. This mixer usually has single or multiple mixing chambers of short length with very high throughput of sand and a low level of sand waste. Improved ease of maintenance is one of its main advantages. Zero-retention continuous mixers are ideal for nobake systems as the mixed sand is

available at the push of a button and minimal amounts of sand remain in the mixer at the end of a mixing cycle. The size of the mixer required will depend on the typical size of the pattern or core box to be filled, the amount of time available for filling, and the packing method.

An important part of the mixing facility is the metering system which is used to control the additions of various components to the mixer. It is essential that the structural materials of the metering devices be accurate, reliable, and compatible with the components of the nobake system. Gear pumps with accuracy within $\pm 2\%$ are recommended for handling liquid resin components. This type of pump provides a constant rate of delivery, whereas the pulsation in delivery rate associated with positive displacement pumps makes them less suitable. Positive displacement pumps should be equipped with a surge chamber if used. To ensure that all systems are functioning properly at the mixer, routine calibrations should be made at the beginning of each shift. The delivery rates of sand, (wet sand flows more slowly), sand binders, catalysts and any special additives should be checked to verify that they are as intended.

The production of molds and large cores using the nobake sand binders is facilitated by the fact that the sand mixtures are highly flowable and thus do not require a high level of molding or coremaking-skill for their use. One should not lose sight of the fact, however, that high, uniform mold and core densities are most essential to the production of good castings. Such conditions are not attained by merely dumping the sand mix into a flask or core box. The following points should be carefully noted:

- Nobake sand must be used and compacted immediately upon mixing, before any real hardening commences. Hardening starts as soon as the binder contacts the catalyst in the sand mixture; then, the viscosity of the binder film gradually increases and hardening begins. Both the viscosity and the curing action greatly affect the flowability of the sand mixture.
- The curing reaction is temperature-sensitive; sand that is above 104F (40C) will hasten pre-curing, quickly reducing sand flowability. The sand should be maintained at a uniform temperature, preferably between 77 and 95F (25 and 35C).
- When making larger molds or cores, high-output mixers are essential in order to prevent undue pre-curing of the sand mixture before the moldmaking or coremaking operation is completed. With larger molds and cores it is essential that the sand, particularly near the mold or core surfaces, be compacted by tucking or tamping it into position. Generally only a 2 inch layer can be compacted at a time. Sand near the pattern should not be disturbed as layers of sand are added above it, once the working time is exceeded.
- Vibration compaction is a good method of consolidating nobake sands and is most applicable to the manufacture of smaller molds and cores. It

is essential that the vibration take place for an optimum amount of time, without overloading the vibrating table. Over-vibration is detrimental and can cause ram-off problems. A more satisfactory practice, however, is to hand tuck the sand at critical areas and at the mold-metal interface, and then vibrate during the filling of the core box or flask.

- Oily-type binders (alkyd resin oil-isocyanate) and low-viscosity binders generally provide more flowable sand mixtures than sands bonded with more viscous binders such as furan-type binders. Any additions that provide green strength reduce the flowability of the mixture and should be as small as possible.
- Hardness tests (indentation or scratch) will not determine the degree of compaction of nobake sands. The only simple method available is to determine the permeability of the surface of the mold or core by means of a portable permeability tester. All compacted sands show a decrease in permeability with increase in bulk density. Many binder systems develop less strength if bulk density is less than a critical value.

Foundry Control Tests for Nobake Sands

The various tests used for chemically-bonded sands are primarily for evaluating and monitoring process parameters. They may also be used for trouble-shooting. These control tests include the following:

Mixer Calibration—though not normally considered a sand test, mixer calibration is the most important control test performed with chemically bonded sands. This test first establishes the exact sand flow from the mixer; it is this flow rate upon which binder and catalyst percentage calculations are established. On large mixers, this rate is usually checked by placing a floor scale with a large container underneath the mixer. Sand is then discharged into the container for a prescribed amount of time and weighed. Normally, this is repeated several times to ensure correct flow rates. Although time-consuming and perhaps awkward, this test is extremely important. Once the flow rate has been established, the binder and catalyst pumps are then calibrated for the correct amounts. If possible, samples are taken from the resin discharge ports in the mixer. If this is not possible, they should be taken from a calibration port which is of the same configuration as the discharge port. This is repeated until the samples procured are of the correct calculated weight. Mixer calibrations should be run at the start of each shift to ensure that the correct sand discharge rate and binder additions are being used.

Tensile Strength—measurements of the tensile strength of the sand mixture should be made periodically throughout the day; the frequency of the testing depends on the process and binder system being used. The purpose of this test is to check for consistency of the sand mix in order to note any trends which might signal a potential production problem. For the test to be effective it is necessary to develop a cor-

relation between tensile strength and core quality (sample weight, permeability).

Work-time/Strip-time—the test for work-time and strip-time can be very useful in a nobake operation. This test need only be performed infrequently, unless a major change in the system should occur. Tests for determining work-time or strip-time are usually run in a series in order to develop charts or data which relate these values to catalyst level. In this manner it is possible to regulate the catalyst pump on the mixer to provide the desired working properties for each job, and avoiding the use of sand which has surpassed its work-time. Some binder systems must be stripped while still plastic. Exceeding this time causes stripping difficulties, damage and reduced productivity (the author has seen 30–40 minutes to strip 400 lb molds because the strip time was exceeded). Similar tests can be used with vapor-cured (coldbox) sand mixes to document the deterioration of the sand-resin mix with time. In this case, the allowable delay time is referred to as bench life as opposed to work-time.

Sand Temperature—chemically-bonded sands are extremely sensitive to temperature. A rule-of-thumb is that for every 18° F (10° C) decrease in temperature, the binder reaction time is doubled. Thus, if a consistent operation is desired, sand temperatures must be consistent. Sand silos should not be outside in cold climates. Operators should know what the temperature is so that corrections can be made to compensate for any possible temperature changes. Temperatures can be monitored by probes in the surge hoppers before the sand mixers, or by the use of an accurate thermometer placed in sand which has been discharged from the mixer. Pattern temperatures should also be controlled.

Grain Fineness—AFS gfn tests should be performed periodically to check the screen distribution and especially the fines content of the sand at the mixer. This is an important test, as an increase in fines can cause drastic decreases in the strength of cores and molds. It is best to make this test at the mixer since sand transportation systems and storage silo configurations can change the fineness value significantly.

Moisture—moisture in the base sand can cause reduced strengths or retard the cure in chemically bonded sands due to the water reacting with the binders. A lowering of flowability and the degradation of the bond between sand grains occurs due to the moisture film. Moisture levels above 0.25% should be avoided. The moisture test can be performed with the same frequency as the fineness test. This will indicate if a moisture problem is developing in the sand, either from high-moisture contents in the delivered sand or from leaks in the sand silos. This test is also helpful in troubleshooting when the cause of low-strength cores or molds is not readily apparent (or binder expiry date).

Acid Demand Value (ADV)—testing the ADV of the base sand can be helpful in several areas. High-ADV sands retard the cure of acid-cured systems. This can result in poor strengths or no cure. It can also contribute to the acceleration of the cure rate in basic catalyzed systems to a point where the

sand is cured before it can be used. The ADV test can also be used to monitor acid buildups in acid-cured reclaimed sands and to check for influxes of basic contaminants into the sand (oxidized aluminum particles will deplete acid catalysts in their neighborhood).

Loss-On-Ignition (LOI)—the LOI test reveals the amount of combustible material in the sand. High levels of combustibles in the base sand can affect both cure rate and strength. The test is most important for monitoring the efficiencies of sand reclamation systems. LOI values above 2% can lead to problems with sand properties and may cause gas defects in castings.

The consistency and uniformity of production using chemically bonded sand technology is dependent upon narrow control parameters. The effects of upsetting the fine balance necessary when dealing with the interacting chemicals, variations in the ADV of the base sand, and minute amounts of moisture in the base sand, should serve to emphasize the need for strict in-process controls and a testing program tailored to the specific process and production requirements of each operation.

Inorganic Binders

Inorganic binders can offer some environmental advantages over organic binders. Organic binders (carbon based) emit carbon monoxide and noxious organic vapors in the pouring and shake-out areas and when levels exceed allowed levels (frequently) additional ventilation may be required. Sand disposal and outdoor storage can be issues if phenolic compounds are present. Organic binders are not 'organic' in the modern food industry parlance, and are seldom natural. The principal types of inorganic binders (other than clay) are: silicates, phosphates, and cement (as listed in Fig. 3-9). Cement has already been discussed under "Cement-Bonded Sand Molds."

Phosphate binder systems consist of liquid mixtures of aluminum-phosphate and phosphoric acids which are hardened by reacting with an addition of magnesium oxide. This inorganic nobake system has found relatively little use in copper-base alloy foundries.

Silicates have been used as mold and core binder materials since the early 1950s, principally in the form of the well-known CO₂-silicate (vapor-cure) system. Nobake silicate binder systems, utilizing organic esters, ferrosilicon, or calcium silicate slag materials as hardeners have found important application in moldmaking for heavy ferrous castings. The silicate system has no supply problems, gas handling, CO₂ scrubbing, sand handling, and environmental or waste disposal issues. As carbon dioxide is heavier than air, appreciable amounts should not be used where there are pits below the floor. The following deals only with the CO₂-silicate system as a coremaking application which finds use in copper-base alloy foundries.

The CO₂-silicate system consists of an aqueous solution of sodium silicate and CO₂ gas. Typical silicate binders are odorless, non-flammable, and nontoxic, contain no sulfur, nitrogen, or phosphorus, and are suitable for use with all types of aggregates in the production of both molds and cores. They produce no noxious gases and a minimum of emissions during pouring, cooling, or at shakeout. On the negative side, the CO₂-silicate system requires control of temperature, CO₂ flow rate and gassing time, is sensitive to high relative humidity, cores have a shorter shelf life than other binder systems, poor core collapsibility, and reclamation is difficult.

Properties of the silicates vary according to the silica (SiO₂)-soda (Na₂O) ratio of the sodium silicate base that is used to formulate the binder. Liquid sodium silicates are commercially available with varying proportions of silica and sodium oxide and with wide ranges of viscosities. The most commonly used silicates are those having viscosities between 48 and 52 Baumé and a silica-to-soda ratio (SiO₂:Na₂O) between 2.0 and 2.8 to 1 (1.9–3.2 may be used in other applications). By controlling this ratio and the water content, it is possible to make various grades of sodium silicate having a wide range of chemical and physical properties. The curing of the silicate process involves two mechanisms. The first reaction is that of sodium silicate with CO₂ gas to form sodium carbonate and silica gel and water. At this stage the system has reached 20 to 40% of its ultimate strength. The second mechanism is the dehydration of the silica gel to form a glass-like bond.

Continuous mixers or batch mixers can be used with sodium silicates, which can be metered through pumps. Overmixing should be avoided as this may reduce the work time (bench life) of a sand mixture. Mixtures normally have a good bench life which becomes shorter when higher-ratio silicates are used. Hoppers of mixed sand should be covered with plastic sheets or damp sacking to prevent premature hardening (crusting).

Molds or cores can be produced from the prepared mix with mechanized equipment or manual methods. Patterns may be wood, plastic or metal, and can be cleaned by washing with water. The sand requires light compaction by tamping, compression, vibration, or blowing. Carbon dioxide gassing is accomplished by spiking the back of the mold and fitting a tube or fitting a rubber cup over the holes. More efficient methods employ a hood over the top of the flask, pattern vents, or use of vacuum chamber and back filling with CO₂ once the air has been evacuated. Production rates are better with core blowers and vacuum chambers. Molds are usually coated with a refractory wash to improve casting finish prior to assembly.

The amount of silicate binder used for cores and molds varies from 3% to 6% depending on the type of sand, grain fineness, and degree of sand contaminants. The type of metal poured, the metal temperature, and the amount of erosion resistance the core or mold will have to withstand are additional factors. A washed-and-dried, rounded, silica

sand grain (AFS gfn 55) requires approximately 2.5 to 3% of binder. Finer sand (AFS gfn 120–140) will require from 1.5% to 3% additional binder. In determining the amount of binder for a specific job, it is recommended that test cores be prepared using an average amount of binder. The initial tensile strength of cores gassed for 5 seconds with CO₂ varies from 37 to 45 psi depending on the binder used. If this same gassed core is allowed to remain at room temperature for 24 hours, the strength increases to a maximum of 100–200 psi. This increase is due to some dehydration of unreacted silicates and the continued gelling of the silicate. Under normal conditions, cores will not deteriorate and can be stored for various periods of time. An exception may occur during periods of high humidity when stored cores are unable to achieve maximum strength by dehydration after gassing. Strength deterioration of sodium-silicate-bonded cores in high-humidity conditions is most prevalent when the binder formulation of the sand mixture contains organic additives such as sugars, starches, or carbohydrates; a short heating cycle is necessary to obtain the desired strength under these conditions. When a core is hardened by carefully controlled gassing and further hardened by dehydration and polymerization during the subsequent 24 hours, good strengths are maintained over a long period of storage. It is always advisable, with sodium-silicate-bonded/CO₂-hardened cores, to date the cores so that the oldest cores are used first. A Japanese variant of the process evacuates the mold/core in a vacuum chamber before introducing the CO₂ gas into the chamber. This not only requires less binder (2%), but avoids overgassing, and considerably reduces the time and the use of fiberglass pipes to facilitate access of CO₂. Although residual sodium normally poisons attempts to rebond the sand, this low binder level allows mechanically reclaimed sand to be successfully recycled.

Considerable care must be used when gassing with CO₂ since overgassing and undergassing adversely affect the properties of the cured binder system. Operators have a tendency to overgas some parts of the core or mold to ensure that all parts are cured. Control of the gassing operation becomes critical when the higher ratio binders are used. Shorter gassing times are needed to harden the higher ratio binders. These materials are easily over-gassed, resulting in molds and cores with a shortened shelf life.

Although using additives in the silicate mold and core mixtures cannot remedy poor formulations or faulty operations, there are many instances when the proper use of additives is necessary and vital to the success of the casting. One of the main reasons for using additives in sand mixtures is to improve shakeout or collapsibility. Sugars are commonly used for this purpose and can be compounded with the silicate binder or added separately to a sand mixture. Improvements in shakeout may also be obtained by reducing the binder level or changing to a higher ratio silicate. Additives, used for the reasons listed below, must be used with caution as the bond strengths can be seriously lowered in many instances. Additives have been recommended for:

- improving collapsibility

- controlling expansion
- preventing burn-on/burn-in and metal penetration
- improving green strength properties
- promoting peel of castings and improving casting finish
- aiding flowability of the sand mixture
- creating proper mold atmosphere
- preventing excessive drying out of the sand mixture
- preventing sticking of sand mixture to patterns and core boxes

When pouring copper-base metals in silicate-bonded sand, additives in general use include:

- iron oxide
- plumbago (blend of graphite, lead and coatings)
- polymers

Approximately 1 to 2 lbs. of CO₂ (8.5 to 17 ft³ gas) are required for 100 lbs. of silicate-coated sand. This figure can be used to estimate CO₂ consumption in order to determine the capacity of the CO₂ supply to be installed. A sufficient supply of CO₂ gas, plus a CO₂ regulator, a flow timer, and a flow meter are necessary to successfully use this process and achieve in-process uniformity. Gassing, which can be accomplished by any number of methods, requires apparatus such as probes, hoods, or cups. The following general rules apply to all gassing techniques:

- The more binder present in a mixture, the longer the gassing time required to develop the required strengths
- Longer gassing times at moderate gas flows and pressures give higher strengths than do shorter times at higher pressures
- The lower the silicate ratio, the more CO₂ is required for gassing and the poorer the collapsibility
- The recommended CO₂ gas pressure range is 20 to 60 psi gauge pressure; for most applications, a pressure between 30 to 40 psig works best.
- The hardening rate is temperature-sensitive and very slow below 50F (10C).

Production of small cores and molds can be successfully accomplished by combining core blowers or core shooters with automatically controlled gassing stations operating on predetermined cycles. High production can be obtained by using two core boxes; while one core box is being gassed, the other can be filled. CO₂ gas is injected through a hollow pattern or double-walled core box, through a hood covering the box, or via a mandrel in a core. Larger cores can be cured by means of lance pipes of approximately 3/16 in. diameter which are open at the lower end. Using a rod, holes are made approximately 6 in. apart. The lance is then inserted in-to each hole successively and the gas applied for 10 to 15 seconds at approximately 25 psig. The gas will permeate and cure a section of sand for approximately a 3 in. radius around the hole. Large cores and molds are easily gassed by

using specially designed covers with gaskets or hoods that fit over the flask or box. It is very important to make sure that the gas will flow through all parts of the sand mass. This is accomplished by proper placement of vents.

Core boxes and patterns may be made of wood, metal, or plastic and should be washed regularly to prevent sticking problems caused by a build-up of sodium silicate. When using metal core box tooling, it is good practice to have liquid holding tanks available in which the tooling can be soaked overnight to ensure crust-free tooling for each day's operation. This soaking treatment will also materially improve the ease with which the blow-vents may be cleaned. Slotted screen vents are very effective when using sodium silicate core-box tooling, but are subject to extensive damage when being cleaned of the hardened and encrusted sand mixture.

REFRACTORY COATINGS FOR CHEMICALLY BONDED SANDS

Refractory coatings or washes are often necessary or desirable for chemically-bonded cores and molds in order to improve surface finish and improve casting quality by minimizing reaction with the molten metal. Such coating materials can be of many kinds, utilizing various filler (refractory) materials and liquid suspension materials. They also may be applied in a variety of ways including brushing swabbing, dipping, flow-coating, or spraying.

It is important to carefully match the coating material and suspension agent to the specific type of chemically-bonded sand it will be used with. If these are incompatible, casting defects can occur. Binder suppliers should be contacted in questionable situations. A general, authoritative reference for the selection of wash coating materials for all foundry applications is the *AFS Mold and Core Coatings Manual*. A few of the more popular chemically-bonded sand systems are described below.

Silicate Binders—refractory coatings may be necessary on cores and molds made with silicate binders to prevent sand burn-in/burn-on, or penetration. Alcohol-base or solvent-base refractories are normally used. Specially prepared pastes containing graphite or zircon refractory are commercially available; these may readily be diluted in the foundry with alcohol or solvent. The use of refractory coatings on silicate-bonded molds and cores not only promotes better casting peel, but also improves collapsibility and aids in suppressing moisture absorption in storage during periods of high humidity. Water-base washes can be used if care is taken to dry the core or mold thoroughly, immediately after coating. This procedure must be conducted carefully because of the softening effect of the water on the silicate bond.

Furan Binders—most commercial core washes, regardless of suspension agent, are compatible with furan nobake binder systems. The wash may be applied in any manner; however, application should be made only on a surface that has been properly and thoroughly cured. Friable surfaces can result if

coatings are applied too soon after stripping. Regardless of the coating suspension agent, the wash should be thoroughly dried by ignition, evaporation, or heating before the mold is closed and poured.

Phenolic Binders—any suspension agent may be used with phenolic binders, as long as the mold or core is adequately cured before application is made and the wash is thoroughly dried thereafter.

Phenolic Urethane Nobake (PUNB) Binders—while nearly all types of coating materials may be used with the PUNB binders, when using water-base washes it is best to make the application immediately after stripping and to dry it promptly. With either "air-dry" or "lite-off" solvent-base coatings, the wash is often applied within 10 to 20 minutes after stripping, followed by ignition of the solvent. There may be a temporary softening of the sand beneath the coating, without any apparent permanent distortion. As with other binder systems, all wash coatings must be thoroughly dried before pouring.

SAND RECLAMATION

Sand reclamation is important because of several factors:

- The high disposal costs posed by the growing use of chemically-bonded sands for molds and cores. The development of more complex chemical binders and partially pyrolyzed binders whose behavior in landfill sites is not environmentally attractive.
- Temporary storage may require concrete pads and water catchment and treatment.
- Rising costs of new sand and higher freight rates for delivery.
- Increasing environmental restrictions on the mining of new sands.
- Introduction of environmental protection legislation in most jurisdictions on the permissibility of solid waste disposal (including foundry sand) and its effects on the availability and cost of using approved landfill sites.
- Moves to ensure reclamation and reuse as opposed to dumping, because of lack of acceptable sites and the movement towards sustainable development.

Most foundries can only achieve high sand recovery rates by reclaiming green sand. This is complicated by the porous layers of burnt clay on the grains, the resultant pH of the reclaimed sand and high operating temperatures required for thermal reclamation of green sand. Nevertheless, European and Japanese plants do recycle green sand. Green sand is typically reused and recycled until the additions of new and core sand dictate that room be made in the sand system, typically from 4 to 20 cycles depending on the relative sizes of cores and molds. In a green sand foundry, spent core sand is normally recycled accidentally, albeit with some costs (including loss of properties). Plants using nobake molds or cores in permanent mold facilities sooner or later must face

the issue of sand costs. In these situations, the sand is used less than once due to downtime and handling problems. (The unused chemically-bonded sands often require different reclamation procedures.)

Strong economic incentives exist for the reclamation and reuse of foundry sands, both as a means to offset higher material costs and to avoid the sometimes exorbitant expenses of waste sand disposal particularly if leachate from the sand includes: formaldehyde, phenol, aromatics, and metallics such as lead. For this reason alone, limited reclamation might make economic sense so that sand can be more cheaply disposed or find alternate uses.

If the foundry decides to reuse the sand, then it becomes its own sand supplier with all the attendant issues and costs. Grain size and screen distribution, cleanliness and refractoriness of the sand, acid demand value, loss on ignition and moisture content need to be controlled. These are critical parameters for many of the chemical binders and processes discussed earlier in this chapter. If sands other than silica are used, mixed sands can affect not only the reclamation processes, but the subsequent reuse of the reclaimed sand or sands. (Heavy sands can accumulate in fluid beds, and reduce the residence times of lighter sands. Chromite reacts with silica sand at higher temperatures.) In the case of shell sand, while the process is more forgiving of impurities than most, very few foundries coat their own shell sand.

There are basically three commercial systems for sand reclamation: the dry method, the wet method, and the thermal method. Some systems may be comprised of more than one of these basic methods, depending on foundry requirements as dictated by the binder systems in use. Figure 3-11 is a flow chart for the reclamation of chemically-bonded sands, showing procedures which are common to all systems.

Dry or Mechanical Reclamation

Mechanical processing is the first step in most reclamation processes. Garbage, castings and rigging must first be separated to protect equipment from excessive damage. Cores and molds are mechanically reduced (by crushing, grinding, abrasive blasting, etc.). Most mechanical systems require the sand be reduced to near-grain size prior to processing to improve efficiency. Early reclaimers subjected the sand to a scrubbing action that abraded the adherent layers of binder on the sand grains by upward airflow and impingement on a plate and the counter-flow as sand falls back. Scrubbing systems need dust collection equipment to remove fines, particularly as the fines contain a high proportion of the removed binder. In some cases, afterburners and recycling systems are necessary to reduce hazardous organics to acceptable levels before the air can be exhausted.

Rotary reclaimers throw sand against a wall and grind the sand grains against each other. The sand can either make multiple passes through a single unit or units can be stacked

one above the other to increase the amount of material processed (up to 5 ton/hr.). Scrubbing is accomplished by either mechanical or pneumatic forces that create sand-to-metal and sand-grain to sand-grain impingements. Both scrubbing techniques work efficiently with chemically-bonded resins, although the pneumatic system is said to be somewhat more effective for clay removal. Abrasive wheels have also been employed to remove surface layers.

Many 'homemade' mechanical systems have been observed in smaller foundries. Sand properties and casting finish suffered as a consequence. Nevertheless, tensile strengths of 200 psi are seldom necessary, and in some cases detrimental to shakeout and foundry atmosphere. Green sand molds sufficed for years with green compressive strength of 30 psi (6 psi tensile), and large steel castings can be satisfactorily made in chemically-bonded molds with strengths of 50 psi. The critical issues are mold wall movement and how much backing sand (and cost) is necessary to stop run-out and wall movement when many heat-affected sands become plastic.

Wet Reclamation

During wet reclamation, the thoroughly crushed shakeout sand is subjected to mechanical scrubbing in the presence of water. The solvent action of the water is highly important here; thus, the wet reclamation system is not well-suited for sands which are bonded with insoluble organic resins. Clay-bonded molding sands respond well to this, however, the residual clay goes into suspension readily and is washed away. In spite of the relatively high water requirements of wet reclamation and the increasingly severe EPA regulations pertaining to waste water disposal, wet reclamation has been receiving renewed attention recently due to growing interest in the use of inorganic binders such as silicates. Silicates respond best to wet reclamation because of the need to reduce residual amounts of Na_2O to low levels. The use of electrolytic polymers to precipitate salts below their saturation levels now makes the treatment and recirculation of the system water supply possible. Wet treatment of alkaline phenolics rapidly removes the alkaline material, with the bulk removed in initial small washes. BCIRA also found acid wash to be beneficial. It is apparent that techniques from ore dressing will find applications in sand reclamation.

Thermal Reclamation

With thermal reclamation, organic binder materials are removed from thoroughly crushed sand by heating to temperatures of 1400–1600F (760–871C). This may be done either in a rotary kiln, a multiple-hearth furnace, or in a fluidized bed system. Thermal reclamation often yields sand which is superior to the new sand entering the system. This is because the grains are not only free of residual binder but are also smoother and more rounded. Likewise, the quartz grains have become thermally stabilized by the treatment. Thermal reclamation is not a new procedure, having been used for reprocessing shell (phenolic resin) sands in a number of installations. Although the most expensive process to

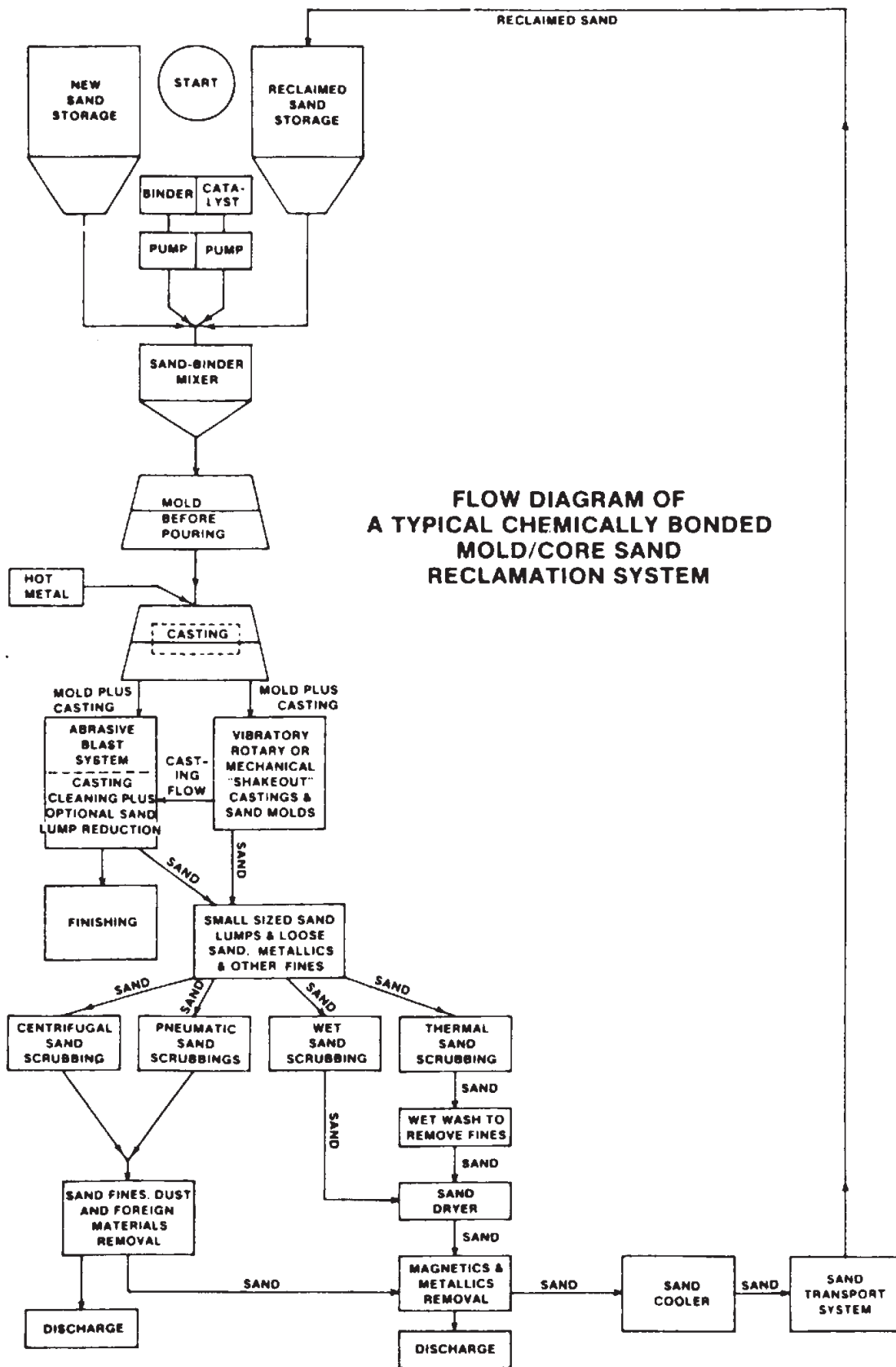


Fig. 3-11. A flow diagram of a typical chemically-bonded mold/core sand reclamation system is shown.

operate, thermal reclamation is the most efficient method for handling organic binders.

PRESSURE DIECASTING

Introduction

The pressure diecasting process utilizes high-pressure injection of molten metal into reusable steel dies to form the cast shapes. At the end of the cycle the casting is ejected and the process repeated. Highly automated die-casting machines are ideally suited for the mass production of small parts. Technological advances have been accompanied by a progressive increase in size capability. One of the inherent advantages of this process is that parts can be cast to close tolerances and require little or no machining other than simple trimming to remove gates and flash.

The pressure diecasting process was invented by H. Doehler in 1905 and was first applied to low-melting point alloys, particularly those of zinc. Here, the injection mechanism could be immersed directly in the metal bath, as there was relatively little attack of the steel components by the zinc alloys at the casting temperatures used. These were called “hot chamber” machines, and they continue to be used today for zinc alloys. For higher-melting-point metals, such as aluminum, magnesium and copper alloys, contact between the steel injection components and the molten metal had to be minimized. To accomplish this, measured quantities of molten metal were ladled into an injection cylinder and the “shot” was made immediately thereafter (the “cold chamber” machine). Sequential steps of the cold-chamber process are shown schematically in Fig. 3-12; a typical casting is illustrated in Fig. 3-13.

Diecasting Machines

Diecasting machines consist essentially of a high pressure hydraulic system, with attendant valves, cylinders, accumulators and electrical servo-controls; a “shot-end” which accepts molten metal in the shot sleeve, where a water-cooled

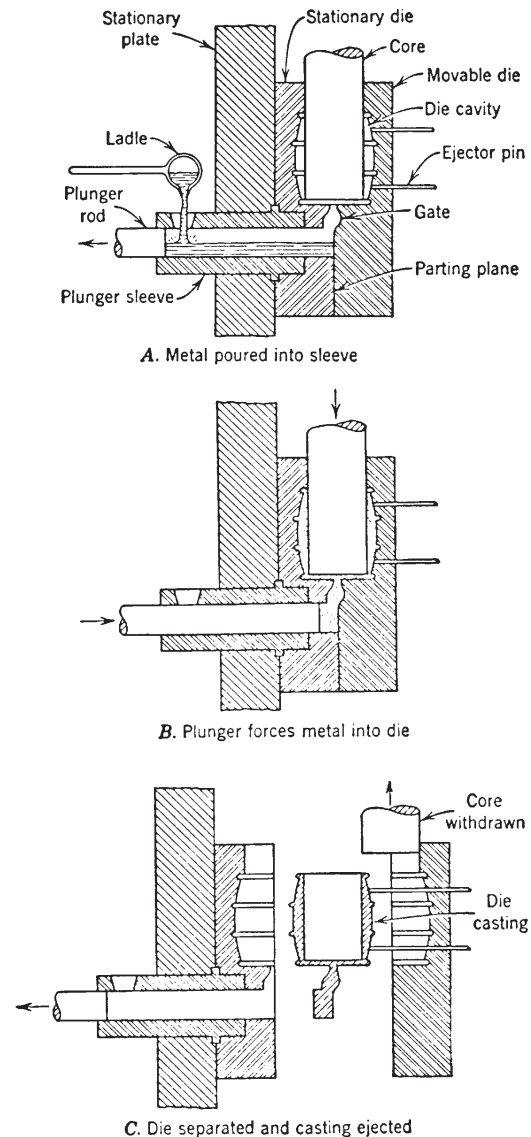


Fig 3-12. Schematic drawings of the cold chamber diecasting process are shown.



Fig 3-13(a & b). A diecast component showing the fixed and moveable die sides of the casting. (Artwork courtesy of the Kohler Company.)



plunger forces it into the die at high pressure; a stationary and a moving platen on which the two halves of the die are mounted; a die locking mechanism which prevents the two halves of the die from being forced apart under the high metal-injection pressure. Important secondary systems include die heating or cooling, die lubrication, core actuators and casting ejection. The machines may be vertical or horizontal, incorporating massive tie bars or frames to give strength and rigidity.

Machines are rated in terms of their die-clamping force, in tons. It is this clamping force, in conjunction with the available injection pressure and the projected area of the maximum die cavity, which limits the size of casting which can be produced. For copper-base alloys, machines ranging in capacity from 250 to 2500 tons are used. The larger the machines are, of course, more expensive and operate at a slower cycle. Usually, the smallest machine capable of producing the casting will be the most economical.

Technical Operation

Heat Balance

With any process involving repetitive casting into the same die cavity it is essential to maintain a balance between the heat input from the metal and that lost by radiation from the die surfaces and mounting platens. Otherwise, the relatively narrow temperature range over which the die will produce satisfactory castings cannot be maintained, and scrap losses will occur. This is usually achieved by the use of a die heating and water-cooling system. Since both metal density and casting temperature are much higher for copper-base alloys than for those of aluminum, it would be expected that more die cooling would be necessary. On the other hand, for copper base alloys, however, the dies must operate at higher temperatures—typically about 932F (500C), and heat losses are correspondingly greater at these higher temperatures. In practice, therefore, less cooling is actually required when casting copper-base alloys. Indeed, in order to minimize heat loss from areas of thin sections remote from the gate, it is often necessary to utilize insulation and “heat dams.” The latter entail machining side clearances between the die insert and the die block itself, to form air gaps which act as barriers to conductive heat loss. Localized hot spots in the die cavity may require selective cooling, utilizing principles of heat flow control shown in Fig. 3-14. In addition, recent advances have been made in the diecasting of pure copper, which involve pre-heating and operating the dies at very high temperatures (greater than 1112F [600C]). These will be discussed in a later section entitled, “Die Casting of Electric Motor Rotors from Pure Copper.”

Metal Flow and Gating

Control of metal flow by proper gating is especially important in pressure diecasting. However, this is a complex subject and requirements will differ with each casting design. General principles will be covered here. Gating design also

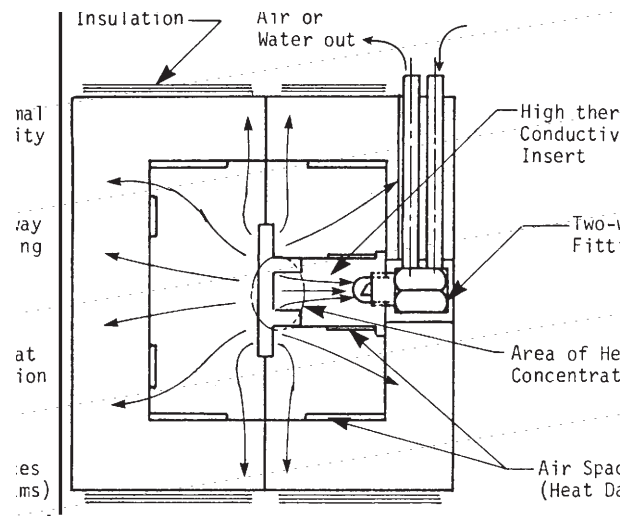


Fig 3-14. Carefully placed air spaces in the seams between the various die components, plus external insulation, can be used to restrict and direct heat flow paths through the die. Areas of heat concentration can be isolated by using inserts and cooling by a forced cooling medium such as air or water.

depends upon the major requirements of the parts being cast (i.e. whether the casting is required to have optimum surface finish, as for plating, or if it is to have maximum strength and soundness).

Diecastings can be produced by two gating and flow methods: maximum-friction or minimum-friction. With the minimum-friction method the die cavity is filled through large ingates with low ingate velocities and low pressures. In this way, virtually all air and gas is vented from the die cavity so as to prevent large gas holes from forming in the casting. Directional solidification is used, with freezing initiating at the casting extremities and progressing toward the ingate. The ingate acts as a riser and feeds the casting under the pressure being applied by the piston. This minimum-friction method is much more applicable to thick castings of simple shape. For this reason it is much less frequently used than is the maximum-friction method.

The maximum-friction method, being unrestricted as to casting size, is more widely utilized for copper-base alloys. This technique employs small ingate cross-sections, with high ingate velocity and high pressure at the end of the fill cycle. Small amounts of gas are entrapped as fine dispersions in the casting, being compressed by the high, final metal pressure. This entrapped gas remains compressed during freezing, forcing the metal outward against the die wall and compensating for the solidification shrinkage of the metal. In this method, metal friction may cause a small degree of heating, amounting to perhaps 7 to 9F (4 to 5C). Because of the high velocity and short filling times involved with this method, die venting is a most important consideration here.

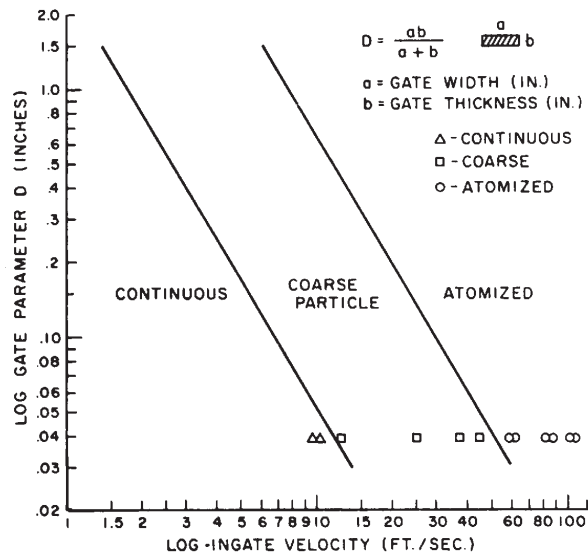


Fig 3-15. Jet flow character of molten brass die-casting alloy as a function of flow velocity and gate parameter D , and data obtained by high-speed filming of the molten metal stream.

The influence of gate dimensions and ingate velocity of the metal stream on the form of metal flow within the cavity are shown in Fig. 3-15.

With high injection rates it is apparent that much gas (air) will be entrained in the metal stream and entrapped within the casting unless precautions are taken. These precautions include the use of a shot cylinder of matching size (molten metal volume should be at least 75% that of the shot sleeve), streamlining of the gating system, programming of plunger speed and pressure and use of adequate venting appropriately located within the die cavity. The influence of injection pressure and cavity fill rate on casting porosity is shown in Fig. 3-16. For maximum soundness, casting pressures in excess of 103,000 kPa (1×10^8 Pa) are recommended.

Process Control

In recent years great progress has been made in the control of the diecasting process by the installation of thermocouples, pressure-transducers, and accelerometers on the machines, and most recently through the use of real-time controlled diecasting machines. Packaged instrumentation can be purchased for measurement of the various operating parameters. Thus, once a new die is in successful operation, a permanent record can be made of casting parameters and these can quickly be re-established for any reruns. Figure 3-17 shows a typical injection trace for a copper-base alloy casting made in a 400-ton cold chamber machine.

Real-time controlled machines, initially introduced to the marketplace in the 1990s, utilize a feed-back loop between the injection system and the programming unit. During the injection of the liquid copper into the die, the programming unit checks to ensure that the actual injection parameters

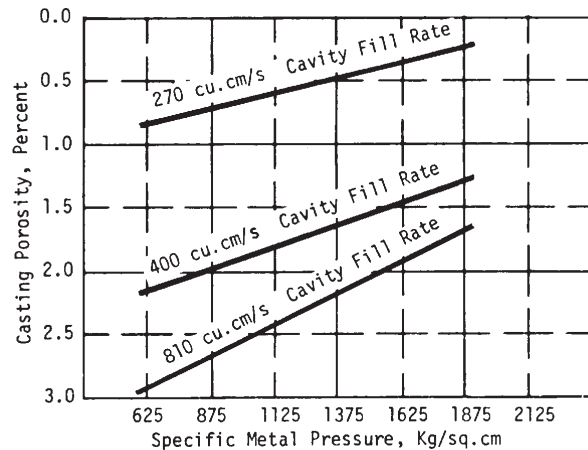


Fig 3-16. Test results show that increased static metal pressure results in increased density. Even with a slow fill rate of 270 cc/sec, the metal pressure had a significant effect.

are closely following those programmed into the machine. If the actual parameters start to diverge from the programmed parameters, the programming unit makes adjustments "real-time" during the actual shot, to bring the actual parameters closer to those programmed. Obviously, to achieve this level of process control requires a hydraulic system on the injection system that can respond extremely quickly to minor adjustments in the injection parameters.

As with any casting process, diecasting has a number of unique casting defects associated with it. For further information on these, the reader is referred to sources listed at the end of this chapter.

Die Materials

Due to the relatively short life of die components, the selection of die and core materials has a considerable economic effect in the diecasting of copper-base alloys. Since the initial cost and subsequent maintenance of the die cavity parts are a considerable fraction of the overall cost of the process, extension of die life to the maximum will greatly improve the competitive position of diecasting against other methods. Heat-checking and thermal-cracking (or fatigue) of the die surface tend to occur relatively early in the service life of dies and cores. Usually, because of the more severe heating and erosion conditions to which metal cores are subjected, they tend to fail somewhat sooner than the die itself. Molten metal entering the die cavity under high pressure will readily penetrate the fine surface cracks caused by heat-checking, and will solidify to form a network of projecting fins on the casting. For most applications these fins are objectionable and must be removed: thus increasing the cost of finishing. More importantly, the degree of cracking eventually becomes so severe that the casting can hardly be removed from the die. At some point, the die must either be reconditioned or replaced.

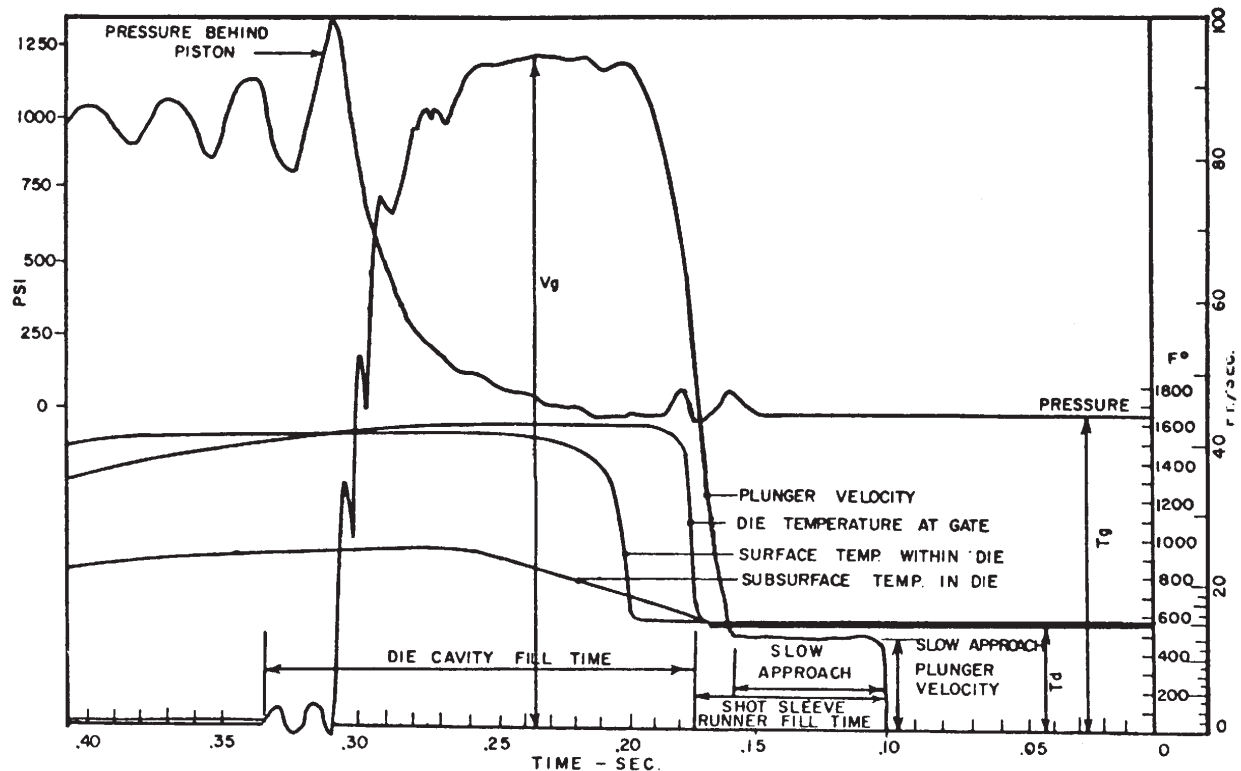


Fig. 3-17. Typical injection trace of velocity, pressure, and temperature measurements during the diecasting of a brass alloy.

Aside from thermal fatigue, or cracking, other types of damage which may occur at the surface of dies and cores include mechanical erosion (or cavitation), chemical attack, and soldering (welding). Mechanical erosion can occur either by wear or by cavitation. Mechanical erosion caused by wear is the result of friction and abrasion between the metal and the die. Cavitation is caused by the stresses induced in the surface of the die during the violent collapse of gas bubbles in the molten metal near the die surface. Chemical attack includes compositional changes to the die surface due to decarburization, oxidation, or corrosion. Soldering is actually the welding, or adhesion of the molten metal to the die surface, resulting in pitting or cratering of the die. The principal purpose of using die lubricants is to avoid soldering, particularly at hot spots.

The high cost of machining die components tends to justify the use of more expensive materials, particularly as cores and die inserts. Considerable experience has been gained with the use of refractory alloys that are resistant to both soldering and heat checking. Recently, superalloy die inserts, pre-heated and operated at extremely high temperatures (greater than 1100F[600C]), have been introduced for the diecasting of electric motor rotors from pure copper (see the section in this chapter entitled "Die Casting of Electric Motor Rotors from Pure Copper").

Table 3-3 gives the nominal composition of typical die insert materials, and Table 3-4 lists recommended heat treatments.

Different materials should be used for the various die components, as suggested in Table 3-5.

Copper Alloys for Diecasting

Although many copper-base alloys have been used in diecasting with varying degrees of success, the choice is generally limited to those with low melting points (with the exception of electrical grade copper used for the rotor casting). Such alloys minimize deterioration of die materials due to heat-checking and soldering. The nominal compositions of the most commonly used diecasting alloys are listed in Table 3-6. It will be noted that one of these alloys (C85800) is a leaded (1%) yellow brass, two (C86200 and C86500) are high-strength yellow brasses, and two (C87800 and C87900) are in the Cu-Si-Zn family (silicon brass and bronze). Alloys C99700 and C99750 are special high-manganese brasses, containing 13 and 19.5% Mn, respectively.

Of the foregoing, alloys C85800, C87800, and C87900 presently are the most widely used. Use of the white, high-manganese brasses is gradually increasing as they are becoming better known.

Effects of Alloy Constituents

Zinc is the major alloying constituent in most compositions, although other elements are present in tailored amounts.

Table 3-3. Composition of Die Materials

Steels										
Material	C	Mn	Si	Cr	Mo	V	W	Co	Fe	
H-13	0.40	0.30	1.00	5.00	1.35	1.00	--	--	Rem	
H-19	0.40	--	--	4.25	0.40	2.10	4.25	4.25	Rem	
H-21	0.40					0.25	9.00	--	Rem	
Refractory Metals										
Material	C	Ni	Al	Cr	Mo	Ti	W	Co	Fe	
Rene 41 ¹	0.1	Rem	1.5	19.0	10.0	3.0	--	11.0	3.0	
Anviloy 1150 ²	--	4.0	--	--	4.0	--	Rem	--	2.0	
Mo-TZM	0.12Zr				Rem	0.5				
Superalloys										
Material	Ni	Cr	Al	W	Co	Mo	C	Nb	Fe	Mn
Inconel 617	Rem	22.0	1.15	--	12.5	9.0	0.1	--	--	--
Haynes 230	Rem	22.0	0.3	14	5.0	2.0	0.1	--	3.0	0.5

¹ Proprietary name of General Electric Co., USA; ² Proprietary name of P.R. Mallory Co., USA

Table 3-4. Recommended Heat Treatments

Material	Anneal Temp. Anneal Time Cooling	Stress Relief Temp Stress Relief Time Cooling	Hard. Temp Hard. Time Cooling	Temper Temp Temper Time* Cooling
H-13	1550-1625F 1/4hr/in. 50 F/hr.	1200°F 2 hrs. at temp. furn. cool	1795-1975F 45-15 min. air quench	1000-1200F 1-2 hr.* air
H-19	1600-1650F 1/4hr/in. 50 deg F/hr	1200F 2 hrs at temp. furn. cool	2100-2200F 15 min. Air quench	1000-1300F 1-2 hr.* air
H-21	1600-1650F 2 hrs. at temp. 50 deg F/hr	1200F 2 hrs at temp. furn. cool	2150-2200F 15 min. air quench	800-1300F 1-2 hr.* air
ORO45	1560F 2 hrs. at temp. 50 deg F/hr	1200F 2 hrs at temp. furn. cool	1830-1975F 15-45 min. air quench	1000-1200F 1-2 hr.* air
Rene41			1950-1975F 4 hrs. air	1400F 16 hrs air
Anviloy 1150.	1850F 1 hr/in. of thickness (Vacuum or Dry Hydrogen Atmos.)			
Mo-TZM	2000-2500F Use manufacturer's recommendation as to temperature, time, and cooling (Vacuum or Dry Hydrogen Atmos.)			

*Double or triple temper is desirable and manufacturer's tables and graphs should be consulted in order to achieve the final desired hardness.

Table 3-5. Die-Set Construction Materials

Ejector pins	H-13, H-13 ^N
Ejector plate	1020
Ejector plate retainer	1030
Pillars and rails	1020
Bottom clamp plate	1020
Movable holder block	P-20
Stationary holder block	P-20
Angle pins	A-2
Slides	A-2
Die inserts and cores	H-13, H-21, H-19, QRO-45 ¹ , Anviloy 1150 ³ , Mo-TZM, Rene 41 ⁴ , superalloys
Runner blocks and Risers	H-21, H-19, QRO-451, TM Special ² , superalloys
Notes: N = Nitrided; 1 = Proprietary name of Bofors Aktiebolaget, Sweden; 2 = Proprietary name of Teledyne Vasco, 3 = Proprietary name of P. R. Mallory, 4 = Proprietary name of General Electric Company.	

The relative proportions of constituents have a profound effect on the corrosion resistance of the alloys. This is an important property of brass die castings because many such parts are used in the plumbing industry where good corrosion resistance is required.

Corrosion resistance is dependent on the amount of zinc in the alloy and its effect on the distribution of phases in the microstructure. Two types of corrosion are encountered: general corrosion and dezincification. Dezincification is most detrimental since it is usually more rapid and is insidious in its behavior. Dezincification involves a preferential dissolution of zinc from the alloy, producing a porous and structurally weak skeleton of copper; this condition, although not always readily apparent, results in ready fracture upon application of low stress.

High-copper alloys generally have the greatest corrosion resistance. Their disadvantages are: higher melting temperatures, higher costs, and, often, lower mechanical properties. Increased amounts of zinc reduce the corrosion resistance of a copper-base alloy in a proportional manner up to 35% Zn. Alloys within this range exhibit the face-centered cubic crystalline structure of pure copper, forming alpha solid solution. Beyond 35% Zn, a second solid solution having a body-centered cubic structure, beta phase, appears in the alloy. At this point, alloys begin to exhibit a duplex, alpha + beta structure. The electropotential difference between these phases is relatively high and the duplex structures suffer from accelerated corrosion rates and dezincification.

Most diecasting alloys fall in the composition range of duplex, alpha + beta structures. Not only does the high zinc level reduce their cost, but the presence of the beta phase is found to reduce susceptibility to hot-cracking during and immediately after solidification. In this regard, improved castability is attained at the cost of reduced corrosion resistance.

It has been shown that heat treatments which agglomerate the beta phase as islands within an alpha matrix can effectively improve the corrosion resistance of these duplex alloys. Two proprietary leaded yellow brasses with silicon, *OM-Metal* and *A-Metal* (no CDA designations) were developed to permit agglomeration of the beta phase, utilizing specific heat treatments for this purpose. These alloys are finding increased application in Europe as a means of enhancing the resistance of plumbing ware to dezincification. Their potential has generated considerable interest in North America as a means of increasing the use of copper-base alloy diecastings.

Tin significantly improves the corrosion resistance of copper-base alloys by increasing the corrosion resistance of the alpha phase, while aiding in isolating any beta which may be present. Antimony and arsenic, although environmentally undesirable, also act as inhibitors to retard the corrosion of the alpha phase. Their presence is limited by specifications to about 0.05 percent.

Aluminum and silicon in small concentrations serve to improve corrosion resistance. Both are powerful deoxidizers and aid in minimizing deposit buildup on die surfaces. They also help prevent volatilization of zinc at normal casting temperatures and improve alloy fluidity (see Chapter 10). If aluminum is present in 60/40-type Cu-Zn alloys in amounts greater than 1% (the zinc equivalent of Al is 6), it may cause higher solidification shrinkage, drossing, and formation of the beta phase. Ductility is also adversely affected by the aluminum content, which should be reduced to 0.50% for maximum ductility.

A nominal silicon content of 1% is specified for alloy C87900. This, in combination with a higher copper content (65%) results in greater strength and corrosion resistance than that found in alloy C85800. The better fluidity imparted by

Table 3-6. Nominal Compositions of Copper-Base Die Castings Alloys

Alloy Number	C87900	C87800	C86500	C86200	C85800	C99750	C99700
Cu	65.00	82.00	58.00	64.00	58.00	59.50	58.00
Sn	< 0.25	< 0.25	0.50	< 0.20	1.00	<0.50	
Pb	0.25	0.15	< 0.40	< 0.20	1.00	1.50	< 1.00
Zn	bal.	bal.	bal.	bal.	bal.	bal.	bal.
Fe	< 0.15	< 0.15	1.00	3.00	< 0.50	< 0.25	
Al	< 0.15	< 0.15	1.00	4.00	< 0.25	1.25	< 1.00
Si	1.00	4.00			< 0.25	< 0.50	
Mn	< 0.15	< 0.15	1.00	3.00		0.50	13.00
Ni			< 0.50				5.00
Sb							
All others	< 0.50	< 0.25			< 0.50	< 0.50	

the silicon makes alloy C87900 easier to diecast, as well; however, C87900 is somewhat more difficult to machine.

Tables 3-6 through 3-8 include alloy C87800, which is known as a silicon brass, or Tombasil. As in other alloy systems, silicon imparts excellent wear resistance, but at the expense of machinability. The machinability of alloy 87800 is 40 (the machinability of free-cutting brass is 100), compared to 80 for alloys C85800 and C87900. With a nominal 4% silicon content, the C87800 alloy possesses the highest fluidity of all the copper-based diecasting alloys. It also has the least tendency to dross.

Silicon has a zinc equivalent of 7; that is, 1% silicon will be equivalent to adding 7% zinc, in terms of the alloy's tendency to develop an alpha-beta structure. Hence, the high-silicon, high-copper alloys are also two-phase and are prone to dezincification unless efforts are taken to minimize the amount of beta.

Lead, in copper-base alloys, is used primarily to increase machinability. Lead has a melting point of 621F (327C) and is essentially insoluble in copper and copper base alloys at room temperature. Hence, at the time when a die casting is ejected from the die, the lead will still be molten. The lead occurs at the grain boundaries, where its presence increases machinability. Lead may also occupy the voids associated with internal shrinkage porosity, thereby increasing pressure tightness. Excessive lead content may exude or "sweat" while castings are held at temperatures above 621F (327C), causing a loss in strength. In alloy C85800, lead is limited to 1.5% maximum.

Manganese reduces the melting point, adds toughness, and increases the mechanical strength of copper base alloys. It promotes stability in the yellow brass alloys and increases the amount of iron which can be taken into solution. The

advantages of these effects can be found in a series of alloys called high-strength yellow brasses or manganese bronzes, and in the high-manganese bronzes, C99750 and C99700. Alloy C86500 is contained in this series and is one of the 60/40-type of Cu-Zn alloys with a manganese content normally varying from 0.5 to 1.5%, and aluminum from 0.5 to 1.5%. As the manganese and aluminum contents are increased, the tensile properties increase proportionately. Low-tensile manganese bronze (alloy C86500) and medium-tensile manganese bronze (alloy C86200) may be diecast. Both alloys exhibit relatively high solidification shrinkage and drossing tendencies, which must be taken into account in die and gating design.

Alloys C86200 and C86500 are very close in zinc content to the common diecasting alloys C87900 and C85800. The major difference between them is in the amount of other alloying elements present such as manganese, iron, and aluminum, which increase the strength of the alloys. These manganese bronzes are being used for components which require high strength, as opposed to corrosion resistance or good electrical and thermal conductivity. A good example of such a component would be a standard transmission selector fork used on trucks. This part, diecast in manganese bronze, is stronger than cast steel, requires a minimum of machining, and has inherent lubricity—a characteristic of copper-base alloys.

Alloys C99750 and C99700 are white (silver) in color and have good corrosion resistance. They can thus be used in the "as-polished" condition in many applications where plating would normally be specified.

Physical and Mechanical Properties

The mechanical properties of the die-cast copper-base alloys are generally superior to those of the light metals (Table

3-7). For example, the yield strengths of the copper-base alloys range from 28,000 to 50,000 psi. The maximum yield strength of any die-cast aluminum alloy is only 27,000 psi. The physical properties of each of the die-cast copper-base alloys are shown in Table 3-8. Copper-base alloy die castings should be considered for products requiring physical or mechanical properties approaching those shown in Tables 3-7

and 3-8. The die caster must be careful to melt and handle the metal properly and to control the diecasting process to assure the required properties are met.

Because casting dies are rigid, the alloys cast in them must have good hot-strength and ductility. The casting material must not crack as it cools and shrinks onto the solid die

Table 3-7. Mechanical Properties of Copper-Base Die-Casting Alloys

Alloy Number	C87900	C87800	C86500	C86200	C85800	C99750	C99700
Tensile Str., ksi	70	85	71	95	55	75	60
Yield Str., 0.5% Ext. ksi	35	70			30		27
0.2% offset, ksi	35	50	28	48	30	40	
Elong. in 2", %	25	25	30	20	15	20	
Hardness							
Rockwell B	70	85			55	82	70
Brinell—500 kg			100			119	
Brinell—3000 kg			130	180			125
Modulus of Elasticity, ksi	15	20	15	15	15	18	16
Impact Str., ft.-lb							
Izod				12			
Charpy notched	50	70			40	75	
Charpy V-notch			32				

Table 3-8. Physical Properties of Copper-Base Diecasting Alloys

Alloy Number	C87900	C87800	C86500	C86200	C85800	C99750	C99700
Melting Pt. (Liq.) °F	1700	1680	1616	1725	1650	1550	1650
Melting Pt. (Sol.) °F	1650	1510	1583	1650	1600	1505	1600
Density @ 68F, lb/in ³	0.308	0.300	0.301	0.288	0.305	0.29	0.296
Specific Gravity	8.5	8.3	8.3	7.85	8.4	7.8	7.9
Coeff. Thermal expansion at 68F, in/in x 10 ⁶		10.9	11.3	12			
Thermal Conductivity at 68F, Btu/ft. /ft./hr/°F		16.0	50.0	20.5			
Electrical Conductivity at 68F, % IACS	15	6.7	22.0	7.5	20	2.0	3.0
Specific Heat at 68F, Btu/lb/°F	0.09	0.09		0.09	0.09		

surface. The presence of beta in the structure at elevated temperatures enhances the ductility of the alloy when shrinkage stresses develop during solidification, but at room temperature the beta is brittle and the alpha is ductile. This explains why copper-base die-casting alloys are compounded to have a mixed, alpha-beta structure in order to achieve a balanced ductility over a wide temperature range.

Another physical characteristic of these alloys is a short freezing range: that is, a narrow temperature range, over which liquid and solid states coexist. This short freezing range allows for early removal of the casting, thereby speeding up the production process. A further consideration is that a wide-freezing-range alloy will be more prone to hot-short cracking as it solidifies and shrinks on the die. Hot-short cracking is caused by the presence of liquid metal in a partially solidified casting when the casting is subjected to stress caused by solidification contraction. Within the copper-base alloy family, the Cu-Zn, Cu-Al, Cu-Si-Zn, Cu-Mn and Cu-Mn-Zn alloys have narrow freezing ranges and are best for diecasting. The red brasses and semi-red brasses, which contain large amounts of tin and lead in addition to zinc, have wide freezing ranges and are therefore difficult to diecast.

Melt Preparation and Treatment

Standard production methods and equipment for the melting and handling of molten metal, as discussed in other chapters, are used in diecasting operations. Hand-ladling from a bale-out holding furnace into the shot sleeve is most common; however, automated metering systems based on vacuum, mechanical tilting, etc., are increasingly being used. Another problem with diecasting, as with permanent molding, is that of prolonged holding times which may result in the need to monitor metal composition (particularly zinc content) and adjust for losses periodically.

Dissolved gas is not normally a problem in diecasting because of the high rates of metal solidification, high injection pressures, and presence of entrained air. Hence, degassing routines are not normally applied to the melt, although the melt must be kept clean from excess oxides, dross and inclusions. One treatment, unique to copper-base alloy diecasting, is the periodic use of small additions of magnesium to the metal being used for die warm-up shots (these castings being discarded). This reduces the rate at which the scale (lubricant plus zinc oxide) builds up on the die. However, if magnesium is used too frequently, scale deposits tend to be cleaned away too thoroughly, exposing heat checks in a badly-worn die sufficiently to cause stickers to occur.

Diecasting of Electric Motor Rotors

Recently, advances have been made in extending die life while diecasting high melting temperature copper alloys, including pure copper. The drive behind this work has been the advantages of using copper for the “squirrel cage” structures of induction motor rotors (Fig. 3-18).



Fig. 3-18. An aluminum “squirrel cage” for a small motor after dissolution of the iron in nitric acid. (Artwork courtesy of Copper Development Association.[www.copper.org])

Typically squirrel cages of rotors are diecast using aluminum alloys. The high melting temperature of copper makes the die life very short making the process commercially unviable and extending this life has been a challenge. However, the higher electrical conductivity of electrical grade copper has been shown to significantly decrease overall losses in rotors, as compared to aluminum counterparts. For this reason, some special purpose motors and motors with a capacity of 250 HP or above, are built with a copper rotor structure, which require expensive fabrication techniques.

Die steels such as H-13 fail quickly when subjected to liquid metals at temperatures approaching 2012F (1100C) and above, due to the extremely rapid on-set of heat checking. Heat checking is a fatigue phenomenon, arising from the difference in temperature between the liquid copper and the die material. When the liquid copper is injected into the casting die, a surface layer on the die will initially heat to a temperature close to that of the liquid copper. Computer calculations indicate that the die surface can have a temperature-induced strain of at least 1.9%, an enormous strain to sustain on a cyclic basis.

Consideration of the temperature-induced thermal fatigue of the die surface indicates that the surface-to-interior ΔT and resulting large strains can be minimized by preheating and operating die inserts (the part of the mold which contacts the liquid copper) at a higher temperature. However, this obviously requires an alloy that has excellent strength at high temperatures, such as nickel-based superalloys. For instance, pre-heating a superalloy die insert to a temperature above 1157F (625C) decreases the temperature-induced cyclic stress below 0.2%, thus minimizing the thermal fatigue that leads to heat checking.

Tests have shown that alloys such as Inconel 617, as well as Haynes 230, are excellent die materials for diecasting copper rotors. The compositions of these alloys are listed in Table 3-3. A practical method, using a combination of heated die inserts and insulation has been developed to achieve the necessary die pre-heat temperatures.

PERMANENT MOLD CASTING

The casting of copper-based alloys by the permanent mold process is becoming increasingly important. It is expected that enacting more environmental laws will add further impetus to adopt this environmentally friendly method. Permanent mold casting (or chill casting, as it is also known) is more efficient and cost effective than sand casting. In Europe, PM casting is known as die casting, whereas die casting is pressure die casting.

The process gets its name from pouring molten metal into permanent molds as opposed to casting in sand or expendable molds. The process dates back some 5,000 years to a time when stone molds were used to cast copper (and later, bronze) axe heads and arrowheads. Molds are made from special metal alloys whose composition depends upon the application and alloy being poured. The same molds are used repeatedly to produce castings of high quality, high precision and high mechanical properties. Mold life depends on the metal being poured, pouring temperature, the mold material, and the physical characteristics of the part being made.

Castings can be solid or cored by the appropriate use of metal or sand cores. When sand cores are used, the process is sometimes referred to as semi-permanent molding, but will be grouped here under permanent molding. Although centrifugal and continuous casting can also be grouped under permanent molding, they are covered elsewhere in this chapter.

Process and Equipment

Permanent mold castings can be made by gravity pour, low pressure, and vacuum cast methods. Gravity pouring as the name implies, utilizes the force of gravity to run the metal down into the mold cavities. On the other hand the low pressure process uses air pressure to push the metal up into the mold cavity. In vacuum casting, the liquid metal is pulled into the cavity by the application of a partial vacuum. These two processes are also referred to as counter gravity casting.



Gravity pouring can be entirely manual, or by semi-automatic machines built specifically for the process. Smaller pieces (with weights as little as a few ounces) and smaller molds are usually poured by hand. During hand pouring, the operator manipulates both the pouring spoon and the mold. The operator must place the required cores, secure and clamp the mold halves together, pour the metal while sometimes rotating the mold, unclamp and extract the casting, dip the mold halves into a water and graphite solution, then lift the mold back onto the pouring station. A schematic diagram showing successive tilt positions is presented in Fig. 3-19. Photographs of a casting being poured are shown in Fig. 3-20.

With larger molds, combinations of rack-and-pinion gearing, screw mechanisms, or hydraulic cylinders are used to open and close the mold, tilt the mold, withdraw simple cores and eject the casting. With such semi-automatic machines, the operator has to place any cores, fill the pouring cup with liquid metal, and extract the casting. The other operations such as mold clamping, rotating and pouring the mold, unclamping and ejecting the casting, and graphite mold dressing are performed by the machine during the controlled cycle.

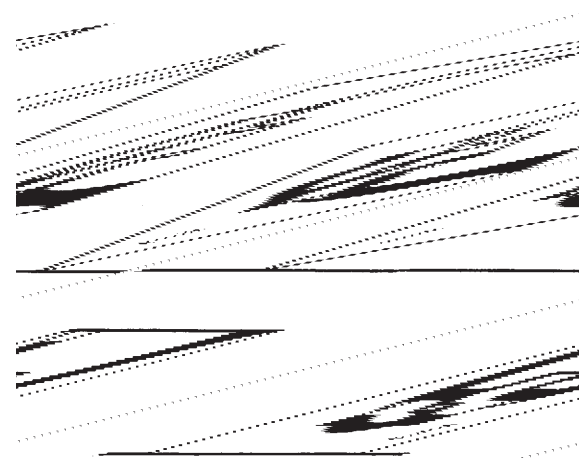


Fig. 3-19. Successive tilt positions of a permanent mold during pouring are shown. (Artwork courtesy of Fonderie)



Fig. 3-20 (a & b). Hand pouring of a permanent mold casting. Note the tilted position of the mold in view b. (Artwork courtesy of Sloan Valve.)

Low pressure and vacuum casting machines are becoming more technologically advanced. These machines require the operator to only set the necessary sand cores. All other motions and operations are performed by the machine. Pouring is accomplished by forcing the metal into the mold at prescribed rates or drawing a vacuum to suck the metal into the mold. Low pressure casting is the more widely used process and is also more automated. The best quality castings are achieved by laminar flow of the liquid metal into all the mold cavities.

The cycle timing must be exactly repeatable for the thermal balance in the mold to be the same from shot to shot and to reproduce the structure from one casting to the next. Pouring temperature, pouring rate, mold temperature, tilt rate of the mold, dwell time of the solidifying casting in the mold, and cycle time between successive pours should be precisely controlled to reproduce all the conditions.

One last factor is required to balance the heat input to the mold by the molten metal and the solidifying casting with the conduction, radiation, and forced air cooling (where required), and lastly by the application of mold wash. In the manual operation, heat balance is affected by the operator technique and his rhythm. More exact control of heat balance is accomplished by measuring mold temperatures, and then programming the appropriate timing of operations (particularly pouring, and casting ejection). In cases where a ceramic wash is applied by spraying the mold, either infrequently or occasionally between casting cycles, the mold temperature will vary between 400–800F (200–450C) when pouring yellow brasses, to a dull red heat 1200F (650C) when pouring aluminum bronzes. Naturally such high mold temperatures not only affect mold life but also require close control of cycle times. When molds are to be dipped into a bath containing the graphite wash, the immersion time and angle are critical in determining heat loss. The level of liquid in the bath should be controlled. The cadence of operations is found by determining the mold temperature range that produces satisfactory castings, and then controlling the timing.

Scrap can result from undue variation in the heat balance from one cycle to the next. High pouring temperatures or premature ejection from the mold can result in breakage of the casting as some sections may not be sufficiently rigid. Broken castings can lodge in the mold, which will cause delays, prolonging the cycle, resulting in colder molds, and even damage to the mold coating.

Gravity Casting

Part size, complexity, number of parts needed, equipment available, and the capacity of available equipment dictate the casting process. Normally, smaller and less complex castings can be produced by the gravity method, but low pressure can be more efficient for the same job when multiple cavity dies are used. High volume jobs can still be run quite effectively on gravity machines. The two main factors in choosing gravity pouring are the cost of labor and the machinery. A gravity casting cell can be set up for 1/6th the cost of a basic low

pressure machine. For this reason, gravity is prominent in Asia, where labor is plentiful and costs are low.

Molds for the gravity process are usually less expensive due to their smaller size, simpler design, and therefore longer life. Multiple cavity molds are quite common for gravity pouring, but depend on part size and design. The metal must enter at top of the gravity mold and flow down through a sprue, then back up to the top for the mold to vent. This requires the metal to change directions during the pouring of the casting. In highly oxidizing metals, such as yellow brass, the mold is usually tilted 65°–75° from the vertical at the start of pouring, and then the mold is rotated back to vertical at a controlled rate. This is to get the metal into the mold as smoothly as possible. Some alloys such as aluminum bronze can be poured directly into the mold without tilting. Machines are capable of pouring in the frontal tilt position or side pour position. Machines controlled by Programmable Logic Controls (PLC) can combine the frontal and side pour motions. The photographs in Fig. 3-21 illustrate placing a core and pouring the metal.

Several gravity machines can be grouped around one furnace to improve productivity. The number of machines that can be grouped around a furnace depends on the combined casting weights, furnace capacity and/or melt rate, and cycle time. Many arrangements and types of furnace are possible, such as coreless induction with exchangeable crucibles or channel induction furnaces. The furnace selection will depend somewhat on the alloys poured, their frequencies, and the casting weights. In gray iron foundries, where mold cooling is required, several molds rotate on a carousel. Channel induction furnaces operated at line frequency were once typical. Often two casting machines are grouped around an 85kW furnace and up to 4 machines around a 125 to 160kW furnace. Two or more casting machines can be grouped around a coreless induction furnace.

Manufacturers produce several different models and designs of gravity permanent mold machines. The size and/or weight of the mold and the castings to be produced must be considered when selecting a model. As each model has a limit on the diameter of the mold it can swing (i.e., 600 mm. max.) and the maximum weight (250 kg.) for the mold and casting. Molds with multiple cavities will quickly exceed such limits. Most machines handle only one mold at a time, although multiple station machines are available. In some cases robots can be incorporated into a layout to automatically scoop metal from the furnace, pour the metal into the mold, and return excess metal to the furnace. One robot can easily service 2 gravity machines. The ladle must be kept scrupulously clean particularly when highly oxidizing metals are poured. In this situation, the robot cleans the ladle with a rotating wire brush following each pour.

Low Pressure Casting

Low pressure casting of copper based alloys started in the late 1970s and the technology has advanced rapidly. Mold assembly, pouring operations, and fill rate are PLC controlled.

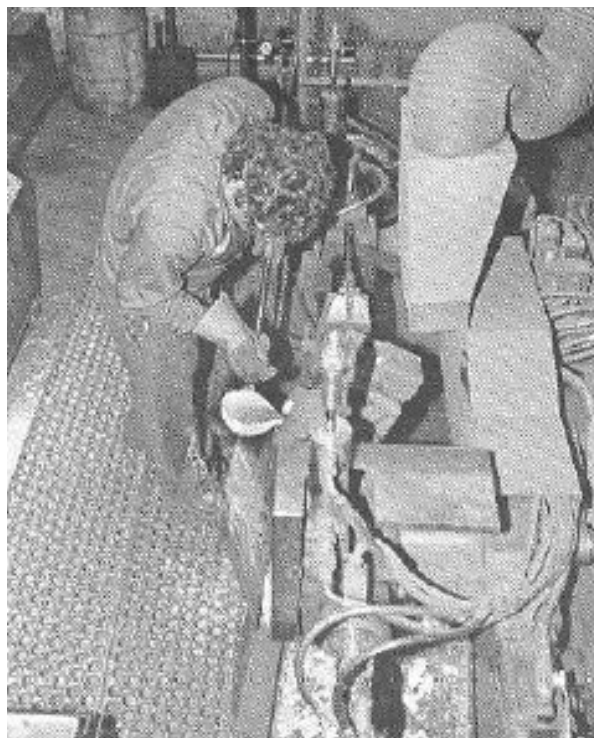
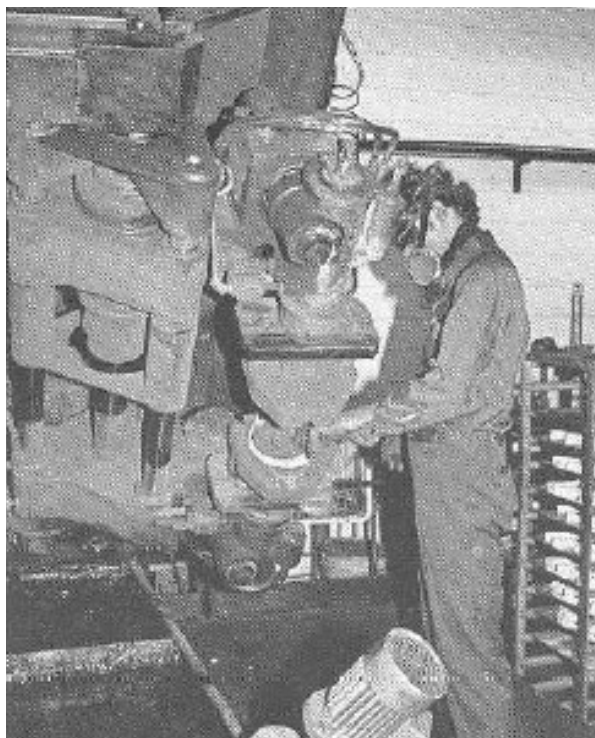


Fig. 3-21(a & b). Two gravity casting machines are shown in operation. (Artwork courtesy of Starline Mfg. Div. of Chicago Faucet Co.)

In low pressure casting, the furnace is surrounded by a metal jacket and lid which permit the chamber to be pressurized. A cast iron stalk or tube with a flange on top projects through the cover and is immersed at least 6–8 inches into the molten metal bath. The mold is moved directly over the tube and the furnace is raised or the mold is lowered to line up with the hole in the tube. When the furnace chamber is pressurized, metal is forced up the stalk into the mold. The pressure is increased at a controlled rate to counteract the weight of metal in the assembly. Earlier machines used a fixed pressure, however, modern machines use pressure transducers and a programable logic (PLC) to control mold filling and the final pressure needed to feed the casting. This ensures that the mold fills smoothly, with less turbulence, and at the lowest possible metal temperature. A typical low pressure casting machine for copper alloys and the typical sequence of operation is presented in Fig. 3-22.

Two primary advantages of low pressure pouring are that each casting is poured in exactly the same manner, thereby eliminating the operator factor and the flow of metal into the mold cavity is smooth and controlled. The liquid metal fills the mold cavity smoothly and evenly from the bottom to the top, thereby eliminating one of the drawbacks of gravity pouring where metal starts at the top, falls down a sprue, before entering the mold cavity and then back to the top of the mold. The low pressure method allows the pressure to be controlled in an appropriate manner to compensate for drastic changes in casting cross-sections so that metal flows into the cavity with the minimum turbulence thereby producing castings of consistently good quality. Even a skilled operator could not duplicate the same pour by hand 8 hours a day.

Another advantage of the low pressure process is the amount of metal that can be poured. Larger castings and multiple cavity molds are the norm for the low pressure method as these machines can handle larger and heavier molds than gravity machines. Advances are being made each year in the size, design and technology of these low pressure casting machines. Castings are made today by the permanent molding process that were not possible some time ago. This trend is expected to continue.

Vacuum Casting

Vacuum casting is similar to low pressure except that the liquid metal is pulled into the mold instead of being pushed. The molds are mounted to a manipulator that has a vacuum pump. A tube extends down from the mold. When the tube is lowered into a molten metal bath, the vacuum pump reduces the pressure in the mold cavity causing the molten metal to be sucked into the mold cavity (Fig. 3-23). As in the low pressure method, the rate and time the pressure is reduced are controlled by PLC to produce good laminar flow and high quality castings.

Mold Materials & Design

North American interest in permanent mold casting of copper-base alloys dates from about 1980. Previously there were few commercial producers of such castings, and they were reluctant to publish data on shop practice. French literature was more forthcoming, and an excellent summary on design and construction principles, although somewhat

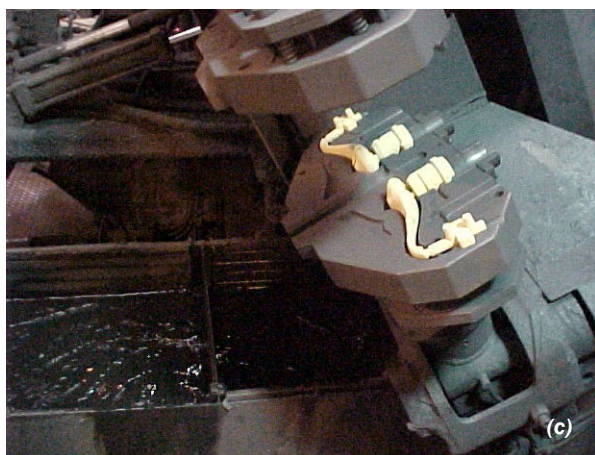
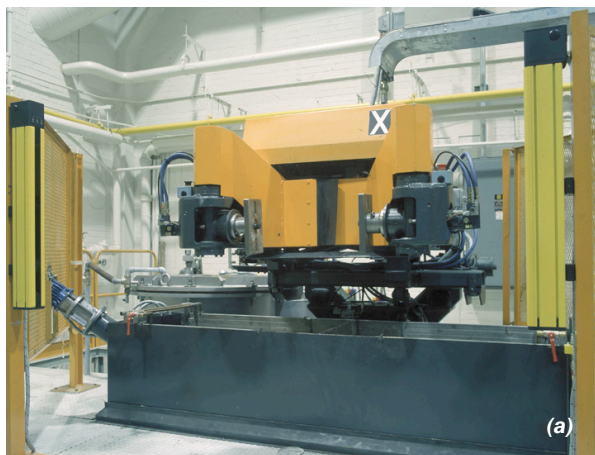


Fig. 3-22. A low pressure permanent mold casting machine, view (a) for copper and views (b-d) show the sequence of operations [Artwork courtesy of CANMET (view a) and Kohler (views b-d)]

brief, is available. European foundries use three types of materials for permanent mold casting of copper-base alloys, they are: fine-grained pearlitic gray cast iron, tool steels, and nonferrous alloys.

Gray cast iron molds are most common for casting the lower-melting-point brasses and silicon bronzes. These gray irons have the composition: 3.4 to 3.5% C, 1.5 to 1.8% Si (varies according to thickness), 0.90% Mn, less than 0.10% S, and less than 0.20% P. Small additions of molybdenum (0.70 to 0.90%) may be used to improve the thermal shock resistance of the iron. Cast blocks for molds must be flawless, as blowholes or spongy areas exposed by machining on the surface of the mold cavity will cause serious surface defects on the casting produced from this mold and early failure of the mold. Fine grained pearlitic cast irons, with or without molybdenum, are claimed to provide mold lives of 15,000 to 20,000 shots.

Some special low-alloy steels provide good results (20,000 to 25,000 castings), although these steels are more prone to distortion. Steels for molds have the average composition 0.25% C, 0.70% Mn, less than 0.40% Si, 1.0% Cr, and 0.15 to 0.35% Mo. European practice is to use high-alloy steels,

such as H13 for the casting of aluminum bronzes. These are air-hardening die steel compositions. These materials were discussed earlier in this chapter under die casting.



Fig. 3-23. Vacuum casting for brass and bronze (Artwork courtesy of Aurora Metals Div. LLC, Hiler Industries, USA)

Brass or bronze molds are used when production is limited to 4,000 to 5,000 castings. Copper-beryllium molds have been employed for high-volume production (30,000 to 50,000 shots), and simulated testing show cast copper-beryllium and nickel-beryllium alloys may be superior to the wrought alloys and H13. Although copper-beryllium is expensive, it is more readily machined than tool steel, and molds can be reworked to further increase service life.

Molds can be manufactured by machining directly from solid blocks of cast iron, forged steel or cast-to-shape blanks of contoured thickness, which are cast from master patterns. Cast solid blocks are generally used as tooling for rather small parts. The second method is the most commonly used, as it provides a means for controlling mold wall thickness and assures an appropriate heat balance which is necessary for good production and casting quality. The French literature provides details on other features of mold design, with emphasis on venting, chills and draft angles for moving parts.

Mold materials fail from soldering and thermal fatigue. While soldering can cause the mold material to be torn out, the early stages of thermal fatigue causes checking, which also cause rough surfaces on the casting. These minor cracks gradually open up and lead to fins on the castings. Fins make removing the castings from the mold difficult and even time consuming and the consequent damage to the castings leads to many more modes of failure.

Cores

Simple shapes such as bolt holes can be formed in a casting by a metal core that can be withdrawn from the casting during the ejection procedure. This usually requires a large backing plate attached to the back of the mold on which springs and hydraulic systems are mounted. As this increases the weight to the whole mold assembly, these systems are normally used on semi-automatic and automatic molding machines. Their weight must then be taken into account when deciding the size of the mold the machine can handle. Metal cores and alignment pins are usually made of H13 alloy as they must withstand heat and wear. These are available commercially from several suppliers in a range of sizes.

More complex shapes are formed using chemically-bonded sand cores described earlier in this chapter. The cores must be able to withstand the mold temperature without sagging for the short period of time until the liquid copper alloy is poured into the mold. Although this is not normally a problem as most sand cores do not collapse until well after the casting is ejected. This lack of collapsibility is a major problem as even shakeout systems and sand blasting equipment do not remove complex cores. If the castings are to be heat treated, then temperatures in excess of 550C (1,022F) will burn out the residual binder. As noted earlier in this chapter, cores should have the lowest strength necessary and no more, so that they can be handled without excessive breakage. This will minimize the energy required to remove them.

Mold Coatings

Mold washes, or dressings are of various materials and serve a variety of purposes including:

- prevent soldering (welding) between the casting and the mold
- improve surface finish
- provide lubrication to facilitate ejection of the casting
- provide insulation to promote directional solidification and feeding
- serve as an aid in venting (coarse-grained washes).

A suspension of colloidal graphite in mineral-free (preferably de-ionized) water is the most commonly used mold wash for the production of copper-base alloy castings. This wash can be sprayed, but is most often applied by dipping the hot mold halves, face down, into a tank of a constantly stirred wash. This dipping technique serves two purposes, other than wash application, which may not be readily apparent. First, the boiling action of the wash against the hot surfaces tends to “explode” away the oxide deposits caused by the volatilization of zinc from the casting alloy. Second, the evaporation of water is effective in cooling the mold. De-ionized water is preferred as dissolved minerals in tap water would leave a deposit. The graphite in the wash coats the mold, and acts as a lubricant and prevents soldering. This constant replacement, cycle-to-cycle, of the wash together with the removal of the oxide deposit, is an effective means of achieving a smooth surface. Small amounts of ammonium chloride are used to adjust the pH of the water, and keep the graphite in colloidal suspension.

Insulating mold washes are usually applied by spraying or brushing to specific locations on the mold, and can be touched up when necessary. Care is required in the application of these washes to assure good adhesion. This is usually accomplished by blast-cleaning the heated mold halves and then immediately applying the wash to the clean, hot surfaces. Temperatures in the range of 400F (205C) are usual. Table 3-9 gives typical compositions of several mold washes used in the production of both copper-base and aluminum alloy permanent mold castings. Proprietary formulations with instructions for their use are available. A disadvantage of these washes is their texture (and consequently the casting finish) changes with repeated use. The thickness of the wash layer can also change with continued operation, building up in areas where successive applications are made or wearing thin where friction occurs. These changes cause commensurate variations in casting dimension, and reduce the tolerance-holding capability of the process.

Although dipped graphite wash coatings are renewed after each shot, refractory coatings may be renewed or patched less frequently. Adjacent areas of the same mold can have insulating or conductive coatings (masks are used with spray coatings). For example, test bar molds should be coated on the test-bar gauge with a conductive graphite coating, while the bar grips and runner system are coated with an insulating

Table 3-9. Typical Compositions of Coatings for Permanent Molds

Coating No.	Composition % by weight (remainder water)									
	Sodium Silicate	Insulators				Lubricants				Boric Acid
		Whiting	Fire-clay	Metal Oxide	Diatomaceous earth	Soap-stone (a)	Talc (a)	Mica (a)	Graphite	
1	2	-	4	-	-	-	-	-	1	-
2	8	-	4	-	-	-	-	-	-	-
3	-	7	-	-	-	-	-	-	-	7
4(b)	12	9	-	-	-	-	-	-	-	-
5	5	11	-	2	-	-	5	-	-	-
6	9	-	4	-	-	14	-	-	-	-
7	11	-	-	17	-	-	-	-	-	-
8	-	-	4	-	-	23	-	5	-	-
9	7	-	1	-	-	23	-	2	-	-
10	23	-	-	-	-	-	20	-	-	-
11	30	-	-	-	5	-	10	-	-	-
12	18	-	-	-	41	-	-	-	-	-
13	8	-	-	60	-	-	-	-	-	-
14	7	-	-	-	-	-	62	-	-	-
15	20	53	-	-	-	-	-	-	-	-

(a) Serves also as an insulator (b) Plus silicon carbide, 2% by weight, for wear resistance.

coating. This will help in feeding the test section and reduce centerline shrinkage.

Gating

Gating systems for the production of copper-base permanent mold castings should follow some simple rules. The pouring cup, sprue and ingates should ensure that the mold cavity fills smoothly and continuously (not interrupted) and be specifically designed for both the casting and alloy. Air should not be entrained in the intruding metal and entrapped air must be vented from the mold cavity as it fills. Any turbulence in the runner system or in the mold cavity during pouring should be minimized to ensure casting soundness. The gating system must permit complete filling of the cavity, and the direction of metal flow and resultant heat distribution be designed to reduce solidification defects.

Isolated massive sections should be avoided wherever possible, as the majority of the brasses and bronzes cast in permanent molds are sensitive to shrinkage, cracking, and oxidation. When they are present, gating should direct metal directly into these heavy sections. Not only does the casting cavity have to be orientated so that the casting can be removed, but the cavity must fill completely and continuously during pouring. Rather than pour straight into the casting cavity, a sprue delivers metal to the lower part of the mold. The most common practice is a bottom gate. Side gates higher up the sprue can be used, but they can cause eddies in the casting cavity. Pouring the mold vertically would accelerate the metal stream unnecessarily causing excessive turbulence, aspirating air, and oxidation. Tilting the mold during the early stages of pouring reduces the flow rate, and as the mold is rotated to the vertical, the back pressure of

the rising metal reduces the flow rate during the later stages. Entrapped and displaced air from the mold is freed by ample vents, relief risers, and even large overflow cavities. These cavities have the advantage of "washing" the mold cavity by the flow of metal through the main casting cavity, thereby improving the surface finish of the casting.

Casting Alloy Characteristics

Compositions

Copper alloys suited to the permanent mold process are those that are easily cast with lower melting points and narrow freezing ranges. As in die casting, the most commonly used alloys for permanent mold casting are the yellow brasses (including manganese bronze) and silicon brass. Aluminum bronzes, particularly C95200 and C95300, are another family of alloys widely used for permanent mold casting. The aluminum bronzes are not pressure die-cast because of their susceptibility to form oxide films when subjected to turbulent flow. The metallurgical characteristics of these alloys are covered in the section on pressure die casting as well as in Chapters 10 through 12. Some common sand-cast alloys are not suitable for permanent molding. Attempts to cast the red brass alloys C83600 and C84400 in permanent molds have not been successful.

Many other copper-base alloys can be successfully cast in permanent molds provided the molds have an appropriate gating system and the mold is filled smoothly and the flow is uninterrupted. High-conductivity copper, chromium-copper, nickel silver, phosphor bronze, and even certain leaded tin bronzes have been successfully cast. The higher melting temperatures of these alloys and consequent higher pouring

temperatures have an adverse effect on mold life. Except for the simplest of shapes, it is more difficult to produce sound castings in a given mold as the freezing range of the alloys increase. In addition, as freezing rates in permanent molds are much higher than in sand, the grain size of the PM castings is finer and tensile properties are greater.

Physical and Mechanical Properties

The physical properties of the many permanent-mold cast alloys are shown in Table 3-10. This table shows the properties of alloys for permanent mold cast bars (Fig. 3-24) according to International Standard (ISO) 1338-1977 (E), "Cast Copper Alloys-Composition and Mechanical Properties." This standard refers to the use of a test bar of French design (DIS 4737), which has since been included in the ASTM standards. Published mechanical properties of permanent mold castings vary somewhat as two different standard test bar molds are used. The annual editions of ASTM Standards list properties from both bars. Both test bars are tilt poured as shown in Fig. 3-25, both suffer from varying amounts of centerline shrinkage, hence, the variation in properties. Only few aluminum bronze alloys can be produced free of these casting defects. This is of concern to the industry as the superior properties of chill-cast alloys can be hard to

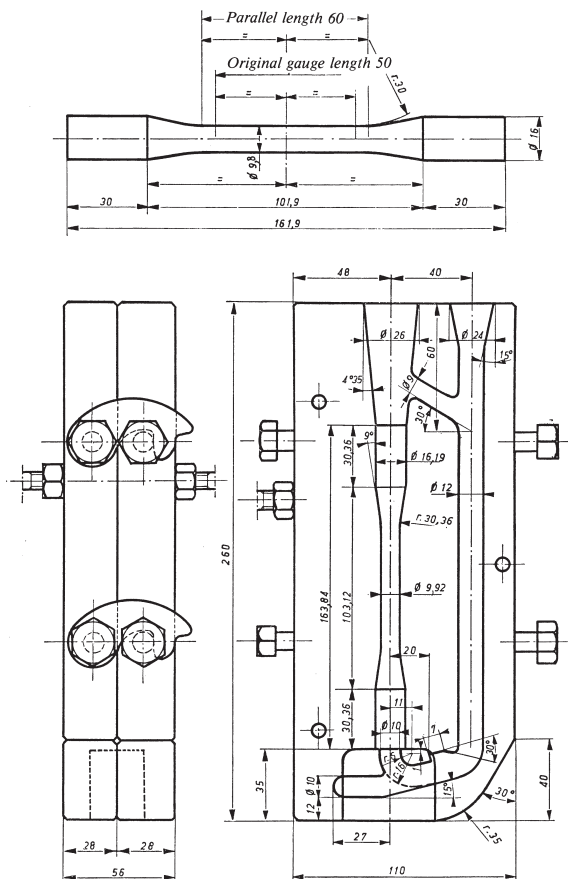


Fig. 3-24 The ISO test bar and mold for copper-base alloys, per ISO 1338-1977(E)

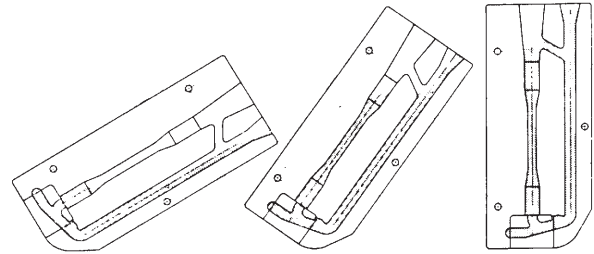


Fig. 3-25. An illustration of the filling sequence of test bar mold poured in the tilted position and rotated to a vertical position.

merchandise. Individual manufacturers also cite properties for various alloys based upon use of their own test bar. Recent work at CANMET showed that bars can be cast free of centerline shrinkage by using a mold in which bars are cast horizontally.

The tensile properties of permanent mold castings are almost invariably higher than those of sand castings or investment-mold castings, and approach those of forgings of the same alloy. The rapid freezing rates in a permanent metal mold cause the formation of fine-grained, dense, solid skin on the casting, which can extend very nearly to the centerline of the section. Any porosity present, whether from shrinkage or gas, occurs along the centerline of the section, which is usually a neutral axis in terms of applied service stress.

Melt Preparation and Treatment

Standard foundry practice is employed for the various alloys, as detailed in the section on pressure die casting and in the various chapters dealing with the specific alloy families. Melting is frequently performed in a furnace room, and the metal then transferred to holding furnaces in the pouring areas. Holding furnaces are designed to facilitate bale-out pouring, either manually or mechanically.

Gas control of the metal is more critical in permanent mold casting than in pressure die casting. Unlike sand casting, where relatively low gas contents are required to avoid internal porosity, the permanent-mold casting process relies on the presence of controlled amounts of gas as a means of dispersing shrinkage in order to avoid interconnected voids which might cause leakage under pressure. Likewise, these controlled levels of gas are found to counter the effects of normal volumetric shrinkage and, in accordance with Pellini's strain theory of hot tearing, assist in feeding hot spots and thus reduce the degree of cracking in castings as they solidify through the critical temperature range. The optimum gas level must be determined empirically for each casting, and will depend not only upon alloy characteristics but upon casting section thickness as well as design.

One complication of the permanent mold casting process, in terms of melt control, is that relatively small amounts of metal are cast at a time. This means prolonged holding times will cause gas levels, composition, and inclusion contents to

Table 3-10. Mechanical Properties of Copper-base Permanent Mold Casting Alloys (Based on ISO test bar data for permanent mold castings) Table courtesy of the Copper Development Association (CDA), "Copper Alloys for Permanent Mold Casting," co-published by AFS, BBIM and CDA, (1998).

UNS Number Alloy Name	Ultimate Tensile Strength		Yield Strength 0.5% Extension		% Elongation		Hardness	
	ksi MPa		ksi MPa		in 2 in. in 51 mm			
	Sand	PM	Sand	PM	Sand	PM	Sand	PM
C80100 Copper	25 172	48 332	9 62	28 192	40 40	42 42	-	HR57B
C85200 Leaded Yellow Brass	38 262	30 205	13 90	14 95	35 35	15* 15*	-	HR40B
C85500 Leaded Yellow Brass	60 414	54 471	23 159	23 160	40 40	34* 34*	HR55B	HR53B
C85800 Yellow Brass	46 319	48 332	20 140	28 192	- -	9* 9*	HR53B	HR61B
C86400 Leaded Manganese Bronze	65 448	56 387	25 172	30 208	20 20	14* 14*	-	HR62B
C87500 Silicon Bronze	67 462	82 566	30 207	36 249	21 21	15* 15*	-	HR83B
C87800 Silicon Bronze	69 474	83 575	30 206	37 255	25 25	25 25	HR77B	HR81B
C89550 Selenium Bismuth Brass	- -	54 371	- -	36 248	- -	6 6	-	-
C95200 Aluminum Bronze	80 562	93 725	27 186	35 240	35 35	38 38	-	HR78B
C95500 Al-Fe-Ni Bronze	100 689	113 780	44 303	62 430	12 12	6* 6*	HR87B	HR99B
C95700 Mn-Ni-Al Bronze	95 655	129 890	45 310	75 520	26 26	1* 1*	-	HR25C
C95800 Ni-Al Bronze	95 655	96 660	38 262	36 240	25 25	17* 17*	-	HR88B
ASTM A-48 ² Gray Iron	24-60 173-410	- -	- -	- -	- -	- -	-	-
ACI CF-8 ³ Stainless Steel	67-92 465-634	- -	31-46 215-331	- -	- -	- -	-	-

¹ Comparison based on ISO test bar data for permanent mold castings and ASTM test bar data for sand castings. Data compiled by Copper Development Association Inc., *Standards Handbook Cast Copper and Copper Alloy Products, Part 7 Alloy Data (Cast Products)*, New York, 1996.

² Range of Properties for 1-in. sections for grades listed under ASTM A48. Yield not normally measured.

³ "18-8" chromium nickel stainless steel. Yield measured at 0.2% offset. Range of tensile properties indicated reflects ferrite content.

* Elongation suspect due to center-line defects in the tensile test specimens.

change considerably within the furnace. It is thus necessary to exercise careful control over the melt quality, with appropriate levels of monitoring and adjustment to ensure the furnace is ready for pouring at all times. Control procedures to adjust the gas level, skim the surface oxides, and replace zinc losses should be evaluated and adopted.

Advantages

The advantages of the permanent mold process over many other casting processes are higher quality, higher precision, nearer net shape, higher mechanical properties, suitable for low and high volume production and less environmental impact. The high quality is from the rapid directional solidification that the alloys undergo, as they go from liquid to solid in a metal mold. For this reason, permanent molding is also known as chill casting.

The molds are made from highly heat conductive materials that absorb the heat from the molten metal causing rapid and directional solidification. As the heat from the molten metal is absorbed by the mold, many grains nucleate and grow at a rapid rate resulting in a very fine grain structure. Although the grain size is already smaller than the grains found in sand casting, grain refiners, such as boron and zirconium, can decrease the grain size still further. The grain fineness is also what gives permanent mold castings superior tensile properties over sand castings. Elongation or ductility usually suffers. There are, however, cases when elongation is critical.

Permanent mold castings are far superior to sand castings for the production of decorative castings that require polishing. The surface of the castings, where the grains are finer, is more suited to excellent polishing results than the dendritic grain structure obtained on the surface of sand

castings. Cases have been documented where polishing scrap has been reduced by 40% when the casting method was switched from sand to permanent mold. The success of newer decorative coatings, such as PVD (pressure vapor deposition), depends on even better surface quality. These coatings show and magnify any imperfections on cast polished surfaces. The coatings have superior appearance and durability. They also offer a greater variety of finishes than was previously available.

The precision of permanent mold castings is another advantage over sand cast parts. Castings produced in a metal mold machined by computer numerically controlled (CNC) equipment have consistent dimensions. Variations of $\pm .002$ " are typical casting to casting variations for the permanent mold process. Nevertheless, dimensions across parting lines vary by $\pm .010$ " up to 1" and $\pm .002$ " per additional inch, while dimensions across the same mold half vary by $\pm .008$ " up to 1 inch and $\pm .002$ inch per additional inch. The closer the casting is to near net shape, the less machining stock on surfaces is required and the less metal that has to be removed during machining. Many fabricated parts have been converted to permanent mold castings as the benefits are higher physical properties, lower finished weight, lower machining costs, less labor and therefore lower cost per piece for a superior product. The repeatability in the casting size also is an advantage for value-added operations such as machining and polishing. Jaws to hold the parts can be made exactly to the shape of the casting so that greater accuracy in machining is possible along with the ability to integrate automatic loading and unloading by robots. The use and productivity of robotic polishing cells has increased due to the part being the same exact shape from the beginning of a production run to the end. In today's world marketplace, automation and the precision of permanent mold castings are the keys to competing with countries with lower labor costs.

The variety of equipment now available means permanent mold castings are price competitive with sand castings and other casting methods for both high and low volume parts. Gravity and multiple station low pressure machines teamed with coreless or channel induction furnaces provide a means to produce castings of various copper-based alloys at many production rates. The newer low pressure machines with larger mold footprints can produce as many castings per mold as some sand molds.

The permanent mold process uses sand only for coring those castings that need complex interior shapes. The amount of used sand generated and its contamination levels are so low that it can be easily disposed. The reduced amounts of fumes, sand, and lower lead levels of the alloys that are cast by permanent mold make the process more environmentally friendly than production in sand foundries. Buildings housing permanent mold foundries are not easily recognizable from the outside, unlike some sand foundries. There are virtually none of the odors produced that are normally associated with sand foundries. The expansion of permanent mold foundries in the United States is assured, given all the new environmental regulations either written or being proposed.

Limitations

The main limitation of permanent mold castings is their size. The maximum weight of a casting is usually about 30 pounds, but newer equipment is increasing this limit. The minimum size is about an ounce. One of the factors that limits the size and weight of permanent mold castings is the size and weight of the mold and consequently the size of the machines capable of handling such large molds. The molds are usually made of beryllium copper, nickel beryllium, cast iron, or tool steel. Besides being expensive to buy, they are expensive to machine and are some of the heavier mold materials. Mold life can be limited to 10,000 to 15,000 shots per mold, but can depend on the size and shape of the mold. Molds with uniform walls and shapes can last as long as 100,000 shots or more. This is also dependent on the alloy poured. Alloys with higher melting temperatures will have shorter mold lives. Castings should be poured at the lowest possible temperature where the mold will still fill properly. This not only promotes casting quality but extends the life of the mold.

Casting shape is also dictated by what shapes can be extracted from the mold. In order for castings to be extracted, the cavities must have appropriate drafts at the parting line with no undercuts. Simple-shaped metal cores can be withdrawn, but sand cores are necessary for more complex cavities. Metal cores are almost exclusively limited to vertical or horizontal movements in low pressure or gravity casting machines. In some cases, the mold can also be made up of several pieces that fit together almost like a puzzle. Molds such as these are bench or gravity poured because the mold must be taken apart and put back together manually and often restrained by a jig to retain casting dimensions.

The microstructure of permanent mold cast alloys is also extremely important in maintaining the superior casting properties. Two or more phases need to be present in the casting for most alloys to achieve the best mechanical and physical properties. An alpha-beta microstructure should be present in the correct proportions in yellow brass. The alpha phase is corrosion resistant and ductile at ambient temperatures, but fractures and is prone to cracking at elevated temperatures. The beta phase is brittle at room temperature, but ductile at elevated temperatures, and subject to dezincification corrosion. The proportion of alpha and beta phases must be kept in a delicate balance so that the castings are strong at elevated temperatures (beta phase property) and corrosion resistant (alpha phase property). The distribution of the alpha and beta phases is more important than the quantities of each. In other alloys the phases may be alpha + beta, alpha + delta and some, such as the aluminum bronzes, may have the kappa phase. Heat treatment can be used in some alloys to modify the distribution of phases as well as improve physical and corrosion properties.

Conclusion

The permanent mold casting process for copper-base alloys appears to be under-utilized in North America in comparison

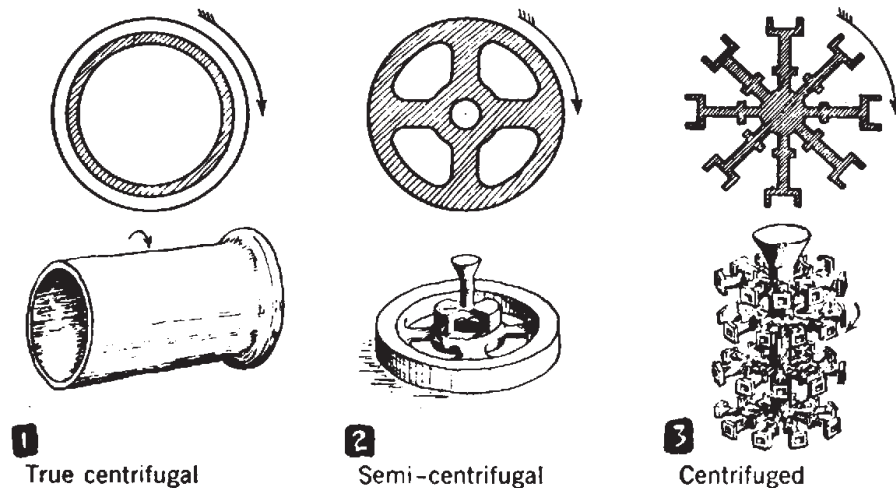


Fig 3-26. Variations of the centrifugal casting process are shown.

to its use with aluminum alloys. The process has much wider application in Europe. Greater use of the process in North America can be expected, particularly if the dezincification problems of the yellow brasses can be moderated to meet plumbing specifications. The permanent mold casting process should gain impetus as public concerns grow over the possible toxicity of foundry wastes (particularly from molding sands).

CENTRIFUGAL CASTING

The essential feature of centrifugal casting is the introduction of molten metal into a mold which is rotated during solidification of the casting. The centrifugal force is relied upon for shaping and feeding the molten metal as the liquid is thrown by the force of gravity into the detail of the mold.

Centrifugal Casting advantages:

- The process lends itself readily to the utilization of progressive solidification.
- Dross and non-metallics, due to their lower density, move toward the inside surface and are removed by machining.
- It develops extremely high casting pressures, which promotes soundness by providing effective feeding, increasing gas solubility, and reducing the low volume of gas which may be trapped or liberated during freezing.
- It is readily adaptable to the use of permanent chill molds, in which fine-grained castings of exceptional soundness and uniformity may be produced.
- It takes advantage of low pouring temperatures because of the high pouring rates possible. The lower temperatures minimize gas absorption from furnace atmospheres and tend to decrease grain size.
- Tubular sections may be cast without a core.

The quality of any centrifugal casting depends upon the extent to which it is possible to utilize all of these factors.

Process Variations

Centrifugal casting is divided into three different categories: 1) true centrifugal, 2) semi-centrifugal, and 3) centrifuged (Fig. 3-26).

True Centrifugal Casting

The most widely used centrifugal process is true centrifugal casting. The mold may be rotated on an axis which is horizontal, vertical, or any angle in between. The essential features are that there are no sprues or runners, the metal is forced directly against the periphery of the spinning mold, and the castings are essentially tubular. No central core is used, so the thickness of the tube and the inside diameter are determined by the volume of metal poured. Figure 3-27 shows variations of this method. Typical examples of this class of product are the thousands of tons of spun cast-iron pipe produced for water and sanitation services, and the large-diameter, copper-alloy, hollow suction rolls used on papermaking machines. Such rolls may be 3 ft. in diameter by 40 ft. long, and castings weighing over 20 tons have been made.

Horizontal-axis Casting

The castings made on horizontal casting machines have a uniform bore, although rims, enlarged ends, etc., may be incorporated in the external configuration (mold surface).

The first metal poured into the spinning mold tends to lie against the bottom mold surface until it picks up the rotational speed of the mold, at which point it rapidly spreads over the entire mold surface. When this occurs, the initial heat extraction rates are very high, and it is therefore important

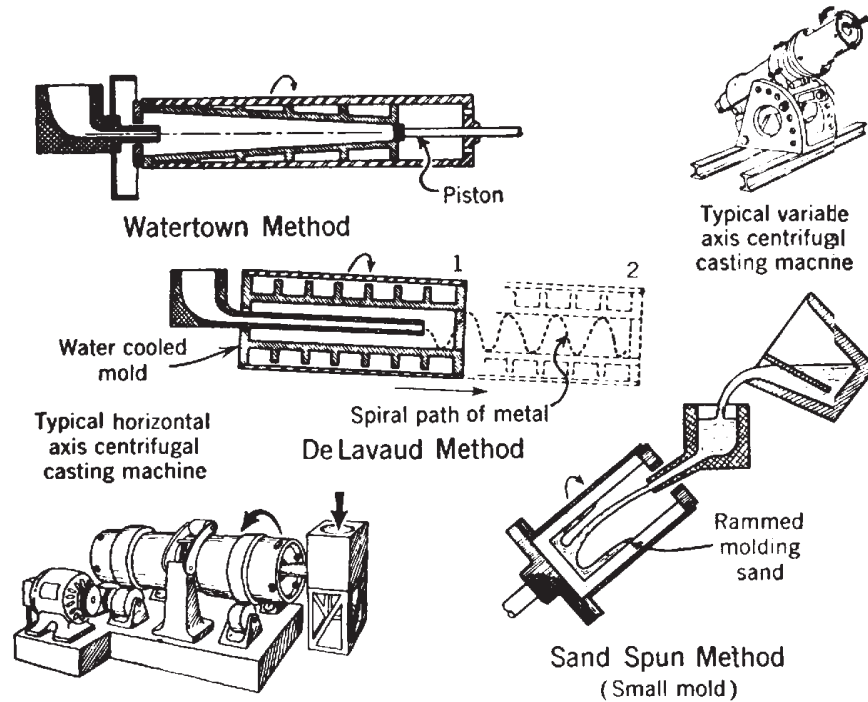


Fig 3-27. Variations of the true centrifugal casting process are shown.

that initial pouring rates into the mold are high enough to ensure that cold shuts and similar defects are not formed. Metal is normally poured against the downward-spinning side of the mold to assist speed pick-up, and much of the technology of horizontal casting, particularly of long tubes, has been concerned with metal delivery into the mold. Thus, some form of pouring spout into the mold is normally used and, in long castings, the spout may be retracted as pouring proceeds. Alternatively, the pouring spout may be in the form of a weir, with metal overflowing along its whole length.

If the rotational speed is too low, metal rests on the bottom of the spinning mold too long and is carried only part way up the mold wall, falling back to cause "raining" (which generates laps and entrapped oxides). The critical velocity at which metal is "picked up" and forms a complete tube increases as the volume of liquid, i.e. the thickness of the tube, increases. In practice this is usually not a problem, as rotational speeds sufficient to generate forces of 50G to 100G are normally employed, there being no demonstrated advantage in exceeding this.

Vertical-axis Casting

Vertical-axis castings are produced by pouring a given weight of metal into a mold rotating about a vertical axis. The metal is accelerated by and distributed around the inside mold surface. Dross, slag, and other non-metallics are centrifuged to the inside. Unlike horizontal casting, it is not possible to obtain a uniform bore. This is because the earth's gravitational force acts in a vertical direction, whereas the centrifugal

force caused by mold rotation acts horizontally. The resultant vector force on the molten metal varies from top to bottom, causing the internal diameter to assume the shape of a paraboloid of revolution. Thus, the lower end of the casting will always have a somewhat thicker wall than does the upper end. The effect of spinning speed can be seen in Fig. 3-28. High spinning speeds result in paraboloid shapes (A), whose walls are more nearly vertical, as compared with (B), those having more inclined walls because of lower spinning speeds. This behavior can be utilized to advantage for the production of tubular parts requiring tapered inside diameters.

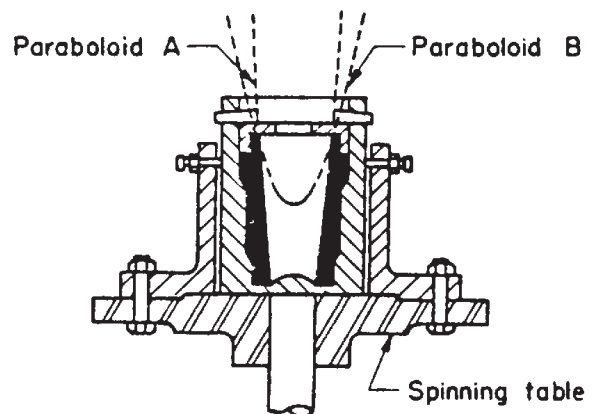


Fig 3-28. Vertical centrifugal casting method showing the effect of rotational speed on the shape of the inner surface.

The vertical-axis method, because of the above mentioned condition, is not well-suited for the production of long, pipe-like shapes. Its greatest application is for relatively short cylinders and rings, particularly bronze bearings and gear blanks.

Inclined-axis casting—This process is illustrated in the “sand spun” method shown in Fig. 3-27, and is basically a compromise between vertical and horizontal casting with characteristics most like the latter (depending on the angle of tilt). For a given mold diameter and rotational speed, increasing the angle of tilt from the vertical reduces the amount of taper along the bore diameter.

Centrifuging

Centrifuging is probably the least important of the three types of centrifugal casting, a typical example being the investment cast “pine trees” with assembled lost-wax patterns. Here, metal is poured down a central sprue while the mold is spinning and flows through runners and gates under the influence of centrifugal force to fill and feed the cavities. Castings are relatively small, the mold of small diameter, and spinning speeds are adjusted to give a relatively low force of about 10G. (G = acceleration due to the force of gravity) An alternate version of the centrifuging process utilizing more conventional sand molds is shown in Fig. 3-29; this can be applied to simple cope-and-drag molds as well as stacks. The

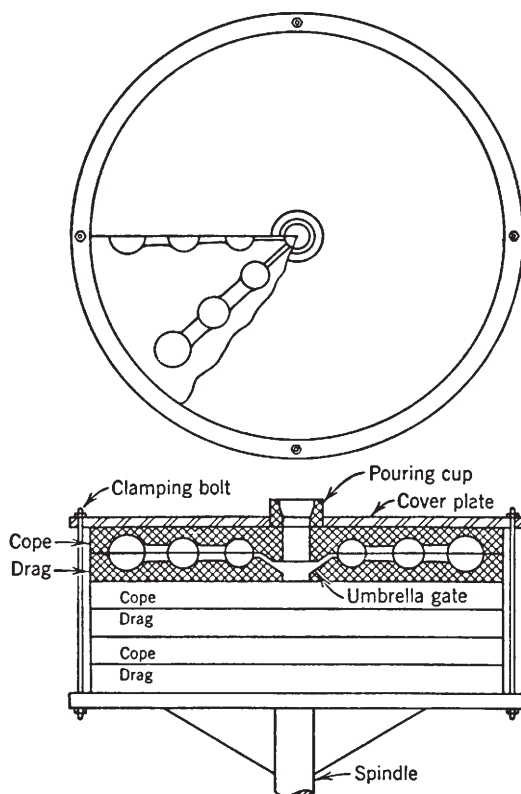


Fig. 3-29. Centrifuging process showing a dry sand stack of three molds.

objective is to fill the mold cavities quickly and uniformly, to utilize the centrifugal pressure in order to get good reproduction of the mold detail, and to enhance feeding. For large casting and sprue sizes, turbulent flow becomes a problem which can be mitigated to some extent by the use of curved “spiral taper” runners whose contours correspond to the movement and acceleration of metal in the runner under the influence of the applied centrifugal force.

Semi-Centrifugal Casting

Semi-centrifugal casting is similar to centrifuging in that metal is poured into a central sprue and the centrifugal force is usually low (<10G). However, the casting is always symmetrical and concentric with the mold, and all contours are formed by the (sand) mold or cores. Again, the objective is to achieve rapid filling, enhanced feeding, and perhaps to induce directional solidification from the periphery to the center. Castings can also be made without a central core. Large gear wheels, where the spokes act as runners to the outer rim, are typical examples of this type of centrifugal casting. The central sprue normally acts as the riser, and, as will be discussed later, the centrifugal force causes the open metal surface to take the form of a parabola. Thus, the riser is “piped” even before solidification starts and it is therefore necessary to make the riser considerably higher than would be the case with static casting.

Theory, Structures and Properties

The mathematical theory governing the forces developed by mold rotation is based on two assumptions: a) the metal is rotating at a constant angular velocity, and b) the metal is rotating at the same speed as the mold.

These assumptions are least valid during the early stages of true centrifugal casting where considerable “slip” occurs between the liquid metal and the mold.

The centrifugal force at any point in a true centrifugal casting is represented by:

$$F = (W 4\pi^2 N^2 R) / (G \times 3600 \times 12)$$

Where

F = Centrifugal force in pounds

W = Weight in pounds

N = Number of revolutions per minute

R = Radius (distance of that point from the axis of rotation in inches).

G = Acceleration due to gravity

This reduces to:

$$F = W N^2 R (0.0000284) \text{ pounds}$$

It is common practice to consider the centrifugal force in terms of times gravity. This does not take into account the weight or density of the metal and the formula simplifies to:

$$CA = N^2 R (0.0000284)$$

Where

CA = Centrifugal acceleration in G

These various forces involve the interaction of particles on one another, giving rise to hydrostatic pressure, and it will be seen that the conditions in a hollow tube casting are different from those in a solid disc even though the G force acting at the same radius is identical. Thus:

$$P_1 - P_2 = 1.415 \times 10^{-5} d N^2 (r_1^2 - r_2^2) \text{ lb/sq. in.}$$

Where P_1 and P_2 are the internal pressures (lb/sq. in) at radii r_1 and r_2 (in.), and d is the metal density in pounds per cubic inch. In a disc casting rotating about its center, P_2 and r_2 are both zero, so:

$P = 1.415 \times 10^{-5} d N^2 r^2$ lb/sq. in. For copper alloys this reduces to:

$$P = 0.000004 N^2 r^2 \text{ lb/sq. in.}$$

In some texts this information is quoted in terms of the metal head.

It is important to realize that these two forces of centrifugal acceleration and metal head have different effects on the structure and soundness of the cast parts, and may be manipulated accordingly when choosing the operating conditions of the casting machine. Thus, the internal pressure or metal head generated by centrifugal casting is a hydrostatic pressure, and it is this, which provides the feed metal to insure a sound casting. Feeding will not be maintained, however, unless solidification proceeds from the outer periphery towards the center.

The centrifugal acceleration, or "G" force, on the other hand, is that which affects the cleanliness of the casting by assisting the migrations of inclusions and dross to the inner surface of the casting where they can be machined off. It also induces segregation by magnifying the small density differences between the various constituents as the alloy solidifies. For this reason, and because of increased machine difficulties, the centrifugal acceleration is usually limited to 100 G maximum, there being no apparent improvement in properties beyond this value.

It is common practice to operate casting machines at a constant times gravity whatever the size of the casting. An alternative, and perhaps more logical, approach is to operate at a constant peripheral velocity which corresponds to a constant hydrostatic pressure at the outer surface of the casting.

The differences in these two concepts can be seen with reference to the nomograms of Figs. 3-30 and 3-31, where it will be seen that a spinning speed of 1050 rpm on a 4 in. dia. casting gives 60 G and a peripheral velocity of 1100 lineal ft. per minute. However on a 36 in. dia. casting, the same 60 G is achieved at 350 rpm but this gives a peripheral speed of about 3000 ft./min; to develop the same 1100 ft./min peripheral velocity the rpm would have to be dropped to only 125.

In practical terms, an 8-in. dia. copper casting spinning at 600 rpm will generate 40 G and a peripheral speed of 1200 ft./min, which corresponds to a metal pressure of about 90 psi at the periphery (pressure rises as the square

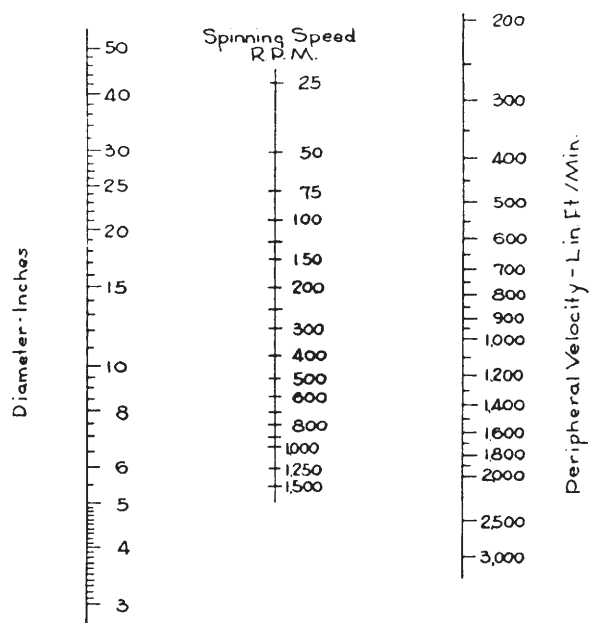


Fig 3-30 A nomogram for calculating spinning speeds to constant peripheral velocity is shown.

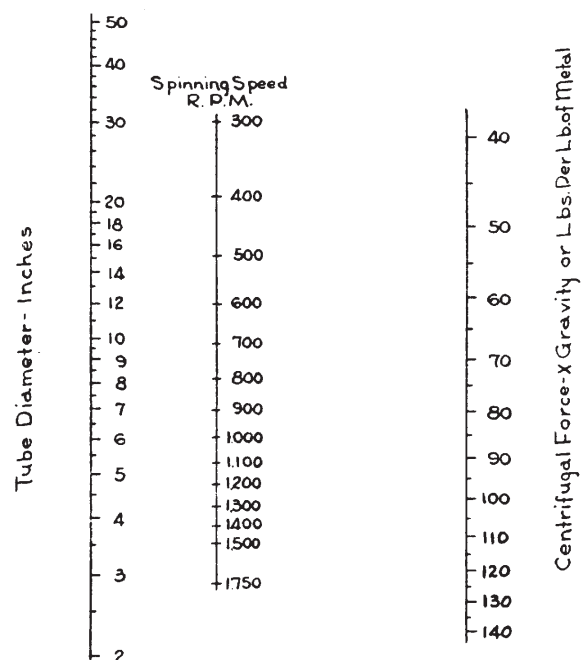


Fig 3-31 A nomogram for calculating spinning speed to constant centrifugal force is shown.

of the peripheral speed). Thus, the feed metal pressure at the periphery should be about six times that in a normal static casting (atmospheric pressure is 14.7 psi), and the same amount of rejected gas will only give 1/6 the volume of porosity. Similarly, the forces causing the separation of slag and non-metallic inclusions toward the inside of the casting will be forty times greater than the separation forces tending to float these same inclusions to the cope surface of a similar static casting. While this is of considerable advantage in obtaining clean centrifugal castings, it may give rise to segregation problems in long-freezing-range alloys due to the density differences between solid and liquid constituents. This applies particularly to alloys containing lead which, because of its greater density, tends to segregate towards the outer sections of the casting. (This can cause problems in centrifugally cast babbitt liners in large bronze bearings.) Thus, "banded" structures typical of segregation are commonly encountered, particularly if there are vibration problems with the machine. These structures can be controlled by choice of mold material and temperature, casting temperature and speed, rotational speed, and to some extent choice of alloy. It will be appreciated that the various forces decrease progressively from the periphery towards the inside diameter and this effect becomes significant in thicker tube castings, discs, etc. Thus, to maximize the beneficial effects of improved feeding and impurity separation it is essential to achieve directional solidification from the mold periphery inward, to keep feeding paths such as spokes or disc sections open and, if possible, to choose alloys of short freezing range.

Concentric banded structures, indicative of segregation or marked changes in crystal structure, often occur in thick-walled spun tubes. However, a very wide range of pouring speeds, pouring temperatures, alloys, rotational speeds, and mold materials with generally different chill rates may be used to limit segregation. A wide variety of micro- and macro-structures may therefore be obtained. The only generalizations that can be made are that the increased G forces, depending on their magnitude, will cause increased relative movement of solid crystallites and liquid metal whenever there is a density difference. Similarly, shrinkage and gas porosity should be reduced by the higher feeding pressure, and defects will tend to concentrate on surfaces nearest to the center of rotation.

As the structure of an alloy largely determines its mechanical properties, it will be seen from the above discussion that a wide range of mechanical properties is possible depending on the casting conditions. Thus, a particular alloy may be cast at high rotational speed against an iron mold to give a sound, clean, rapidly cooled casting with very high mechanical properties, whereas the same alloy, centrifuged into a sand mold, may have properties no different from a static sand casting. Thus, the mechanical properties required of "Copper-Base Alloy Centrifugal Castings" in ASTM B271-15 are the same as in ASTM B584-14 "Copper Alloy Sand Castings for General Applications."

Safety

Most centrifugal casting machines are purchased from specialist manufacturers or are operated in companies with a long history of machine development. Even so, the dangers of heavy rotating equipment should be fully appreciated. For example, utilizing Figs. 3-30 and 3-31, and assuming 600 rpm, it will be seen that at 20-in. dia., all the material would have an equivalent weight 100 times more than normal (this includes the mold, the machine components, and the liquid metal) and would be moving at a peripheral speed of 2650 ft./min (30 mph). The disastrous consequence of any misalignment or out-of-balance of the mold, equipment or casting, or of bursting of the mold because of the high pressures developed, need only be imagined.

Mold Materials

Almost any mold material can be used for centrifugal casting provided the characteristics of the mold and the machine parameters are taken into consideration. Metal molds (usually cast iron) are used for high production runs and where rapid heat extraction is required. Such molds are usually dressed with wash, or even with dry sand. In the case of nonmetallic molds, green sand is usually too soft to be considered for use, but other materials ranging from ceramic investments to shell or oil-baked core sands are widely used depending on cost, complexity, dimensional stability, chill rates, and collapsibility, to ensure freedom from hot tearing. Molds may be cooled externally to increase production rates and induce directional solidification. In the case of thick-walled tin bronze castings, water is sometimes sprayed into the bore of the casting to reduce segregation of tin-rich constituents.

Special Processes

By careful control of casting conditions and alloy selection it is possible to cast duplex or even triplex tubing for special applications. The second metal may be poured either before or after the first is completely solid, depending on melting points, relative densities, ease of bonding, etc.

Another development is the use of the centrifugal process to produce hollow castings similar to "slush castings." Sufficient metal is poured into the rotating mold to form only a shell, which is held in place by the centrifugal force until the metal is solid.

PLASTER MOLD CASTING

For many years, ornamental and statuary bronzes were cast into plaster molds consisting of gypsum plus various additives. The exceptional surface finish obtained stimulated ideas on possible applications. Today, plaster mold casting has achieved the status of a commercial precision casting process, both for aluminum alloys and for certain copper-base alloys.

The plaster usually is compounded with various types of fibrous and refractory aggregates. A composition widely used for the preparation of such molds is comprised of 70% to 80% gypsum (plaster of Paris), and 20% to 30% other mineral substances. In some formulations, a frothing agent is added to promote the formation of a foamy suspension of air as the plaster is mixed with water; this produces a permeable, cellular structure throughout the mold. In use, the plaster formulations generally are mixed with a relatively high proportion of water, in the range of 120–180 parts per 100 parts of the dry mix, by weight. The slurry thus formed is poured over the pattern (sometimes with vibration) and allowed to set.

Once the mold has hardened and the pattern is removed, the mold is dehydrated to remove both free and chemically-combined water. Dehydration is accomplished by heating the mold to temperatures ranging from 400–1400F (200–760C) for a period which depends on the size and shape of the mold. This dehydration is necessary to insure complete removal of moisture, as the presence of even minute amounts at the time of casting would possibly result in gas-related defects (larger amounts may erupt even explosively). This problem is somewhat less critical with the permeable, semi-porous plaster formulations.

The high temperatures employed for dehydration result in mold shrinkage, usually ranging from 1% to 2%. Likewise, the strength of the mold is reduced by approximately 50% as a result of dehydration.

Process Variations

Plaster formulations have found some use as molding compounds for investment casting (see the following section), using either wax or plastic expendable patterns or flexible, synthetic rubber patterns. In some cases, these applications involve the use of the proprietary Antioch process which is based on a molding compound of 50% sand, 40% gypsum, 8% talc plus other ingredients. In this process, molds are specially treated by autoclaving under steam pressure to control the crystalline structure and properties of the gypsum cement.

The major process used in plaster molding for commercial production of copper-base alloy castings has been the so-called Capaco process that utilizes conventional, reusable patterns. This process is highly mechanized, automatic, and continuous in operation, resulting in closely timed operations. The plaster formulation consists of approximately an 80/20 weight ratio of gypsum to fibrous mineral. This process requires a high weight ratio of water to plaster; generally, 140–160 parts water to 100 parts plaster is used. The high water content serves to improve mold permeability after dehydration.

Advantages of Plaster Mold Casting

- Accurate reproduction of fine surface details is possible with plaster mold casting. Plaster molds are claimed to be superior to sand molds in producing smooth and finely detailed surfaces.
- Due to the superior dimensional accuracy achieved with plaster mold casting, savings in machine finishing operations are frequently more than sufficient to compensate for the increased cost of mold materials and processing of plaster composition molds.
- Large-scale production of finely detailed castings is possible. Efficient production line operation is obtained by the use of multiple cavity molds.
- Smaller gating systems and lower pouring temperatures can be used because of the high refractory value of the molds.

Preparation of Molds for Casting

To produce good molds and good castings, the molding operation should be checked for:

- Proper proportioning of plaster and water.
- Proper mixing to insure uniformity.
- Proper use of the right separating medium.
- Proper gating and job set-up with gates, runner, and sprues cast into the plaster mold.
- Complete dehydration of the mold in a proper type of oven for a sufficient time.
- Proper metal temperature at the time of pouring.

Patterns may be of metal, shellacked gypsum cement, or of flexible pattern material such as plasticized polyvinyl chloride. Wood patterns are also usable if properly sealed. Unless carefully protected, wood patterns may absorb water from the plaster mix, with resultant warpage or distortion. Flexible patterns may be advantageous for producing intricate castings, where the release from a rigid pattern is impractical.

In standard production it is advisable to include all gates, runners, and risers in the pattern equipment. The customary metal shrinkage allowances must be made on the pattern. In addition, allowance must be made for mold shrinkages. These vary with the drying or burnout temperature.

Foundries develop procedures and plaster-to-water ratios best suited to their individual requirements and equipment. Usually, 10 parts metal casting plaster are mixed with 14–18 parts water by weight to a consistent density (hydrometer).

Metal casting plaster has an average setting time of 15–20 min, which may be quickened or retarded depending on shop conditions. If shop conditions allow the equipment to become contaminated with set plaster, the setting time will be decreased considerably.

In mixing, plaster is added to water (both by weight) and permitted to soak until all dry powder is wetted (1–3 min). Mechanical mixing is preferable for the production of a uniform slurry and complete elimination of pinholes. A 3-blade standard pitch propeller having 2–3 in. diameter, rotating at 1760 rpm is recommended. The direction of rotation forces the slurry downward.

The propeller should clear the bottom of the mixing bucket by 1 to 1½ in. and should be centered about midway between the center and the side of the container. The mixer shaft should enter the bucket at an angle 15–20 degrees from vertical. Bucket dimensions should be such that the depth of the slurry is 1½ to 2 times the diameter. Mixing is performed for 1 to 3 min, as required for plaster to cream. If hand mixing is performed then mixing should continue for three to five minutes after soaking to produce a uniform slurry.

Molds should not be poured until a slight thickening or creaming occurs with either hand or mechanical mixing, particularly when thin mixes are used. Mechanical vibration during pouring of the molds helps to reduce air pinholes and produce smooth mold surfaces.

The pattern must be covered with a thin film of a separating medium in order to remove the set-up plaster from the pattern. A light coating of lard oil, paraffin oil, or potter's soap should be applied to the pattern. One mixture which has proved successful is composed of 75 % kerosene, 25% light machine oil and 0.1% wetting agent. Another widely used parting medium is made by shaving 6 oz. of stearic acid into 3 pints (40 oz. by weight) of hot kerosene; 0.1 oz. of wetting agent dissolved in this solution promotes even coverage of pattern surfaces. The mixture should be used warm. The use of heavy greases should be avoided because they result in soft mold surfaces and loss of detail. When the final pour of plaster has set completely, the mold is parted at its central plane and the pattern removed.

Whether in the form of a piece mold (a mold made up of several parts) or the more conventional cope and drag type, an air jet has been found quite effective in removing the pattern from the set plaster. A high-pressure air jet directed at the joint of the metal casting plaster and the pattern will loosen the pattern so that it may be removed from the mold. Another method is to make a small hole with a wire through the plaster mold to the pattern. An air jet directed into this hole will release the pattern from the set plaster.

After the plaster has set and the pattern has been removed from the mold, the parts of the mold should be laid face up or on edge on a flat, perforated metal plate, a rigid metal grid, or other level support, and placed in the drying oven.

The time necessary to properly cure a plaster mold depends upon several factors:

- Degree and volume of heat employed
- Circulation of gases
- Weight and thickness of mold and surface exposed.

If an oil or gas oven is available that can attain a temperature of 1400F (760C), the molds may be dried and calcined rapidly by placing the wet molds in the furnace at full heat. The mold temperature should be monitored, and the amount of time and furnace temperature necessary for the mold to reach a maximum center temperature of 700–900F (371–482C) should be noted.

Tolerances

Generally, plaster mold casting can maintain a dimensional tolerance of ± 0.005 in. (± 0.13 mm). Where the dimension crosses the parting line the tolerance is increased to ± 0.010 in. per in. (± 0.1 mm per cm). However, more exacting tolerances can be expected in particular sections of a casting.

Typical Applications

Industry has found many applications for plaster mold castings. Their uniform, homogeneous grain structure has made them highly acceptable for use in electronic equipment, for which purpose the slightest porosity or imperfection would be unacceptable. Such items as cable clamps, pole line hardware, wire connectors, brush holders and contactors can be cast in plaster molds from high-conductivity copper. Other electrical components can be cast from silicon bronze, manganese bronze, aluminum bronze or yellow brass alloys.

An outstanding application of the plaster mold process is the casting of impellers in copper-base alloys. By means of intricate cores, laborious and costly machining and hand-filing operations can be eliminated. Shrouded impellers are cast in one piece. The efficiency of an impeller depends upon the condition of the inside surface. Impellers cast in plaster have a high efficiency, because cored interior surfaces have the same satin smooth finish as external surfaces. Here, too, a wide variety of castable alloys provide high strength and good corrosion resistance.

Gears are an ideal application for the plaster mold process. Several alloys can be used for gear production, making a wide range of mechanical properties possible. Hobbing, milling, and much costly machining are entirely eliminated in the production of bevel gears, racks, spur gears, etc. The teeth and pitch diameters are held to close tolerances and, in most cases, are ready for immediate installation. Where an application requires extremely close tolerances, the gear may have to be sized. Gears cast in plaster molds are used to replace costly cut gears in the manufacture of outboard motors, washing machines, vending machines, gas meters, communication control units, etc.

In addition to the above-mentioned applications, this process is well suited for the production of hardware such as fittings, hinges, sprockets, and plumbing supplies. Spark proof tools such as wrenches, pliers, screwdrivers, etc., which are used in explosive environments can be cast in beryllium copper or other high-strength copper-base alloys.

The railroad industry uses many plaster mold castings such as locks, handles, lighting fixtures, ornamental and miscellaneous hardware, and plumbing supplies. The aircraft and marine industries also utilize this process to cast hydraulic system parts, instrument fittings, control mechanisms, wing nuts, communications parts, and many other larger parts.

INVESTMENT CASTING

The investment casting process is characterized by the unique manner in which the mold cavity is created. Unlike other casting processes, investment casting utilizes expendable patterns which are completely surrounded or invested—that is, with no parting lines in the mold, using a molding aggregate in slurry form. The slurry hardens by chemical reaction. Patterns are most often made of fusible materials such as waxes, plastics, or fusible alloys (at one time, even frozen mercury was used) which permit their removal from the mold by melting-out. Since wax was commonly used for centuries, the process has also come to be known as the lost-wax, or *cire-perdue* process. It is also known as the precision casting process.

As an art casting technique, the investment casting process has been used for centuries in the production of statuary and fine jewelry, utilizing fireclay washes to invest the wax patterns produced from the original art. Natural plant and animal specimens have also been used as patterns, in which removal is accomplished by total ignition and extraction of residual ash. Ancient artifacts of this type, cast in gold and silver as well as in bronze, have been found in the archaeological remains of many early cultures.

Prior to about 1940, the major commercial applications of the investment casting process were for the production of statuary, jewelry, and dental hardware (crowns, bridges, and inlays). The molds for small, intricate castings were frequently centrifuged, or spun, at low speeds to assist the filling of the mold cavity.

The potential of the investment casting process as a means for producing intricate, precision parts requiring little or no machining was first exploited commercially during and after World War II, especially for the casting of refractory alloys. Since that time, the technology of the process and its materials, as well as automation, has progressed to the point that investment casting is now a most important commercial process.

There are two modifications of the investment casting process: 1) investment flask casting, which utilizes a solid mold contained in a flask; and 2) investment shell casting, in which the pattern material is enclosed in a shell of the molding aggregate, sufficiently strong to permit pattern removal and casting. The latter is obviously more economical in terms of consumption of mold material and is generally restricted to smaller parts. A flow-chart for each of these process modifications is shown in Fig. 3-32.

The first step of any investment casting process is the production of expendable patterns of specially formulated waxes or plastic. Commercially, these are produced by hot injection into relatively complex, expensive steel or aluminum dies. The dies can vary in their degree of mechanization, the simplest type being manually operated and the most complicated type being fully automated with multiple side-pulls (impeller blades, etc.). As with pressure diecasting and permanent mold casting, the initial cost of tooling is a major consideration in the selection of the process, since this cost must be amortized against production within a reasonable and economic time period.

The cavities in the pattern dies are provided with triple shrinkage allowances, taking into account the anticipated dimensional changes of the pattern, the mold (during drying and firing), and the casting. Properly sized patterns are cleaned, inspected, and then assembled by means of gates and risers to a suitable runner and/or sprue system. This system includes a pouring cup and sufficient individual runners to direct the molten metal through the gates into the mold cavities. The pattern pouring system is assembled by use of heated tools resembling electric soldering irons. The “tree” or “cluster” thus produced may be comprised of dozens, or even hundreds of patterns, depending on their size and complexity. The pattern assembly is now ready for investment.

If the solid mold method is to be used, the pattern assembly is placed in an inverted position on a pedestal and is then surrounded by a flask which is sealed against the pedestal. Slurry is then poured into the flask to invest the pattern cluster, with vibration or low vacuum applied in order to dislodge and remove any bubbles of entrained air. The mold aggregate is then allowed to harden chemically. With the shell process (which invariably utilizes a ceramic slurry), the pattern cluster is first dipped into the slurry to form a thin, continuous bubble-free coating. Shortly afterward, the coated assembly is uniformly covered with a dry, granular refractory layer. This alternate dip-coating and dusting with granular material is repeated until the desired shell thickness is obtained. The ceramic shell is then allowed to harden and dry. The purpose of the shell-building technique just described is to minimize mold shrinkage and cracking tendency, while utilizing a minimum of mold aggregate material.

After the molds have been dried, the patterns can be removed by a process known as dewaxing, a term applied whether the patterns are made of wax or of plastic. This critical process, involving the heating of the entire pattern/mold assembly, requires the pattern material to melt and drain from the mold. Any residual material is completely vaporized or oxidized. Undue expansion of the pattern material during the early stages of dewaxing can cause cracking and destruction of the shell-type mold which, at this stage, is still relatively weak. To minimize problems of mold crazing or cracking, or combustion of the melted wax, dewaxing is normally done under steam pressure in an autoclave. Following the low-temperature dewaxing cycle, molds are slowly heated for final firing at incandescent temperatures.

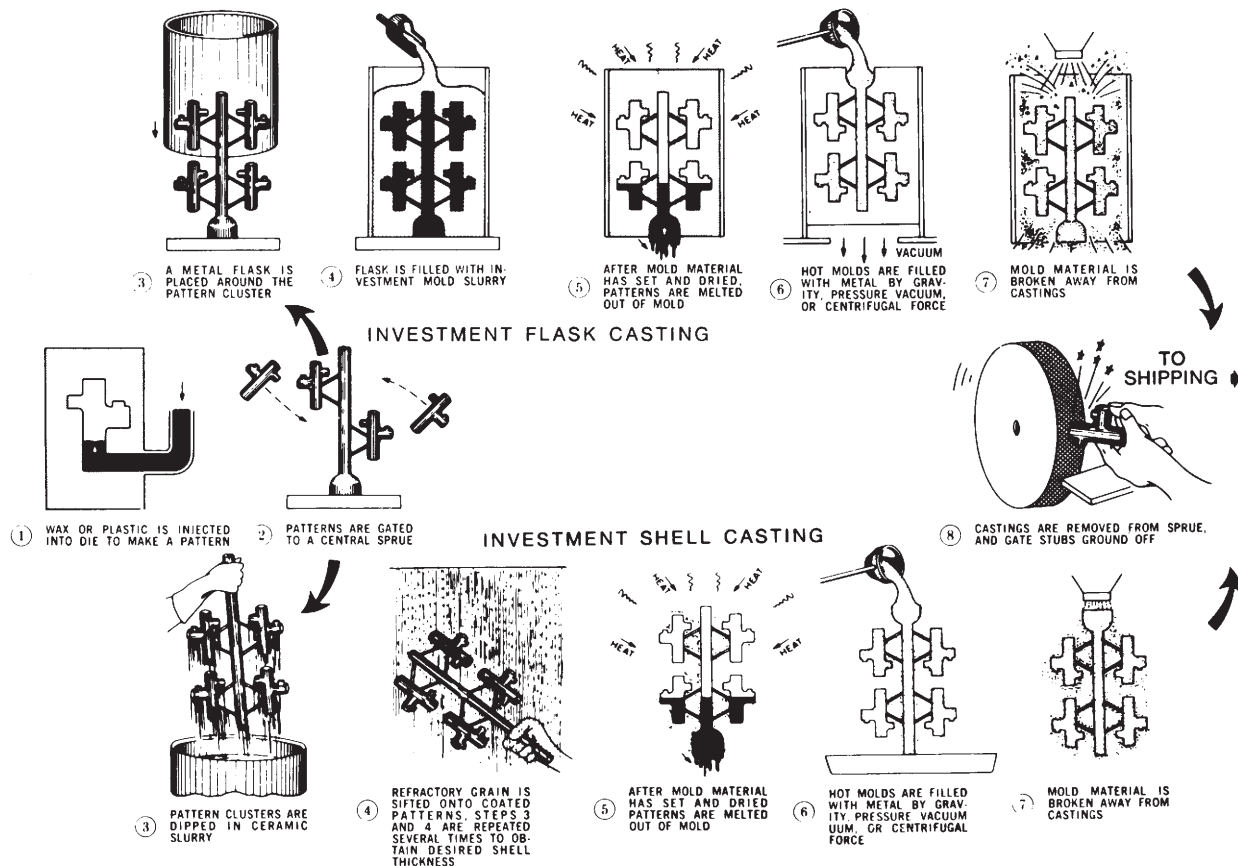


Fig 3-32. The basic production steps for investment casting methods.

The fired molds, often preheated, are subsequently cast. They may be gravity-cast in a conventional manner, vacuum-cast, low-pressure cast, or centrifuged. After the metal has solidified, the ceramic mold material is broken away and castings are cut from gates and finished. Vapor-blasting with fine abrasive effectively removes adherent ceramic without destroying casting finish and accuracy.

Advantages of Investment Casting

With investment casting processes, very intricate, complex castings with thin walls and smooth surface finish can be produced.

Investment casting provides a normal linear tolerance of ± 0.005 in. (± 0.13 mm) for dimensions up to one inch, with an additional ± 0.005 in. for each inch thereafter. Closer tolerances are actually possible, depending on the alloy selected and the configuration of the part.

The investment casting lends itself allowing prototype parts made by 3D CAD (computer-aided design) systems to be attached to a gating system and quickly made and evaluated.

When using this casting process, there are relatively few limitations on the type of alloy which may be cast.

CERAMIC MOLDING

Introduction

Ceramic molding techniques are based on proprietary processes that employ permanent patterns and ceramic slurries for molding. The Shaw and Unicast Processes discussed herein are variations of the ceramic molding process. The Unicast process uses fine grain zircon and calcined high-alumina mullite slurries for molding. In the Shaw process, the refractory slurry is composed of a mixture of coarse and fine sillimanite, hydrolyzed ethyl silicate, and a liquid catalyst. The Unicast process also differs from the Shaw process principally in the method of mold stabilization employed, the wider range of ceramics used, and additional binder options. Mold stabilization refers to the treatment given to the fine ceramic facing of a composite mold, or the total mass of an all-ceramic mold, shortly after it has set. The Unicast Process has for the most part replaced the Shaw Process as it simplifies the process and lowers cost.

The composition of zircon slurries used in ceramic molding processes are similar, except for distribution of grain size, to those used in ceramic shell investment molding. Like investment molds, ceramic molds are expendable. However, unlike the monolithic molds obtained in investment molding,

ceramic molds consist of a cope and a drag or, if the casting shape permits, a drag only.

Both investment molding and ceramic molding can produce castings with fine detail, smooth surfaces and a high degree of dimensional accuracy. The ceramic mold surface has refractory properties that enable it to withstand high metal pouring temperatures (such as those necessary for steel and heat resistant alloys), give it excellent thermal stability, and do not permit metal penetration or burn-in.

The ceramic molding process relates to two distinctly different types of ceramic molds: a one-piece all-ceramic mold and a composite ceramic mold consisting of an inexpensive fireclay backup material with a relatively thin facing of ceramic slurry. Selection of mold type depends almost exclusively on the size of the casting and the cost of the mold material. Many small castings can be produced economically in one-piece all-ceramic molds, because the amount of expensive ceramic slurry needed for the mold is moderate and the additional pattern and labor costs for composite molding cannot be justified. The castings produced by the two processes are comparable in quality and surface finish, and several foundries are licensed to use both processes. Although the Unicast process commonly uses a solid ceramic mold for smaller and short-run castings, it generally employs a composite-ceramic mold for large parts and for those produced in high volume.

Another difference between the Shaw process and Unicast process relates to the sequence followed in preparing composite molds. In the Shaw Process, preparation of the coarse mold backup precedes pouring the fine ceramic facing. In the Unicast process, this sequence is reversed. In this case, the Unicast ceramic is used as a 6.4 to 13 mm ($\frac{1}{4}$ to $\frac{1}{2}$ in.) facing backed by a specially blended, coarse sand aggregate for support. This technique sharply reduces mold cost by conserving the ceramic material, and permits the mechanized production of molds.

Both ferrous and nonferrous alloys are cast in ceramic molds, but ferrous applications are more numerous and account for the major tonnage of castings produced. Alloys of aluminum, copper (especially beryllium copper), nickel, and titanium are nonferrous alloys that are cast in ceramic mold casting.

Typical copper casting alloys include food-machinery parts, marine hardware, and decorative trim items used in architectural applications. Complex castings with thin sections (≤ 1.6 mm or 0.063 in.) can be cast in ceramic molds, using special techniques. Casting surfaces have excellent smoothness—usually 3.2 μm (125 μin) or better.

Patterns

Most of the common pattern materials are used, including the denser hardwoods, plaster, aluminum, plastics and hard rubber. Wooden patterns, however, tend to change dimensions due to moisture absorption despite the application of wax. Since the casting can be no more accurate than the pattern from which it is produced, molds from mounted

aluminum and brass patterns produce castings that are the most accurate and smooth. The patterns must be of good quality because the slightest flaw or defect in the pattern will be reproduced on the final casting. The reproduction of detail is such that even fingerprints on a pattern coating are likely to transfer to the casting.

Since the mold material is poured over the pattern rather than being rammed against it, there is negligible wear on patterns over time. Low pattern costs permit design changes to be made quickly and very inexpensively. The use of conventional types of pattern equipment that contain a parting, however, reduces the dimensional control obtainable at right angles to the parting.

Patterns for Composite Molds

Two sets of patterns are commonly required for the production of composite molds: a set of oversize pre-form patterns for molding the coarse backup material and a second set of patterns, representative of the dimensional accuracy desired in the casting, for molding the ceramic facing. Thus, for cope and drag molding four patterns may be required.

The pre-form patterns are made 2.5 to 10.0 mm (0.1 to 0.4 in.) oversize to allow for the thickness of the ceramic facing. In some applications, the pre-form pattern can be eliminated by using the final pattern backed with a sheet of plastic, cardboard, or felt of suitable thickness, to mold the pre-form impression in the coarse fireclay backup. Solid ceramic molds are made without backup material and only the final patterns are required for molding.

The pattern materials used for ceramic molding are conventional: plaster, wood, epoxy, aluminum, brass, tool steel and cast iron. Wood, epoxy and aluminum are most widely used. Prior to use, wood patterns are coated with a sealant that will not dissolve in alcohol.

Ensuring a high degree of accuracy in the alignment of the cope and drag is usually done by mechanically meshing certain surfaces. It is common practice in ceramic molding to incorporate parting blocks and locators in the cope and drag halves of patterns. These are molded into both the backup and the ceramic facing, together with the casting contours.

Mold Materials

The refractory slurry is composed of a mixture of coarse and fine ceramic material, hydrolyzed ethyl silicate, and a liquid catalyst. These are mixed together in less than a minute and poured over the pattern. Subsequent gelation of the slurry can be controlled by the amount of catalyst used. During the gel stage the mold is moderately flexible which facilitates the stripping operation.

Following stripping, the mold is flamed with a high temperature gas flame. The mold continues to support combustion due to its alcohol content. Flaming causes the mold surface

to form a system of craze-cracks. Crazing is progressive throughout the mold mass producing a mold of high permeability and partial immunity to thermal shock.

After the closing operation, the mold is fired at red heat for approximately 30 minutes per inch (2.5 cm) of mold material thickness. This further strengthens the bond and produces an inert, gas-free, erosion-resistant, collapsible mold which can be poured hot or cold.

Advantages

Ceramic mold processes, both Unicast and Shaw processes, provide accurate dimensional control, and warpage is almost eliminated. As a result of the stabilized molecular growth, the mold develops a cellular or sponge-like structure caused by the interstitial separation of particles. This structure provides for gas venting and particle expansion during casting. The advantages of this structure are metal soundness, ease of casting long, thin sections, elimination of veining and reductions in traditional mold venting. Molds can be poured hot or at room temperature without any changes in thermal characteristics. Directional solidification of the cast alloy is fully controlled, resulting in high physical properties and outstanding metal soundness.

The major advantages of solid ceramic mold casting include the following:

- Only a short lead time is necessary due to simple tools and a fast mold build cycle.
- A modest installation cost can be maintained using simple equipment. The manufacturing cost is considerably lower than that of machining or other alternate methods. Patterns are usually inexpensive and quickly prepared. These processes can be used for prototype work.
- The die life of cast tooling is longer than that of dies made from wrought materials.
- Cast tooling can be used without further machining. Castings with excellent surface finishes can be obtained. A surface finish of 125 μ in (3.2 μ m) or better is obtained in a steel casting.
- Precision cast tooling can frequently be used as-cast without further machining. Dimensional tolerances of ± 0.003 – ± 0.015 in. (0.08–0.38 mm) are obtainable, depending on section size and configuration. The process is good for prototype work.
- The process is suitable for impossible-to-machine grain and texture details for large injection mold bodies.
- The process is feasible for casting sizes ranging from very small to very large. Very thin sections can be cast as high mold and metal temperatures can be employed.
- Design complexity far exceeding that of conventional sand castings is possible. This is because the fluid mold material becomes strong, smooth, and yet at one stage flexible, making possible a mold release

from the pattern with no draft. Thus, a mold is produced with faithful registration of detail.

- Due to the inert and erosion-resistant properties of the mold material, metal sections are unusually clean and free from gas defects provided that slag from furnace and ladle is not entrapped in the metal.

Limitations

While the Shaw process has many significant advantages, it also has limitations and may not be a process that will compete with investment casting for long runs when the castings are in the size range considered typical for investment castings. Also, casting tolerances may not be as good as with the investment process, particularly across parting lines.

The following designs tend to be undesirable for production with the process:

- Thin, flat, rangy components
- Designs necessitating large print areas
- Designs requiring deep mold pockets.

The nature of the Shaw process is such that high material and labor costs are incurred. The use of exothermic materials helps to reduce these costs and improves casting quality. An evaluation of the advantages and limitations of the process indicates a definite place for it in the precision casting field. The Shaw process may, therefore, be considered an important supplement to existing casting methods, adding much needed flexibility to casting design and production by offering a quality range intermediate to that of conventional sand casting and precision casting. The Shaw process provides many of the advantages of precision casting at a lower cost.

CONTINUOUS CASTING

Approximately 90% of the annual production of copper-base alloys consists of wrought shapes such as sheet, strip, wire, tubing, and rods which are derived from cast shapes, most of which are produced by continuous casting. In addition, a substantial quantity of material is continuous-cast for direct machining into parts such as bearings, bushings, gears and tubular shapes. The technology of the continuous casting process is well developed but neither widely understood nor applied in the typical copper-base alloy foundry. The continuous casting process offers the progressive foundry an opportunity to diversify its product mix and minimize the cost of production of regular geometric shapes of the types described above. A modest capital investment in continuous casting equipment can provide significant returns as compared with investing in the production of similar shapes by the more conventional processes.

Equipment and Process Parameters

As shown in Fig. 3-33, the basic equipment for continuous casting is comprised of a tundish for holding the molten metal, attached directly to a machined graphite mold of

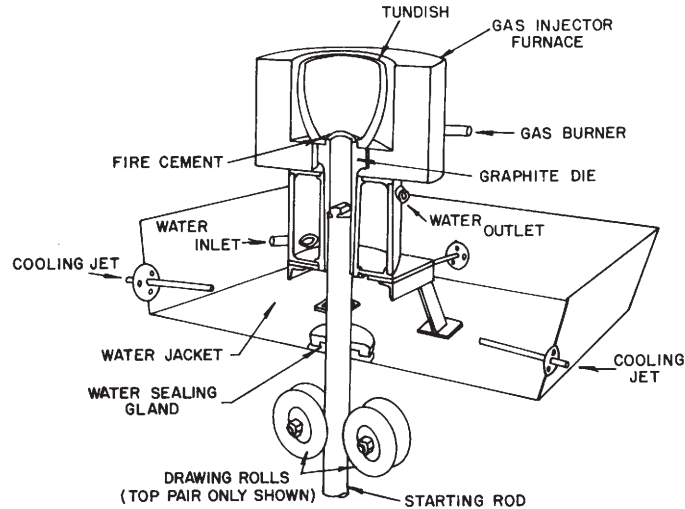


Fig 3-33. A schematic diagram of the original Tin Research Institute vertical casting system for bronze rod, with secondary water cooling is shown.

the desired cavity configuration. (The mold is fitted with an additional graphite mandrel if hollow cast sections are to be made). The lower end of the mold is fitted with a water jacket for heat extraction, an extraction bar for closing the lower end of the mold during start-up operations, and an extraction mechanism (usually in the form of power-driven rolls).

The extraction mechanism serves to withdraw the solidified shape from the mold at the rate the casting solidifies by water-cooling. Additional water-cooling spray may be provided below the mold in order to accelerate solidification and increase casting rate.

In modern practice, the top of the mold may be attached directly to the crucible of the holding furnace rather than to an open tundish. This is referred to as closed head casting. For smaller sections, the graphite mold may be provided with more than one cavity; alternatively, more than one mold may be fitted to the bottom of the crucible. These techniques permit multiple strands to be cast simultaneously. Continuous casting can also be done horizontally, as shown in Fig. 3-34. The same basic features apply to both processes.

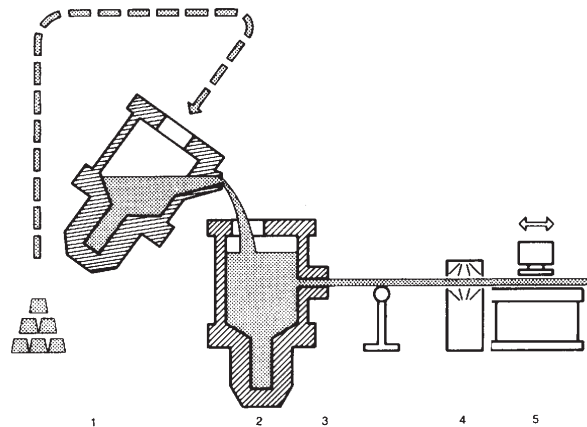
Although the process is called “continuous,” extraction is actually performed intermittently at intervals of a few seconds. This delay period allows time for a short length of the casting to solidify before it is withdrawn from the bottom of the mold. Parameters such as casting temperature, delay time between extractions, and roll speed depend upon the section thickness being cast (and cooling rate) and also upon the characteristics of the individual alloy. These relationships are shown for a series of copper-base alloys in Table 3-11. Examples of cross-sectional shapes that can be cast are shown in Fig. 3-35.

The improved mechanical properties of parts produced by continuous casting can be noted by comparing the values

listed in ASTM B505 with those for the same alloy in the form of sand castings (ASTM B584, for example). These intrinsic metallurgical advantages, combined with the high yield (98%) of the continuous casting process and the low cost of operation, have been widely exploited in the production of leaded bushing stock, particularly of alloy C93200.

Safety

Machine processes for continuous casting involve the close proximity of relatively large amounts of molten metal and water. To avoid the potential for explosions, care must be taken to avoid contact between the two. Piping systems must be shielded against damage which would cause leakage and, even more importantly, any run out of molten metal from the furnace or mold must be channeled away from any wet surfaces.



- 1 Melting furnace
- 2 Holding furnace
- 3 Primary cooling system (water-jacketed graphite die)
- 4 Secondary cooling station
- 5 Withdrawal machine

Fig 3-34. A schematic layout of horizontal continuous casting equipment is shown above.

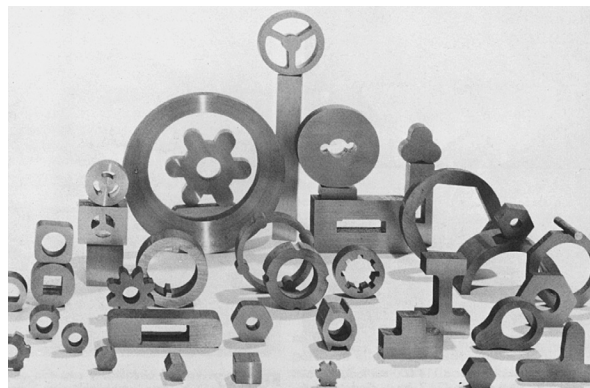


Fig 3-35. Sections of cast shapes produced in a vertical closed head continuous casting system. Hollow shapes result from use of an uncooled graphite mandrel suspended in the mold. (Artwork courtesy of ASM Metals Handbook Vol. 15 "Casting.")

Table 3-11. Typical Continuous Casting Parameters

Alloy	Composition	Section, in.	Tundish, °C	t_{on} sec	t_{off} sec	S in./min	V in./min
L.P.D. Copper		1.25	1200	2	5	24	7
Gunmetal	85-5-5-5	0.5	1210	4	4	10	5
	81-3-7-9	1.25	1170	2	2	24	12
		3.0	1150	2	4	13	4.3
Tin Bronze	90.10	0.125	1225	0.5	0.5	18	9
		0.5	1200	2	2	9	4.5
		1.25	1150	1	1	18	9
		3.0	1120	2	4	12	4
Brass	10 Zn	1.25	1160	3	2	24	14
	20 Zn	1.25	1140	2	3	24	9.6
	30 Zn	1.25	1100	2	2	24	12
	40 Zn	1.25	1070	0.2	6	54	2
	40 Zn	3.0	1070	0.2	7	180	5.0
Mn Bronze		1.25	1050	0.2	10	84	2.0
Al Bronze	8 Al	1.25	1150	0.2	4	130	6.5
	8 Al 3Pb	1.25	1150	0.2	4	130	6.5
	9 Al 5 Fe 5Ni	1.25	1170	0.2	4	180	10
	7 Al 3 Si	1.25	1150	0.2	4	130	6.5
t_{on} = Period of extraction, rolls ON t_{off} = Dwell period, rolls OFF S = Roll speed during t_{on} V = Casting rate = $t_{on}S/(t_{on} + t_{off})$							

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MELTING EQUIPMENT

INTRODUCTION

As with every other aspect of the metalcasting business, a variety of new developments in metal melting have greatly changed the copper-base foundry's approach to this operation.

The economics of melting have changed. The costs of electricity, gas and other fuels increased rapidly between 1972 and 1984. Electrical rates have since kept pace with inflation. Although electrical rates are lower where natural gas replaced coal, elsewhere, political decisions have caused rapid increases. The cost of electricity depends on consumption, power demand, load factors, and time-of-use, which can each vary by a factor of two. The blended rate for a small foundry (6-100 kW, 100-25,000 kWh) varied from 8 cents in Seattle to 23 cents per kWh in San Francisco and New York in 2015. The price of natural gas in the US is expressed in \$ per MMBtu for future delivery of large lots of gas at the Henry Hub in Louisiana. One million Btu of energy is equivalent to about 1,000 cubic feet of natural gas, 28 m³, or 1 GJ. The cost is variable, but with fracking, horizontal drilling, and storage facilities gas prices dropped between \$2.00-\$2.40 by June 2016, similar to the prices 10 to 20 years prior. The cost to metalcasting facilities depends on their location, volumes, and supplier contracts, plus costs for transport, storage and taxes. Not only has capital and installation costs of melting equipment increased, deregulation will force metalcasters to consider how much, where and when they purchase energy. Capital costs of melting equipment have increased, as have installation costs.

Environmental problems in handling molten metals continue to be another critical area, which may yet affect the foundry industry's survival. Requirements for removing particulate matter from the atmosphere and for controlling emissions of alloying elements such as lead, beryllium, or even nickel may be so stringent that the cost of control is unaffordable. Employees can no longer be exposed to excessive noise or heat conditions on the job. The penalties of OSHA or EPA violations can have a harmful effect on the financial well being of any business.

Obtaining satisfactory labor for melting operations continues to be difficult. It is increasingly difficult to recruit competent personnel for many areas of the foundry industry. The job

of melting brass and bronze will need to be made more favorable in order to attract personnel in this area.

An important consideration is the ever-increasing demand for higher and more consistent casting quality in brass and bronze foundries. With more castings being specified to meet rigid ASTM and ASME requirements and federal regulations, metal quality must be dependable and repeatable. The choice of melting equipment should be influenced by these factors. Brass foundries, like ferrous foundries, will require the appropriate analytical equipment, such as spectrographs, to maintain chemistry control.

TYPES OF EQUIPMENT

Brass and bronze alloys are melted in either fuel-fired or electric furnaces. The advantages and disadvantages of each type of equipment are discussed in the section "Choosing Melting Equipment," in this chapter. Descriptions of the available equipment follow.

Fuel-Fired Furnaces

Natural gas and fuel oil were once the most common fuels used in melting copper-base alloys. For the most part, either can be used with the same type of furnace merely by changing burners. Such furnaces melt by burning oil or gas with sufficient air to achieve complete combustion. The heat produced then melts metal either directly or indirectly by heating refractory material that in turn transfers heat by radiation or conduction to the metal. Heat is added until the solid metal becomes liquid, and the metal is then supplied with enough superheat so that it can be transferred and poured into molds. Fuel-fired furnaces used in foundries are described below.

Crucible or Pit Furnaces

The crucible or pit furnaces are the simplest. They were once the most common type of melting equipment. Non-tilting (pit-type) crucible furnaces consist of a steel shell, a refractory lining, a refractory pedestal on which a crucible sits, a refractory cover, and a burner (or burners). The refractory lining may be prefabricated or rammed into place. The burner is usually connected to an external

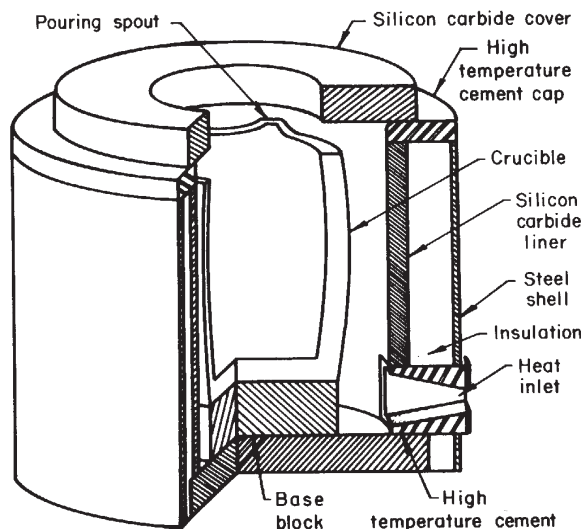


Fig. 4-1. This schematic of a lift-out crucible furnace shows key components. The furnace may be floor-mounted or installed in a pit, and can be fired with gas or fuel oil.

air blower, and the volume of air and fuel are metered, ignited and automatically controlled to provide a constant melting atmosphere. Automatic ignition systems are often used. Figure 4-1 shows a schematic of a crucible furnace. The crucibles are made of either clay-bonded graphite or carbon-bonded silicon carbide and vary in size from holding capacities of 5 pounds to about 700 lbs of brass, the maximum weight that can be safely lifted out of the furnace. Clay-bonded graphite crucibles are less expensive and more widely used. They are even more common in electric induction melting where the high electrical conductivity of silicon carbide crucibles will cause the heat to be concentrated in the crucible instead of in the charge.

In fuel-fired or electric resistance furnaces, the higher thermal conductivity of silicon carbide assists heat transfer through the crucible wall and improves melting. These crucibles may also be more resistant to attack by certain fluxes. To pour the molten metal directly, the crucible is lifted out of the furnace with special weight-actuated, equalized clamping tongs. The crucible can also be transferred to a pouring cradle for mechanical assistance in tilting the crucible while pouring.

This method allows different alloys to be melted in different crucibles, thus avoiding cross-contamination. Capital costs are low, although operating costs (crucible and fuel) may be higher than for some other methods. The furnace should be sized for the type of casting being poured. A crucible's size number indicates its capacity in lbs of aluminum. Since copper is three times more dense than aluminum, a No. 50 crucible that nominally holds 50 lbs of aluminum will hold 150 lbs copper. If many small castings are being made and only a limited number of molds can be poured because of temperature requirements, smaller crucibles such as No. 50 (150 lbs metal) or No. 80 (240 lbs of metal) can be used.



Fig. 4-2. A battery of gas-fired, lift-out crucible furnaces is shown. (Artwork courtesy of Cochran Foundry, York, PA.)

For larger castings, a No. 100 (300 lbs metal) or a No. 225 (675 lbs metal) can be used. In production shops, a battery of crucible furnaces, either at floor level or in a pit, facilitate charging and crucible lift-out. Figure 4-2 shows a typical installation.

In operation, the furnace and its crucible are usually preheated at the beginning of the workday. The first charge of ingot, or ingot plus gates and risers, is placed into the crucible and melted. The heat transfer is from the flame to the refractory, to the crucible, and then to the metal. In more recently designed furnaces, the flame does not impinge on the metallic charge projecting above the crucible, and flue gases do not come in contact with the metal but are directed out through a flue rather than up through the furnace lid. This reduces gas pick-up. Additional material is added progressively as the initial charge melts and sinks to the bottom of the crucible. It is good practice to add this material before all the metal in the crucible is liquid and to preheat it on top of the furnace cover before addition. This practice minimizes the risk of splashing and explosion, or gas pickup from damp material. In addition, by utilizing waste heat, this charging procedure ensures more rapid and efficient melting. After the metal is completely melted and superheated (to allow for temperature loss in handling between furnace and mold), the crucible is removed from the furnace, the metal skimmed and deoxidized (where necessary), the temperature measured and, when the proper pouring temperature is reached, the metal is poured. Other degassing procedures, such as nitrogen bubbling are usually performed in the furnace prior to removing the crucible to reduce heat loss.

Most foundries pouring a variety of alloys use a separate crucible for each class of alloy. Crucibles can last for 100 or more heats if care is taken in preheating, charging, pouring, and mechanical handling. Nevertheless, as crucibles become increasingly porous on repeated use, heat transfer will be reduced and energy consumption will increase. Obviously, there comes a point where refractory savings are not warranted at the expense of energy savings. Either minimum crucible weight or maximum melt time could be established, and translated

to an unacceptable crucible appearance. Both clay-graphite and silicon carbide crucibles should be used in mildly reducing atmospheres. The glazes used to protect the crucibles from oxidation can be easily chipped by rough handling.

In simple burners, the ratio of air to fuel is constant and only the volume is adjustable. In complex burners, regulators provide for fine adjustment of either air or fuel to the proper ratio, and the operator cannot vary the mixture. More sophisticated burner controls usually will maintain the proper melting atmosphere and reduce the influence of furnace operator adjustments. Melting atmosphere is important in controlling metal quality. In the melting of copper-base alloys in older style furnaces, it is desirable to maintain a slightly oxidizing atmosphere (a slight excess of oxygen or CO_2 in the products of combustion). Highly oxidizing conditions are hard on refractory crucibles, and in the case of clay graphite crucibles, cause the graphite flakes to burn out. This can lead to decreased thermal conductivity, and may well be the reason some furnace manufacturers claim crucibles should be replaced once increasing energy consumption and melting losses offset the economics of replacing the crucible. Burners should be tuned and tested periodically and air leaks into furnaces sealed and patched.

The melting of copper-base alloys in gas-fired crucible furnaces is less efficient than aluminum that melts at 35% efficiency. About 60% of the energy is exhausted in the flue gases. This drops to 50% on holding. Heat recuperation from furnace stack gases can reduce fuel consumption by 15–20% when heated air is used in the burners. Furnace designs that do not mix metal fumes with the flue gases facilitate heat recuperation. Stack gases from larger reverb furnaces offer potential sources of makeup air. Induction furnace cooling systems and air compressors are also potential sources of makeup air heating.

Tilting Furnaces

Tilting furnaces are frequently used when larger amounts of molten metal are needed for pouring brass and bronze alloys (such as in high-production shops or for making larger castings). The tilting furnace is similar to the pit furnace in design and operation, except for size and the tilting mechanism. Tilting furnaces are lined with a clay graphite or silicon carbide crucible cemented into the furnace shell with refractory cement, as shown in Fig. 4-3.

Furnaces can be tilted with a hand-operated gear system, hoist, electric or hydraulic tilting mechanisms. Tilting furnaces are mounted on trunnions, either at the midpoint which has the effect of moving the spout up and down or pivoted about the spout, so that the spout remains stationary. The molten metal is poured into either a refractory-lined ladle or a preheated crucible, and then poured into molds. The size of the ladle can vary depending on the size of the castings and the number of molds. When pouring many molds from a single ladle, the ladle should not be over filled; otherwise, the first few molds may contain cold shuts from intermittent pouring and splashing of the first metal, and the last few molds

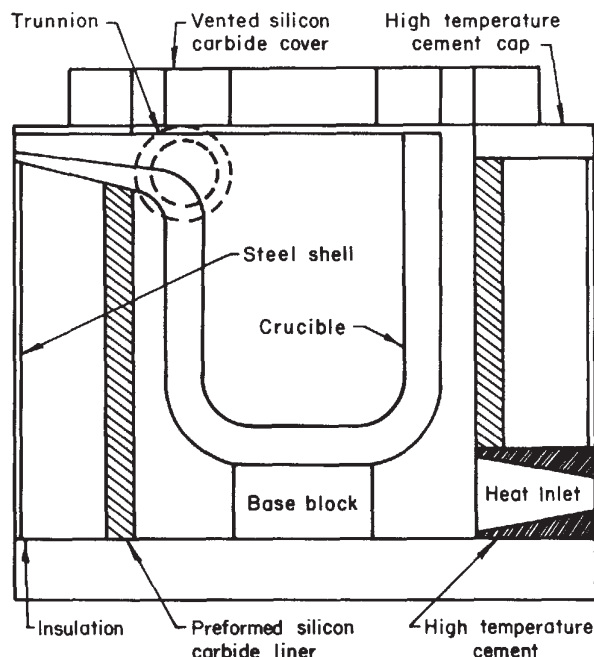


Fig. 4-3. This schematic of a tilting-type, fuel-fired crucible furnace shows the melting crucible cemented in the operating position.

may have misruns, etc., from cold metal. Generally, a small ladle should not be used to pour from a large furnace since this requires a high degree of superheat and the furnace can only be emptied slowly. Holding metal for long periods at high temperatures is a major factor contributing to gassing of the molten bath and loss of volatile alloy constituents (see the chapter on *Melt Control*).

As alloy changes may require relining, wash heats, or at least careful cleaning of the furnace, tilting furnaces are most efficiently used when only one alloy is being melted and poured. Tilting furnaces can be quite large, up to a No. 600 crucible (1,800 lbs of bronze), but are not considered practical for melting less than 350–400 lbs of metal at one time.

The melting procedure for tilting furnaces is similar to that described for pit furnaces. Melting times and costs are minimized by prompt reuse of the furnace to make maximum use of the heat retained in the lining. Since large furnaces have high thermal mass, the energy efficiencies for the first few melts each day are poor. Although melting times will vary with operators and conditions, tilting furnaces can melt approximately 500–600 lbs of brass or bronze per hour.

An additional factor with tilting, reverberatory or rotary furnaces is the cost of using preheated ladles to transfer metal from the furnace to the mold. Preheated ladles should be covered at all times to reduce energy loss. For this reason, ladle preheat stations using tightly fitting lids are often superior. Most burners can raise a covered ladle to 1832F (1000C) within an hour. The combustion efficien-

cy of burners when air and gas are balanced is between 62–65%. However, if a blue flame issues from the ladle, indicative of carbon monoxide burning, efficiency can be 58% or lower. Best flame temperatures seem to be between these two conditions.

A development in fuel-fired tilting furnaces is a furnace that provides better control of combustion, better insulation of both noise and heat, and easier charging and pouring. Although the development of this equipment enhanced the competitive position of fuel-fired furnaces as opposed to electric furnaces, it is not known whether this improvement along with the increased availability of natural gas renewed the interest of nonferrous metalcasters in fuel-fired melting.

Rotary Furnaces

For pouring large volumes of molten metal, from 1,000 lbs to 100,000 lbs, rotary melting furnaces can be used. While there are variations in designs, most rotary furnaces consist of a refractory-lined, cylindrical steel shell with the burner at one end and a flue at the other. A rotating device is used which completely or partially rotates the furnace during melting. Some furnaces tilt on the horizontal axis to facilitate charging and pouring; some pour from an opening at the center of the shell. Melting is accomplished both by the action of the flame directly on the metal and by transfer of heat from the refractory to the charge by rotation of the shell. Such furnaces have long been used in the brass smelting (ingot) industry and can handle a variety of raw materials satisfactorily.

Operator skill is an important factor in rotary-furnace melting. Close control of furnace atmosphere and bath temperature requires experience. The massive refractory lining becomes impregnated with the metal being melted, so only alloys within a narrow composition range can be melted without serious danger of contamination.

Reverberatory Furnaces

The reverberatory furnace, usually stationary, is characterized by a large, rectangular, shallow hearth (so that the metal bath has a large surface-area). The flame source is at one end, and melting is accomplished both by direct flame impingement on the metal charge and by reflected heat from the refractory roof. Large furnaces of this type are traditionally used in the brass ingot smelting industry and may hold up to 200,000 lbs of metal. Small stationary reverberatory furnaces were popular in some high-production foundries many years ago because of their ability to melt almost continuously. However, serious refractory problems and minimal temperature control of the molten bath eventually led to their reduction in use.

Electric Furnaces

Although copper-base alloys have been melted with electrical energy for well over 50 years, there recently has been

a marked transition from fuel-fired melting equipment to electric melting equipment. Both the threat of a possible fossil-fuel shortage and the fact that electricity can be produced from a variety of sources (such as oil, gas, water power, and nuclear power) have been factors contributing to this transition. Advantages other than energy availability have also prompted foundries to convert to electric melting equipment, and these will be discussed.

Induction Furnaces

The use of induction melting equipment, particularly medium- or high-frequency coreless induction furnaces, have become the most popular method for melting brass and bronze alloys. The principle of induction melting is analogous to that of a transformer where the water-cooled coil (representing the primary coil) surrounds the metal charge (the secondary core). When the coil is energized, a secondary electric current is induced in the metal charge within the crucible, the resistance to the current heats the metal until the metal melts and becomes superheated. About 60% of the energy goes into heating brass and bronze alloys in a coreless induction furnace.

The transition from the older motor-generator sets to solid-state electrical conversion greatly contributed to the increased use of induction furnace equipment. Modern induction power units basically draw 440-600 volt, 50-60 cycle power and by means of solid-state electronic devices convert three phase power at 60 hz, to single phase 180 cycles (180 hz), 540 cycles, 980 cycles or even 3,000 cycles. (Hertz (Hz) = 1 cycle / second) Although the conversion can be accomplished in a number of ways; the most common route is AC to DC to AC. Induction furnaces are characterized by the electromagnetic stirring of the metal bath. As the amount of stirring is affected by power input and frequency, they must be coordinated with the furnace size. For this reason, most copper alloys are melted in 1,000-cycle or 3,000-cycle units (high frequency or 3,000 Hz). Larger melts are usually handled with 1,000 cycle (or lower) frequencies. Input power ratings may range from as little as 1 to 5 kW for special purpose units where only 5 to 10 lbs of metal are required, up to 750 kW where 3,000-4,000 lbs of metal are needed. The melting rate is a function of power input or approximately 500 kWh for each tonne. (Tonne = metric ton (t) = 1.102 short tons) Hence, a foundry's molten metal requirements and casting size will dictate equipment needs.

Coreless Induction Furnaces

There are three types of coreless induction furnaces: box furnace with rammed refractory or crucible, or crucible furnaces with a push-up crucible or lift coil. A coreless induction furnace is comprised essentially of a water-cooled copper coil in a furnace box made of transite with steel or aluminum angle brackets. The metal is contained either in a crucible (similar in size and shape to that used in fuel-fired furnaces) or in a refractory lining that is rammed up inside the coil. Though varieties of designs are available, these furnaces are of two general types, tilting and stationary.

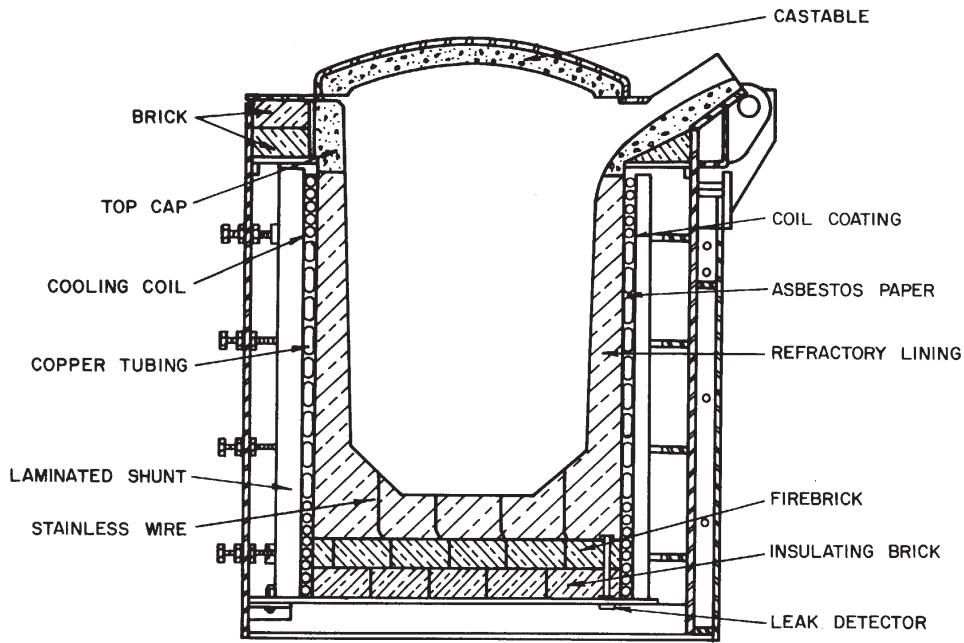


Fig. 4-4. A schematic of a tilting-type, coreless induction furnace (nose tilt) is shown.

Tilting furnaces are similar in concept to those available as fuel-fired equipment; they consist of a box with either a crucible or, more often, a refractory lining rammed in next to the coil. They can be tilted by a hydraulic lifting system or a hoist. The molten metal is transferred into a ladle which, in turn, is used to pour the molds. Figure 4-4 shows a typical configuration.

Non-tilting (stationary) furnaces are of three distinct types, each characterized by the different methods used to remove the crucible for pouring. In the "lift-swing" design, the coil (protected by a box) is cantilevered from a center post and can move up and down vertically and swing horizontally about the post in a 90° arc. Usually there are two crucible positions, one crucible can be poured, recharged, and made ready to melt while the other is melting. When the metal is ready to pour, the coil is lifted (by hydraulic or air cylinders), pivoted to the side and lowered over a second crucible. The ready crucible is now standing free and can be picked up and poured while melting proceeds in the second crucible.

A second type of non-tilting furnace is designed so that the furnace box is lifted with a simple hoist. The crucible sits on a small cart that moves away from the box so that the crucible can be picked up and poured. Again, two crucibles can be used.

In a third type of stationary furnace, the coil and box (one or two coils in a box) are stationary and are often located in a pit. As shown in Fig. 4-5, the crucible(s) stand on refractory pedestals that can be raised or lowered by hydraulic cylinders. This unit, called a "push-up" furnace, operates by lowering the crucible into the coil for melting and then raising the crucible out of the coil for pickup and pouring. Molten

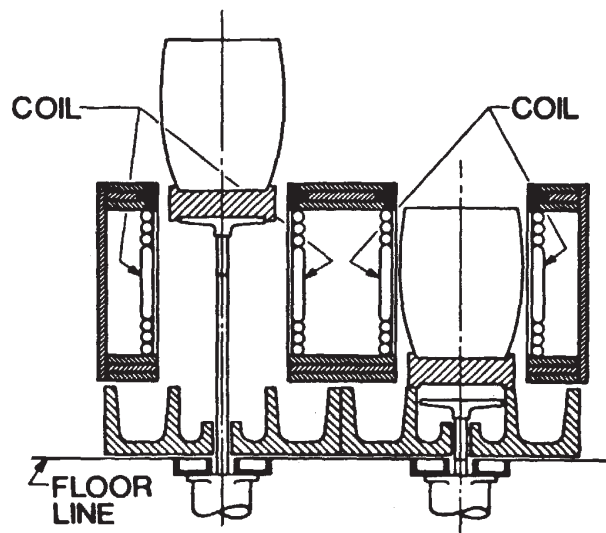


Fig. 4-5. A schematic of a double pushup type, coreless induction furnace (right crucible in melting position is shown).

metal falling into a pit will sometimes damage the hydraulic lifting equipment. Neither the push-up nor the lift coil furnaces require ladle preheating as the melting crucibles are subsequently used for pouring. Different alloys can and should be melted in labeled crucibles to avoid contamination.

The power conversion unit containing solid-state components and control circuitry is usually fed by three cables (usually 3 phase 440V) of identical length. One or more of the furnace types previously described are attached to the power unit by a bus bar and flexible water-cooled furnace

leads. Some older units had two furnaces, so the power pack had switches to provide power to the selected furnace, as only one furnace could be run from one power unit at any given time. Modern units can now supply any portion of the rated power to each furnace (up to the maximum of the power supply), so one furnace can be melting while the other is held at temperature. A water-cooling system circulates water through the electrical components (the power pack, furnace coils and the furnace leads) to remove heat. The water must be cooled and circulated continuously through the system. A heat exchanger is usually mounted outside the foundry. In cooler climates, this requires a water-glycol coolant. As conductive corrosion inhibitors cannot be used, the heat exchanger must be made of corrosion resistant materials. Heat exchangers can be expensive. The waste heat in the cooling water may be recovered for space heating.

For melting, the water supply is turned on and the furnace is charged with metal. The power is turned on and adjusted if necessary. Metal is then added to the charge to fill the crucible or furnace, and is heated until the appropriate pouring temperature is reached. The power is then turned off and, by means of suitable equipment, the crucible is picked up or tilted and the metal is poured.

Induction furnaces cause the molten metal to be stirred by the electromagnetic currents. This increases uniformity of both alloy composition and molten bath temperature. Because of the rather vigorous stirring action, it is difficult to use any type of flux, and none is necessary. Under most circumstances, gassing of the molten metal is unlikely because the atmosphere over the bath does not contain products of combustion (see the chapter on *Melt Control*). Nevertheless, hydrogen can be introduced into copper-base alloys in induction furnaces under any of the following conditions: high absolute humidity in the foundry, excessive metal superheats, new crucibles or new linings not thoroughly dry, or charge materials contaminated by wet sand or oily swarf. Graphite plates and granular graphite covers are occasionally used to cover the molten metal.

Once the power is turned off, the metal cools rapidly because it is relatively close to the water-cooled coil and both the furnace shell and crucible are cooler than the metal. In contrast, fuel-fired furnace shells and crucibles are superheated and continue to increase the metal temperature for some time after shut-off. To compensate for this, a higher bath temperature may be required in induction melting to give a constant temperature at the pouring station. With properly sized melting equipment, it is possible to melt metal in an induction furnace in about half the time it would take to melt the same amount using fossil fuels. Oxidation losses for some alloys may be less than losses experienced with fuel-fired furnaces; however, the actual loss depends upon the type of alloy involved, furnace practice, and the nature of the charged material. With carefully controlled furnace practice, copper-base alloy borings or chips can be melted, although these are usually melted in combination with heavier material.

Induction melting equipment is usually quiet (limited to 85 db). Plant ventilation and space heating are easier to control. Makeup air is not needed to replace air used in combusting fuels or air escaping up the hot stacks nor is there a need to dilute combustion products. Nevertheless, exhaust systems may be placed around the furnace opening to collect zinc fume and products from oily scrap. The absence of noise, flame, combustion products, and excessively high temperatures greatly improves working conditions in the furnace area and minimizes pollution problems. These factors can influence the attraction and retention of good melting personnel.

Channel Induction Furnaces

Brass mills or large, high-production brass foundries, that use a single alloy and require a constant source of molten metal, typically used vertical ring or single-channel-type induction equipment, as illustrated in Fig. 4-6. In these furnaces, the primary coil is interfaced with a laminated iron core surrounded by a secondary channel, which is embedded in V- or U-shaped refractory material located near the bottom of a cylindrical hearth. The channel is usually off to the side so that the furnace need only be tipped away from the channel so that it can be replaced. This furnace stirs and circulates molten metal through the channel, and liquid metal must be maintained in the channel at all times except during complete shutdown. An entirely solid charge cannot be used to begin melting. Charge additions are made into the liquid "heel," which is maintained in the bottom of the bath. The charge fills the secondary channel, and because of the excellent heat transfer, melting is rapid. The channel is often air-cooled by a fan, so coil efficiency is higher than in coreless furnaces.

In view of its low cost, simplicity of operation, and ability to turn out good metal at high production rates, the channel furnace is best suited for continuous or long production runs with a single alloy. This type of furnace was often used in high-production, copper-base alloy foundries such as those that make castings for plumbing goods, where autopour equipment could be used. Because oxides of copper are highly abrasive to refractories in the channel, the molten metal is covered with graphite chunks and phosphorous levels are kept elevated. Degassing has to be conducted in a ladle with the consequent loss of superheat. Metal from furnaces equipped with autopour and transfer launders is not so treated.

Indirect-Arc Furnaces

The electric indirect-arc furnace, known as a "rocking arc" furnace, enjoyed great popularity in brass and bronze foundries before the advent of solid-state induction melting equipment. They are now quite rare.

Resistance Furnaces

The newest type of electric melting furnace is based on very old electric heating technology involving passing a current

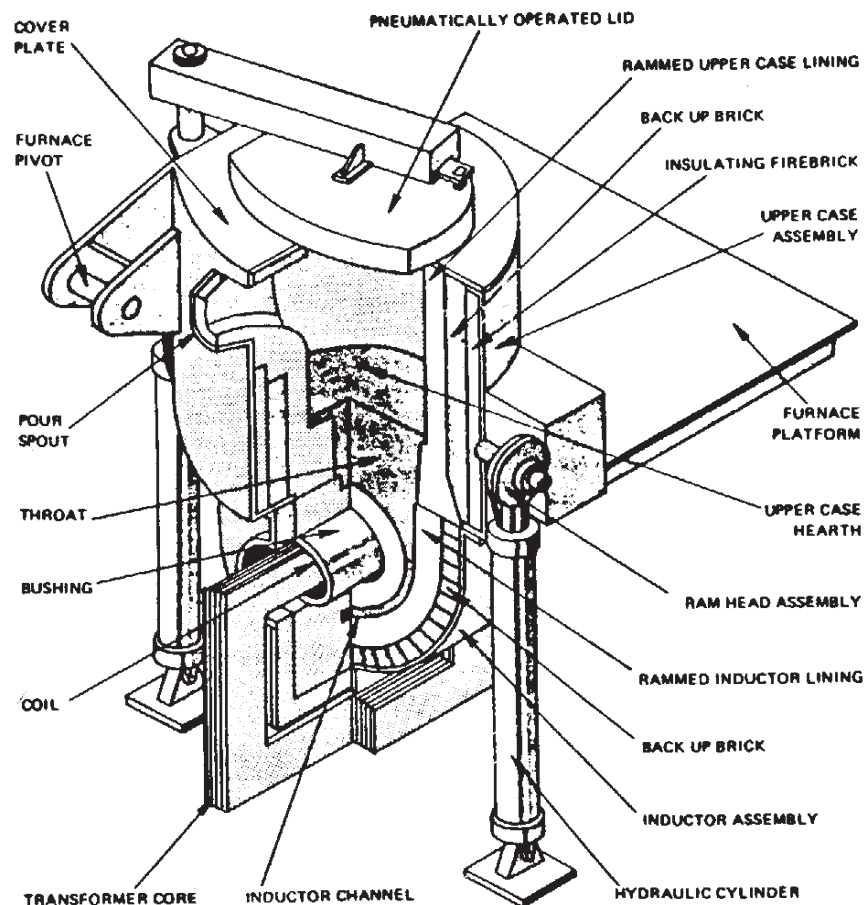


Fig. 4-6. A channel induction furnace with a bottom channel for melting a single copper-base alloy is shown above.

through a material that becomes incandescent from electrical resistance. In the past, this technique was used for heating applications and holding pots rather than for alloy melting. Recent improvements in materials and electrical circuitry have resulted in new furnace designs that are claimed to be capable of melting copper-base alloys.

Resistance furnaces outwardly resemble crucible-melting furnaces. Metal is charged into silicon-carbide crucibles and heated by the effects of both radiation and conduction. The resistance elements operate at approximately 3000F (1650C) and the furnace is well insulated. Thus, the crucible heats up rapidly, and provides melting rates comparable to those of other melting units.

Because this type of melting equipment is still new in the United States, a limited amount of data based on experience is available. A number of claims have been made for resistance-furnaces: melting efficiency is higher than for fuel-fired or induction furnaces, that refractory life is excellent, oxidation losses are very small because the metal bath is not agitated, the resistance furnace is non-polluting and does not require extra ventilation equipment, nor does it produce noise or smoke. Melting energies for resistance furnaces melting aluminum have shown very high efficiencies, however, melt rates

were often quite low. This type of furnace is ideally suited for continuous casting or permanent molding operations where the metal must be held at constant temperatures for long periods. Maintenance costs are reported to be low.

Depending upon the size, a resistance-type furnace can melt between 150 lbs of brass or bronze (rated at 30 kW maximum input) and 2,000 lbs of brass or bronze (in a tilting-type furnace rated at 250 kW maximum input). The cost of resistance furnaces is about the same as for induction melting equipment; installation costs are comparable to or less than those for induction furnaces.

CHOOSING MELTING EQUIPMENT

Because of the variety of melting methods and equipment available, each of the factors discussed below should be considered when choosing a furnace.

Operational Requirements

Among important operational considerations are: 1) the amount of metal needed at one time to pour off available molds; 2) metal production needed over a certain period of

time (per shift, per day, etc.); 3) whether it is necessary to change quickly from one type of alloy to another; and 4) whether production involves many molds of lightweight castings or fewer molds of heavy castings.

For maximum flexibility, a furnace should be used which utilizes a single crucible for both melting and pouring, such as fuel-fired pit furnaces or push-out induction furnaces.

If many small molds are to be poured or if very close control of the pouring temperature is required, small crucibles (No. 50 to No. 100) will probably be best. Larger tilting furnaces may also be used, in combination with smaller pouring ladles. In this way, any amount of metal can be taken from the furnace at one time. However, care must be taken to avoid excessively long holding periods for the molten metal bath in the furnace.

If large quantities of a single alloy are required for two or three shifts a day, channel induction furnaces may be the most efficient. Large tilting furnaces, either fuel-fired or electric (induction or resistance), may be satisfactory as well. If many alloy changes are to be made, removable furnace shells or crucible furnaces are a necessity. By using a number of crucibles, a variety of copper-base alloys can be poured without the risk of alloy contamination.

Environmental Considerations

Noise

Fuel-fired furnaces are generally noisier than induction melting equipment and may exceed 110 db, although some manufacturers claim their gas-fired melters meet OSHA noise regulations. Most manufacturers of induction furnaces will warrant that their operating equipment will not exceed 85 db. Arc melting furnaces (no longer common for melting copper-base alloys) were noisy and can be expected to exceed OSHA requirements.

Heat

Fuel-fired furnaces by their very nature produce considerable heat in the immediate vicinity of the furnace. If hot exhaust gases are not vented away by means of furnace hooding and ducting, heat escapes to the surrounding atmosphere and causes discomfort for personnel in the immediate area. Since radiation accounts for much of the heat transfer in fuel-fired furnaces, the furnace and crucible must be superheated well above the metal temperature. Whenever the furnace cover is removed for recharging, or the incandescent crucible is removed for pouring, considerable heat is radiated to the working area that make it necessary for furnace crews to wear protective clothing.

In induction-melting crucible furnaces only the surface of the molten metal is exposed, hence radiation losses are small and there are no exhaust gases to heat the atmosphere in

the melting area. Although melting department personnel must wear some protective clothing, it is generally more comfortable to operate induction furnaces than it is to operate fuel-fired equipment. Resistance-type melting furnaces, while producing no effluent hot gases, do melt by heating up the crucible to incandescence. Hence, removal of the crucible from the furnace for pouring may create problems similar to those encountered with fuel-fired crucible equipment.

Since metal transfer from any kind of tilting furnace into a pouring ladle generates a certain amount of splashing and gives off heat to the atmosphere, protective clothing is recommended for personnel. Clothing and other devices are covered in "PPE Guide for Metalcasting Operations, 4th Ed.," published by the American Foundry Society.

Smoke and Fumes

In gas or oil melting, as both flame and refractory temperatures are high and up to 90% of the energy goes up the stack, there is considerable potential for smoke and fume problems. If high-zinc alloys are melted, or if the molten bath is allowed to superheat excessively, volatile alloy components may be driven off creating a serious effluent problem. Zinc oxidizes preferentially and creates smoke and fume problems that require extensive furnace hooding and fume collection equipment. Lead seems to be a problem from oxidized scrap (particularly burnt lead-clad cable) and sand. Lead-bearing alloys and scrap/returns must have adequate fume control to meet emission standards.

Induction and resistance furnaces, while not fume-free, produce considerably fewer fumes than fuel-fired furnaces. If the metal bath is excessively superheated, volatilization of zinc and lead will occur; however, since there are no combustion gases present, fewer effluents are produced and simpler collection equipment is required. In this way, electric melting greatly reduces smoke and fume problems for any given alloy and degree of superheat. Generally, leaded red brasses should not be heated above 2320F (1270C), and higher zinc alloys still lower.

Economic Considerations

Melting Costs

The costs of electric energy, natural or propane gas, and fuel oil have increased at an alarming rate in recent years and further increases can be anticipated. Sales prices of castings have also increased, but not at the same rate as direct melting costs.

The cost of converting a ton of copper-base alloy from room temperature to pouring temperature will vary, depending on the location of the foundry and the relative fuel costs at that location. These relative costs are changeable, and future costs are difficult to predict. In addition, fuel consumption varies between foundries, depending on the equipment, melting practices, alloys, pouring temperatures, and shift

lengths being used. The theoretical energy required to raise one ton (2,000 pounds) of copper to 1260°C (2300°F) is 190 kWh or 650,000 Btu. Reducing the tapping temperature by 100°F lowers the energy required by 7.2 kWh/t or almost 4%.

Older literature gives only a very general comparison of melting-energy requirements, which can be made from the following estimates of fuel consumption, each based on melting one ton (2,000 lbs) of alloy and raising it to its pouring temperature:

- Gas-fired crucible: 5,000 ft³ natural gas @ 1,000 Btu/ft³
- Oil-fired crucible: 35 gal fuel oil @ 180,000 Btu/gal
- Electric induction crucible: 350 kWh.

More recent work suggests typical melting energies for copper alloys in induction furnaces range from 360 to 1,000 kWh/t with an unweighted average of 480 kWh/t, aluminum alloys 520-1,460 with an average of 870 kWh/t (not including water and hydraulic pumps). The low end of the range more closely reflects the capabilities of melting equipment in the hands of a good crew. The higher numbers reflect what happens in many foundries when molten metal is ready ahead of schedule, lengthy conditioning operations, delays, etc. Typical melting energies for lift coil furnaces are 485 kWh/t for aluminum bronzes, 380 kWh/t for brasses, 800 kWh/t for aluminum, and 600 kWh/t for cast iron. The largest casting poured from a lift coil furnace can be effectively doubled by melting in two crucibles and flipping the coil from one crucible to the other. The melting energy is increased to 485 kWh/t from 380 kWh/t. Refractory lined coreless furnaces melt red brass at about 450 kWh/t. Coil efficiencies for induction furnaces ranged from 0.51-0.61 with an average of 0.58. Energy consumption of gas-fired furnaces ranged from 1,700 to 10,000 kWh/t (5,800-34,000 ft³) with an average of 4,200 kWh/t (14,500 ft³) for copper alloys (not including blowers) and 1,400-6,500 kWh/t (4,800-22,00 ft³) and an average of 3,900 kWh/t (13,500 ft³) for aluminum alloys. Holding times and poor efficiencies at holding were responsible for these high numbers.

A number of other factors need to be considered in estimating production costs, namely:

- Furnace electrical demand, which ranged from 33-90% of the foundry demand and averaged 59%. Demand cost is a fixed cost and varies widely per kW each month. Furnaces are the main cause of peak demand, and in brass foundries should be considered fully additive, i.e., 100% contribution to plant demands. Lift coil furnaces can achieve high utilization rates as the time to switch from one crucible to the other can be of the order of 22 seconds (full power, off and back up to full power on the other crucible). Modern power packs with two furnaces with power sharing can also achieve 100% power and power pack utilization.

Coreless induction furnaces in brass foundries are usually operated at or near maximum power, so they do not contribute to power factor penalties.

- Furnaces used 13 to 84% of the foundry's electrical energy with an average of 38%; this means that the total energy in good castings shipped ranged from 2,700 to 14,600 or an average of 8,700 kWh/t, while electrical consumption varied from 2,700 to 5,800 and an average of 3,100 kWh/t.
- Overall casting yield was found to vary from 36-73% with an average of 53%; this implies that metal is melted twice in the foundry before becoming part of a good casting. Therefore, energy, labor and refractory costs are doubled.
- Tilting furnaces need ladle preheating stations, which require gas burners that typically operate at 62% combustion efficiency (range 46-70%). Inefficient scheduling and use of ladles, poor design and lack of covers increase ladle heating costs.

Labor Costs

In the selection of melting equipment, another important consideration is the availability of labor. All foundries are finding it difficult to attract employees; many foundry operations create unattractive workplaces due to noise, heat, and the nature of the work, particularly in the melting operation. In order to attract and retain competent personnel, the working conditions in melting departments must be improved.

Since electric equipment is more comfortable to work around than is fuel-fired equipment, the use of electric furnaces should make it easier to attract employees to the melting department. In addition, the actual cost of labor may be less because with an electric furnace the reduction in heat and noise fatigue may make it possible to accomplish the work more efficiently and with fewer people. In addition, electric equipment often produces much higher melting rates.

It was found that typical monthly production varied from 1 to 10 tons shipped per foundry employee (average 3.7 t) and 0.33 to 3.7 tons shipped per plant employee (average 0.8 t). The sample size was 15 Canadian foundries and included plumbing manufacturers with extensive machining and packaging facilities.

Maintenance Costs

All furnaces require maintenance. Generally, electric furnace equipment requires less maintenance of the furnace proper than does fuel-fired equipment. Since fuel-fired furnaces melt by superheating the refractories, these furnaces must be relined regularly. Induction furnaces also require relining

when melting is done in a rammed-in crucible. When crucibles are used, both crucible life and lining life are generally excellent. Foundries operating both electric and fuel-fired furnaces usually find that maintenance costs for electric furnaces are far less, as well as costs for labor and supplies.

Maintenance costs for electric furnace power units, on the other hand, are high. This equipment is usually sophisticated, containing solid-state components and complex wiring circuitry, and may be unfamiliar to maintenance department personnel. Malfunctions of the equipment are to be expected and, while recent design changes have improved service life, electronic components do fail and must be replaced. Usually some repair work can be done by foundry personnel; in large operations, maintenance personnel may be capable of handling almost any malfunction. Most users of induction equipment keep spare component inventory on hand; however, many replacement parts may have to be ordered from the manufacturer at considerable part cost, freight cost, and time loss.

If repair personnel are required, the transportation and living costs for the technician and the daily fee charged by the manufacturer result in expensive service calls. When induction equipment is used, such expenses must be anticipated from time to time; delays must also be expected due to lack of parts or unavailability of service personnel. These potential delays make it advisable that a foundry keeps fuel-fired furnaces on standby, even if the foundry normally operates with electric melting equipment. One other important aspect of electric induction equipment maintenance involves the need for water cooling of the furnace coils, furnace leads, and internal electronic components. Overheating of components is a principal cause of furnace breakdowns. Design of the water cooling system is crucial to successful operation of the melting equipment. In order to be assured that the cooling system functions effectively; constant attention must be given to the equipment and to the condition of the water. Wherever possible, it is desirable to use "closed" water systems in order to minimize water maintenance and to recapture waste heat.

Capital Costs

While direct melting costs for electric furnaces may be somewhat higher than such costs for fuel-fired equipment, the flexibility, speed of melting, convenience, gas control, and greatly improved working conditions make electric melting highly desirable and perhaps crucial to the survival of the brass and bronze foundry. However, the costs of electric equipment are much higher than the average costs of fuel-fired furnaces of comparable melting capacity.

A fuel-fired furnace is relatively simple; many foundries build their own furnace. Installation costs are minimal and may involve little more than hooking up a gas line and blower. Operation is also simple, and can be mechanized to become operator-proof. Although simple maintenance must be performed regularly, it requires no highly technical skills. When

a furnace breaks down, it can usually be repaired quickly; in the alternative, it is possible to have a replacement on standby so that a minimal amount of production time is lost.

Electric furnaces require large capital investments. An induction unit (power supply, furnace, cooling equipment and installation) may cost more than ten times as much as a comparable gas-fired melting unit may. The final cost of an induction unit can double when installation costs for a 440-volt power feed to the melting area, water supply and drainage, along with below-floor excavation and concrete work are included.

The recent impressive growth in the use of electric melting equipment indicates that its many advantages outweigh the high cost of equipment and installation. Fuel-fired furnaces, which have served the nonferrous foundry industry for most of its 6,000-year life, may still perform satisfactorily. However, today's environmental considerations, governmental regulations, decreased availability of cheap fossil fuels, and changed attitudes of foundry personnel all make electric melting of copper-base alloys a practical solution, in spite of the large capital investments required for such equipment.

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MELT CONTROL

INTRODUCTION

The term ‘melt control’ means the control of furnace and atmosphere conditions in order to supply molten metal of the quality necessary to produce high-quality castings. Melt control is only one of several processing variables which act together to affect the quality of castings. Although this chapter focuses primarily on the control of melt chemistry and dissolved gases, other process variables affecting melt quality are identified below along with references to the chapters that provide supplementary information on each when the variable is outside the scope of this chapter.

- *Furnace selection*—the type of furnace used influences melt quality control. Specific furnace types are discussed in the chapter, *Melting Equipment*. It should be noted that different liquid-metal processing procedures might be recommended depending upon the melting unit used.
- *Input material*—input materials may be cataloged as commercial-purity raw materials, scrap, secondary ingot, returns, and late additions. Depending upon availability, cost, and the casting quality required, all of these may be considered as input material.
- *Melt covers*—melt covers are used to reduce exposure of the metal to the atmosphere, minimizing dross formation during the melting process. This practice can reduce melt losses. However, as will be pointed out in the section on gases, the use of melt covers may aggravate gas problems.
- *Degassing practice*—copper and copper alloys can dissolve gases during the melting process. Control over the type and amount of gas and its removal prior to pouring are important elements of melt control.
- *Mold materials*—the chapter, *Casting Processes and Materials*, addresses the common mold materials. All mold materials can produce gas to varying degrees, and mold gas coupled with gas derived from melting may result in “gassy castings.”
- *Gating practice*—improper gating can result in gas pickup and porous castings. Recommended gating practice is discussed in the chapter on *Gating*.

Melt quality can be indirectly affected by the following factors. For example, the demand for increased fluidity may warrant

an increase in pouring temperature that in turn will affect the melt quality.

- *Fluidity*—the complexity of the casting and section size normally dictates the pouring temperature, as will be discussed in the chapter on *Pouring*. However, higher pouring temperatures make chemistry and gas control more difficult to achieve.
- *Solidification and shrinkage*—since both gas porosity and shrinkage may occur in the portions of the casting that are the last to solidify, the defects are often indistinguishable. See the chapter *Solidification, Feeding, & Design* for an in-depth discussion of the solidification characteristics of the copper alloys.
- *Mechanical properties*—several chapters in this book, and specifically the chapter, *Properties of Cast Copper-base Alloys*, focus on the mechanical properties of copper-base alloys. Although typical cast properties are generally provided, it should be noted that melt control plays an important role in the achievement of these properties.

The factors affecting and controlled by melt quality will be discussed in this chapter as they relate to melt control. This chapter will first treat chemistry control, followed by an extensive discussion of gases in copper-base alloys, an important topic since gas porosity is difficult to control in everyday metalcasting operations.

CHEMISTRY CONTROL

Although dissolved gases are chemical elements which must be controlled, this section will be limited to chemistry control of input materials (including late additions) and melt losses.

Input Materials

Commercial-purity raw materials—although the use of relatively pure input materials provides optimum chemical control, the cost is seldom justified except, possibly, for new alloy development. Furthermore, some elements, such as silicon in the silicon bronzes and iron in the aluminum bronzes, do not readily go into solution in copper. It is for these reasons that most foundries do not prepare their own

alloys from the raw materials, except for use in short-run specialty chemistries.

Scrap—the opposite extreme of using commercial-purity raw materials is to purchase scrap, melt it, conduct a chemical analysis, and adjust the chemistry before pouring. Occasionally, intermediate ingots may be poured and solidified for use as remelting stock later.

The practice of using an all-scrap charge creates the risk of possible pickup of detrimental elements. On the other hand, scrap such as copper bus bar, wire, and piping provides excellent charge material of known characteristics. Another example of scrap utilization is the melting of soldered brass automotive radiator cores for plumbing alloy castings.

Melting purchased scrap may have an impact on operating permits and change the facility classification. Changes to basic operating practice should be evaluated with respect to the regulatory environment. The economic advantages of scrap metal charges are most often appreciated by the large foundry with ready access to chemical analyses and with the ability to suitably modify the chemistry during the melt operation.

Secondary ingot—most foundries do not have the capability to perform smelting, refining, and chemical analysis. Therefore, large quantities of scrap can not be used and the purchase of ingot with a known chemistry must be relied upon. In effect, foundries become remelters and producers of engineering shapes.

Although 100% secondary ingot charges may be used, charges comprised of ingot, returns, and scrap are more commonly used. The exact proportions will be dictated by experience, the quantity of shop returns, and cost.

Secondary ingot producers provide metal chemistries within the specified chemistry limits indexed in Chapters 1 and 2. Furthermore, they will often provide modifications in chemistry or tolerance limits to meet special customer requirements.

Returns—every foundry generates returns from gating systems, risers, and occasional scrap castings; a shop with its own machining operation will also produce considerable quantities of turnings and borings. It is common practice to absorb these materials in the melting operation as a portion of the charge makeup rather than to use a 100% return charge. This does not mean that melts comprised of 100% returns will not result in high-quality castings; much depends upon the quality of the returns, and the type of treatment during melting. For example, gates and risers from sand castings may not be completely clean of mold materials, turnings may be covered with cutting fluids, and residual deoxidizers or impurities may be building up in the return materials. Each one of these factors can contribute to casting defects, which can become more pronounced as the quantity of returns in the charge increases.

Late additions—small quantities of special agents are often added to the melt prior to pouring. Examples are deoxidizers, degassing agents, grain refiners, and additions to make up for melt losses. Although the added quantity may be small, the effect on casting integrity and performance may be great.

Melt Losses

Even if secondary ingot charges are well within the chemical specification range, melt losses may result in molten metal with a composition outside the specified range. The most common causes of melt losses are dross formation due to reaction with the atmosphere, refractory material, or ladle material, and losses due to vaporization of low-boiling-point elements.

Dross formation—much of the dross in copper-base alloy melts is due to reaction between the metal and the atmosphere. Since it is usually not possible to exclude the atmosphere, its effect must be considered. For example, combustion products from a gas furnace contain a great deal of water vapor that can react with the metal to form dross. Even with induction melting, a high degree of magnetic stirring on a hot, humid day may still result in the formation of large quantities of dross.

However, several techniques can be used to minimize dross formation. First, the use of lower temperatures will result in lower chemical reaction rates, which in turn generally produces less dross. Due to this same kinetic effect, shorter holding times at a given temperature will also produce less dross.

Secondly, the use of refractories or crucibles that are inert to the melt will result in less dross. The common practice of using clay graphite crucibles presumes that the carbon in the crucible will react with the atmosphere in preference to the metal reacting with the atmosphere. However, the presence of oxides in the clay graphite still allows some dross formation to take place. The use of an all-carbon crucible is generally not possible since it oxidizes or burns at copper-alloy melt temperatures. An optimum crucible material may be silicon carbide, although expense may be a deterrent.

The third approach to minimizing dross formation in melting is the use of melt covers or fluxes; however, as will be pointed out in the following section on gases, the use of melt covers may show mixed results. Melt covers are used to reduce exposure of the metal to the atmosphere and thus reduce dross formation. Charcoal is one example of a melt cover; however, it should not be used in nickel-bearing copper alloys due to carbon solubility. Fluxes must be used carefully since some that are reactive enough to reduce dross are also capable of rapid reaction with the crucible, furnace refractories, and mold materials.

In summary, melt losses due to dross formation can be minimized by the use of lower temperatures, shorter furnace holding times, inert crucible materials, and the application of melt covers or fluxes.

Vapor losses—fortunately, the same techniques used for dross minimization will also reduce vapor losses. The most notable element lost from molten copper alloys is zinc; however, this is easily replaced by a zinc addition just prior to pouring.

If the melt temperatures are low, the zinc loss will also be low. However, as will be pointed out in a later section, a “zinc flare” can be advantageous to gas removal. On the other hand, such vapor losses pose an environmental hazard, and care must be exercised so as not to exceed the standards for air quality. For example, many copper alloys that contain zinc also contain lead in amounts that may exceed the maximum allowable lead concentration in the air. Similarly, the vaporization of beryllium can create a potential health hazard. A more complete discussion of environmental control is provided in the chapter on the *Health and Safety Aspects of Copper-Base Foundry Alloys*.

It cannot be overemphasized that chemistry control directly relates to mechanical properties and casting performance. In some copper alloy families, the chemistry limits are quite broad; this reflects that their properties are less sensitive to chemistry and possibly that the alloys should be used for less critical applications. On the other hand, narrow chemistry limits are necessary for a number of alloys due to their easily modified microstructures and properties.

Additional information on melt control, chemistry sensitivity, and the role of impurities can be found in Chapters 9 through 14.

GASES IN COPPER-BASE ALLOY MELTS

Although the problem of gases in copper alloys often appears to come and go for no apparent reason, there are chemical and physical principles that govern the presence of these gases and their removal. Furthermore, the presence of gases need not always be detrimental; they can play an important part in the production of successful castings. One important example of the positive role of gases in copper alloys is their use in dispersing shrinkage. Sometimes, gases can also be used to remove gas from the melt.

At this point, the different types of gas that might be considered detrimental to copper casting integrity will be identified. These gases are categorized as either simple gases, such as hydrogen, or complex gases, such as water vapor.

Simple Gases

The solubility of hydrogen in molten copper, tin, and copper-tin alloys is shown in Fig. 5-1. In pure copper, hydrogen solubility is greater in the liquid than in the solid state (approximately 5.5cc vs. 2cc/100g). That is why hydrogen gas porosity is a problem in copper castings. During the solidification process, the solid rejects gas to the remaining

liquid, because hydrogen is less soluble in the solid state. Once the gas exhibits a pressure greater than the pressure of the surrounding atmosphere and local metal head, a gas pore will be formed.

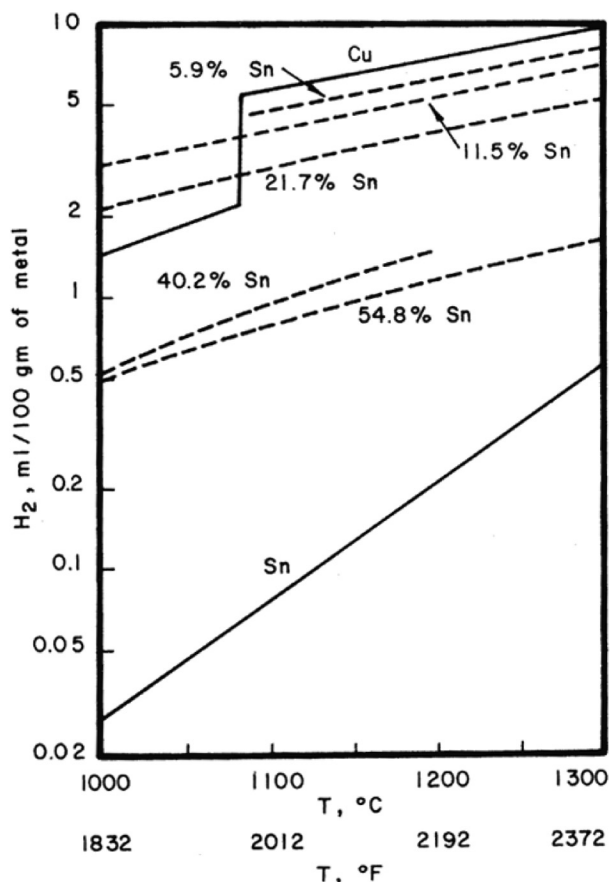


Fig 5-1. The solubility of hydrogen at atmospheric pressure in pure copper, pure tin, and in copper-tin alloys is shown.

Since higher temperatures of the liquid result in higher gas solubility (Fig. 5-1), higher pouring temperatures allow higher gas contents and create a greater possibility of gassy castings.

The data show that hydrogen solubility is less when the tin content in copper is increased. (As will be pointed out later, oxygen then becomes the more important problem.) The nature of the gas solubility curve should also be noted. In pure copper, the gas is released only at the freezing point. In an alloy, the gas is released within a temperature range between the liquidus and the solidus.

With these observations in mind, a comment should be made about the units of gas solubility (cc/100g) shown in Fig. 5-1. If we divide 100g copper by its density of 8.96g/cc, we obtain 11.16cc of metal. Upon solidification, copper rejects approximately 3.5cc H₂/100g. Dividing 3.5cc by 11.16cc gives 31 volume percent of evolved hydrogen, which could easily result in porosity. Other units are used,

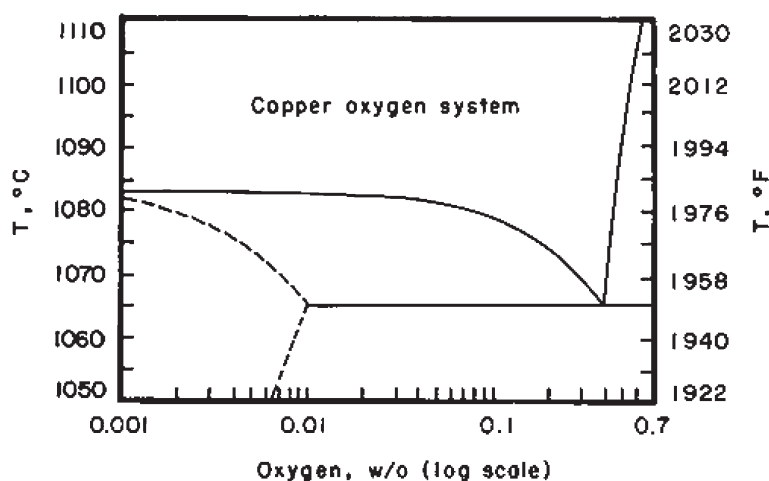


Fig. 5-2. Constitution diagram of the copper-oxygen system. The eutectic occurs at 0.39 wt% oxygen.

but the small values can create a false sense of security. For example, 1 part per million hydrogen (ppm) in copper indicates 0.0001% by weight, which is approximately equivalent to 11.16cc/100g or 10 volume percent.

Furthermore, all of the gas contents are given at standard temperature and pressure (20C and 760 mm Hg). When the gas is evolved at elevated temperatures, the actual volume occupied by the gas is almost five times greater, due to the natural expansion of gases at higher temperatures.

Although Fig. 5-1 presents some important concepts, it appears to be limited since a casting condition in which a copper melt is exposed to pure hydrogen at 1 atm pressure is unrealistic. However, the data are still useful because of the concept in chemical equilibrium known as Sievert's Law (see page 101), which relates the quantity of gas dissolved in molten metal to the concentration (or partial pressure) of the gas in the furnace atmosphere.

It should be noted that Sievert's Law refers to equilibrium, a condition seldom achieved in casting. However, the concept that a reduction in the atmospheric partial pressure leads to a reduction of gas in solution is important as it explains the melt practices of purging and vacuum degassing. These practices will be covered in detail in a later section.

If the gas problem in copper alloys could be completely explained by the hydrogen example, the control of gas porosity would be greatly simplified. Unfortunately, this is not the case. Most molten copper-based alloys are likely to dissolve another simple gas, oxygen, other than hydrogen.

Oxygen in copper is usually present as cuprous oxide. It forms a eutectic with copper at 0.39% by weight. Although 0.39 wt percentage oxygen sounds high, it is possible to achieve this level even with low initial oxygen levels. During solidification the dissolved oxygen is rejected by the solid and concentrated in the remaining liquid. The Cu-O phase diagram shown in Fig. 5-2 shows that as little as 0.01 wt

% oxygen in the initial melt will produce 0.39 wt % oxygen in the last liquid to solidify (the eutectic composition). This will form Cu-Cu₂O eutectic at grain boundaries. In alloys with other elements this simple reaction becomes more complex. Again, oxygen alone does not cause any problems in copper alloys.

The interaction between these two simple gases as well as with various other dissolved elements must also be considered; that is, the complex gases formed due to the reaction between hydrogen-oxygen and carbon-oxygen must be studied to understand the gas problem in copper alloys.

Complex Gases

In many copper-base alloys, the most important gas causing porosity is water vapor. Water itself is not dissolved in the liquid metal, but both hydrogen and oxygen are dissolved in their atomic forms. The hydrogen combines with the available oxygen to form water vapor until the dissolved oxygen is depleted thus creating gas porosity when the gas pressure exceeds 1atm or 760 mm Hg; hydrogen is then produced as a separate species. Since different alloy chemistries have varying affinities for oxygen, the amounts of water vapor and hydrogen also vary.

This hydrogen-oxygen equilibrium interaction in pure copper at its melting point (1981F[1083C]) is shown in Fig. 5-3. The shape of the curves (representing different total pressures of water vapor) shows that low dissolved oxygen leads to high hydrogen, and vice-versa.

Consider a situation in which a gas hole might be formed in pure copper. With only hydrogen present, the maximum solid solubility is 2 cc/100 g (Fig. 5-1). With more hydrogen present in the melt a gas hole would form. By Sievert's Law, this is equivalent to:

$$2\text{cc}/100\text{g} = 5.5\sqrt{p\text{H}_2} \text{ and } p\text{H}_2 = 0.132 \text{ atm}$$

Sievert's Law

Using hydrogen as an example, the gas dissolves in the atomic form rather than in the molecular form (due to the size difference). Or:



We then write the solubility relationship:

$$K \text{ (a constant)} = \frac{(\text{conc. of hydrogen dissolved in metal})^2}{(\text{conc. of hydrogen in furnace atmosphere})}$$

We then express the concentration of hydrogen in the metal as cc/100g, and that in the furnace atmosphere as partial pressure.

Sievert's Law then states:

$$H \text{ (dissolved)} = K' \sqrt{p_{H_2}}, \text{ where } K' = \frac{K}{4}$$

From Fig. 5-1, molten copper at 1083C dissolves 5.5 cc/100g hydrogen when a pure hydrogen atmosphere is present.

Therefore:

$$5.5 \text{ cc/100g} = K' \cdot 1 \text{ atm}, \text{ or } K' = 5.5$$

Now, to be more realistic, assume we have a partial pressure of hydrogen of only 0.01 atm over the melt.

$$\text{Then: } H \text{ (dissolved)} = 5.5 \sqrt{0.01 \text{ atm}} = 0.55 \text{ cc/100g}$$

(The value K' is dependent only upon the temperature for a given alloy composition.)

This result is significant because it illustrates that a 100-fold decrease in partial pressure of hydrogen over the melt leads to only a 10-fold decrease in the gas solubility.

The hydrogen in the furnace atmosphere must therefore exceed 0.132 atm in order for a gas bubble to be formed.

Now, if we consider point B in Fig. 5-3 (a total pressure of 760 mm Hg, or 1 atm of water vapor derived from hydrogen and oxygen in solution), the oxygen concentration is 0.39 wt % and the hydrogen is 2×10^{-5} wt % (0.00134 atm). In this case, hydrogen partial pressure even as low as 0.00134 (100 times less than 0.132 atm) will cause gas porosity if oxygen is also present.

The important point is that even very low hydrogen content in the melt can result in gas porosity when oxygen is also present. The enrichment of the remaining liquid in both hydrogen and oxygen during solidification adds to the problem of gas porosity. To prevent such porosity, the solid solubility must not be exceeded and the sum of the individual gas partial pressures must be less than 1 atm (760 mm Hg) throughout the solidification process.

Curves similar to those for the hydrogen-oxygen relationship are obtained for sulfur-oxygen and carbon-oxygen. Sulfur pickup may occur in the combustion of high-sulfur fuels in the melting furnaces. This is much less common today due to an increase in the use of electric melting or the use of low sulfur fuels. Sulfur may also be available for pickup from acid catalysts used with furan or phenolic no-bake binders. Low sulfur contents result in higher amounts of dissolved oxygen and vice versa. The reaction produces SO_2 gas.

Nickel-bearing copper alloys, such as cupro-nickels, are prone to dissolve carbon and in these cases the important equilibrium becomes carbon-oxygen rather than hydrogen-oxygen and the gas evolved upon solidification is CO. Water vapor may also exist at low nickel contents. Hence, the nickel bearing alloys commonly have three gas species, CO, H_2O and H_2 . Again, an increase in one gas species provides a decrease in the other. However, it cannot be overemphasized that the sum of the species—whether hydrogen, carbon, sulfur, or oxygen—determines the presence of gas porosity.

The literature can provide specific numerical values for the quantities of gas species contained in alloys. Table 5-1 summarizes some of the more important results.

Identification of Gas Defects

Briefly, as mentioned before, the gases most often found in porous copper base alloys are H_2 , H_2O and CO . Determination of the type of gases is important in order to identify

their effect on casting quality. Since the gases found are dependent upon the alloy family as well as the melt practice, a simple solution to the gas species identification problem is not available.

In similar manner, identification of defects caused by gas content is not always easy since gas and shrinkage porosity often occur at the same geometrical position. Shrinkage occurs at the site of a hot spot or in the last portion of a casting to solidify. Comparison of dendrites in defective areas poured with and without gassy metal will show subtle differences, as seen in Fig. 5-4. Under the microscope, the rough texture of dendrites can be identified (Fig. 5-4a). Gas may also occur in the last portion to solidify. This is because a solid can dissolve less gas than a liquid metal. Therefore, dissolved gas is continually rejected to the remaining liquid until it reaches a pressure greater than atmospheric-at which time a bubble is formed. If the supersaturated gas enrichment occurs in the last metal to solidify, gas porosity and shrinkage porosity will occur at the same point. Hence, it must be determined whether the casting defect is due to shrinkage or gas. The presence of gas tends to blunt the somewhat sharp dendrites, possibly due to the pressure of the evolved gas, making the porosity bright and shiny (Fig. 5-4b).

This does not mean that gas will always be associated with macroshrinkage. For example, some wide-freezing-range copper alloys such as C83600 (85-5-5-5) tend to have interdendritic shrinkage (microshrinkage) which is not visible to the naked eye. The problem becomes more acute in the absence of a sufficiently high thermal gradient, because gas can then disperse the shrinkage so that it is not interconnected. However, too much gas will result in small gas defects that tend to be spherical in shape. The degree of sphericity, distribution, and coloration are dependent upon the copper alloy family and the composition of the gas.

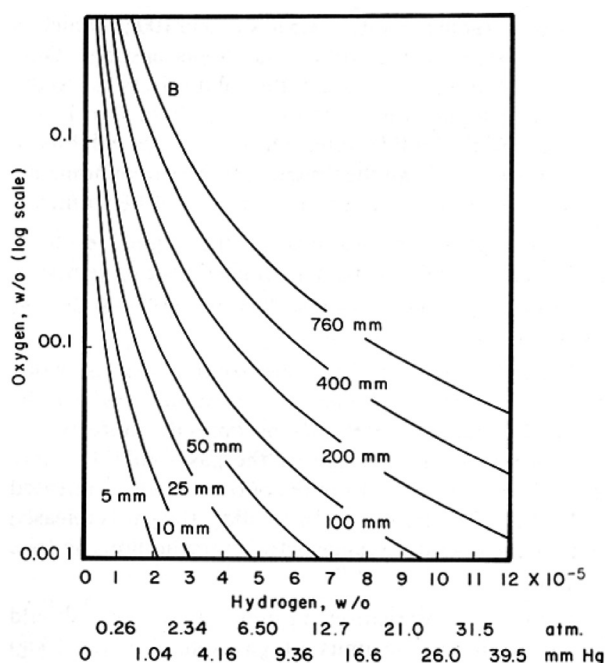
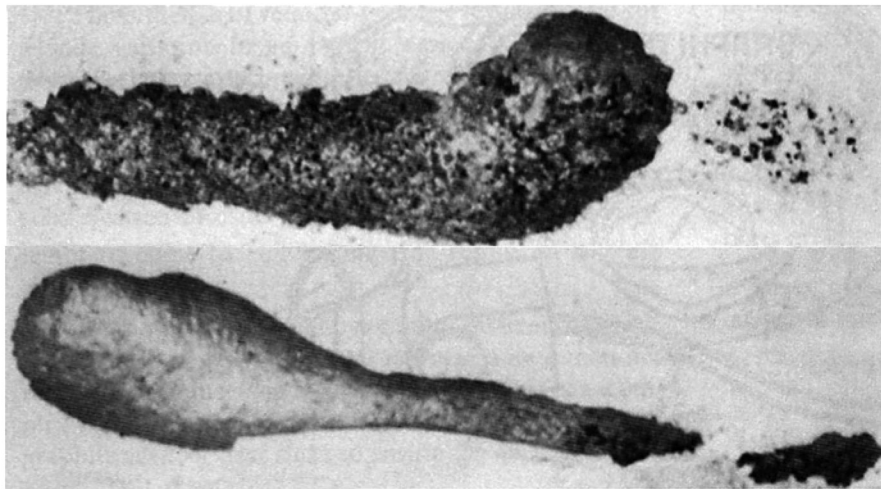


Fig. 5-3. Equilibrium of water vapor with molten copper at 1083°C (1981F). Point B shows equilibrium between 0.39 wt% oxygen and 2×10^{-5} wt % hydrogen at 760 mm water vapor pressure.

Table 5-1. Summary of Gases Found in Copper-Base Alloys

Alloy Family	Gases Present	Remarks
Pure Copper	H_2O , H_2	Approximate H_2O/H_2 ratio of 1:0. Higher purity increases the H_2O level and lowers H_2 .
Cu-Sn-Pb-Zn Alloys	H_2O , H_2	Pb does not affect the gases present. Increased Sn lowers the total gas. Increased Zn increases the H_2 , with a loss in H_2O .
Aluminum Bronze	H_2O , H_2 , CO	The presence of 5 wt.% Ni in C95800 causes CO to occur rather than H_2O . Lower Al leads to higher total gas.
Silicon Brass and Bronze	H_2O , H_2	Approximate H_2O/H_2 ratio of 0:5. Increased Zn decreases the H_2 and increases H_2O . (This is opposite to the effect when Sn is present as in b above.)
Cupronickel	H_2O , H_2 , CO	All three species present up to 4 wt.% Ni, beyond which only CO and H_2 are present. H_2 increases with Ni to 10 wt.% Ni. H_2 decreased at 30 wt.% Ni.



(a) Shrinkage porosity

(b) Gas porosity

Fig. 5-4. Close-up of porosity cavities in (a) shrinkage in 1-inch chilled Y-block poured from degassed C95400 metal. Note the rough appearance characteristic of dendrites. (b) Close-up of gas porosity in C95400 alloy poured in a 1-inch chilled Y-block. In this case, the cavity is smooth.

Testing for Gas

There are several qualitative methods to estimate the gas content of copper base alloys. The simplest, most common procedure is merely to observe the surface shrinkage, or "set," of a sample bar (or even a sprue or riser top). All else being equal the greater the degree of sink, the lower the gas content. Since some copper alloys tend to show relatively little localized shrinkage even when free of gas, AFS research was conducted in 1949 to develop a standardized fracture test for 85-5-5-5 (C83600) which would provide a more sensitive index of gas content. The fracture test involves a special test piece cast against a chill, whereby the color and texture of the fractured surface are evaluated as a measure of the gas content of the metal. Although this test never gained wide acceptance due to difficulties in interpretation, the examination of fractured castings in the foundry is a common practice and provides useful information for distinguishing between high- and low-quality melts.

The reduced-pressure test measures the total gas content of the metal, including the vapor pressure of easily volatilized elements such as zinc. Quantitative chemical analyses of metal pin samples extracted from the molten metal or of gas samples taken from above the solidifying alloys are very expensive. Although these analyses are important for the proper selection of degassing techniques, their interpretation is difficult.

A more quantitative approach to measurement of the gas content of the metal was necessary, and research was therefore initiated in 1972 and jointly sponsored by the International Copper Research Association (now known as International Copper Association, ICA) and the American Foundrymen's Society (AFS, now known as the American Foundry Society). This effort resulted in the development of

the reduced-pressure test that is more useful with respect to both cost and promptness of results.

Reduced-Pressure Test

The reduced pressure test being used by the aluminum industry to measure the gas content, known as the Straube-Pfeiffer test, has been successfully modified for use with molten copper-base alloys. In practice, a small liquid metal sample is taken from a larger melt and is allowed to solidify under a variable but known reduced pressure. If the gas pressure in the melt is greater than the controlled reduced pressure over the melt, then a gas bubble will form and escape from the sample. On the other hand, if the reduced pressure is higher than the dissolved gas pressure in the melt, then a bubble will not form and the small sample will have a flat or depressed surface upon solidification.

The chamber used for the tests is illustrated in Fig. 5-5. The principle of reduced-pressure testing allows for a wide variation in equipment design. The literature describes successful procedures for construction along with data from field experiences. The objective is to obtain a reduced pressure only slightly less than the dissolved gas pressure. The surface of the sample will then rise and the solid surface membrane will not fracture. A summary of an idealized set of samples is shown in Fig. 5-6.

The key to the reduced-pressure technique is the establishment of a solid surface skin and directional solidification in order to produce wave-front freezing. In the formation of the solid from the crucible sidewalls, gas is rejected to the remaining liquid. Upon exposure to the reduced pressure, the gas in the remaining liquid and the atmosphere above the sample attempt to come to equilibrium, the results are shown schematically in Fig. 5-6.

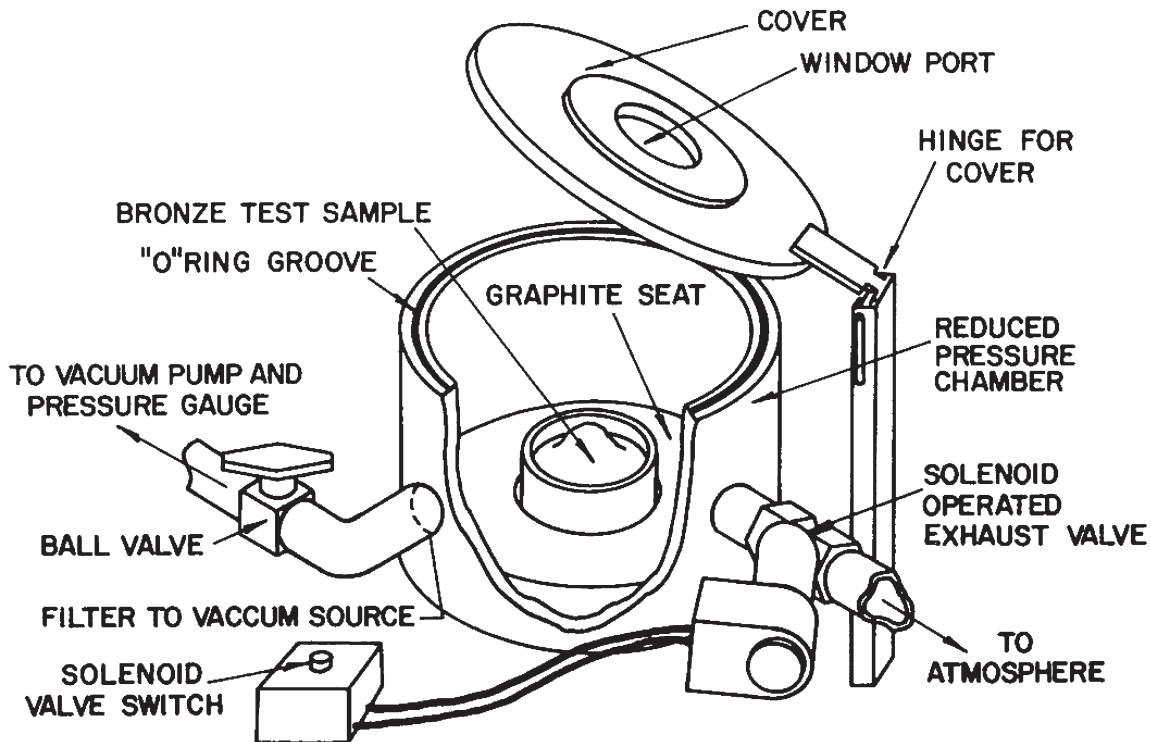


Fig. 5-5. The test chamber as used in the reduced-pressure test is shown above. The remainder of the apparatus is described in the literature.

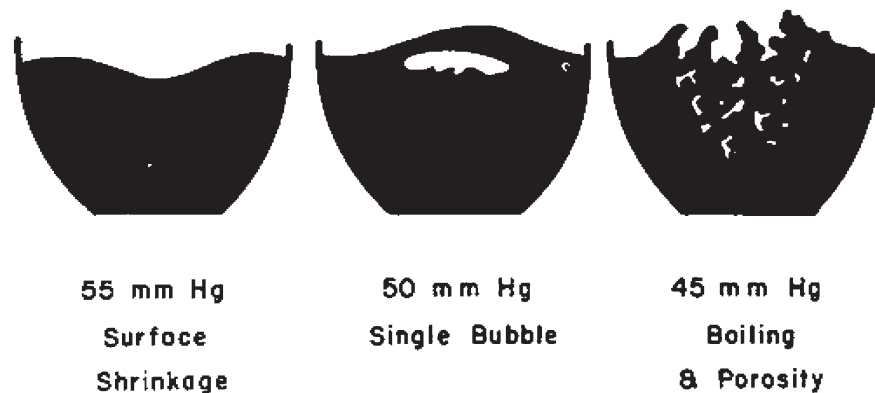


Fig. 5-6. These cut-away samples display the different responses of the same amount of gas dissolved in the liquid metal when exposed to different pressures in the test chamber of the reduced-pressure test.

Since the copper-base alloys exhibit different liquidus to solidus temperature ranges, varying cooling rates are required to induce wave front freezing. This is accomplished by a selection of different crucible materials and graphite seats or heat sinks to ensure the necessary thermal gradients.

There are three combinations of crucibles and seats that have proven successful (shown in Table 5-2). A brief explanation of the rationale for the correct selection is appropriate.

In a pure material such as pure copper (C81100), a solid surface membrane does not readily form due to the occurrence of a melting point rather than a melting range. Here, the test is successful when a "copper rain," rather than the formation of a surface bubble, is viewed through the window port. The "copper rain" is caused when bubbles of gas formed during the freezing of the sample burst through the molten surface of the metal. Small droplets of the metal are carried upwards by the bursting bubbles and the visible copper rain is formed.

Table 5-2. Crucible and Seat Combinations for the Reduced Pressure Test.

Alloy Type	Crucible	Seat (Graphite)	Time Before Exposure to Reduced Pressure
Pure Copper (ex. C81100)	Preheated Porcelain	Flat with small depression	15-30 Sec.
Short Freezing Range (ex. C95400)	Preheated Porcelain	Loose fitting to top of crucible lip	30-45 Sec.
Wide Freezing Range (ex. C83600)	Steel	Tight fitting to top of crucible lip	5-10 Sec.

This method is highly reproducible and more sensitive than the surface-bubble method used for copper alloys.

The short-freezing-range alloys, such as aluminum bronze (C95400), easily provide wave front freezing and a solid surface membrane if a porcelain crucible is used. The crucible must be preheated in a small box furnace (a component of the reduced-atmosphere apparatus) to prevent it from cracking due to thermal shock. Since the crucible fits loosely in the graphite seat, the same crucible is used for dipping and testing.

In wide-freezing-range alloys such as red brass (C83600), a high thermal gradient is necessary to approximate wave-front freezing. The tight-fitting steel crucible in the graphite seat makes it necessary to dip the sample with a second steel crucible. Metal adhering to the dipping crucible sidewalls would prevent a tight seat between the crucible and the heat sink.

Using one of the described methods one can successfully test most copper alloys. Occasionally, modifications are necessary, such as the placement of a graphite block over the crucible to guarantee a thick, solid surface membrane. This latter technique gives the most reproducible results for beryllium copper (C82500). The test results from the reduced pressure are presented in Fig. 5-7. The correlation between total gas and reduced pressure is very good except in the case of C81100 and 87500.

High-copper alloys such as C81100 require the onset of "copper rain" to provide a reproducible result. As mentioned previously, this test is more sensitive than the standard surface-bubble test. The alloys containing silicon are not sensitive to gas tests, may be due to reasons discussed in the following section.

Experiments were conducted to measure the gas content of various alloys. All heats consisted of 30 lbs. of secondary

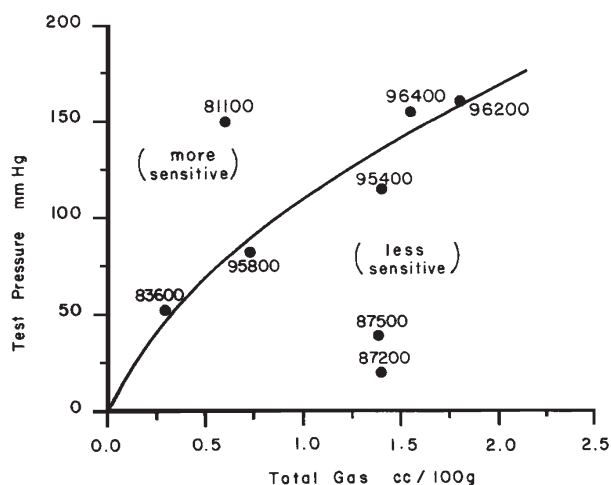


Fig. 5-7. The sensitivity of the reduced-pressure test shows good correlation with the total gas content of the melt. The data are for saturation in a gas furnace atmosphere at 300F (149C) superheat. The text discusses the anomalies with copper (C81100) and the silicon-bearing alloys (C87200, 87500).

ingot melted in a gas furnace. The type of crucible used is the same as that which was used in the reduced-pressure test. Other than the total gas content, the saturation pressure and the time taken for saturation was also measured. The saturation pressure and time provide an index of the sensitivity to gas pick-up.

Table 5-3 summarizes the gas content for several of the more common copper casting alloys measured using reduced pressure test. The table shows the effective deoxidation and/or degassing procedures employed (discussed later) and the gas content after degassing for each alloy. The anticipated gas species were summarized in Table 5-1. (The effect of gas content on mechanical properties will be presented in a later section.).

Table 5-3. Gas Content of Copper Alloys after Melting and After Degassing

CDA No.	Type Alloy			Type Crucible	Saturation pressure (mmHg)	Time Required (Hours)	Metal Temp. (F)	Degassing Method	Pressure After Degassing
81100	Cu			Porcelain	150	1.75	2300	6 oz. P-Cu/100 lb	<23
81500	1 Cr			Porcelain	57	2.00	2300	As Melted	<23
82500	2 Be			Steel	240	1.50	2100	N ₂ Purge	<23
86300	25 Zn, 6 Al, 3Mn			Porcelain	85	1.50	1900*	Flared	40
86500	40 Zn, 1Al			Porcelain	100	1.00	1820*	Flared	55
	Sn	Pb	Zn						
83300	4	6	7	Steel	57	1.00	2200	6 oz. P-Cu/100 lb	<23
83600	5	5	5		53	1.00	2200	"	<23
84400	3	7	9		60	1.00	2200	"	<23
84800	3	6	15		74	1.00	2100	"	35
90300	8	-	4		46	1.00	2200	"	<23
92200	6	1.5	4.5		42	1.50	2150	"	<23
92600	10	1	2		44	1.00	2250	"	<23
92700	10	2	-		62	1.50	2150	"	<23
93200	7	7	3		45	1.50	2150	"	<23
93400	8	8	-		50	0.75	2100	"	<23
93500	5	9	1		50	1.00	2200	"	<23
93700	10	10	-		49	1.25	2100	"	<23
93900	6	15	-		50	2.00	2150	"	-
	Al	Fe	Ni						
95200	9	3	-	Porcelain	120	2.00	2250	N ₂ Purge	<23
95300	10	1	-		108	1.50	2250	"	<23
95400	11	4	2		105	1.50	2250	"	<23
95500	11	4	4		70	1.00	2250	"	<23
95800	9	4	5		82	1.75	2300	Prop. #77 ½%	<23
	Ni	Fe	Cb						
96200	10	1.5	1	Porcelain	160	1.00	2450	Prop. #77 ½%**	30
96400	30	1	1	Porcelain	155	1.00	2500	"	30
	Sn	Pb	Ni						
97600	4	4	20	Steel	115	1.50	2400	Prop. #77 ½%**	<23
	Al	Ni	Co						
99300	11	15	1.5	Steel	76	2.00	2300	Prop. #77 ½%**	<23
	Si	Zn							
87200	4	4		Steel	22	2.00	2100	None	<23
87500	4	14		Porcelain	40	1.00	2000	As melted	23
*Lower temperatures because of zinc flare **Melted under charcoal; all others melted without covers									

A high saturation value need not cause concern especially if it takes a long period to achieve this value. This merely indicates that the particular alloy must be brought up to temperature rapidly and must be poured immediately.

The reduced-pressure test measures the total gas content, including the presence of easily vaporized elements. Higher-zinc alloys such as C86500 exhibit higher total gas levels, partially due to the zinc level. The normally low reduced-pressure after degassing is not achieved with C86500 since the zinc level is still high (the 55-mm Hg is due to the presence of 40-wt % Zn). The minimum recorded value of less than 23-mm Hg represents the lower limit of the reduced-pressure test used in the alloy comparisons.

It should be noted that charcoal covers were used for the C96200 and C96400 melts listed in Table 5-3. The carbon level is high, and the relatively high saturation levels are due to the presence of CO and H₂. This is important since degassing procedures must be able to remove both oxygen and hydrogen.

Casting Variables Affecting Gas Content and Gas Control

Variables that may affect the gas content of castings are: alloy family, charge materials used, furnace type, temperature, the use of metal covers, mold materials, and solidification rate. In each case, the reduced-pressure test was used to compare different practices; however, the absolute value of a reduced-pressure test is useful only in the context of the total foundry practice.

For example, a reduced-pressure value of 50mm Hg may provide excellent castings in one shop but not in another, even if the two shops are pouring the same alloy. This may be due to differences in mold materials or gating practices. The objective here is to properly identify these variables and to control their effects to produce better quality castings.

Alloy sensitivity—various copper alloys react in different ways to gases. As discussed earlier the most common gases present in the copper alloys are hydrogen and oxygen. In addition, it was discussed that the independent gases are not the sole contributors to the defects but reaction between them to form water vapor or their reactions with other elements such as sulfur and carbon. The presence of nickel in copper-base alloys contributes to carbon pickup when melting is done in a graphite crucible or with carbonaceous covers. During solidification, carbon can react with residual oxygen and form CO gas. Other sources for carbon and sulfur have been discussed earlier.

The silicon-bearing copper alloys C87500 and 87600 have been discussed by foundrymen with regard to their gassing tendencies. Although Fig. 5-7 indicates that these alloys have a high gas content, with H₂ levels being higher than H₂O levels, the reduced-pressure test (RPT) is not very sensitive to the presence of these gases. There are possibly three rea-

sons for this lack of sensitivity. First, the alloy does not readily form a solid surface membrane during the reduced-pressure test—thus, gas may be lost. Secondly, silicon is known to form at least two stable hydrides, and these may aid hydrogen pickup but inhibit rejection of the gas to the remaining liquid during the reduced-pressure test. Third, the affinity of silicon for oxygen tends to keep the metal deoxidized, preventing the concentration of residual oxygen that leads to the formation of H₂O late in the solidification process.

Charge materials—aside from the question of high residual phosphorus (discussed later), the use of returns should not be problematic since the dissolved gas is removed by solidification. However, this will be true only if the metal is not held for a long period upon remelting.

Furnace—the furnace type, the crucible material, and the atmosphere all affect the gas content of the melt. Due to the hydrogen-oxygen equilibrium of the melt (Fig. 5-3), an oxidizing condition will help to minimize hydrogen. The dissolved oxygen is, generally, can be more readily removed.

Melting in an induction furnace, because of its magnetic stirring action, will result in lower gas levels compared to fossil fuel fired (gas or oil) furnaces. However, it is possible to achieve same level of gas in both the induction and the gas melted alloy after treatment with adequate amounts of P-Cu. It is only when the melt is exposed to the combustion by-products for an extended period of time that the furnace atmosphere creates problems.

The furnace lining or crucible material should also be taken into consideration. For example, cupronickels and nickel-bearing aluminum bronzes exhibit CO gas evolution during solidification. The presence of nickel allows carbon to go into solution. At higher carbon levels, the oxygen is low; and at lower carbon levels, the oxygen is high. Therefore, the carbon level of the furnace lining material must be considered when melting these alloys.

Temperature—higher temperatures increase gas solubility. Furthermore, shrinkage defects become more pronounced with increased temperature. These two observations, coupled with the fact that greater oxidation losses and poorer casting surface quality can result from higher temperatures illustrate why the melt must be poured at a temperature no higher than that which is necessary to completely fill the mold. It is also important that the time at temperature be minimized in order to limit gas pickup and oxidation losses. Extended holding time would allow the metal to absorb undesirably high levels of gases.

Melt covers—are intended to control the atmosphere at the melt surface and to protect the melt from changing its characteristics. However, improper use of melt covers can cause gas problems to worsen. Consider the following cases:

Case 1: Secondary ingot is gas-melted and the metal is held for two hours at temperature. A cover of charcoal is then added. The gas content upon pouring is deter-

mined to be high. The problem is that the cover was added after the melt had become saturated with gas. A greater degree of protection would have occurred if the cover had been added immediately upon melting.

Case 2: Secondary ingot is induction-melted, and a charcoal cover is added immediately. Again, gassy metal is observed. Careful examination indicates that the charcoal contained moisture; hence, hydrogen and oxygen were picked up by the melt. A carbon product that picked up moisture during outdoor storage can also introduce gas.

Case 3: As a third example, an induction-melt charge contained a large quantity of turnings. After melting, a glassy slag cover was added and the melt showed a high gas content. In this case, the turnings contained cutting fluids, and the magnetic stirring could not produce gas rejection through the thick cover.

Although these examples illustrate some disadvantages of melt cover use; they also point out several important considerations in their utilization. First, if the melt is initially gassy, a cover may prevent gas removal. Secondly, the cover itself can introduce gas into the metal. Therefore, the correct use of melt covers requires knowledge of the metal's gas content prior to cover application as well as knowledge of the gas condition of the cover material. Melt covers cannot solve problems induced by poor melt practice.

Mold materials—can act in combination with metal to produce gas defects in castings. All mold materials add some gas to the metal. However, if the metal's initial gas content is low, the common mold materials will provide sound castings. When gas is present in the metal, the additional gas derived from the mold material can cause gas porosity in the casting. Hence, scrap castings can be the fault of both the melting and molding departments.

Gating practice is also important, since metal turbulence will add gas to the metal. Correct gating design becomes quite significant when dealing with borderline control in metal-gas equilibrium and with gas-producing agents in the mold material. (See the chapter, *Gating* for more details on gating design.)

Solidification rate—it is possible to reduce the defects caused due to gas content by controlling the solidification rate, or thermal gradient. The gas is rejected from solidifying metal to the remaining liquid and pushing this gas out to the risers could be achieved by directional solidification. However, this is highly dependent upon the alloy system, due to the natural variation in dendrite formation among the alloys. The more extensive the dendrites, the more difficult it becomes to remove gas, which is typical of long freezing range alloys.

Gas Removal

It is evident from the previous discussions that both hydrogen and oxygen can be present in copper alloys. However,

due to the interaction between them as shown in Fig 5-3, only one of can be present in higher concentration in the melt. The normal practice will be melting in a slightly oxidizing atmosphere to prevent hydrogen pick-up and then remove oxygen prior to casting. This process may not be possible for alloys that show high affinity to oxygen, such as, aluminum bronzes since the oxygen will be tied down by aluminum and will not prevent hydrogen pickup. Hence, it is necessary to remove hydrogen from these alloys. Removal of hydrogen and oxygen are different and will be discussed separately.

Hydrogen removal—most of the methods used to remove hydrogen are mechanical rather than chemical. The methods depend upon the principle that the melt attempts to come to equilibrium with the surrounding atmosphere. For example, a melt's gas pickup from a gas-fired furnace results from the atmosphere's rich combustion byproducts, essentially H_2O , CO_2 , CO , and excess oxygen.

Conversely, exposure of a gassy melt to a high degree of magnetic stirring in an induction furnace can result in gas removal, as long as the atmosphere is low in detrimental gases such as water vapor. The removal of dissolved gas by this technique would therefore be much more efficient in a dry climate than when humidity is very high.

The most common method for mechanical removal of gas is purging with another gas. The introduction of a gas bubble beneath the melt surface creates a bubble containing an atmosphere with which the gas in the metal tries to come to equilibrium. If the purging gas is inert and the dissolved gas is hydrogen, the hydrogen migrates to the gas bubble in order to satisfy Sievert's Law, as discussed in an earlier section. The gas bubble then rises and is swept away. It is important in purging that the gas be introduced deep in the bath and that the bubbles be small. This maximizes the contact time and the surface-to-volume ratio of the purging gas.

In a few alloys such as aluminum bronzes, research has shown that significant levels hydrogen may be present even when the alloy is susceptible to oxygen pickup. It can be assumed that the oxygen is tied down by aluminum and does not prevent hydrogen pickup and hence a gas purge is required to remove dissolved hydrogen. An example of purging with an inert gas (dry nitrogen) in aluminum bronze (C95400) is shown in Fig. 5-8.

In this example, initially the metal had been artificially gassed with wet clay discs. The effect of magnetic stirring on gas removal in a low-humidity atmosphere is represented by the "no purge" line. The reduced-pressure test was used to determine the total gas content of the melt. Purging at 2 liters per minute reduced the dissolved gas approximately three times faster than when magnetic stirring only was used. Although high purging-gas flow rates might show still greater efficiencies, 2 liters per minute represents the maximum purging rate which would not create excessive metal splash in 100 lb melt used in this experiment.

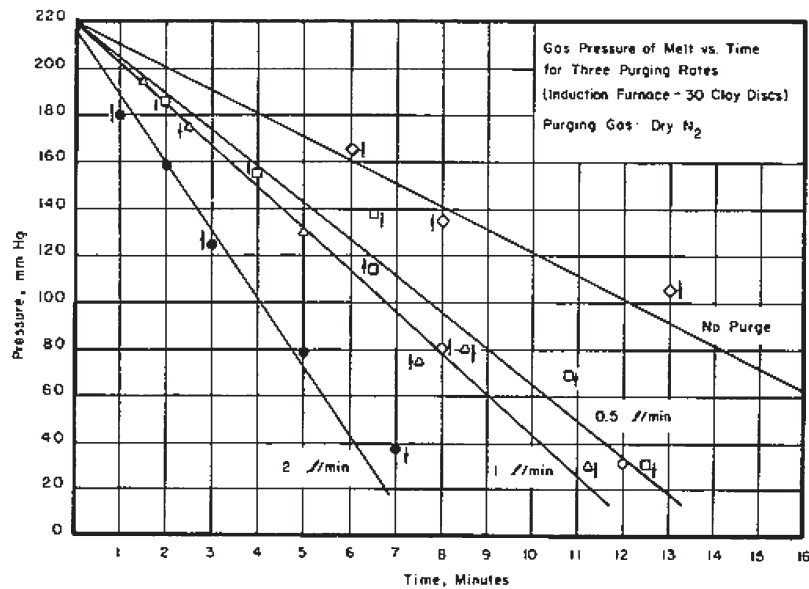


Fig. 5-8. The effect of nitrogen flow rate during purging on the residual gas pressure of a C95400 melt. At a constant temperature of 2250F (1232C), the magnetic stirring of the 100-lb melt reduces the gas on a low-humidity day even in the absence of purging.

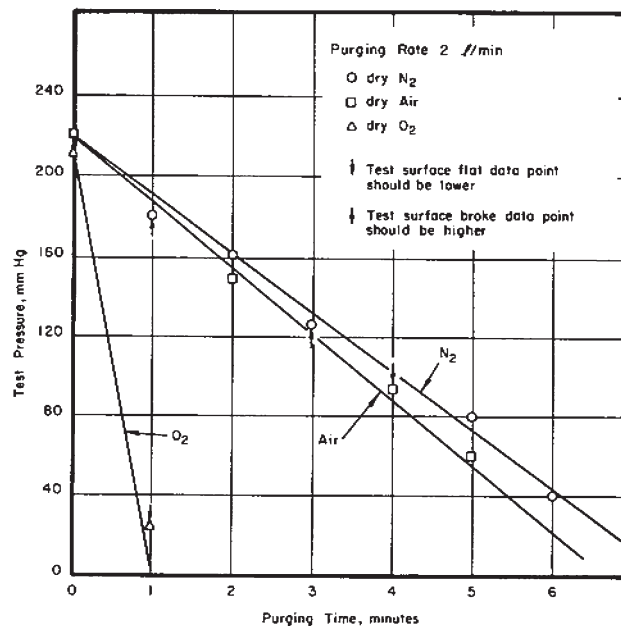


Fig 5-9. The effects of different purging gases on the rate of gas removal in alloy C95400 (aluminum bronze) at 2250F (1232C) in an induction furnace.

The effects of various purging gases on aluminum bronze are shown in Fig. 5-9. A number of foundries have effectively used dry oxygen as a purging gas for aluminum bronze. The data show that low gas levels can be obtained in approximately one-fifth the purging time by using dry oxygen. However, purging for too long a period with oxygen may cause excessive loss of alloying elements due to oxidation, especially aluminum and generation of abnormally large quantities of dross.

The increased purging efficiency of oxygen is not well understood. It might be effective only for alloy systems high in hydrogen, in which high local oxygen requires low hydrogen in accordance with the hydrogen-oxygen equilibrium shown in Fig. 5-3.

Purging can also be accomplished with solid addition agents that form gas bubbles at liquid-metal temperatures. One com-

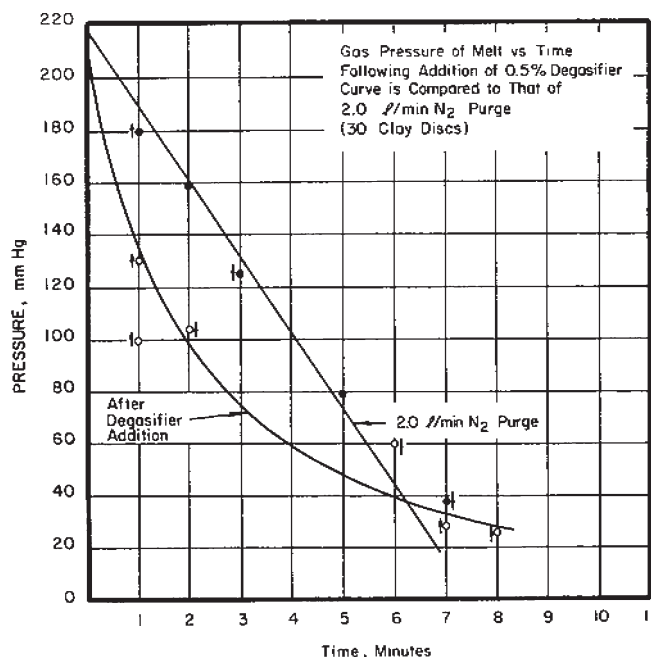


Fig. 5-10. A comparison of a high-nitrogen purging rate with a commercial degasifier. The metal is alloy C95400 (aluminum bronze) at 2250F (1232C). Note that the degasifier does not produce the minimum gas level immediately.

mercial product consists of a briquette form of polytetrafluoroethylene (Teflon) which produces a purging gas when plunged beneath the metal surface. In case of aluminum bronzes, chemical additives are available in the form of proprietary "degassers," which combine with both of these dissolved gases and remove them from the solution. Such degassing agents often contain highly reactive metals, such as zirconium and titanium, which readily form stable oxides and hydrides. The degassing efficiency of such an addition agent is shown in Fig. 5-10 in direct comparison with the efficiency of purging; essentially the same low gas content is achieved with both methods after approximately 6 minutes. The solid degasifier is often preferred, since supplementary equipment is not required. However, rapid pouring after the addition should be avoided, since a considerable length of time is required to cleanse the melt properly of the dissolved gases.

Another useful method for high-zinc alloys is to overheat the melt, thereby vaporizing some zinc (flare) and purging the bath of dissolved gas. However, this may cause excessive loss of zinc in the melt and calls for addition of zinc to compensate the loss. Finally, an often-overlooked technique is to allow gassy metal to solidify, thereby ejecting the gas.

Deoxidation—here the objective is to tie up the dissolved oxygen chemically by the addition of an agent that has a greater affinity for the gas than does the molten metal. Two examples will serve to show this phenomenon.

As discussed earlier for alloys susceptible to oxygen and hydrogen pickup, melting is carried out in oxidizing atmosphere.

For these alloys such as red bronzes and tin bronzes, it is common practice to add phosphorus-copper to deoxidize the melt. During this process, the oxygen present in the melt reacts with the phosphorus to form an insoluble phosphorus-oxygen compound. This effectively removes the oxygen from the melt and prevents it from reacting, during freezing, with any hydrogen to form water vapor (steam reaction). It is important to note that phosphorus additions to the melt do not remove hydrogen directly. Excess additions merely go into solution in the melt, and, if hydrogen levels are high because of improper melting practice, hydrogen porosity may still occur due to solubility change, as shown in Fig. 5-1. The high hydrogen levels can be avoided by maintaining oxidizing conditions during melting.

The absolute addition requirement of phosphorus-copper is not fixed, since each foundry must determine the maximum amount of melt gas that can be tolerated, commensurate with the production of sound, leak-free marketable castings without visible porosity. Figure 5-11 shows the results of the use of such additions by several foundries for the reduction of the dissolved gas. The effect of the quantity of P-Cu addition used to chemically tie up the dissolved oxygen is most apparent.

One of the disadvantages of solid addition agents for chemical removal of gases is their residual level in gates, sprues, and risers, since these are normally added to the charge stock. High residual phosphorus has been found to cause at least two problems. First, the surface roughness of the castings may increase. This is due to increased metal fluidity

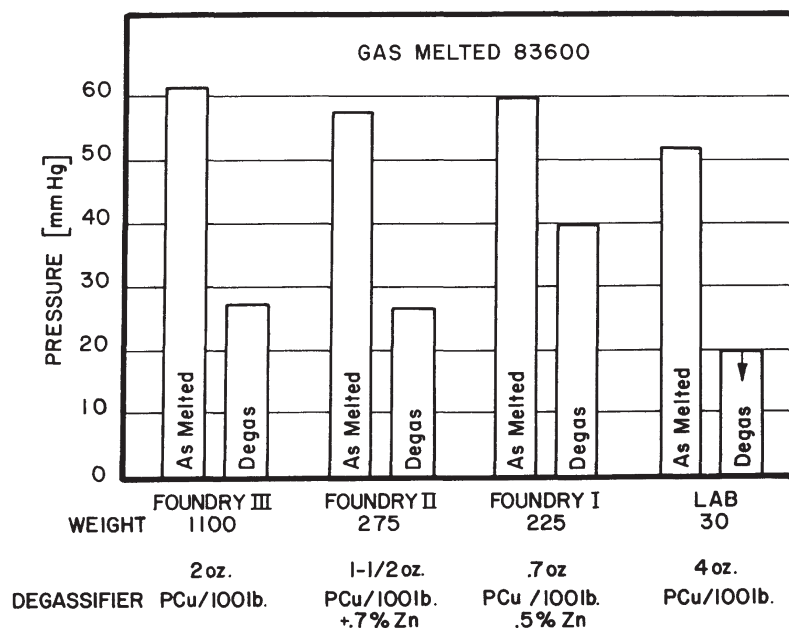


Fig. 5-11. The effect of quantity of phosphorus-copper (15% P) and zinc additions on the gas content of C83600 (red brass). The individual commercial foundries and laboratory data in the as-melted condition compare quite well.

resulting from low-melting eutectics and from reaction between the phosphorus oxides and the sand-bonding agents.

Second, high levels of residual phosphorus make it difficult to suppress hydrogen absorption by the melt. This is because sufficiently high oxygen concentrations cannot be achieved during melting; the oxygen is largely consumed by its preferential reaction with the phosphorus. Obviously, this problem only increases as the percentage of high-P returns in the charge is increased.

It should be noted that P-Cu is effective only in the removal of dissolved oxygen; hydrogen may persist, and the dense melt cover formed by the dross prevents adequate oxidation of the bath. If the gates contain a high residual phosphorus level, this may have prevented oxidation of the melt that resulted in higher hydrogen.

On the other hand, insufficient levels of residual phosphorus can also be troublesome, since the deoxidized metal is subject to reoxidation during pouring due to moisture in green sand molds. It is thus important that the foundry determine what the minimum residual phosphorus level may be for particular operations. As a general guideline, many foundries find that residual phosphorus levels between 0.015 and 0.030% are normal and practical and that lesser amounts are preferable for castings with section thickness' in excess of 1/2 inch. Similar problems may be encountered when boron and lithium are used as deoxidizers, although quantitative data were not available.

It is unfortunate that so few understand or pay close attention to residual phosphorus levels since this may

be a major source of gassy castings. Foundries tend to make arbitrary additions of 15 wt % P-Cu to the pouring ladle or to the crucible in amounts ranging from one to four ounces per 100 lbs. of melt. Such additions often are not adjusted, regardless of charge makeup or section size of the casting being produced. Each foundry should make a systematic effort to determine the maximum level of residual phosphorus that can be tolerated. With this information at hand (which should reflect product mix as well as melting and molding practices) additions of P-Cu deoxidizer should be adjusted so as to maintain this level as constantly as is practical. This means monitoring the phosphorus level in the accumulated gates and risers by periodic chemical analysis, watching for upward or downward trends, and adjusting the percentage of returns in the charges accordingly.

As a final comment, some chemical degassing agents also serve as grain refiners because they produce more uniform mechanical properties in complex sections.

Table 5-3, which was discussed in an earlier section, suggests successful deoxidation or degassing procedures for a number of commercial copper-base alloys.

Effects of Gas on Structure, Quality and Properties

The effect of gas in copper alloy manifest as porosity either dispersed or concentrated. Although porosity will affect mechanical properties of the casting, it should be pointed out that the presence of some gas is useful in dispersing shrinkage in some alloys. When this concept is used for

pouring into permanent molds, the reduced pressure test helps to maintain the presence of a predetermined amount of gas so that shrinkage dispersion can be controlled.

On the other hand, interconnected porosity will reduce the pressure tightness of the casting. In this section, the effect of gas on mechanical properties is briefly discussed.

As-cast mechanical properties are dependent upon section size. As an example, consider the experimental data for aluminum bronze C95400, in both gassed and degassed conditions, shown in Table 5-4. In general, lighter sections will meet the minimum specifications regardless of whether or not the original metal is gassy. However, in the 3-in. and 6-in. sections, the yields and tensile strengths are higher for the degassed metal. The elongation of the degassed bars exhibits much higher values. It is thus possible to exceed minimum specifications with a standard Web-Webbert bar, or with 1-in. Y-blocks and still have gas-induced lower values for the properties in heavier sections. This observation is, of course, dependent upon the alloy since the dendrite network, gas effect, and section size are all related to the liquidus-to-solidus temperature range.

An index of the general alloy response to gas level in terms of mechanical properties is provided by the data for 3-inch Y-blocks shown in Table 5-5. In all cases, the gassy condition refers to the normal saturation value in Table 5-3, plus approximately 50% more gas which is achieved by the addition of wet clay discs to the melt surface.

The difference in mechanical properties in Table 5-5 does not represent the effect of gas alone; rather, it establishes

a comparison of the best and worst conditions for a 3-in. Y-block. A chill at the base of the Y-block was employed in the degassed condition in order to minimize shrinkage defects. The gassed condition was unchilled in order to combine the effects of shrinkage and gas porosity.

Therefore, narrow-freezing-range alloys, such as C81100, C81500, C86300, and C86500, show little or no effect of gas. The gas is readily rejected ahead of the freezing front even in the unchilled casting.

In wide-freezing-range alloys, such as C90300, C92200, C92700, C93200, and C93700, the degassed properties are far superior when a chill is used. The gassed condition may also meet the specifications in those cases where the gas can distribute the shrinkage evenly.

In alloys of intermediate freezing range, there is only a modest decrease in mechanical properties due to the presence of gas. However, in all cases listed in Table 5-5, the properties of metal in the gassed condition are lower and the extent of property degradation varies with the alloy system.

SUMMARY

A summary of some of the major points discussed in this chapter is in order. Detailed recommendations for the melting of specific types of alloys, where relevant, are given in the respective alloy chapters. A general summary of melting and deoxidation and/or degassing practices for the principal alloy families is presented in Table 5-6. Gas removal is an important factor in the production of sound castings. It should be

Table 5-4. Effect of Gas Content on the Mechanical Properties of C95400

Section Size	Treatment	Tensile Strength (ksi)		Yield Strength (ksi)		Elongation (%)	
		Gas	Degas	Gas	Degas	Gas	Degas
Specification		min 75	-	28	-	12.3	-
WW	As cast	88	88	35	35	19.0	15.4
1 in.	As cast	95	95	32	33	20.9	20.0
1 in.	Chilled	96	96	34	-	17.7	16.9
3 in.	As cast	63	81	31	39	6.1	10.7
6 in.	As cast	57, 47, 42	73, 70	28, 28, 28	36, 36	1.1	7.4
6 in.	Heat Treated	61	109	31	45	5.0	12.1

Note: WW is standard Web-Webbert test bar while other sections are from the bottom of Y-blocks.

**Table 5-5. Mechanical Properties of 3-in. Y-Blocks
(Gassed-Unchilled; Degassed-Chilled)**

Alloy No.	Composition			Specification*			Degassed			Gassed		
				Y. S. ksi	T. S. Ksi	El. %	Y. S. ksi	T. S. Ksi	El. %	Y. S. ksi	T. S. Ksi	El. %
81100	Cu			6.5	19	20	10	26	20	9	24	27
81500	Cr	Cu	-Not as cast-				15	31	39	14	32	33
86300	Cu	Zn	60.00	110	12	66	110	19	66	107	15	
86500	Cu	Zn	25.0	65	20	26	66	47	30	72	29	
	Sn	Pb	Zn									
83300	4	6.0	7.0	10	32	35	-	-	-	5.3	13.5	8
83600	5	5.0	5.0	14	30	20	14.5	33.8	30	9.7	18.3	16
84400	3	7.0	9.0	13	29	18	-	-	-	10.8	19.3	16
84800	3	6.0	15.0	12	25	15	-	-	-	10.8	16.0	9
90300	8	-	4.0	18	40	20	20.2	49.5	66	17.0	34.4	24
92200	6	1.5	4.5	16	34	22	20.5	35.0	Flaw	15.2	29.5	19
92600	10	1.0	2.0	18	40	20	-	-	-	16.7	26.3	13
92700	10	2.0	-	-	35	10	21.0	50.0	55	13.0	18.0	7
93200	7	7.0	3.0	14	30	12	20.0	43.0	36	12.0	18.0	8
93400	8	8.0	-	-	25	8	20.1	12.0	45	15.3	21.1	10
93500	5	9.0	1.0	12	25	8	22.4	40.2	33	13.3	18.8	10
93700	10	10.0	-	12	25	8	22	45.3	35	16.6	21.1	6
	Al	Fe	Ni									
95400	11	4	2	30	75	12	36.0	95.0	17	37.0	74.0	6
95500	11	4	4	40	90	6	49.0	117.0	9	46.0	102.0	8
95800	9	4	5	35	85	18	33.0	85.0	26	36.0	88.0	23
	Ni	Fe	Cb									
96200	10	1.5	1	25	45	20	37.8	62.3	21	25.7	46.8	23
96400	30	1.0	1	32	60	20	43.0	81.3	32	30.9	54.9	18
	Sn	Pb	Ni									
97600	4	4	20	17	30	8	55.3	67.0	5	Large holes		
	Al	Ni	Co									
99300	11	15	1.5	55	95	2	47.0	83.3	5	49.6	67.1	3
	Si	Zn										
87200	4	4		18	45	20	16.3	46.8	42	18.6	43.7	30
87500	4	14		24	60	16	35.0	72.5	14	35.5	70.2	13

*Properties are typical, not minimum. Also, note that test bars for specification are 1-in. sections.

To convert ksi to MN/m²: 1 ksi = 6.9 MN/m²

Table 5-6. Treatment to Remove Gas from Copper Alloys

Type	Treatment
Yellow Brasses, Silicon Brass and Manganese Bronze C85000-86000 and 87000 Alloys	No degassing treatment necessary with high zinc content.
Aluminum Bronze and Phosphor Bronze C95000 and 91000 Alloys	Flush with dry nitrogen until gas test is passed.
Pure Copper, Copper-tin-lead and Cupronickels C80000, 90000, 92000 and 96000 Alloys	Melt under strongly oxidizing conditions. * Dexoidize (P-Cu, etc.)
All others	Melt under mildly oxidizing conditions. Dexoidize (P-Cu, etc.)
*There are some exceptions depending on zinc content and presence of easily oxidized alloying elements such as phosphorus, aluminum, and chromium. Note that it is good practice to melt all materials under slightly oxidizing conditions and to degas with nitrogen if the gas is suspected	

noted, however, that no amount of degassing of the molten metal will yield sound castings if gas contamination of the melt occurs at some later stage of holding or pouring.

Charging Practice

Use clean, dry, preheated charge materials; try to minimize the use of scrap, returns, turnings, borings, etc.

Furnaces

Fuel-fired furnaces—contain high water vapor levels in the products of combustion in contact with the melt, hence causing a strong tendency for gas pickup.

Induction furnaces—the furnace atmosphere (shop air) is generally low in water vapor content and high in oxygen; therefore, there is a low potential for gas pickup. Reaction and diffusion are aided by magnetic stirring.

Melt Time

Melting time (especially superheating) should be minimized in order to prevent establishment of equilibrium between the furnace atmosphere and the melt, particularly in the case of fuel-fired furnaces. Power to induction furnaces should be controlled in order to avoid violent stirring, with its attendant oxidation and melt loss.

Melt Temperature

Superheat temperatures should be minimized in order to obtain homogeneous, clean melts suitable for transfer and successful casting. Increased temperatures dramatically increase gas pickup, drossing and melt losses.

Melt Atmosphere

Melt atmosphere should be mildly to strongly oxidizing, depending upon how readily the alloy will dissolve oxygen as compared to how readily it will form insoluble oxides (dross). Where oxidation losses are of particular concern (aluminum bronzes, high strength yellow brasses, etc.) a proper melt cover material should be used.

Degassing

Alloys which dissolve hydrogen (e.g., aluminum bronzes) should be purged with dry inert gas to remove dissolved hydrogen.

Alloys which dissolve oxygen readily (copper, red brasses, and cupronickels) or moderately (tin bronzes) should be melted under oxidizing conditions to suppress hydrogen solubility and should be deoxidized with just enough deoxidant to prevent reoxidation during transfer and pouring. If indications of gas persist in spite of adequate residual deoxidizer, the gas is probably hydrogen, which can be removed only by purging with an inert gas.

High-zinc alloys are self-degassing because of the high vapor pressure of zinc.

Melt Covers (Fluxes)

Oxidizing melt covers (copper oxide, silicate-borate mixtures) can be used to remove hydrogen or maintain it at low levels, and to consolidate drosses and oxides for ease of removal. Neutral melt covers (glass, dry silica sand) form a mechanical barrier between the melt and the furnace atmosphere. This can reduce exposure to hydrogen sources but may also

prevent oxygen absorption; it is generally not reliable for gas control but is advantageous for dross removal and reduction of vaporization losses.

Reducing melt covers (charcoal, graphite) prevent excessive oxidation losses but may be a source of hydrogen if they contain moisture or hydrocarbon additives. If used in excess they may prohibit oxygen absorption from the melt atmosphere, thereby allowing hydrogen pickup. Reducing melt covers are useful in retaining a low oxygen level in the metal after deoxidation and prior to pouring.

As mentioned at the outset of this chapter, melt control demands control of all metal variables ranging from the selection of charge materials through control of metal solidification. Only with proper consideration of all variables will control be possible.

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POURING

INTRODUCTION

To meet today's needs, many metalcasting operations have become increasingly sophisticated. Sands are better formulated and controlled; advanced molding machines and systems have been developed to improve productivity; and induction melting has been widely adopted to improve melt quality as well as to satisfy environmental regulations. All of these developments have enabled foundries to produce castings more efficiently and of better quality to meet the demands of casting buyers.

Many metalcasters, however, continue to experience casting losses due to improper pouring practices, even though careful attention is otherwise paid to the quality control of materials, molding and coremaking, melting and the gating and risering of patterns. This is perhaps due to the lack of training offered to operating personnel in the area of pouring.

INFLUENCE OF ALLOY TYPE ON POURING CONDITIONS

As will be noted in the chapters on *Gating and Solidification*, *Feeding and Design*, the copper-base alloys may be divided into different categories based on their oxidation behavior during melting and pouring. Several families of alloys form rather tenacious, insoluble films of oxide on the surface of the melt. Such alloys are quite susceptible to both surface and internal defects caused by the entrapment of these oxide films on or within the casting. This is the case for such alloys as the aluminum bronzes, manganese bronzes, certain high-zinc alloys, chromium-coppers, beryllium-coppers and the silicon bronzes and brasses. In order to produce high-quality castings from these alloys, great care is required in pouring, especially with regard to the following:

- Stirring of the molten metal should be avoided in order to prevent oxide films from being thrust below the melt surface. After the ladle is filled or the crucible has been removed from the furnace, the metal should be carefully skimmed just before pouring. Solid metal should not be added to the ladle at this point, as it is sometimes done to lower the pour temperature. Other forms of agitation should likewise be avoided. If the metal is melted in a tilting-type furnace, for example, and must be

transferred to a pouring ladle, effort should be made to minimize the height of fall of the metal during transfer. This means holding the ladle as close to the furnace spout as possible. In this respect, a nose-tilt furnace offers less difficulty than does a trunnion-mount furnace.

- As will be noted later in the chapter on *Gating*, proper sprue design is essential in minimizing the aspiration of air into the metal stream and in avoiding various forms of turbulence during pouring. The use of a rectangular (preferred) or round, tapered sprue, with an enlargement well at its base to dissipate the energy of the first metal poured, is strongly recommended. Excessively large sprues are difficult to fill, and this leads to the aspiration of air into the metal stream. The same problem occurs with straight-walled sprues, regardless of sprue size.
- The pouring cup (or basin) should be placed near the edge of the flask so that the lip of the pouring ladle or crucible can be held close to the sprue opening.
- Pouring should be done smoothly and evenly, in such a manner as to avoid splashing and interruption of the metal stream. With careful pouring of these sensitive, skin-forming alloys it is possible to form and maintain an oxide "sleeve" around the metal stream entering the sprue, thus protecting the molten metal from undue exposure to the surrounding air.

Adherence to the foregoing suggestions when pouring this group of alloys will result in the transfer of metal from ladle to mold cavity with minimum damage. Failure to follow these procedures may result in the entrapment of oxide films within the casting, reduced mechanical properties, internal shrinkage caused by impeded feeding, and extensive surface or subsurface defects which sometimes are seen only after machining.

The majority of the alloy families listed in the chapter on *Standard Designations for Copper and Copper Alloys*, fortunately, comprises a second category of materials that do not tend to form strong oxide films when exposed to the atmosphere. This is because these alloys do not contain any significant amounts of the "skin forming" elements (aluminum, silicon, chromium, and beryllium). This second category of alloys, which includes not only copper itself and

the cupronickels, but the many Cu-Sn-Pb-Zn alloys as well, are therefore much less sensitive to damage by turbulence during melting, transfer, and pouring. Oxidation of these alloys in the molten condition has two effects. First, a significant amount of the copper oxide that forms at the surface of the melt is immediately dissolved. Second, oxides of alloying elements such as tin, lead and zinc, which are not soluble in the melt itself, tend to form either as dry, flocculent particles or crusts (dross) on the melt surface. This dross is a complex mixture, which may also include copper oxide. Where fluxes are used to cover the melt, much of this dross is dissolved to form a glass-like slag.

Under normal conditions, dross or slag are easily skimmed off the melt and the alloy is then deoxidized before pouring by controlled additions of such elements as phosphorus, boron or lithium (see the chapters on *Melt Control* and *Quality Control*). The products of deoxidation (borates and phosphates) are fluid slag which rise to the surface and readily separate from the metal. Residual deoxidant enables deoxidation to continue during pouring, protecting the molten metal from being re-oxidized during its passage from the ladle into the mold cavity.

For this category of alloys, the object is to prevent the entrapment of floating particles of dross or slag in the casting. When pouring these alloys, the sprue should be filled quickly and kept full to prevent any dross and slag from entering the mold. This can best be accomplished by the use of properly tapered sprues, in conjunction with pouring boxes or cups (see the chapter on *Gating*). Turbulence during transfer and pouring should be minimized, although these alloys are more tolerant and offer wider latitude in pouring practice than do those of the first category. Thus, automatic pouring can be used successfully with these materials.

POURING TEMPERATURE

In order to maximize the yield of high-quality castings it is essential that pouring temperature be closely controlled. The term “pouring temperature” means the temperature of the molten metal as it enters the sprue. Metal poured either too hot or too cold may cause defective castings. Ideally, the lowest possible metal temperature should be sought which will produce the greatest number of satisfactory castings. Usually, the optimum pouring temperature range must be determined by experimentation.

In production shops where pouring is done manually, several molds will be poured from the same ladle, and there will be a continuous drop in metal temperature from the first to the last mold poured. Trial runs can be made to determine the quality of castings poured over a rather wide temperature range using visual examination, fracture testing, or other means of testing for quality (such as pressure testing, etc.). Tests of this kind, in combination with studies of gating and risering systems, will provide data that include the establishment of:

- initial pouring temperature (and allowed variation)
- permissible number of molds poured per ladle
- pouring rate (lb per sec) for each mold

Foundries in which this information is well established, and where pouring is consistently controlled, produce minimal amounts of scrap. In far too many cases, however, pouring is not considered as important as melting and molding, resulting in the production of excessive levels of inadequate castings.

Effects of Pouring at Extreme Temperatures

The dangers of pouring metal at excessive temperatures are numerous. The effect of increased metal temperature on gas absorption and casting porosity was covered in the chapter on *Melt Control*. Alloys with wide freezing ranges are inherently prone to exhibit microshrinkage and, when poured too hot, may develop macroshrinkage and severe internal unsoundness. Metals likewise oxidize excessively at high temperatures, leading to problems of dross and slag formation and possible casting inclusions. Certain alloys will exhibit reduced mechanical properties because of enlarged grain size caused by high pouring temperature.

High pouring temperatures also increase the reactivity between the metal and the mold or cores, forming excessive amounts of steam and other mold gases that must be vented to prevent defects. Excessive heat is a common cause of premature weakening or collapse of mold and core surfaces, resulting in expansion defects, burn-on, burn-in and penetration.

Pouring areas should be located as close to the melting operation as is practical in order to minimize temperature losses during metal transport, thus minimizing the amount of superheating required. If cold metal must be added to the pouring ladle to adjust the pouring temperature, such additions should be clean, dry, and preheated.

Effects of Pouring Cold

The most obvious, visible effect of pouring too cold is the presence of misruns and cold-shuts (although these defects can also be caused by other factors, as listed in the chapter on *Common Defects*). Even more serious, however, low pouring temperatures may result in partial loss of directional solidification (as well as feeding by existing risers), resulting in internal shrinkage porosity or cavities. In cases where this condition may develop, it may be necessary to reduce the number of molds poured per ladle, or to insulate the ladle against heat loss during pouring.

The reduced fluidity and increased surface tension associated with metal temperature loss may also contribute to increased entrapment of loose solid particles (sand, dross, slag) or gas bubbles by the solidifying casting. The terms pouring rate and pouring speed are often used interchange-

ably and are usually expressed in terms of pounds of metal poured (into the mold) per second. The number is determined by timing the start and end of pouring and by weighing the total casting—including sprues, gates, runners, risers, and so on. It is important to understand, however, that as the level of the metal rises in the mold cavity, the backpressure, or “head,” causes a continuous decrease in the instantaneous rate of filling. This effect is most significant for tall, bottom gated castings. The so-called pouring rate, as calculated, is actually the overall average rate required to fill the mold completely.

POURING RATE

Regardless of the gating system used (see the chapter on *Gating*), the maximum pouring rate will be that which keeps the sprue and pouring basin full (a condition which should always be maintained). By filling the sprue as quickly as possible and keeping it full throughout the pour, it is possible to minimize the aspiration of air into the metal stream and the entrapment of solid inclusions such as sand, slag, and dross. Furthermore, each mold will thus be filled in a consistent, reproducible manner. Hence, all molds should be poured at, or close to, the maximum rate permitted by the gating system. In the *Gating* chapter, determining the proper fill rate will be discussed, as well as designing the size and location of “chokes” to achieve such a fill rate.

MANUAL POURING

In the majority of today’s copper-base alloy foundries pouring is done manually. The equipment provided for the transfer, handling, and pouring of metal depends upon the size and production level of the foundry, the size range of the castings being produced, alloy type being poured, and melting facilities available.

Crucible Pouring

In smaller foundries, melting may be done in stationary (lift-out) crucible furnaces that are fuel-fired, or in small, high-frequency induction furnaces of either the push-out or the lift-coil type. In each of these cases, the metal is poured from the same crucible that is used for melting. With the lift-out furnace, it is first necessary to remove the crucible from the furnace by means of tongs, different types of which are shown in Fig. 6-1. Except for very small melts, it is preferable that the tongs be equipped with either a ring or a bail, through which a crane hook may be inserted for hoisting the crucible. Regardless of any special features, tongs should be designed to fit the crucible contour smoothly below the bilge without danger of crushing the upper circumference (Fig. 6-1, right). Note also that tongs should be provided with threaded, adjustable stops that can be set to limit the degree of gripping pressure. These features are intended to prevent undue stress or possible cracking of the crucible as it is gripped and hoisted from the furnace. Clay-graphite crucibles, in particular, lose strength at elevated temperatures and can be damaged if handled carelessly. Silicon-carbide crucibles exhibit somewhat greater strength when hot and, although more expensive, are preferred by many. Note that silicon-carbide crucibles cannot be used in high-frequency, induction-melting furnaces because silicon carbide is an electric susceptor and impedes melting.

For pouring, the crucible is transferred to a shank, usually of the type shown schematically in Fig. 6-2, with a safety catch provided to prevent the crucible from sliding out of its retaining ring during pouring. (When transfer is made, it is good practice to avoid setting the hot crucible against a heat-conducting or chilled surface in order to avoid thermal shock.) The shank is often placed in a bail, suspended by chain-hoist from a monorail, for greater ease in transport and pouring. In such cases, the bail should be mechanically latched to the shank so that the latter cannot tilt until disengaged by the pouring operator.

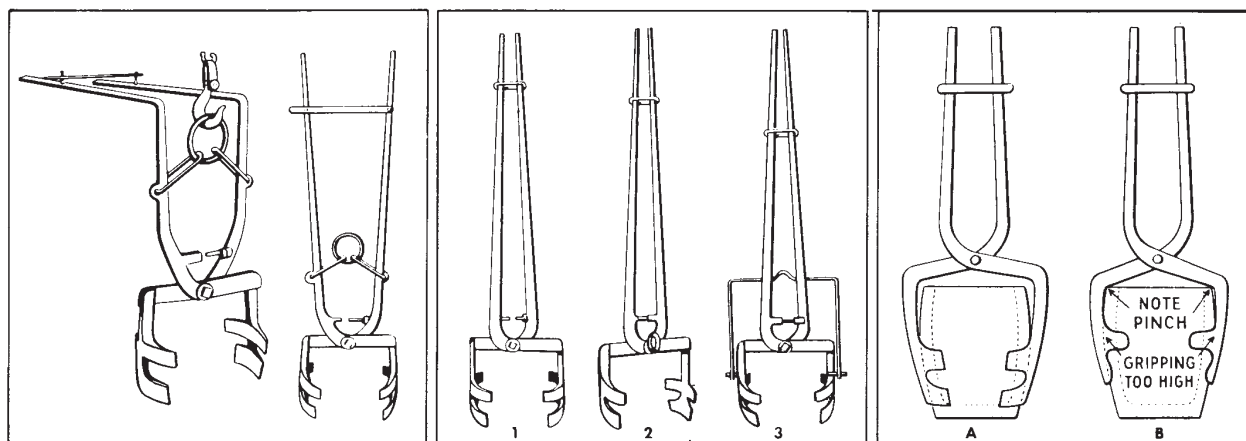


Fig. 6-1. Left: Side-operated and vertical lift-out tongs both equipped with stops limiting maximum pressure on the crucible. Center: 1) Hand lift tongs, 2) with an eye bolt for mechanical hoist, 3) with side trunnions and bail for lifting. Right: Tongs that fit increase crucible life. Correct fit of tongs is shown in A.) Crucible may be cracked by tongs pinching across the top, as shown in B.).

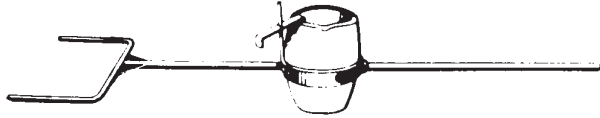


Fig. 6-2. A pouring shank equipped with a safety catch over the top of crucible.

A pouring shank design intended for use with lift-coil or push-out induction furnaces is shown in Fig. 6-3. Notice that the support ring holding the crucible is actually hinged, permitting the ring to be opened and closed around the crucible as it sits on its pedestal. The ring is locked in the closed position by inserting a hinge pin.

Where numerous small heats must be cast regularly, crucible pouring offers flexibility and versatility to foundry operations. It must be recognized, however, that the good thermal conductivity of crucible materials, which is most advantageous from a melting standpoint, is a decided disadvantage once the crucible is removed from the furnace. This is because of the rapid loss of heat by radiation and conduction from the crucible walls and the consequent fast drop in metal temperature. Unless delays in metal transfer and pouring are minimized, control of pouring temperature when using crucibles can be a serious problem. This explains the preference for refractory-lined ladles in foundries pouring moderate to large quantities of metal.

Ladle Pouring

The larger-capacity melting furnaces used in copper base alloy foundries were discussed in the chapter on *Melting*

Equipment. Whether tapped by tilting of the furnace or by gravity runout, the metal from these furnaces is usually transferred to preheated, refractory-lined ladles of suitable design and capacity and then delivered to the mold storage area for pouring. In general, ladles are designed to hold a minimum of about 400 lbs. of metal and are sometimes much larger, as in foundries producing marine propellers or large valve and pump parts. Ladles used for pouring copper-base alloys are generally of two basic types: the conventional lip-pour ladle (Fig. 6-4), and the so-called “teapot” ladle (Fig. 6-5).

The teapot ladle receives its name from the fact that it is provided with a deep, internal well adjacent to the lip. Since the opening to this well is near the bottom of the ladle (as in a teapot), metal enters the pouring spout from beneath the metal surface, thereby retaining in the ladle any particles of floating slag, dross or other solid impurities. In effect, the spout acts as an automatic skimmer. As general practice, pouring ladles are lined with high-silica refractory mixes that may be the ramming, castable or vibratile-plastic type. For handling aluminum bronzes, it may be advantageous to use alumina/silica refractories; the value of the longer life of these refractories often outweighs their higher initial cost. All types of refractory mixes require care when lining in order to avoid areas of low density or inclusions of air pockets. Manufacturers’ recommendations should be followed explicitly with regard to curing, preheating and firing before use. Heat losses from ladles are minimized by placing a layer of insulating material between the outer steel shell and the refractory lining. Graphite ladle liners are sometimes used in place of refractories for special applications. These liners are available in limited size ranges for both the conventional lip-pour (Fig. 6-6) and the teapot-type (Fig. 6-7) ladle.



Fig. 6-3. A pouring shank with a support ring for use with crucibles in push-out or lift-coil induction furnaces is shown. (Artwork courtesy of H. Kramer & Co.)

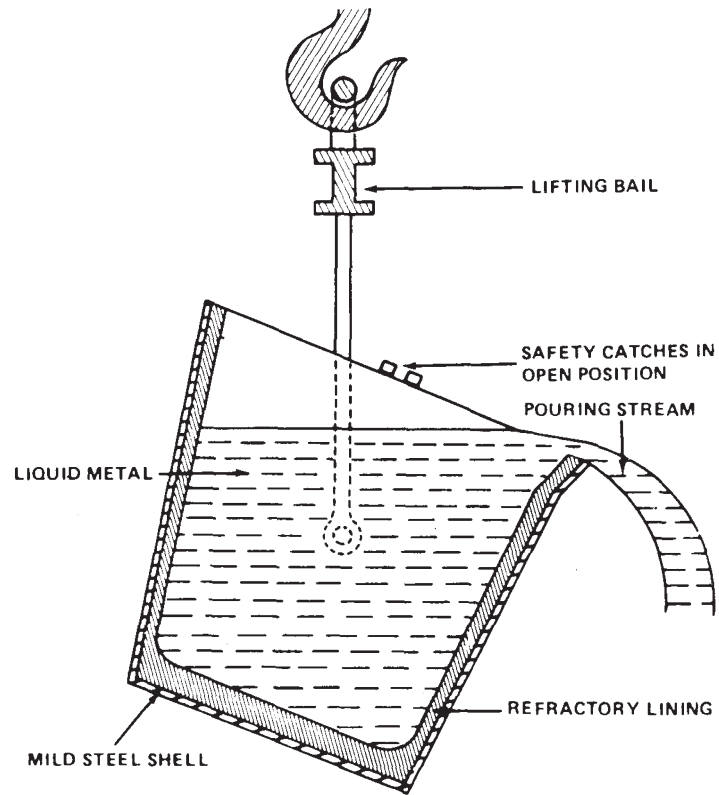


Fig. 6-4. Cross-section through a lip pour ladle.

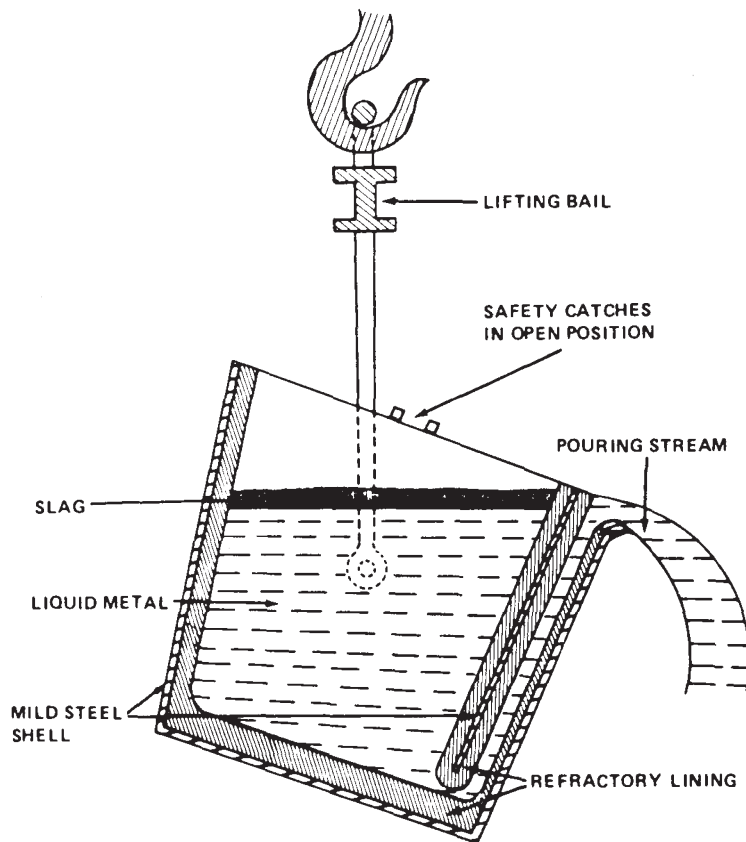
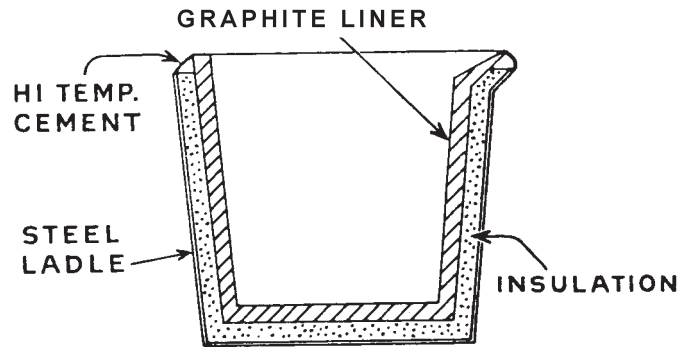


Fig. 6-5. Cross-section through a teapot ladle.



INSTALLATION -GRAPHITE LADLE LINER

Fig. 6-6. Diagram of installation of a graphite liner with insulation in a steel shell, lip-pour ladle.



Fig. 6-7. Pouring bronze castings from a ladle shell lined with graphite; teapot-type liner providing skimmer and bottom-pour tube. (Artwork courtesy of Fresno Valves and Castings, Inc., USA.)

The size and weight of pouring ladles necessitate that they be mechanically raised and lowered during pouring. For this reason, they are invariably provided with trunnions that are suspended by a bail, permitting the assembly to be raised and lowered by a crane, hoist or rack-and-pinion gear. The rack-and-pinion gear (Fig. 6-8) is commonly used with smaller ladles, operated by a single pouring operator. With larger ladles, pouring is done by means of a hand wheel-operated, enclosed worm-gear device (Fig. 6-9), with separate operators for skimming and control of ladle height.

There are several important points to be kept in mind in the operation and selection of pouring and handling equipment:

Selection considerations

- Ladle size should be tailored to the average size and quantity of molds to be poured, taking into account time lapse, rate of temperature drop, and degree of temperature control required.

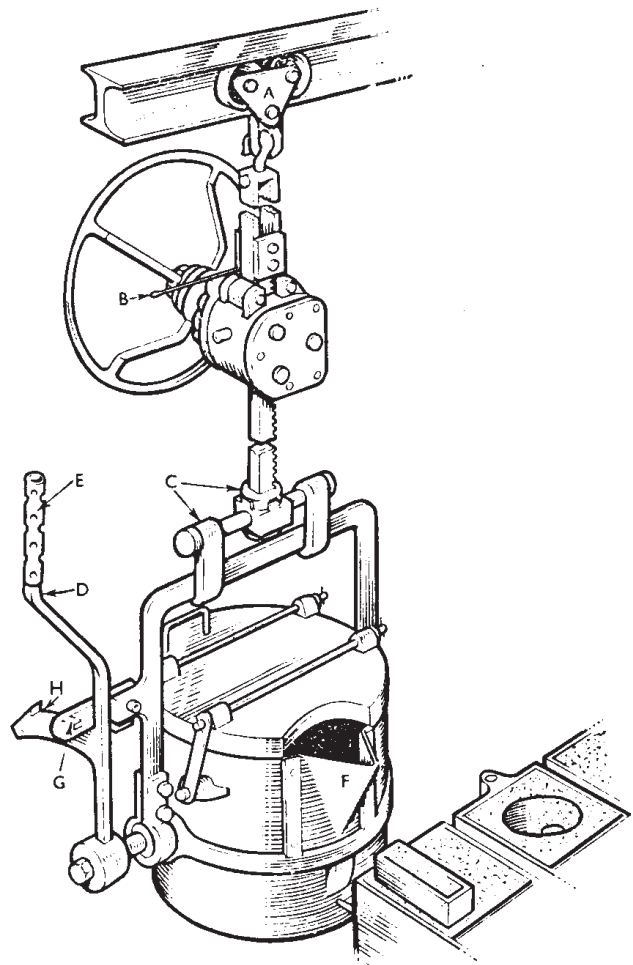


Fig. 6-8. One-man pouring ladle (with cover), provided with enclosed rack-and-pinion gearing and hand wheel for height adjustment.

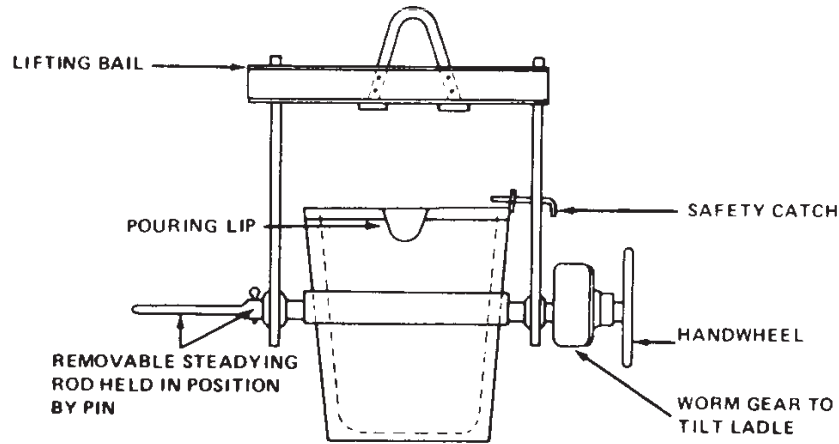


Fig. 6-9. A typical large lip-pour ladle equipped with enclosed worm gearing and hand wheel for pouring.

- Skimming of ladles should be provided for, either by personnel or by mechanical devices (including a teapot ladle design).
- Foundry layout, metal transport systems, and production scheduling should be selected and controlled to permit prompt pouring of metal with a minimum degree of superheating. Insulating top covers on ladles should be considered as a means of reducing radiant-heat losses during transfer.
- Pouring temperature control should be established at the pouring stations and not in the furnace room.
- Sprue locations should be standardized on molds, preferably along the front edge of the cope flask, and not impeded by placement of mold weights. Where practical, suitably designed pouring boxes should be used.
- High-intensity lighting should be provided at all pouring stations in order to ensure good visibility for operators.
- Pouring areas should have ample horizontal and vertical clearance for ease in handling and manipulation of ladles and for unimpeded pouring.
- Pouring areas should be provided with clean, dry, firm, and safe footing.
- Mold filling rate and sequence, as established by carefully designed gating systems, are compromised by the practice of pouring molds on an incline; molds should be level when poured.
- Ideally, the opening of the sprue or pouring box should be at a level midway between the knees and hips of the pouring operator. Outside of this range, pouring becomes more difficult. Ergonomically designed workstations allow the employees to move efficiently and safely within their work area. The relative heights of conveyors, flooring, flasks, monorails, ladle trunnions, and so on, should all be considered with ergonomics in mind.

- Good ventilation in the pouring area is important not only for worker health and safety but for improving operator visibility. Ventilation hoods and ducts, however, should be located as to avoid shadows being cast on the sprue location.

Operations

- In establishing a temperature control system for pouring, specific authority and disposition procedures should be defined for cases where metal does not meet the required temperature; cold metal should be returned to the furnace room or pigged, not poured into molds on the off-chance that some good castings may result.
- Consideration should be given to offering quality incentives to pourers.
- Constant effort should be made to avoid spillage and splashing and to maintain a pouring height (ladle to sprue) no greater than six inches mold-to-mold (preferably less).
- In automatic molding operations, every means should be considered to avoid pouring molds manually when they are moving continuously or intermittently along a mold conveyor (see the following section on Automatic Pouring).
- Lips and spouts of pouring ladles should be kept free from obstructions or accumulations that impede pouring.

Failure to consider or apply the above-mentioned considerations has resulted in substantial monetary and productivity losses for many foundries over time. Observance of these points can result in great savings, often with little expenditure.

AUTOMATIC POURING

The problems associated with manual pouring of stationary molds, as just described, become even more difficult (if not impossible) when dealing with non-stationary molds. Such is the situation when foundries use automated molding systems capable of high rates of mold production. Attempts to pour metal manually into continuously or intermittently moving molds create serious problems of spillage, splashing, interruptions in pouring, washed-in sand, misruns and cold shuts. Time simply does not permit adequate pouring temperature control, and scrap losses can become exorbitant. In the early days of automatic, high-production molding lines it was observed that those foundries most efficient in mold production were those which suffered the greatest losses from manual pouring operations.

Automatic pouring systems were seen as the practical solution and, during the past three decades, research and development has led to the introduction of dozens of patented systems for automatic pouring. Virtually all systems are based on the concept that the molds pass directly beneath the pouring device that is adjacent to a holding furnace and melter. Furthermore, mold size and sprue location are standardized. Several basic features are common to all automatic pouring systems:

- close control of metal temperature is provided, usually by means of an electric induction holding furnace,
- a means for dispensing a metered quantity (by weight or volume) of molten metal within a time span corresponding to the required pouring cycle is provided,
- the metal is directed, without turbulence, into the sprue opening (incorporating some type of tracking technique if the mold is moving during pouring),
- sequential indexing of the pouring spout from one mold to the next is provided, with an indicator to signal the start of pouring.

The many types of automatic pouring systems currently in use will not be listed here. By design, many systems are more efficient for use with large molds or for use with ferrous alloys. Of those which have been adopted for use in copper-base alloy foundries, virtually all have been of the “pressure-pour” type, involving a channel-type induction holding furnace.

With the pressure-pour automatic pouring system, the holding furnace receives metal one of three ways; by transfer ladle, through a refractory fill tube, or by launder from adjacent melting furnaces. When air pressure is applied to the interior of the holding furnace (see Fig. 6-10), molten metal rises in the pour tube as well as in the fill tube. Since the exit level of the pour tube is well below that of the fill tube, molten metal can leave the furnace only through the pour tube. The weight (or volume) of metal dispensed from the furnace is determined by the degree and duration of the applied pressure, the working level of the bath, and the diameter of the pour tube opening.

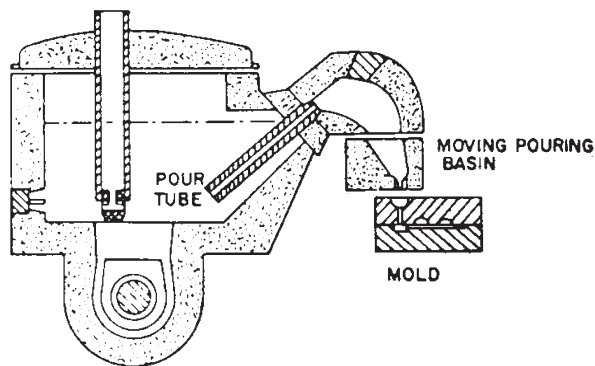


Fig. 6-10. A schematic view of a channel-induction furnace with fill tube and pour tube, designed for automatic pressure pouring.

Pouring Moving Molds

The pouring system depicted in Fig. 6-10 is designed to pour molds as they move along a conveyor. To accomplish this, a metered quantity of metal from the furnace is discharged directly into an elongated pouring basin, which is lined with refractory and equipped with a replaceable orifice at one end. At the beginning of the pouring cycle the basin is indexed in such a position that its orifice is directly over the sprue opening of the mold to be poured. The basin locks mechanically to the mold and actually travels with it along the conveyor as metal is dispensed from the furnace, via the basin, into the mold. The length of the basin is such that its opening remains beneath the pour tube of the furnace long enough to receive all the metal that is dispensed. The basin travels along the conveyor, with the mold, until it is drained of metal. At this point, contact with a limit switch disengages the basin from the poured mold and causes it to return to its original index position, awaiting the arrival of the next mold in line in order to repeat the cycle.

In a somewhat different version, the movable basin is replaced by a launder that is hinged so it may pivot horizontally in order to track the sprue opening of the moving mold. The launder is also designed to “telescope” its length in tracking along a straight conveyor line.

Pouring Stationary Molds

A somewhat more specialized application of the pressure-pour system involves the use of an elongated pour spout for directing metered quantities of metal into stack-mold assemblies which are sequentially indexed in pouring position (Fig. 6-11). An important feature in the operation of this system is the maintenance of a “ready level” of metal in the pour spout by means of controlled internal pressure on the bath, and using timed application of “over-pressure” to dispense the amount of metal required.



Fig. 6-11. Automatic pressure pouring of indexed mold stack are shown. (Artwork courtesy of Sloan Valve Company, USA)

Advantages of Automatic Pouring

Aside from eliminating the many causes of defects arising from manual pouring variations, the use of automatic pouring can result in many economic and qualitative improvements, as follows:

Temperature Control

Pouring temperature, mold-to-mold, can be held easily within $\pm 10^\circ\text{F}$ (5.6°C), permitting selection of an optimum pouring temperature for every mold poured. This compares with an average range of some 100°F (56°C) for manual pouring. Nominal pouring temperature can be markedly lowered without danger of misruns, thereby achieving not only energy savings but improved casting soundness and strength as well.

Control of Poured Weight

Since there is no splashing or spillage during pouring, more molds can be poured with the same amount of metal and the system sand will remain relatively free of contamination from metallics. The control systems available today permit replication of poured weight with only a small ($\pm 2\%$) variation.

Increased Casting Yield

If yield is considered as the ratio of weight-of-castings produced to weight-of-metal melted, it can be appreciated that much higher yields result from the elimination of “handling” losses when automatic pouring is used. For example, there are no losses due to spillage and pigging of cold metal. Equally important, the ability to control precisely the amount of metal entering the mold makes it possible to allow the metal height in the mold to drop below that of the sprue cup in many cases, without compromising the filling of the mold cavity or feeding of the casting.

Metal Cleanliness

With automatic pouring using the “pressure-pour” system, clean, dross-free metal is delivered to the sprue of every mold. To minimize the oxidation of zinc and other alloy constituents, flake graphite is often spread on the surface of the molten metal in the holding furnace (dross and expended graphite should be skimmed away regularly). Deoxidation of the metal is best accomplished by metered additions of 15% phosphor-copper shot to the metal stream while additions are made through the fill tube. Dross formation and heat losses are further minimized by placement of gas burners (with a slightly reducing flame) at such locations as:

- at the top of fill tube,
- above launders,

- at the top of the pour tube, and
- in the movable pour basin.

The momentary exposure of the melt to reducing atmospheres does not appear to allow ample time for gas absorption to occur.

Control of Pour Rate

With the use of a movable pouring basin in conjunction with the pressure-pour system, pour rate is established by the size of the orifice in the basin. The latter is adjusted to match the flow rate of the choke in the gating system. The initial rate of metal delivery should momentarily be somewhat greater in order to fill the sprue; once this is accomplished, the rate of metal delivery should be such as to keep the sprue full. When metal from the pour tube is being discharged directly into the mold sprue, this variability in flow rate can be programmed into the controls of the automatic pouring system, achieving a consistency in pouring which cannot be matched manually.

As with any mechanized system, maintenance of equipment is essential if consistent results are to be expected. Proper adjustment of controls is also critical.

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GATING

INTRODUCTION

The major function of a gating system is to deliver clean metal into the mold cavity from the ladle without deteriorating the quality of the metal. Secondary considerations, such as ease of molding, removal of gates, and high casting yield, should not result in a gating design that hinders the production of high quality castings.

ALLOY SYSTEMS

Copper-base alloys are commonly classified into three groups based upon freezing range, a factor that is relevant to their feeding and risering characteristics. This grouping system also serves to classify the alloys according to their gating requirements.

Group I consists of alloys with a narrow freezing range, or a range of less than 90F (50C) between the point where solidification begins (liquidus) and the point where the alloy is completely frozen (solidus). Specific alloys in this group are the aluminum bronzes (C95200-95800), yellow bronzes (C85200-85800), manganese bronzes (C86100-86800), copper and chromium-copper (C81100 and C81500) and white manganese brass (C99700). The narrow freezing range is caused by alloying with large amounts of elements such as zinc, aluminum or manganese, or with smaller amounts of chromium. All of these elements are readily oxidized and form tough, insoluble oxide skins. Hence, the pouring and gating systems for this class of alloys must be carefully designed to avoid turbulence that might result in oxide skins being trapped as inclusions in the casting. These inclusions cause marked deterioration in mechanical properties. Pure copper is a special case since it can readily absorb large quantities of oxygen under turbulent conditions. This dissolved oxygen, in combination with dissolved hydrogen, can then give rise to “steam” porosity when the casting solidifies. If an excess of deoxidant is present, pure copper is less sensitive to turbulent flow (see the chapter *High-Conductivity Copper and High Copper Alloys*).

The alloys having intermediate freezing ranges (Group II) have a range between liquidus and solidus points of about 90 to 200F (50 to 110C). Alloys in this group do not form oxide films as readily as do those in Group I; however, with the use of a more turbulent gating system a considerable

amount of dross can be generated. It is safest, therefore, to use non-turbulent gating systems with these alloys. Group II alloys consist of the silicon bronzes and bronzes (C87200-87600) and the copper-nickel alloys (C96200-96600). It may be noted that in alloys containing silicon, the presence of lead increases the tendency for dross inclusions to form. Similarly, an increase in alloying elements such as columbium (niobium), beryllium, and chromium causes greater problems with oxide inclusions in cupronickels.

The wide-freezing-range alloys (Group III) generally have a freezing range of well over 200F (110C) and often closer to 300F (167C). This is especially true for tin bronzes, where the tin-rich phase is the last to solidify. In leaded alloys of this group, the lead phase is not completely frozen until a temperature of 621F (327C) is reached. Group III alloys have a relatively low oxidation tendency and are usually deoxidized with phosphorus. The residual phosphorus inhibits oxide film formation during pouring by combining with any free oxygen present to form small globules of a fluid slag (copper phosphate), which readily rises through the molten metal to the top of the mold cavity. Thus, there are no internal oxide films to impair properties. Since these alloys are relatively insensitive to turbulence, many different gating systems may be used; simplicity of design, and gate placement to enhance proper sequence of solidification would be important considerations here as opposed to the avoidance of turbulence. Alloys in this group include the leaded red bronzes (C83600-84200), leaded semi-red bronzes (C84400-84800), tin bronzes (C90200-91700), leaded tin bronzes (C92200-92700), and high-leaded tin bronzes (C92800-94500).

POURING BASIN

The production of high-quality castings requires not only proper melting and molding operations and properly designed pattern equipment but also an understanding of the principles of gating so that clean metal can be delivered to the mold cavity with a minimum amount of turbulence. A pouring basin allows a sprue to be filled quickly and maintains a constant head throughout the pour.

If the weight of poured metal in a mold exceeds about thirty pounds, a pouring basin offers many advantages. The pourer can direct the flow of metal from the ladle into the basin with

less chance of spillage, and the sprue need not be located near the edge of the mold. The pouring ladle can be brought to within an inch or two of the basin and a continuous flow rate may be more easily maintained through a larger pouring head. If there are any brief interruptions in pouring the metal into the basin, the surplus metal will take up the slack until pouring has resumed. The major disadvantage of using a pouring basin is that yield is lowered, resulting in more metal to be recycled; however, if pouring is discontinued before the metal reaches the top of the risers, the excess metal from the pouring basin will drain into and fill the risers, thus minimizing waste. Recommended pouring basin shapes are shown in Figs. 7-1 and 7-2. Several excellent techniques have been used to produce basins in a uniform and consistent manner. These include air-set or oil-bonded cores that are placed on top of the sprue just after the mold reaches the pouring station. For squeeze molding, a pouring basin may be rammed up when the follow board squeezes the cope. For cleanliness and ease of pouring, a basin is most necessary for molds whose poured weight exceeds about thirty pounds. The reduction of metal spillage will more than pay

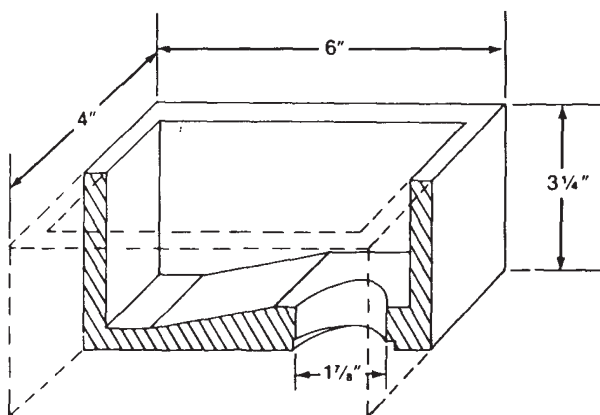


Fig. 7-1. A cross-section of a pouring basin is shown above.

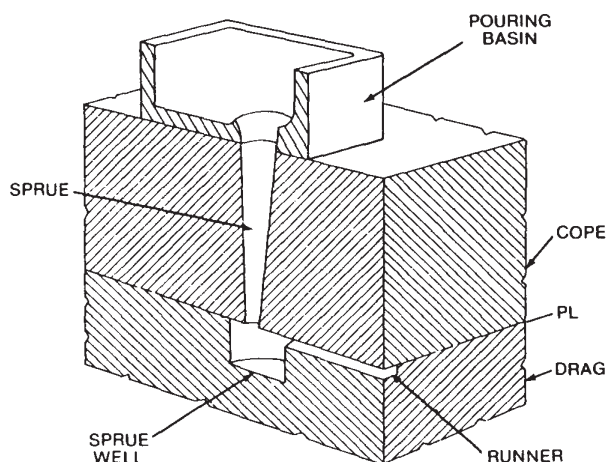


Fig. 7-2. A cross-section of a typical sand mold with a pouring basin located on the top of the mold.

for the small cost of producing the pouring basins. When pouring, the metal stream should be directed to the back of the basin, away from the sprue area, and the metal level in the basin itself should be maintained at a height of about two inches or greater.

SPRUE

The correct sprue size is the single most important factor in the gating system. If a wrong size is selected, or if the sprue has either no taper or a reverse taper, the damage done to the metal entering the mold cavity may be extensive and difficult to correct. Since most molders can select their own sprues, a good supervisor will see that molders are limited to the use of sprues that meet the requirements for a non-turbulent flow of metal into the gating system. If a pouring basin is not used, the sprue acts as a funnel that delivers metal into the mold cavity. A wide-topped sprue will accomplish this with minimum spillage.

Since most high-production molds that require less than about 30 lbs of poured weight involve flasks with 4 to 6 in. cope height, a standard sprue size may be used with these for all copper-base alloys. The top third of the sprue is the funnel portion, which should have an opening diameter of about two inches. The remaining portion of the sprue should taper downward to a final opening diameter of between 1/2 and 7/8 in., depending upon the desired pouring rate (Fig. 7-3). Since separate pouring boxes are not used for making smaller castings in high-production molding, the design of the sprue shown in Fig. 7-3 may be vertically compressed to fit, for example, a 6 in. cope, and the pouring box can be replaced by a "funnel" which is molded or cut into the top of the cope.

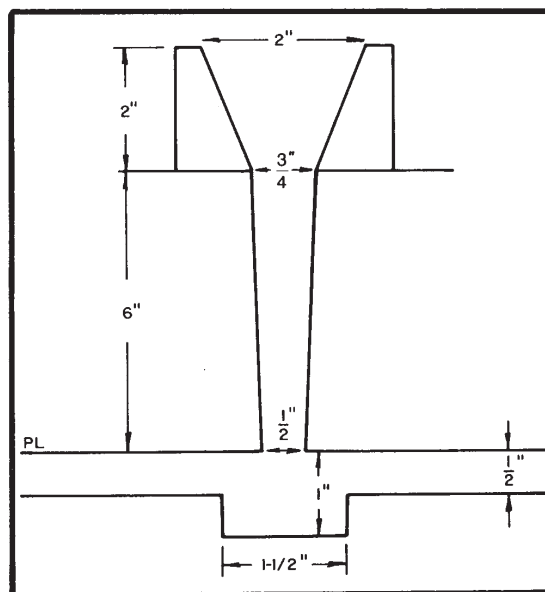


Fig. 7-3. This typical sprue is designed to reduce turbulence.

There are many charts and formulas for calculating the dimensions of a tapered sprue (excluding the pouring cup, which may be of any shape—from a hand-cut cone to the more elaborate pouring basin shown in Fig. 7-2). First, the desired pouring rate is selected and then the required sprue exit diameter is determined (Fig. 7-4) based upon the expected height of metal in the sprue and the pouring basin (if any). (Selection of the pouring rate will be discussed later.) Once the sprue exit diameter is obtained, the proper entrance diameter can be determined (Fig. 7-5). Correct sprue dimensions become increasingly critical as the sprue height increases beyond 12 inches. For short sprues (4 to 6 in.), it is common practice to taper sprues 5 to 10 degrees per side. No harm will be done by too much taper other than that the total weight of metal poured will be increased.

In many cases, such as in horizontal shell molding or with some automatic molding machines, a reverse-taper sprue must be used. One way to compensate for this is to make a separate, tapered sprue-core as shown in Fig. 7-6 (a) and to insert this core in the reverse-taper sprue cavity before the mold is closed for pouring. Metal pressure is usually sufficient to keep the core insert in place, and this technique works quite well in shell molding.

The importance of using a proper sprue cannot be over-emphasized; a sprue with a downward taper is filled much more quickly, is kept full during pouring, and causes a minimal amount of air to be sucked into the metal stream as it flows downward. In conjunction with correctly designed runner and gate systems, a proper sprue also ensures that each successive mold is filled in exactly the same way. This helps assure that all castings are of uniform, reproducible quality.

In addition, the sprue is of great benefit in trouble-shooting, since defects will also be produced consistently, and can therefore be eliminated by logical procedures. This is often difficult under turbulent flow conditions where defects appear and reappear in different locations.

SPRUE BASE

Since maximum stream velocity is at the bottom of the sprue and is proportional to the square root of the height of fall of the metal, it is mandatory that a well be used at the sprue base to cushion the falling stream of metal. The well also changes the vertical flow of the metal into a horizontal flow with the least amount of turbulence in the runner. Recommended size for the well depth should be about twice that of the drag runner; the diameter should be two to three times that of the sprue base. A well with a depth of 1 to 1½ inches and a diameter of 1½ to 2 inches is usually adequate for most sprue sizes and pouring rates. The use of larger well dimensions will cause a slight reduction in casting yield percentage.

CHOKES

The optimum method for controlling pouring rate is by properly sizing the exit diameter of a downward-tapered sprue. The exit diameter becomes the “choke” in the entire runner and gate system, since it is the smallest cross-sectional area through which the metal flows on its way into the mold. If the downward-tapered sprue cannot be used, it is necessary to employ an alternative method of providing a choke at or near the sprue base.

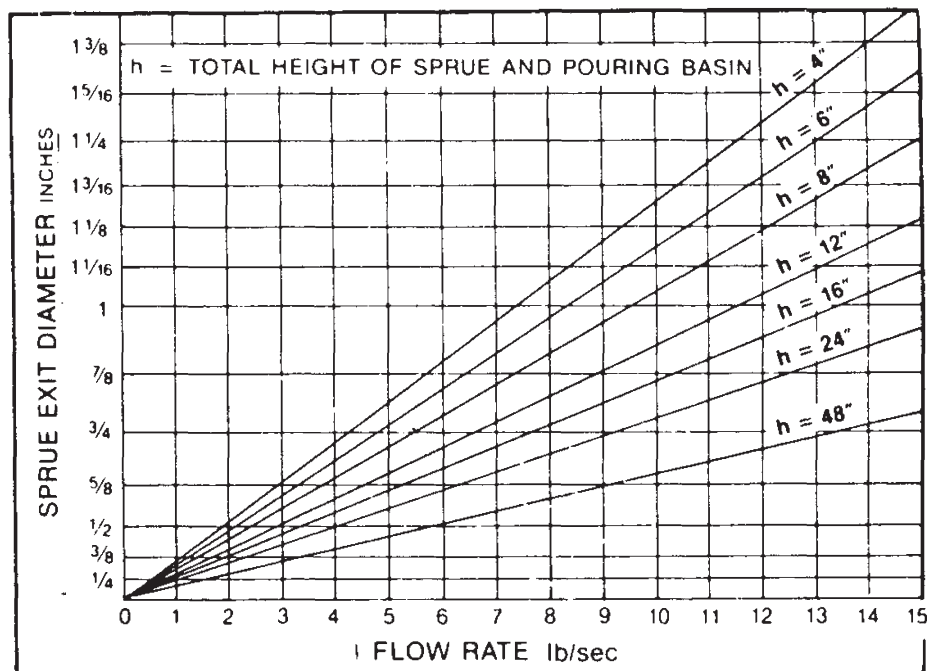


Fig. 7-4. This graph illustrates the flow rates of copper-base alloys through tapered sprues of varying diameters and heights.

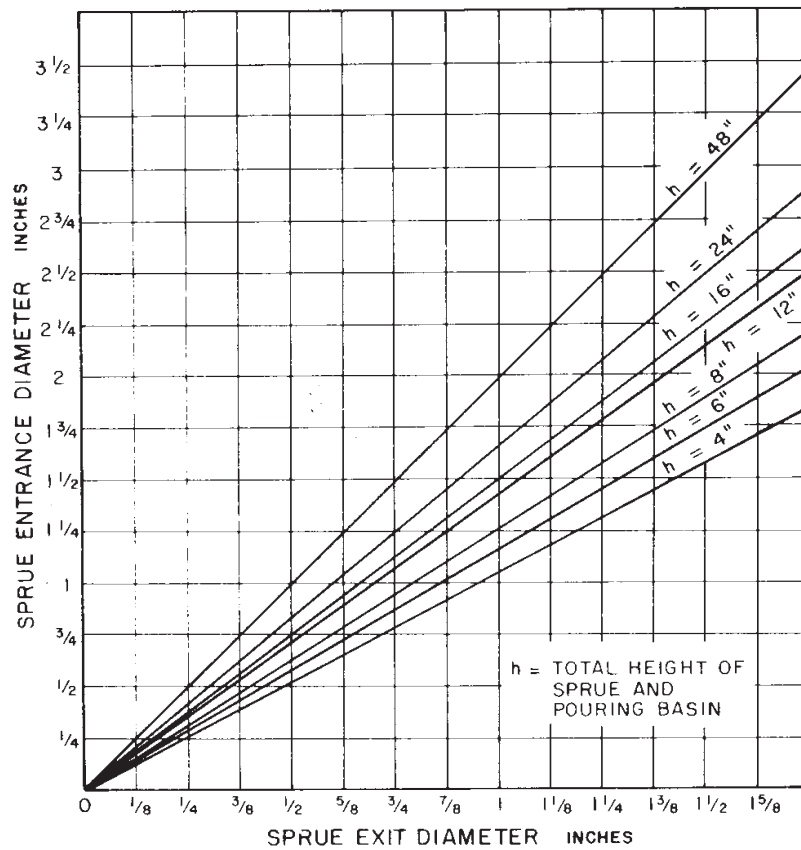


Fig. 7-5. Suggested entrance and exit diameters for sprues of various heights are shown above.

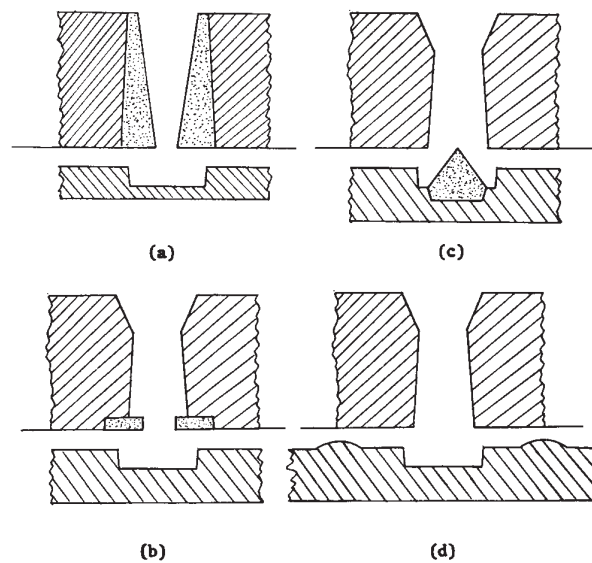


Fig. 7-6. Alternative methods for correcting the problem of a reverse-tapered sprue.

One technique, often misapplied, is the use of so-called “strainers” or “strainer cores” at the base of the sprue. Strainers with multiple holes can only remove the larger pieces of dross or non-metallic particles and divide the metal flow into multiple small streams, thus increasing turbulence, exposure to air, and formation of oxides and dross inside the mold. These strainers, made of core sand, tinned steel, mica, fiberglass or ceramic, only restrict the rate of metal flow. For this reason, it is best to provide only a single hole that has the correct exit diameter of a properly tapered sprue, as shown in Fig. 7-6 (b). Such choke cores should never be placed at the top of the sprue as in a pouring basin.

A somewhat less common, though effective, technique is to use an equilateral cone-shaped core, which is placed in the center of the pouring well at the sprue base as shown in Fig. 7-6 (c). In this case, the ring-shaped opening between the sprue opening and the cone must be sized to provide the proper choke area.

Perhaps the most familiar technique (Fig. 7-6, d) is to provide a restriction in the runner about one inch from the pouring well (never at the gate area). These restrictions should be smoothly contoured and placed at the bottom of the drag runner, as shown. The thickness of the choke opening should be from one-fourth to three-fourths that of the full runner height and the cross-sectional area of the choke should not exceed one-fourth the area of the sprue base. Placement of the choke close to the pouring well ensures that the sprue can be filled quickly and be kept full throughout the pour. This also permits dissipation of any turbulence before the stream reaches the gate locations.

Unless they are removed during cleaning operations, choke cores represent a possible contaminant when recharged to the melting furnace. Tinned steel is the worst in this regard since it can introduce excessive amounts of iron into the melt, resulting in hard spots that damage tools during machining. The best choke core materials are mica and fiberglass, since they are relatively thin and can be placed over the sprue well at the parting line before mold closure, requiring no special prints on the pattern.

POURING RATE

Pouring rate depends upon factors such as weight of the casting, section size, sprue height, and alloy system. For small work (30 lbs or less), most Group III alloys are poured manually at about 4 lbs per second. Light memorial-plaque castings are successfully poured at 10 lb/sec, and many automatic pouring units operate at 8 to 10 lb/sec. Where the weight poured per mold is under 30 lbs, Group I alloys are poured at between 2 and 4 lb/sec in order to obtain clean, non-turbulent conditions.

Figure 7-4 shows sprue exit diameters required, at varying sprue heights, for specific flow rates during pouring. Table 7-1 shows values of flow rate at sprue exits for commonly used sprue sizes of varying heights and diameters. When

a sprue height of 4 to 6 in. is used, a sprue exit diameter of $\frac{1}{2}$ to $\frac{3}{4}$ in. is adequate to obtain a flow rate of 2 to 4 lb/sec. This is quite satisfactory for castings with gross weight of less than 30 pounds. It should not be necessary to use a $\frac{7}{8}$ to $1\frac{1}{8}$ in. sprue exit unless pouring plaque work or using automatic pouring. Sprues for most production work have exit diameters between $\frac{5}{8}$ and $\frac{3}{4}$ in., which is sufficient to pour most molds at a rate of up to 30 lbs. in 8 to 10 seconds. The total pouring time in seconds may be estimated by dividing the total poured weight of the mold (castings plus gates and risers) by the flow rate indicated for the selected sprue exit diameter, as shown in Fig. 7-4. Actually, the flow rate through the bottom of the sprue does not remain constant throughout the pour. Instead, it decreases as the metal level in the mold cavity increases, thus causing “back pressure” by the decrease in the effective height (head) of metal in the sprue. This reduction of flow, causing an increase in pouring time, is called the “delivery factor,” and is greater for tall castings of height approaching that of the sprue than it is for flat castings. Thus, if the casting is one-fourth as high as the total height of the sprue and pouring basin, the delivery factor is 1.1 times the calculated pouring time. This information is shown in Table 7-2 and in Fig. 7-7.

As noted, the optimum pouring rate varies, depending on the size and thickness of the casting. An estimate of the best pouring rate may be obtained from the equation:

$$W = \frac{Wt}{0.86 + 1.09T}$$

Where

W = Flow rate in lbs per second

Wt = Weight of the casting in pounds

T = The average of the thinner section thickness in inches

This is also shown graphically in Fig. 7-8 for different section thicknesses. None of these calculations give absolute values because of the effects of friction, imprecise dimensioning of the sprue, runner and gates, casting design, relative volume of the casting above and below the parting line, height of the pouring lip above the sprue, and so on. However, the calculations provide a starting point from which sprue dimensions can be modified as a result of actual, measured pouring times plus an assessment of casting quality and surface finish.

It would be expected that large castings would require much larger sprues in order to give reasonable fill times. However, large castings require large flasks and, therefore, higher sprues; thus, the effect is self-compensating. A 1 in. diameter sprue with a height of 24 in. delivers 16.5 lb/sec and should fill a 320 lb casting in 26 seconds, assuming a 1.3 delivery factor. A $\frac{3}{4}$ in. sprue will fill the same casting in 43 seconds. Many large, high-grade castings have been produced using

Table 7-1. Flow Rates of Copper-Base Alloys through Tapered Sprues of Varying Diameter and Height

Sprue Dia. (In.)	Area (In. ²)	Flow Rate (lbs/sec) for Sprue Height				
		4 in.	6 in.	12 in.	24 in.	48 in.
½	0.200	1.8	2.0	3.0	4.0	6.0
⅝	0.300	2.8	3.3	4.5	6.0	9.0
¾	0.440	4.0	4.5	6.5	9.0	13.5
⅞	0.600	5.5	6.5	9.0	12.5	18.0
1	0.785	7.5	8.5	11.5	16.5	24.5
1½	1.000	9.5	10.5	17.0	20.5	30.0

Table 7-2. Delivery Factor for Bottom-Run Castings

If casting is as high as sprue	X 2
¾ as high as sprue	X 1.3
½ as high as sprue	X 1.2
¼ as high as sprue	X 1.1

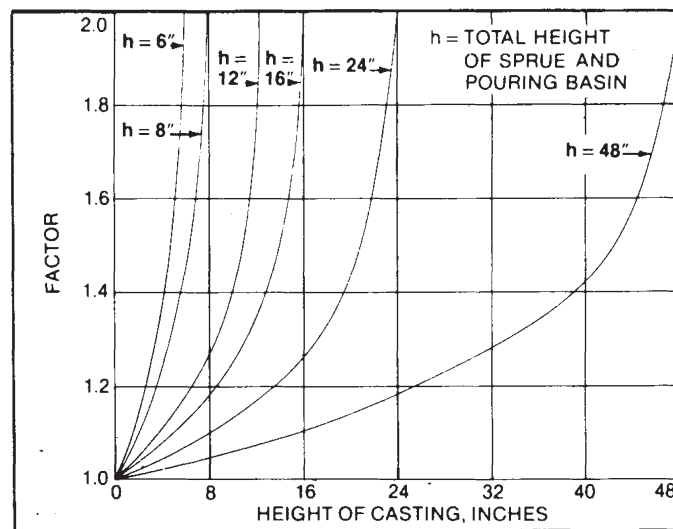


Fig. 7-7. Delivery factor for bottom-run castings of various heights.

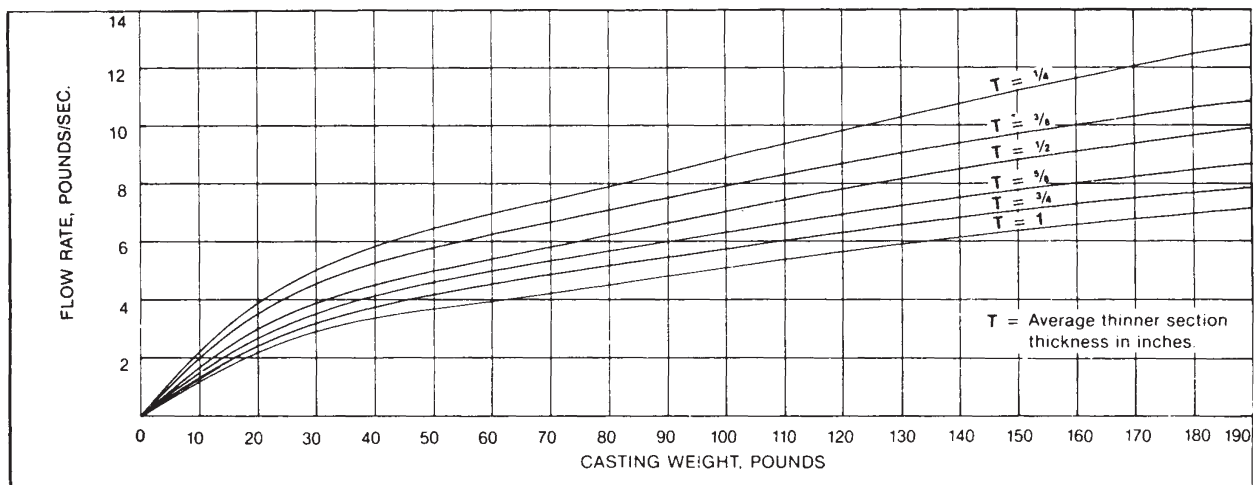


Fig. 7-8. This graph depicts horizontal flow rate as a function of casting weight.

relatively small sprues. In most cases, where high (3 to 4 ft) sprues with large diameters (2 to 3 in.) are used, they do not fill completely until the mold is more than half full, and fill rates are not nearly as high as the calculated values based on designated sprue size.

Where higher flow rates (greater than 10 lb/sec) are required and relatively small-diameter sprues are used, such quantities of metal cannot consistently be delivered into the sprue opening without the use of a pouring basin. For Group I alloys, it is good practice to plug the sprue opening with a heated graphite or refractory stopper until the pouring basin is filled. This ensures rapid and complete filling of the sprue when the stopper is removed. Such a technique is even more essential with high sprues because of the problems of increased metal velocity and turbulence. Similarly, tapered rectangular sprues are often used, as these can be readily made and modified and are less prone to vortex formation than are circular sprues.

In smaller castings, if a pouring basin is not used, it is important to place the pouring ladle as close to the sprue as possible in order not to increase the sprue height effect. If a pouring ladle is too full and cannot be tilted, or if the sprue is located too close to the center of the mold so that the pouring ladle must be raised in order to reach the sprue, the pouring rate will be increased significantly because of the additional pouring distance. This effect is minimized when a pouring basin is used; however, the distance between the lip of the ladle and the sprue opening should still be minimized in order to attain the least possible turbulence.

RUNNERS & GATES

For alloys in Group I and II, it is mandatory that all runners be placed in the drag, with as much of the casting as possible placed in the cope. In this manner, all runners will be filled completely before any metal enters the gates that are placed in the cope. The metal will then leave the gates with a minimum amount of turbulence and begin to fill the casting cavity. This practice is also recommended for Group III alloys since it results in entrapment of slag or dross from the ladle and loose sand from the gating system, and provides uniform filling of the mold. If necessary, however, more traditional runner and gate systems can be used to achieve good quality castings from Group III alloys since these alloys are less sensitive to the formation of dross and insoluble oxides, and merging streams of metal tend to flow together without the entrapment of oxide skins or dross particles.

Runners should be as rectangular as possible, and their total maximum cross-sectional area should be two to four times that of the choke area (sprue exit area where no separate choke is used). The runner cross section must be large enough to prevent premature chilling of the metal during pouring. A rectangular runner, whose width is greater than its depth, works best. In general, runners should be dimensioned so that their width is about twice their depth, but an essentially square runner would be second choice. The

least desirable runner would be one whose depth exceeds its width; however, space limitations sometimes necessitate this design in order to maintain the desired runner cross section in relation to the choke area.

The concept of “gating ratios,” commonly used in the design of gating systems, is expressed as the ratio of the total cross-sectional areas of the runners and gates to that of the choke (choke:runners:gates). If there is no separate choke system, the choke area is that of the bottom opening of a downward-tapered sprue. The significance of gating ratios is based on the fact that, for a constant volume flow rate of liquid, the velocity of the stream is inversely proportional to the cross-sectional area of the channel in which it is flowing. It is most desirable to have the metal enter the casting cavity at minimum velocity and, hence, with minimum turbulence. In order to achieve this, the cross-sectional area of the gates must be at least equal to, and preferably greater than, that of the runners. The runners should be equal or greater in area than the choke. Such a system, in which the liquid metal moves at ever-decreasing velocity through successive channels of increasing cross sectional area, is referred to as an “unpressurized” gating system. Unpressurized gating is particularly recommended for Group I and Group II alloys, with gating ratios as high as 1:4:6 being common.

As an example of such a ratio, consider a gating system in which $\frac{7}{8}$ in. diameter sprue with a cross-sectional area of 0.6 in.² is used. The total runner area (four times that of the sprue) would be 2.4 in.² and the total gate area would be 3.6 square inches. If the system employed a double-runner design with each runner having four ingates, then the area of each individual runner would be 1.2 in.² and that of each gate would be 3.6/8 or 0.45 square inches. Thus, with the $\frac{7}{8}$ in. diameter sprue we might use two runners—each 1 in. x 1.2 in., and eight gates—each 0.375 in. x 1.2 in. As sprue size increases, the respective areas of the runners and gates also increase in proportion to the selected gating ratio; therefore, for the best yield of castings (percent of poured mold weight), smaller sprue sizes are advantageous.

The design of a runner and gating system should also assure that equal volumes of metal will flow from each gate whenever more than one gate is used with a given runner. If a runner of constant cross-sectional area is used with multiple gates, the volume of metal that passes through each gate will be different, depending upon the gate's location in the runner. The gate furthest from the sprue passes the greatest volume of metal, that closest to the sprue the least amount, and intermediate gates pass amounts proportional to their location. This information is explained in detail in several of the references cited for this chapter and should be studied carefully. It is possible to achieve uniform metal delivery through each gate by varying the runner cross-section along its length in either of two ways (Fig. 7-9). One way is to reduce the runner cross-section by an amount equal to the area of each gate as it is passed, thus resulting in a stair-stepped runner design as shown in Fig. 7-9a for a single casting and in Fig. 7-10 for multiple castings.

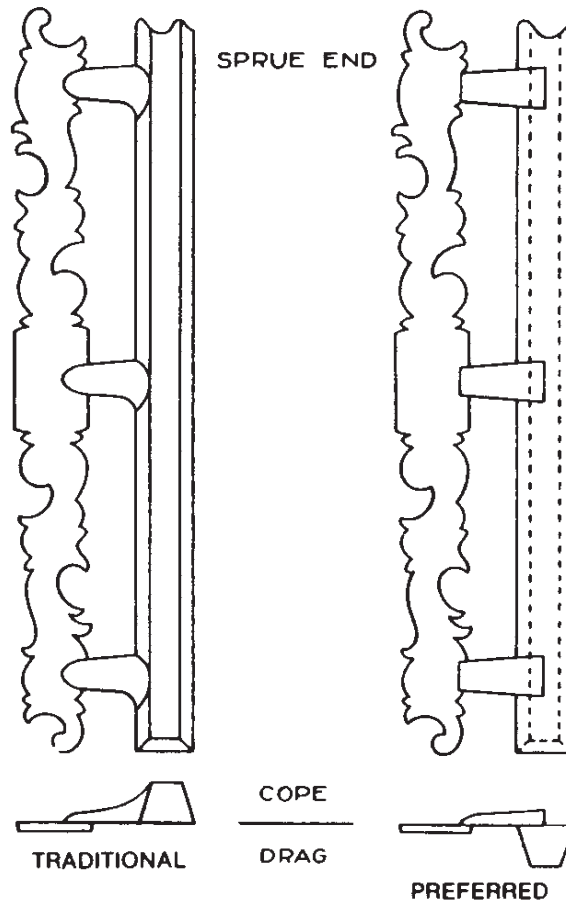


Fig. 7-12. Redesign of gating system that prevented misruns and roughness in yellow brass sand castings.

As an example, a 1:4:4 gating system consisting of a single runner with four ingates, where the initial runner area (adjacent to the sprue base) is one square inch. Since total gate area equals the maximum runner area, each individual gate will have an area of 0.25 square inches. To achieve equal flow through each gate, the runner would be reduced from 1.00 in.² to 0.75 in.² after passing the first gate, from 0.75 to 0.50 in.² after passing the second, and from 0.50 to 0.25 in.² after passing the third. There is no need to reduce the runner area after it passes the last gate; therefore, if a stepped runner is used, there will be one less "step" than there are gates. A second technique (Fig. 7-9b) is to simply taper the runner from one end to the other to reduce the cross-sectional area at the same rate as if a stepped runner were used.

The use of stepped or tapered runners to obtain uniform flow through gates assumes that the molds are horizontal and level. Because accidental or deliberate tilting of the mold or pouring conveyor dramatically affects the way in which the metal flows within the mold, this technique should be restricted in its use in order to obtain progressive or sequential filling of molds.

A further refinement of runner design is the use of an overflow well at the extreme end of the runner, with or without a vent to allow the escape of displaced air. Studies with transparent molds (or X-ray cinematography in the case of sand molds) show that metal flowing through a dead-end runner strikes the end wall with considerable force, and the momentum causes a shock wave to travel back along the runner in the opposite direction. This wave may cause premature, interrupted flow through the gates, resulting in cold shuts and misruns. An overflow well, as shown in Fig. 7-11, serves to absorb the impact of the metal as it reaches the end of the runner and prevents the backward shock wave.

As illustrated in Figs. 7-9 through 7-12, the preferred location of gates is in the cope, overlapping the runner at the parting line. Rectangular, flat gates are more desirable than square gates, and a gate with its wide dimension in a vertical plane is least desirable. As noted previously, in order to avoid a pressurized gating system, it is necessary that the total gate area for each runner be at least equal to that of the runner itself. In cases where numerous small patterns are mounted on a single pattern plate, it may be necessary that

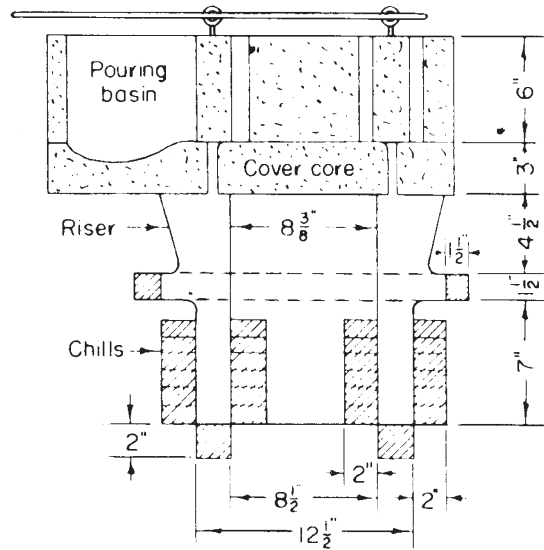
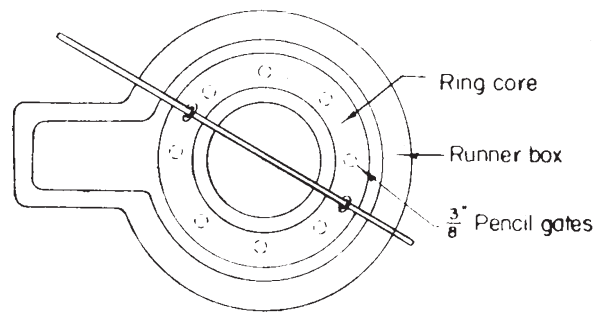


Fig. 7-13. Top pencil-gated flanged cylinder of 88-8-0-4 alloy (C92300).

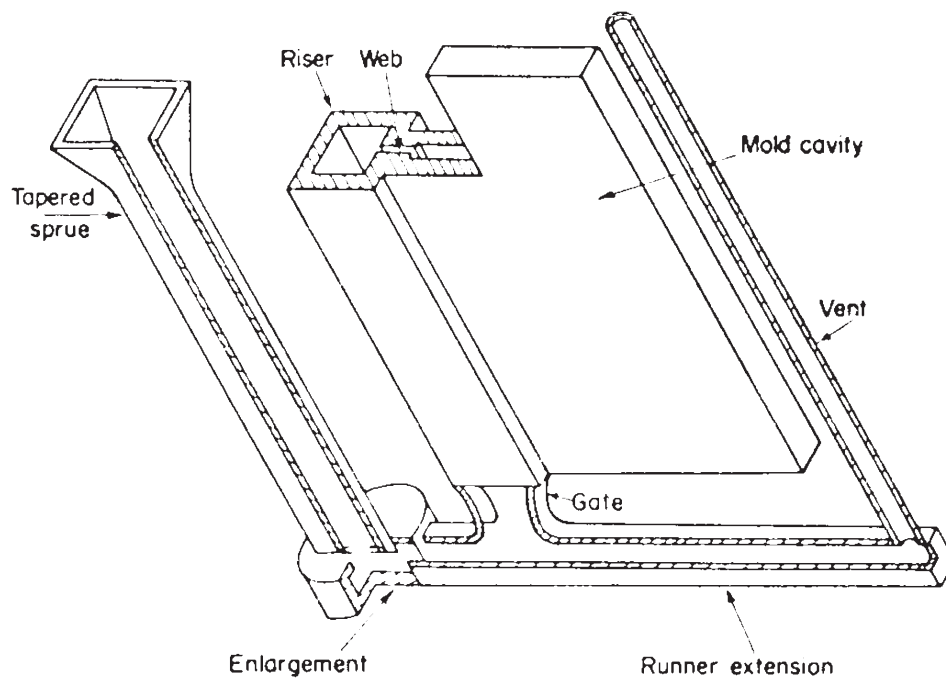


Fig. 7-14. A schematic sketch of an improved vertical gating system.

the total gate area be many times that of the runner so that individual gates are sufficiently large to fill the mold cavities. This deviation from the usual ratios is acceptable since the gating system remains unpressurized.

Figure 7-9 (a) and (b) illustrate a good gating system, with streamlined and right-angle gates. Tests have shown that streamlined gates are only slightly superior to right-angle gates in reducing turbulence to a minimum. Gates should deliver metal to the mold cavity at the lowest possible level in order to minimize the tendency toward erosion and turbulence associated with a falling stream of metal. To ensure non-turbulent filling of the cavity nearest the sprue, and to avoid any dross being swept into the cavity, the first gate should be no nearer than two inches from the base of the sprue. Dross is often trapped by adhering to the mold on the top surface of the runner between the sprue and the first gate; therefore, increasing the length of this section is beneficial, especially for alloys in Group I.

Although wide, flat gates are generally recommended, if a riser or “shrink bob” is placed on the gate, round or square-section gates help maintain an open feeding channel and serve as riser necks. Alternatively, a normal riser neck connection is used on the casting, and the calculated wide rectangular gate is cut into the back of the riser nearest the runner. The position of the gates determines the flow of hot metal into the casting cavity and affects the sequence in which the casting freezes. In order to achieve the desired pattern of solidification, the positioning of risers and chills must always be considered when choosing the location of gates (refer to the chapter on *Solidification, Feeding and Design*).

The same basic principles apply in vertically parted molds as for horizontal gating systems, with only a few deviations necessary to minimize the added turbulence characteristic of vertical gating systems. For alloys in Group III, vertical gating of castings does not usually present any serious problems since conventional bottom gates or horn gates can be applied without undue metal damage. For these alloys, the metal can also be introduced into the mold through gates at various locations along the parting line. For tall, hollow, cylindrical castings (such as liners or bearings) of Group III alloys, a ring of pencil gates is commonly used at the top of the mold (Fig. 7-13). This delivers the hottest metal to the top sections of the casting, thereby improving feeding. The flanged cylinder of tin bronze shown in Fig. 7-13 is poured through eight pencil gates in a ring runner box located at the top of the mold. A ring core in the runner box seals the gates until the runner box is full. This ring core is then lifted and removed, allowing all the metal to flow simultaneously through the gates. Chills placed in the mold cavity assure that the casting wall section will be sufficiently sound to withstand a pressure leakage test of 1000 psi.

The foregoing conventional systems cannot be recommended for alloys in Groups I or II where dross-free castings are required. For these materials, Fig. 7-14 illustrates the basic, recommended design for vertical gating systems. A modification of this basic design is shown in Fig. 7-15, where an

overflow well or trap is located just beyond the vertical gate. In both cases, the vertical riser is connected to the casting along its entire height by means of a web gate. The initial turbulence of the falling metal has largely been spent by the time the metal begins to pass through the web gate, resulting in a relatively quiet flow into the mold cavity. The momentum of the metal passing upward through the vertical gate and riser tends to carry the hot metal to the highest level in the riser before it then flows through the web gate into the casting. The thickness of the web gate is somewhat critical, and should be approximately $\frac{3}{8}$ to $\frac{1}{2}$ inch. Webs thinner than this give rise to cascading of the metal as it passes through the web, with consequent severe dross formation. Thicker webs allow the metal to flow continuously into the mold cavity at the lowest point of entry, forcing cold metal from above back into the riser. This results in erratic and unfavorable temperature distributions that hamper proper feeding of the casting. Sprue dimensions and taper, as well as the sprue base, should be selected in the same manner as for horizontal gating systems. The ratios of choke:runner:gate areas should also be similar to those of horizontal systems, ranging typically from 1:2:2 to 1:4:4. The vertical gate should enter at the bottom of the riser and should be provided with ample fillets at both ends, as shown in Fig. 7-15.

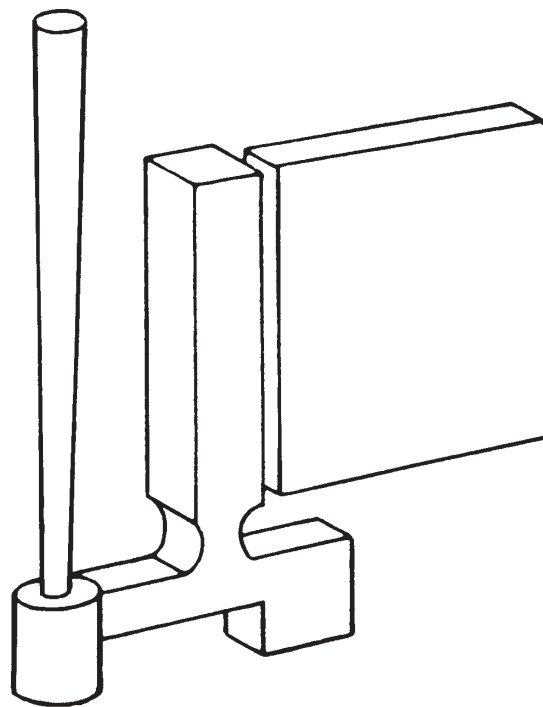


Fig. 7-15. Vertical system, single cavity. Web thickness— $\frac{1}{4}$ in., gating ratio 1:4:4, tapered sprue, $\frac{1}{2}$ in. choke.

For the less sensitive, wide-freezing-range alloys of Group III that do not require extensive risering, vertical gating may be applied to multi-cavity molds (Figs. 7-16 and 7-17). Where cavities are spaced at different levels in the mold (Fig. 7-16) it is especially important to use a tapered sprue which will

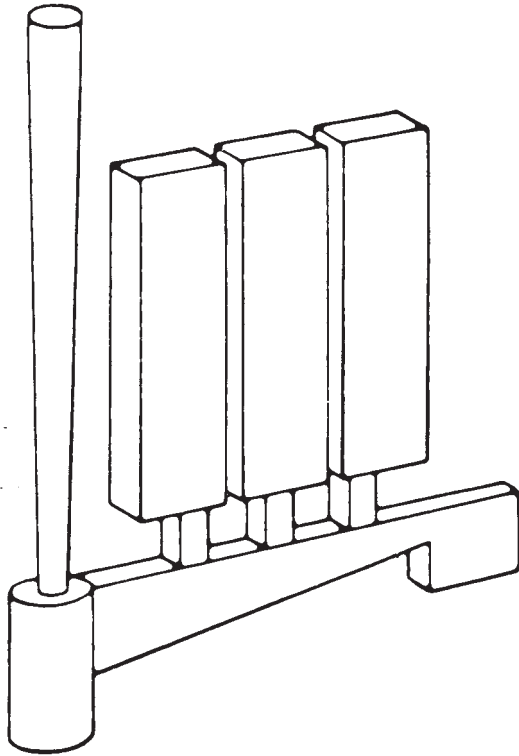


Fig. 7-16. Vertical system multiple cavity. Gating ratio 1:6 (1:2 at each level) tapered sprue- $\frac{1}{2}$ in. choke.

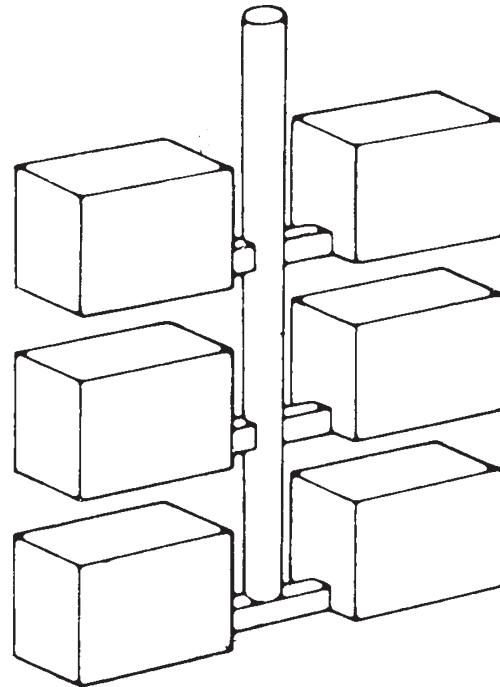


Fig. 7-17. Vertical system multiple cavity bottom runner. Gating ratio 1:4:4, tapered sprue- $\frac{1}{2}$ in. choke

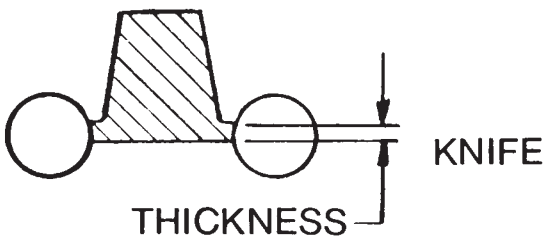
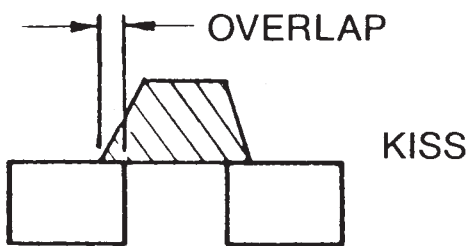


Fig. 7-18. Basic kiss and knife gates are illustrated above.

fill rapidly, thereby achieving nearly simultaneous filling of all mold cavities. To assure simultaneous filling, the gates at the top must be proportionally larger in area than those that are lower, thus compensating for the differences in metal head pressure. In vertically gated molds where all cavities are located at the same level (Fig. 7-17), the same rules apply as for horizontal gating. Again, uniform rate of flow through each gate is achieved either by tapering or by stepping down the runner cross-section as previously described.

KNIFE-GATING AND KISS-GATING SYSTEMS

Specialized gating systems can be used for certain castings; for example, knife-gating and kiss gating are popularly used for certain size ranges of Group III alloy castings. These gating systems are not recommended for alloys in Groups I and II, however, because of the dross-forming tendencies and high solidification shrinkage characteristics of these alloys. Even with Group III alloys, castings with heavier section sizes may develop surface shrinkage (draws or sink marks) when thus gated, because of the inability of these gating systems to provide feed metal to the casting during solidification.

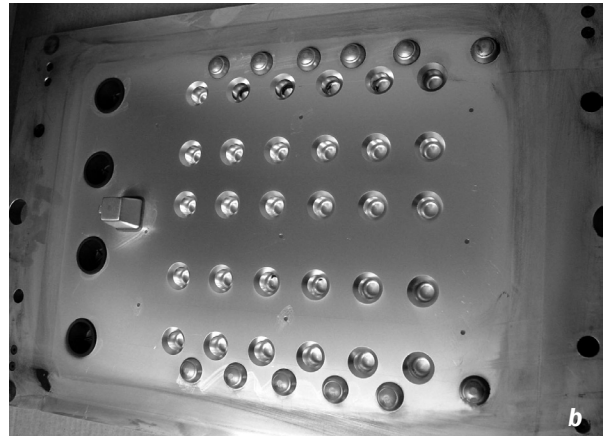
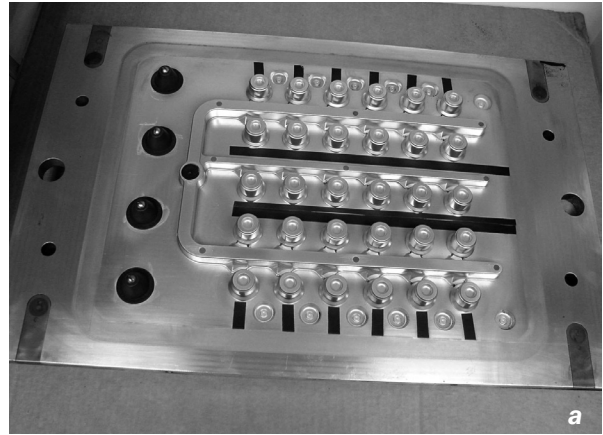
Advantages of these special gating systems are: 1) high casting yield, 2) ease of removal of castings from gates, and 3) reduced grinding requirements in the cleaning room. Perhaps the major disadvantage is the fact that castings often become detached from the gates at shakeout, necessitating



Figs. 7-19a, b & c. These three photos illustrate a kiss gated pattern system for a valve cap. (Artwork courtesy of Ford Meter Box).

the use of special screens, or manual retrieval from mechanized systems. Figure 7-18 is a schematic representation of both knife gating and kiss gating.

In kiss gating, where the gate slightly overlaps (or “kisses”) the casting, the mold cavity must be entirely in either the cope or the drag. The runner itself, which is in the opposite half of the mold, also serves as the gate since it overlaps the edge of each casting by some $1/32$ to $3/32$ inch.



Figs. 7-20 a, b & c. These three photos illustrate a knife gating system for a 5/8" coupling thimble. (Artwork courtesy of Ford Meter Box)

In knife gating, the castings are partially in the cope and partially in the drag. The runner that may be in either half of the mold, passes very close to the mold cavities and requires only a short gate connection to each cavity at the parting line. Gate thickness ranges from $1/32$ to $3/32$ inch. Figures 7-19 and 7-20 illustrate successful applications of kiss gating and knife gating.

Most knife and kiss gating systems are necessarily pressurized. There is no upstream choke in the system, and the total cross-sectional area of the gates is less than that of either the runner or the sprue. Thus, the metal velocity will be at a maximum at the gates, causing the metal to be jetted into the mold cavity to fill thin sections. It is essential to maintain continuous flow through each gate. Runners must be filled as quickly as possible, unless molds are tilted to achieve progressive filling of cavities. If flow through a given gate is interrupted even momentarily, or if gates are too small, misruns are certain to occur. Misruns will also occur if gates in a multi-cavity mold are so large that the metal cannot be poured rapidly enough to assure that all cavities fill quickly, simultaneously, and uniformly. In both cases, misruns result from an interruption or slowing of the flow of metal into the mold cavity after it has started to fill. This causes the gates to freeze off partially or completely, so that adequate flow cannot resume once the metal supply has been re-established. These gating systems demand the utmost care and consistency in pouring practice.

VENTING

A common problem occurring with many gating systems is the build-up of gases in the mold resulting in defective castings. This issue is often particularly problematic with Group III alloys which are sensitive to metal turbulence. Mold gases, including entrapped air, can result from a variety of factors often making it difficult to determine the precise root cause of the gas. If a pathway is provided to permit the gas to escape the mold thus preventing the gas from impeding the flow of metal into the mold cavity, defective castings may be prevented. Such a pathway is referred to as a vent, or mold vent. Vents are typically located in areas where gas build-up has been observed or is expected to be likely, such as off of the open end of cores. In some cases, the practice of “stick” or “straw” venting is employed, where a rod (usually 1/8” in diameter or smaller) is inserted vertically into the cope of the mold immediately prior to pouring above the area where gas build-up is suspected. The vent need not extend completely to the mold cavity, as the permeability of the sand is sufficient to allow gas to pass through into the vent while not permitting metal to enter the vent which would then need to be removed from the casting after shake-out. Though often effective, when done manually this method is labor intensive and subject to the skill of the molder for proper vent placement. Vents of this type may also be produced by adding a permanent rod to the cope side of the plate as part of the pattern. This approach puts the vent in contact with the mold cavity resulting in metal rise into the vent but eliminates the concerns raised by manual vent placement. Another method of venting is “parting-line” venting, where a channel is located on the cope side of the plate leading from an area of suspected gas build-up out to the parting line of the mold. This channel may be designed as part of the pattern or formed by the use of shim stock, cut rod or even thick tape, particularly when trouble-shooting problem jobs. With this technique, the vent need not penetrate completely to the mold cavity, thus taking advantage of the permeability of the sand and eliminating the need for subsequent removal

of metal from the casting. Though all care should be taken to prevent the formation of mold gases initially through proper melt practice and gating system design, the application of venting techniques may correct or prevent problems and help assure quality castings.

GENERAL COMMENTS

Some of the defects commonly attributed to incorrect gating and pouring are: cuts and washes; dirt, slag, and other inclusions; expansion defects; misruns and cold shuts; open grain structure; rough surface; surface and sub-surface shrinkage (see the chapter on Common Defects).

The layout of patterns on a plate should allow flexibility, since certain changes may become necessary in order to minimize scrap rate. Frequently, as many patterns as possible are placed on a matchplate, with little room left for adequate gates and runners and with little consideration for the importance of directional solidification. Patterns, gates, risers and runners should occupy no more than 50 to 60% of the pattern plate since ample sand volume must be available to absorb and dissipate the heat of the molten metal. Gates should never be placed nearer than two inches from the sprue base.

For the high-shrinkage Group I alloys, it is important to employ hot risers, gated directly from the runner where possible. Conversely, for Group III alloy castings with both thick and thin sections, it is preferable to gate into one or more thin sections in order to minimize temperatures in the heavy sections. “Dead” risers may be attached to the heavier sections as required in order to prevent sink marks or draws when these sections freeze (see the chapter on *Solidification, Feeding and Design*). Gating into thin sections has the added advantage of permitting reduced pouring temperature without the danger of misruns and cold shuts.

Finally, regardless of how well a gating system is designed, castings of acceptable quality will not be produced unless the ladle is maintained as close as possible to the pouring basin or sprue cup, and unless the sprue is filled quickly and kept full throughout pouring.

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SOLIDIFICATION, FEEDING AND DESIGN

INTRODUCTION

The commercial copper-base alloys as a group are almost unique in the range of solidification characteristics they exhibit. Knowledge of solidification behavior is especially important to foundry personnel since this behavior controls the incidence of shrinkage porosity, the patterns that this shrinkage porosity takes, and the feeding techniques required. Because of the wide variations in the mode of freezing of the copper-base alloys, a particular casting which requires a specific risering and gating procedure when cast in one alloy may require a different procedure when cast in another alloy. Therefore, copper-base alloy foundries frequently need to make radical changes in practice. A thorough understanding of the freezing characteristics of copper alloys and their impact on risering and gating procedures is of importance to all engaged in the manufacture of castings using these alloys.

This chapter aims to provide foundry personnel with an understanding of the basic mechanism of solidification; to indicate the connection between the solidification mechanism, shrinkage phenomena, and feeding practice; to consider the rates at which copper alloys freeze; and to discuss certain other phenomena taking place during freezing, such as grain refinement and segregation.

The risering of copper-base alloy castings is discussed in some detail in the second part of this chapter. Methods of determining riser size are given for the different alloy groups, and related topics such as the use of riser insulation and chills are considered. Certain factors in the design of copper-base alloy castings that are important in view of risering techniques are discussed in the third part of this chapter.

INFLUENCE OF SOLIDIFICATION CHARACTERISTICS ON SHRINKAGE POROSITY

Effect of Composition on Solidification

For practical purposes, it is convenient to divide the copper-base alloys into two groups to discuss solidification. This classification will be somewhat rough, as these groupings represent behavior extremes, some alloys will fall into an intermediate classification.

Group I—Alloys Freezing by Skin Formation (Short-Freezing-Range Alloys)

This group encompasses pure copper in its various forms and the “high coppers” such as cadmium-copper, chromium-copper, and beryllium-copper. Also included are the near-eutectic alloys such as many of the aluminum bronzes, in addition to certain yellow bronzes. When a molten alloy of Group I is poured into a sand mold there is first a delay period during which the mold extracts the superheat from the liquid metal. Solidification begins once the temperature of the metal adjacent to the mold wall has fallen to the freezing point, or liquidus temperature in the case of alloys (slight undercooling sometimes will occur in practice). The onset of freezing is marked by the formation of numerous small crystallites against the mold walls. The crystallites which are most favorably oriented then begin to grow rapidly, both sideways and inward, linking up with adjacent crystallites to form a continuous skin or shell of solidified metal, known as the solidification front (see Fig. 8-1). The front, which is actually the boundary between liquid and solid metal, then advances into the interior of the casting in a direction perpendicular to the mold walls.

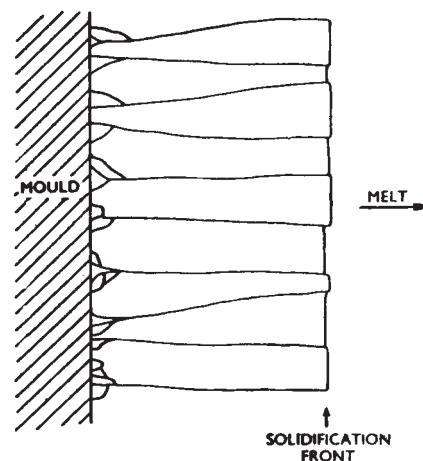


Fig. 8-1. The solidification front in high-purity copper is shown.

This mode of freezing, shown in Fig. 8-2, illustrates the progressive stages in the freezing of a section of a plate casting. The conditions shown here are, strictly speaking, typical only for pure metals such as elemental copper, or for alloys of exactly eutectic composition—both of which freeze at a fixed temperature. The solidification of metals containing small amounts of alloying elements or impurities (oxidized copper, chromium-copper, etc.) is quite similar except that instead of being smooth, the solidification front is somewhat roughened due to a tendency toward dendritic growth of the crystals. Freezing for these alloys is depicted in Fig. 8-3.

The characteristic feature of all materials in Group I, therefore, is that they have a very short freezing range or none at all. The macrostructures of castings made from these alloys usually exhibit columnar crystals.

Group II Alloys—Freezing in a Mushy Manner (Wide-Freezing-Range Alloys)

Group II is comprised of alloys of long freezing range such as the tin bronzes, red brass, certain yellow bronzes, nickel silver, and other alloys as listed in Table 8-1. The mechanism of freezing for this group of alloys is completely different from that of alloys in Group I. As before, freezing begins with the deposition of numerous crystallites on the mold walls. From this point on, however, all similarity to freezing characteristics of Group I alloys vanishes. Growth of the crystallites formed on the mold walls is almost immediately retarded or even halted temporarily. The reason for this is that the crystallites initially frozen are considerably poorer in alloying elements than the liquid from which they froze.

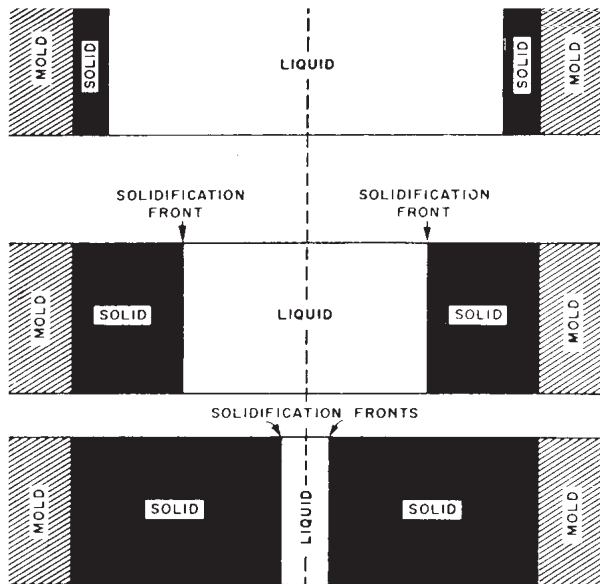


Fig. 8-2. Stages in the freezing of high-purity copper.

When these crystallites are formed, atoms of the alloying elements are rejected into the surrounding liquid, thus greatly enriching this liquid in these elements. This substantially lowers the freezing point of this liquid so that crystal growth temporarily cannot continue.

Table 8-1 Classification of Copper Alloys by Solidification Type

Group I. Alloys freezing by skin formation. (Pure metals and alloys of short freezing range)	Group II. Alloys freezing in mushy manner. (Alloys of long freezing range)
Deoxidized Copper	Tin Bronze*
O.F.H.C. Copper	Leaded Bronze*
Tough Pitch Copper	Red Brass*
Chromium Copper	Semi-red Brass*
Tellurium Copper	Nickel Silver*
Cadmium Copper	
Beryllium Copper*	
Manganese Bronze*	
Yellow Brass*	
Aluminum Bronze	
Silicon Bronze*	
Manganese Aluminum Bronze	
Cupronickel	

*Classification dependent on precise composition and conditions of freezing; longer-freezing-range alloys in the group tend toward mushy freezing.

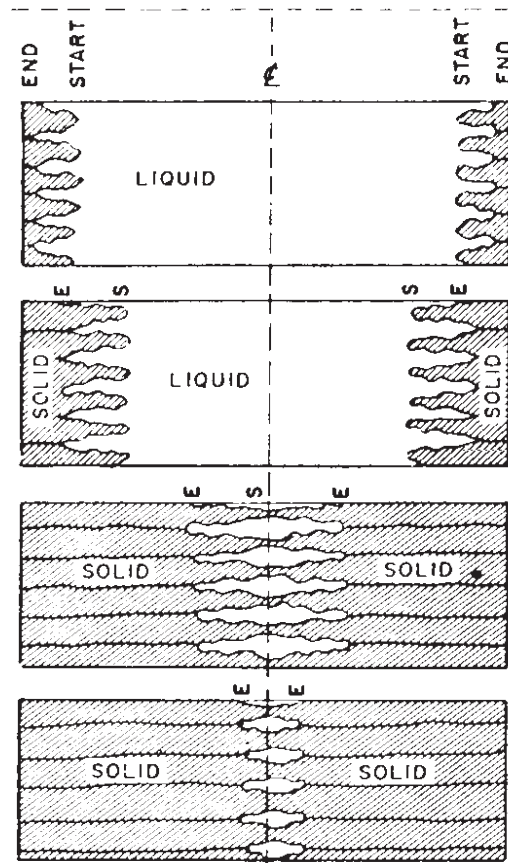


Fig. 8-3. Stages in the freezing of copper alloys with low alloying content. Freezing by skin formation.

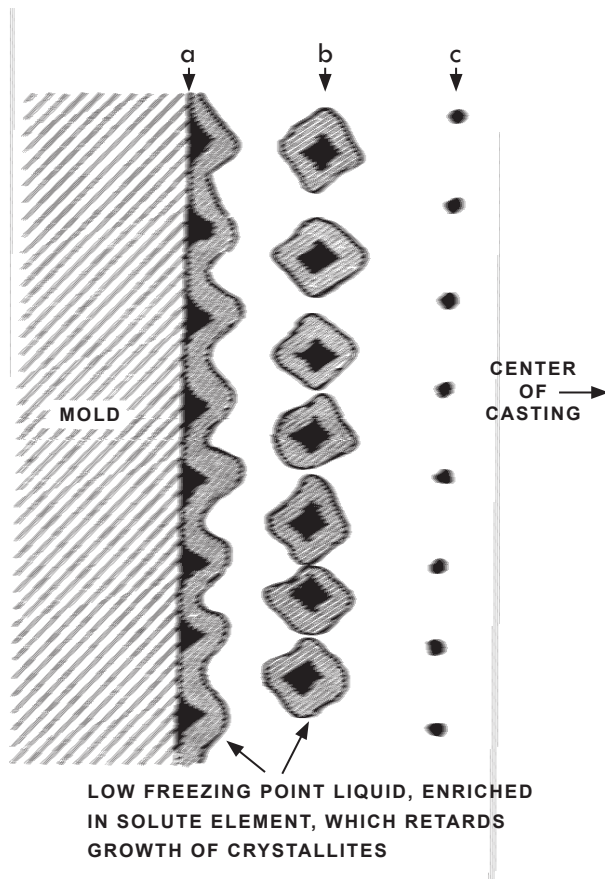


Fig. 8-4. Diagrammatic representation of the restriction of crystal growth in the freezing of copper alloys with high alloy content.

Heat extraction by the mold continues and slightly lowers the temperature of this liquid as well as of the liquid in the unaffected region beyond it, nearer to the interior of the casting. This decrease in temperature causes a second batch of crystallites to nucleate just outside the enriched area, as indicated in Fig. 8-4. In turn, growth of this second crop of crystallites is restricted and a third batch of crystallites quickly forms towards the interior of the casting, just beyond the enriched region which now surrounds the second batch of crystallites. The process is repeated until small crystallites have been nucleated throughout the entire casting in the manner indicated in Fig. 8-5. Freezing continues by the gradual enlargement of all the crystallites. This process takes place simultaneously throughout the entire casting. The crystallites closest to the mold wall grow slightly faster than do those near the center of the casting, but the differences are not especially marked. The process of freezing in these alloys is analogous to the setting of cement—the material at first being fluid, then becoming mushy, and finally becoming rigid. Keeping in mind the mode of freezing, it is easy to understand why the macrostructures of these castings show equiaxial crystallization.

The freezing mechanisms described above represent two extremes. In practice, there is no sharp transition from the

skin-forming mode of freezing to the mushy stage of freezing as the alloy content of copper is increased; instead, continuous intermediate stages of freezing are observed as the alloy content increases. The precise mode of freezing is also affected by solidification conditions, such as rate of freezing. Melts of the same composition will normally exist in Groups I or II. However, under extreme cooling conditions, either columnar or equiaxial structures or both may be produced in the casting.

In the intermediate mode of freezing the first-formed dendrites struggle towards the interior of the casting, as illustrated in Fig. 8-6; however, because the liquid metal separating them becomes enriched in alloying elements, the dendrites are not able to link up until very late in the freezing process when the entire casting is almost solid. The spindly dendrites of the kind illustrated in Fig. 8-6 will sometimes continue to grow until they reach the center of the section; in this event, the macrostructure of the casting is wholly columnar. Frequently the growth of these dendrites stops altogether at a certain stage, as indicated in Fig. 8-6, and the central region of the casting freezes in the mushy manner typical of alloys of Group II. The central zone of the casting then possesses an equiaxial macrostructure, whereas the outer regions have a columnar structure. Note that in these alloys a liquid pathway may extend through the solidified crystals to the mold wall itself, almost until the end of freezing.

EFFECT OF SOLIDIFICATION ON SHRINKAGE POROSITY

The different freezing mechanisms that have been described are vitally important from the viewpoint of feeding a casting, since they govern the type and distribution of shrinkage porosity that tends to occur.

Group I Alloys

Alloys of Group I are characterized by the formation of deep, symmetrical pipes. The way in which these pipes form is illustrated in Fig. 8-7. High-purity copper and other pure metals form smooth pipes of perfect shape.

Copper containing small amounts of alloying elements or impurities tends to form less regular pipes whose walls are somewhat roughened, corresponding to the “hill-and-valley” appearance of the solidification front (compare Figs. 8-1 and 8-3).

In plate or bar sections, alloys of Group I, give rise to centerline shrinkage of the type indicated in Fig. 8-8 when not fed properly. This type of shrinkage arises toward the end of freezing because the tips of the crystals approaching the centerline from opposite directions make contact with one another (Fig. 8-3); thus, the residual liquid metal in the valleys is sealed off from any access to the reservoir of feed metal in the risers. Unfed “heat centers” in Group I alloy castings give rise to pronounced, smooth-walled cavities as shown in Fig. 8-8.

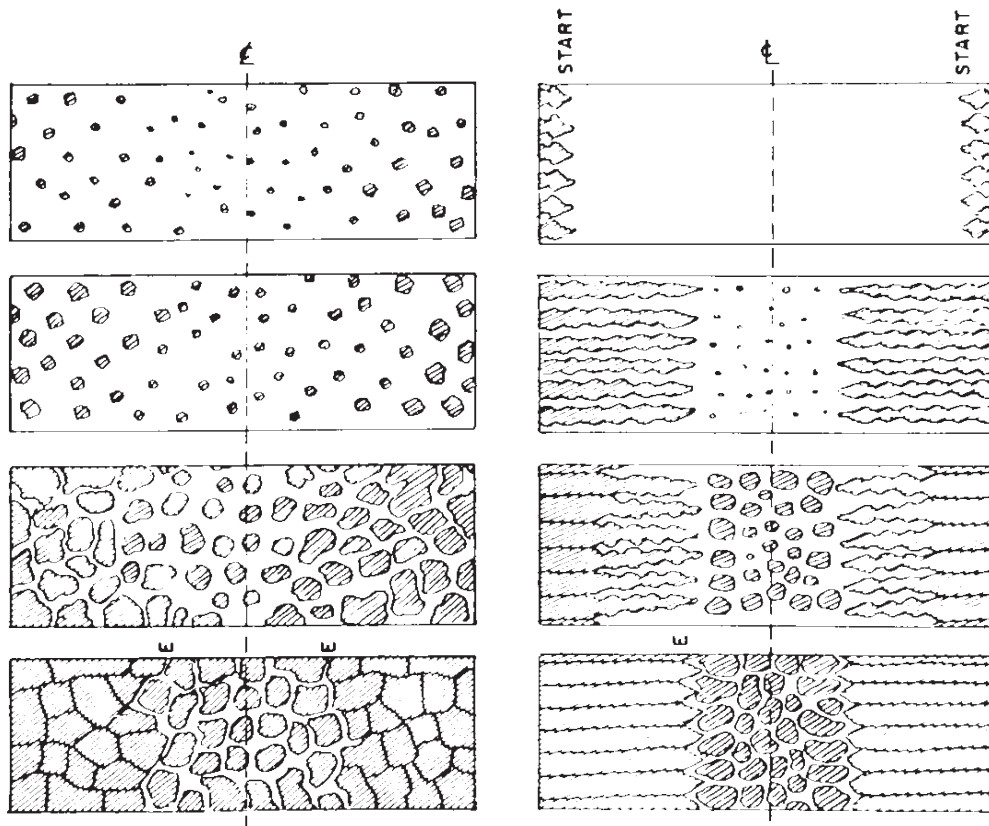


Fig. 8-5. Left: Stages in the freezing of high-alloy copper is shown.

Fig 8-6. Right: Stages in the freezing of a copper alloy in the intermediate manner.

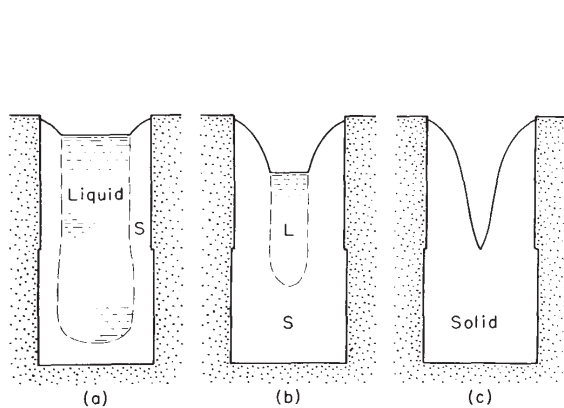


Fig. 8-7. Formation of pipe in copper alloys freezing by skin formation.

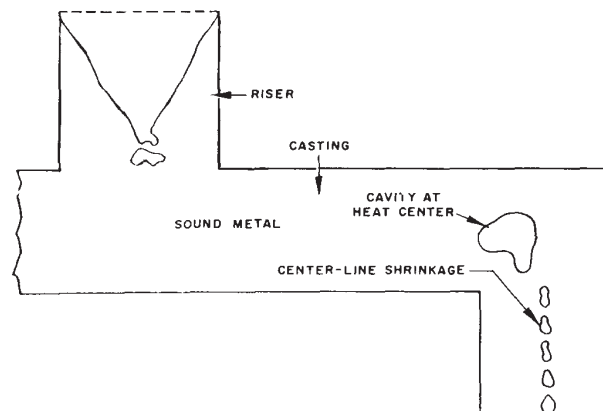


Fig. 8-8. A representation of shrinkage in castings made from copper alloys freezing by skin formation is shown in this diagram.

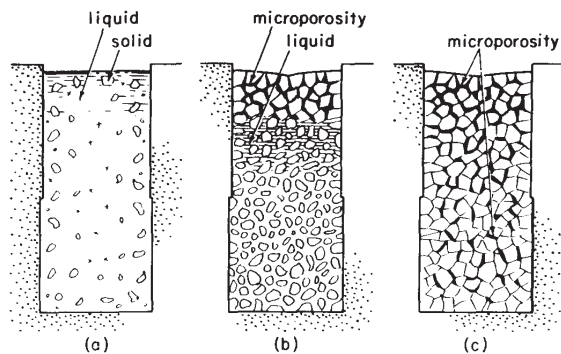


Fig. 8-9. Mass feeding in copper alloys with a long freezing range.

Group II Alloys

In the early freezing stages of Group II alloys, the metal consists of a liquid with suspended tiny, solid crystallites. At this stage in freezing, the metal is still quite fluid and the shrinkage that occurs as the crystallites grow is readily compensated by a fall in the level of the essentially liquid mass. Some fluidity is maintained, in fact, until the alloy is approximately 70% solid. Toward the end of this period, the solid-liquid mixture is naturally becoming very sluggish, but shrinkage in volume can still be accounted for by settling-out of the solid material. This process has been termed mass feeding, and it accounts for roughly two-thirds of the total solidification shrinkage of the alloy. Thus, for an alloy whose total volumetric solidification shrinkage is 6%, approximately 4% is due to mass feeding. This mechanism is illustrated in Fig. 8-9.

The process of mass feeding is normally aided by atmospheric pressure that acts on the walls of the casting, tending to oppose the formation of any cavities within the casting. For example, if a chunky casting is made in red brass without any feeders at all, it is found that the casting surprisingly contains only about 2-3% porosity. The reason for this is that atmospheric pressure has dished the walls of the casting, thus compacting the solidifying mass and aiding mass feeding. Attachment of a tall, small-diameter riser to the casting results in only a slight reduction in porosity, but much of the dishing of the walls is avoided.

When solidification is about 70% complete, the growing crystals have become so large and numerous that they interlock with each other and the casting begins to become rigid. At this stage, mass feeding necessarily stops; thereafter, the growing dendrites compete with each other for the remaining liquid metal which is now isolated in numerous small pools scattered throughout the alloy (see Fig. 8-9). It is not difficult to see how this mode of freezing gives rise to finely

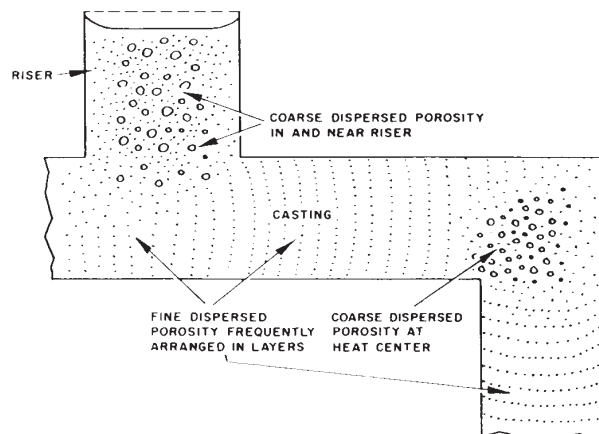


Fig. 8-10. Diagrammatic representation of shrinkage found in castings made from copper alloys with a long freezing range.

dispersed microporosity since, each of the isolated pools of liquid eventually freezes giving rise to a small pore as the result of its freezing shrinkage.

Figure 8-10 illustrates the kind of shrinkage porosity generally found in alloys of this group. Throughout most of the casting fine microporosity is observed, but at the heat centers and within the riser the porosity tends to be somewhat coarser- although still dispersed. In castings of certain alloys (for example, grain-refined tin bronze), the microporosity tends to be arranged in definite layers. This type of porosity is extremely harmful to mechanical properties and pressure tightness and is sometimes known as layer porosity.

The shrinkage porosity in castings of alloys of the intermediate freezing group is in some ways similar to that of the skin-forming alloys and to that of alloys freezing in the mushy manner. For example, the tendency toward pipe formation is considerably greater than it is for alloys of Group II (where it is almost totally absent) but this tendency is less than for alloys of Group I. These alloys show a tendency toward the formation of dispersed porosity which is normally considerably coarser than that found in the mushy-freezing alloys of Group II. At the same time, some tendency toward the formation of centerline shrinkage is observed especially when columnar crystal growth penetrates to the mid-section of the casting.

When alloys with either wide or intermediate freezing ranges are sand-cast in relatively thin (less than 3/8 in.) sections, or are chill-cast, they freeze quickly enough to form a dense skin or surface layer that is essentially free of porosity. The last metal to solidify at the center of the section, since it freezes more slowly, will often exhibit dispersed shrinkage porosity. This explains why castings made with wide-freezing-range alloys, cast in thin sections, may be pressure-tight throughout (except for machined areas causing removal of the dense surface layers).

FREEZING RATES

The freezing rate of the skin-forming alloys of Group I may be expressed in terms of the rate at which the solid shell formed at the mold wall thickens. If d is the shell thickness after a time, t , measured from the instant of pouring the casting, then:

$$d = q\sqrt{t}$$

Where q is the solidification constant of the alloy.

For most sand-cast copper-base alloys of short freezing-range, the solidification constant q is approximately 0.27 in./min.^{1/2}

For obvious reasons, the freezing rate of alloys of Group II cannot be expressed in this way, although a similar equation involving the weight of metal frozen can be derived. With alloys of this group, however, the main interest is the total freezing time of the casting that is given approximately by Chvorinov's Rule:

$$t = \frac{1}{q^2} \left(\frac{V}{A} \right)^2$$

Where; V is the volume of the casting and A is its surface area. For copper alloys, the quantity $1/q^2$ is about 13.7, the units being inches and minutes.

CHILL CASTINGS

With some exceptions, copper alloys cast in chill molds exhibit much the same freezing characteristics as they display in sand molds. Freezing in chill molds is about four times faster than in sand molds and this higher rate of solidification results in somewhat narrowing the zone of partial freezing. Alloys freezing in the mushy manner, when sand-cast, tend toward the intermediate mode of freezing when cast in a chill mold; similarly, alloys freezing in the intermediate manner in sand molds show a more pronounced tendency toward skin formation when they freeze in a chill mold. This is well exemplified in Fig. 8-11, which shows the movement of the start and end of freezing waves in copper, yellow brass, and red brass. In these diagrams, the vertical distance between the start and end of freeze curves indicates the size of the zone of partial freezing at any particular time. The horizontal distance between these two curves indicates the time the concerned location was in a state of partial freezing.

Figure 8-11 shows that copper freezes by skin formation both in sand and in chill molds. Red brass, on the other hand, has a long period during which the entire casting is semi-solid. In chill casting, the higher rate of freezing certainly reduces the period during which the mushy state obtains, but this period is still very long, as Fig. 8-11 shows.

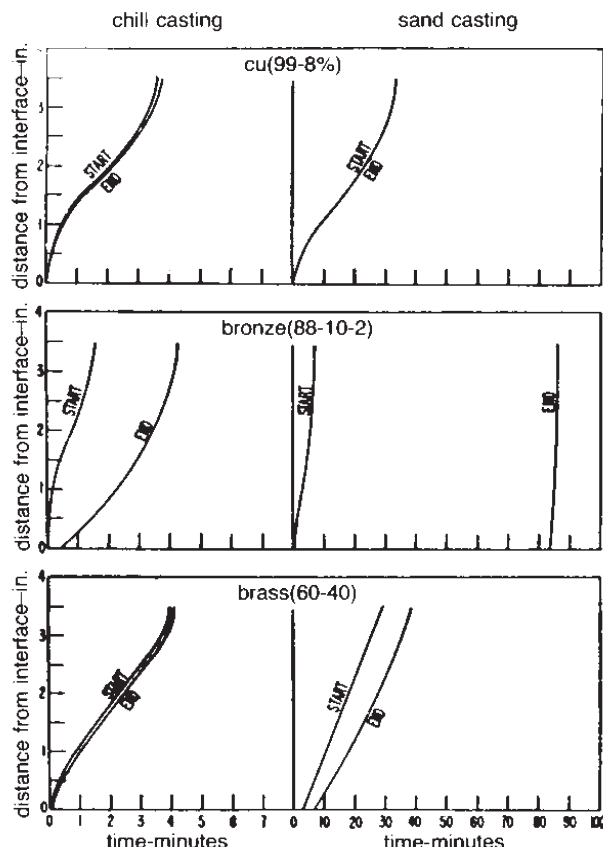


Fig. 8-11. A freezing comparison for copper alloys made in sand molds and chill molds.

The yellow brass is exceptional in exhibiting quite a wide partial-freezing zone when sand-cast, whereas in chill castings the depth of the zone is markedly reduced and the mechanism of freezing approaches skin formation.

GRAIN REFINEMENT

The number of crystals nucleated in copper alloys of long freezing range governs the grain size. This number depends on the number of nuclei for crystallization present in the melt when it is poured or generated prior to the onset of freezing. Consequently, a reduction in grain size can be secured by artificially increasing the number of these nuclei.

Grain refinement of copper alloys has never been utilized extensively, although methods for use with aluminum bronze, red brass, and gunmetals have been developed. Red brass can be grain-refined by the addition to the molten alloy of 0.05% zirconium; the presence of about 1% iron also produces some refinement.

Iron additions of this order also refine the cast grain size of the aluminum bronzes and of manganese bronze; iron is present in many of these alloys and the grain size of cast-

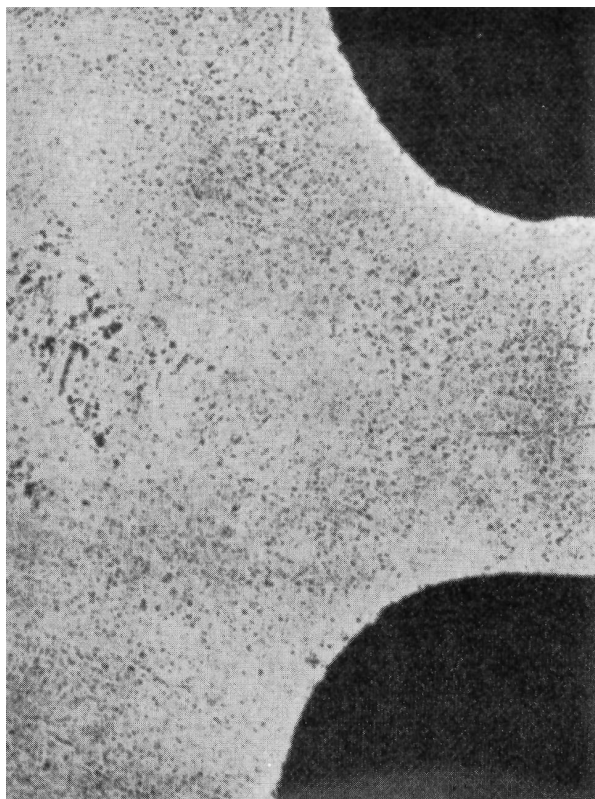


Fig. 8-12. The microstructure of a coarse-grained red brass casting is shown.

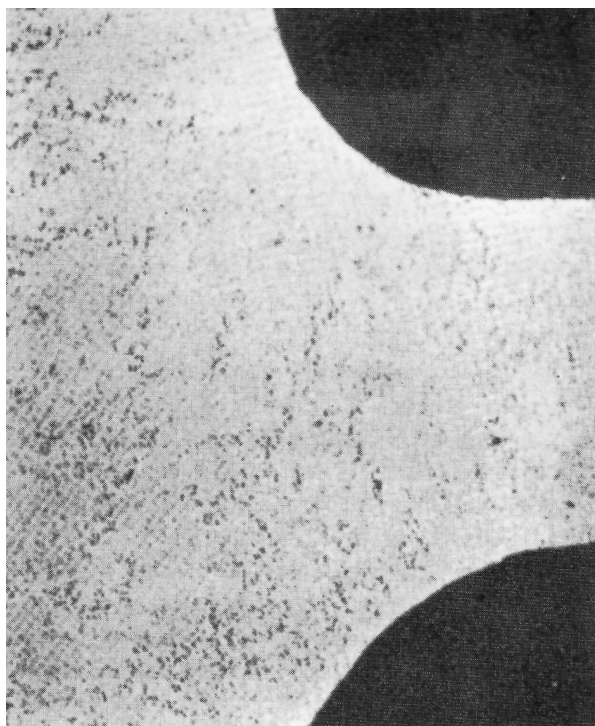


Fig. 8-13. The microstructure of a fine-grained red brass casting is shown with layer porosity.

ings made in them is normally fine. The iron-free aluminum bronzes and beta brasses may be refined by the addition of 0.03% zirconium together with 0.02% boron, or by the addition of boron alone; many of the rare earth metals can also be added.

In the case of the iron-free aluminum bronzes, the grain refining methods produce a useful improvement in strength. The effects of grain refinement on bronzes and gunmetals are more complex.

The majority of bronze and red brass castings are not particularly well fed, and in these castings the effect of grain refinement may be disastrous. The reason for this is that grain refinement, for reasons which are not well understood, is liable to convert ordinary well-dispersed microporosity into layer porosity or concentrated, interconnected porosity; these characteristics are extremely deleterious both to mechanical properties and to pressure-tightness (Figs. 8-12 and 8-13). Therefore, grain refinement does not appear to be generally useful for bronzes and red brass.

SEGREGATION

Although a detailed account of segregation in sand-cast copper-alloy castings will not be given here due to space limitations, it is worth mentioning that the type of segregation observed is closely connected with the freezing mode. Alloys of Group I which freeze in the skin-forming manner usually show normal segregation. In sand castings, the extent of this is seldom marked and is usually negligible. On the other hand, castings made in alloys freezing in the mushy manner often show inverse segregation caused largely by constitutional factors. The surface layers of the casting are often found to be considerably enriched in alloying elements.

Gas evolution in the late stages of freezing may tend to force enriched liquid to the surface of the casting through the channels that are still open between the crystals, thus forming "beads" of enriched metal on the surface of the casting. Tin sweat is a common example of this kind of segregation. Minor segregation (microsegregation) is common in copper alloys. Coring of tin bronzes is typical of this kind of segregation.

DIRECTIONAL SOLIDIFICATION

The desire to produce quality castings is as old as the foundry industry, but the concept of directional solidification was not appreciated until the early 1930's. Directional solidification is defined as that process by which metal in the mold begins to solidify at points farthest from the risers and continues to solidify progressively toward the riser, which is the last part to solidify. In this way, the shrinkage occurs in the riser and a sound casting is produced. Directional solidification ensures that solidification from the sidewall of the casting will not be so rapid as to create bridging across the section, preventing the flow of liquid metal from the riser to the farthest part of the casting.

Solidification from the sidewall is called lateral solidification, and solidification parallel to the mold walls is called longitudinal solidification. When the rates of the lateral and longitudinal solidification are adjusted to produce a sound casting, controlled directional solidification is achieved. Directional solidification means, as depicted in Fig. 8-14, that the gradation of the rates of progressive freezing along the casting are such that positions on the centerline near the casting edges freeze before those points closer to the riser.

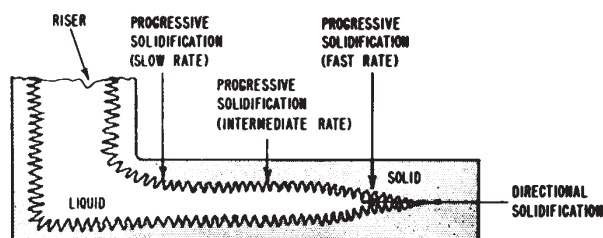


Fig. 8-14. Features of progressive and directional solidification are shown.

The discussion of directional solidification so far pertains to the freezing of pure metals, low-carbon steel, aluminum bronze, and other alloys that solidify in an essentially skin-forming manner. Unfortunately, most copper-base alloys have a mushy mode of freezing. As foundry personnel know, sand castings in these alloys invariably contain a certain amount of distributed porosity (microporosity) and the tendency toward this defect increases with the size of the casting. Castings of this type of alloy present a problem because they stubbornly resist the most determined efforts to make them sound by directional solidification methods. The average casting of this type may contain 1 to 2% porosity; it is very difficult to reduce the amount of porosity to less than about 1% in all except small castings. Attempts to reduce porosity by increasing the size of the risers are often unsuccessful and may actually decrease the soundness of the casting.

RISERING PROCEDURES FOR COPPER-BASE ALLOYS

Group I—Alloys with Narrow Freezing Ranges

The feeding technique for Group I alloys is similar to that used in the manufacture of steel castings. Gates and risers are disposed so that directional solidification is assured, with due consideration being given to the feeding range of the alloy in question. To avoid hot spots, local chills may be applied to bosses, ribs, etc.

The general principle in risering these alloys is to make use of the retarding effect of the risers on solidification, and the accelerating effect of external corners and edges of the casting, so as to obtain a V-shaped solidification front with the broad end toward the riser (Fig. 8-14).

Thus, ready access of feed metal is ensured to the region of the casting where, at any instant, freezing is being completed (i.e., the apex of the "V").

A single riser located, for example, on a bar or plate section will only feed for a limited distance along the section. This distance is known as the feeding range of the riser. Frequently, feeding-range limitations necessitate the use of multiple risers, each feeding a section of the casting, or the use of chills which act to increase the effective feeding range.

Feeding Ranges of Group I Alloys

Since all parts of a casting must be within the feeding range of at least one of the risers, it is important to have quantitative information regarding feeding ranges. The feeding range values for Group I copper-base alloys have not been well documented. In the absence of specific data for particular alloys, satisfactory results can often be attained by applying values that have been developed for carbon steels. The following approximate values for feeding ranges (Table 8-2) have been quoted in the literature and should be used with caution:

Table 8-2 Approximate Values for Feeding Ranges

<i>Alloy</i>	<i>Shape</i>	<i>Feeding Distance in Terms of Thickness (T)</i>
Manganese bronze	Square bars	$4 T$ to $10 \sqrt{T}$, depending on thickness
	Plates	$5.5 T$ to $8 T$, as above
Aluminum bronze	Square bars	$8 \sqrt{T}$
Nickel-Al bronze	Square bars	Less than $8 \sqrt{T}$
Cupronickel	Square bars	$5.5 \sqrt{T}$

Typical values for manganese bronze plates, summarized in Figs. 8-15 and 8-16, indicate that feeding range increases more or less linearly with section size, having a value of about $6T$. This statement applies to sections which are terminated by a free end. It will be noted that about two-thirds of the feeding range is actually contributed by this end effect. Therefore, if end effects are absent, as in the case of a ring-shaped casting, the feeding ranges will be quite short and such castings may have to be fed by a number of risers whose spacing is such that the distance between them does not exceed about four times the section thickness. Conversely, the spacing between risers may be increased to about ten times the section thickness if chills are located midway between each riser (Fig. 8-17).

Riser Shape Considerations

From the viewpoints of thermal efficiency and ease of molding, a cylinder with a height-to-diameter (H/D) ratio in the range of 1:0 to 1:5 is the most desirable shape. Cylindrical,

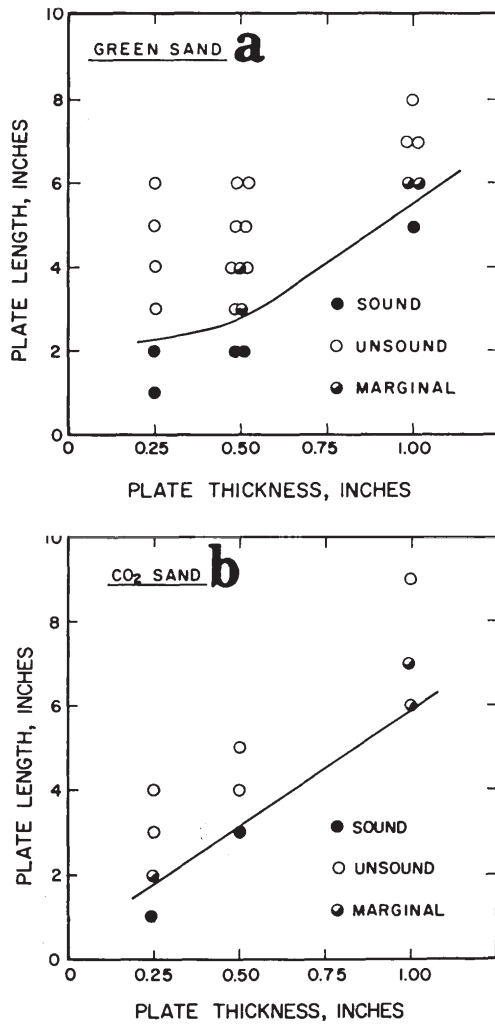


Fig. 8-15. Feeding distance for manganese bronze plates are shown, (a) cast in green sand, and (b) cast in sodium-silicate bonded sand.

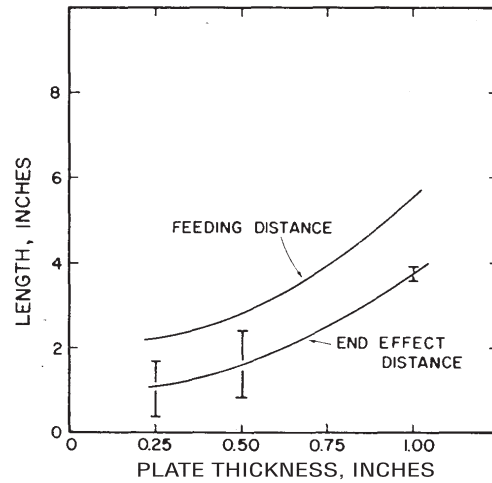


Fig. 8-16. The end effect distances are compared to the feeding distances in manganese bronze plates. The range of values observed for the end effect distances are also shown.

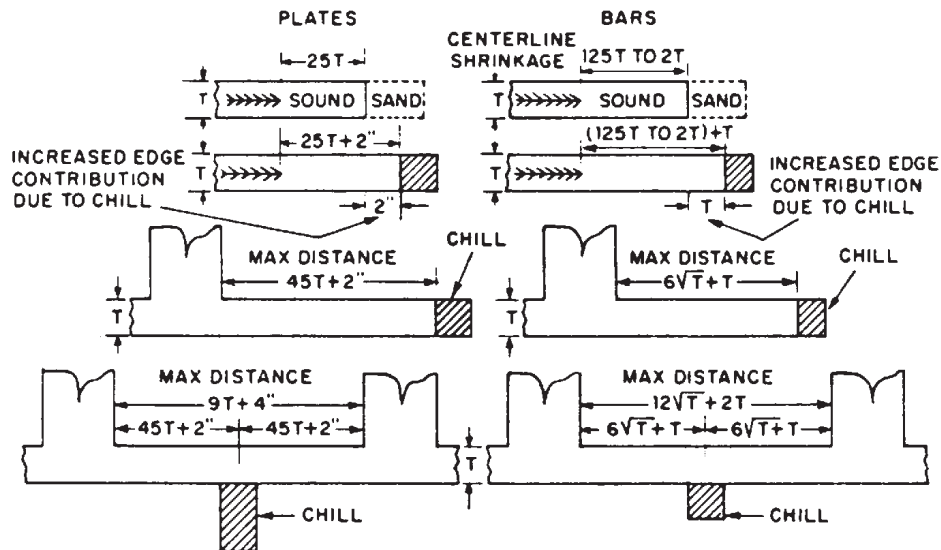


Fig. 8-17. The effect of chills in increasing feeding-range of risers is shown.

blind side-risers with a hemispherical top and bottom may be used with smaller castings. Such risers are connected to the casting by a short neck and the gate is usually attached to the riser for best results. In castings that have multiple risers located at different vertical levels, the risers located near the top of the casting will feed the lower sections of the casting (and the risers associated with them) until such time as the interconnecting section freezes off. This places a significantly increased feed demand on the upper risers, possibly making them inadequate. In this situation, the size of the upper riser must be increased so that it is capable of meeting the increased feed metal demand. The volume increase required is usually about one-half the sum of the lower section plus associated riser and neck, multiplied by the total shrinkage of the alloy between the pouring temperature and the solidus temperature. This effect can be minimized (but not eliminated) by chilling the interconnecting section. The easiest way to increase the riser volume is to increase its height.

Extremely high yields of 80% or more can be obtained when insulated risers are used. For Group I alloys, the volume of the riser may be only 15 to 25% that of the casting section fed.

Heat losses by radiation from the exposed top surface of the riser represent a considerable percentage of the total heat loss, amounting to 25% and 50% for non-insulated and insulated risers, respectively. Therefore, regardless of riser type, the top of the riser should always be covered with either exothermic or insulating material in order to promote maximum feeding efficiency. It is recommended that the minimum depth of cover material used be one-tenth the diameter of the riser. It is most important to prevent premature freezing-over of the top of the riser in order to avoid isolation of the feed metal from contact with the surrounding atmospheric pressure. Atmospheric pressure acts to force-feed the liquid metal into the adjacent casting section as it shrinks.

Exothermic sleeves, which were once popular, have now been largely discontinued in favor of insulating sleeves that are more economical to use and cause fewer problems. Substantial savings can be achieved with the use of either type of sleeve, as will be briefly discussed.

Calculating Riser Dimensions

From time to time, various methods have been advanced for the calculation of the optimum riser size to be used to feed a particular casting or casting section. One of the more popular methods was developed at the U.S. Naval Research Laboratory, and empirical relationships were established between volume ratio and shape factor, where:

$$\text{Volume ratio} \\ \text{(Casting volume/Riser volume)} = \frac{V_c}{V_r}$$

$$\text{Shape factor} = \frac{L + W}{T}$$

(L, W and T being casting length, width, and thickness, respectively)

Much of the published work on risering of short freezing-range copper-base alloys involved the application of this so-called NRL method, and numerous examples of this technique can be found in the foundry literature.

In recent years, greater attention has been given to what has become known as the "modulus method" for calculating riser size, including the development of pertinent data and computer programs. This method is now, and will no doubt continue to be, the most widely used technique in the industry.

Modulus risering methods have been most extensively developed in connection with the production of steel castings, but they have also been applied to riser design for short-freezing-range copper alloys. A brief description of this method is given below. (For greater detail the reader is referred to the bibliography appended to this chapter.)

Chvorinov's Rule states that the freezing time, t , of a cast shape is given by the relationship:

$$t = k \times \left(\frac{V}{A} \right)^2 \quad (1)$$

In this expression, V and A are the volume and surface area, respectively, of the cast shape and k is a constant of proportionality whose value is dependent on the thermal properties of the metal and the mold.

For convenience, the term (V/A) in Chvorinov's equation is generally replaced with the symbol, M , a value referred to as the "modulus" of the shape. The term "modulus" is merely a shorter way of saying, "volume divided by surface area." Equation 1, above, can be rewritten more simply to read:

$$t = k \times M^2 \quad (2)$$

Since Chvorinov's equation can be applied to any cast shape, it applies equally to what is intended to be the casting itself and to the attached riser. When dealing with connected shapes, such as a riser and a casting, the surface area of each shape to be considered includes only those portions which contribute to the loss of heat during freezing.

Two equations are required to describe the freezing times of the casting and the riser, respectively, and the subscripts c and r will be used to distinguish one from the other for all terms of the equation:

$$\text{Casting: } t_c = k \times M_c^2 \quad (3)$$

$$\text{Riser: } t_r = k \times M_r^2 \quad (4)$$

In a practical sense, we are not so much concerned with the actual time required for solidification to take place as we are about the relative solidification times for riser and casting. Obviously, to be effective the riser must solidify after the casting has done so. Mathematically, this means that t_r must be greater than t_c by some amount. Another way of saying the same thing is to state that:

$$\frac{t_r}{t_c} = F^2 > 1 \quad (5)$$

This means that the ratio of the solidification times of riser and casting is some number whose value, when squared, is a number greater than one. This can be written as:

$$\frac{t_r}{t_c} = \frac{k \times M_r^2}{k \times M_c^2} = F^2 \text{ (or) } M_r^2 = F^2 \times M_c^2 \quad (6)$$

Further simplified, this becomes:

$$M_r = F \times M_c \quad (7)$$

This means that the modulus for the riser, M_r , must be greater than the modulus for the casting by some factor, F . Experience has shown that the proper value of F depends on the metal being cast. A value of 1.2 is commonly used for steel and ductile iron, whereas a slightly larger value of about 1.3 is preferred for the short-freezing-range copper-base alloys.

As a practical working equation, therefore, we may say that with these alloys the modulus of the riser should be about 1.3 times that of the casting (or casting section) to be fed; that is:

$$M_r = 1.3 M_c \quad (8)$$

Note that this is only one factor to be considered in designing a suitable riser, however. Equation 8 merely gives an empirical way of proportioning a riser so that it will freeze more slowly than the casting. The other basic requirement of any riser is that it must have sufficient volume to provide the necessary amount of feed metal to the casting or casting section to which it is attached.

To further clarify this point, consider two different geometric shapes of casting, each having the same modulus value (M_c):

1) Consider first a cube, having dimensions of 5 in. per side:

$$V_c = \text{length} \times \text{width} \times \text{thickness} = 125 \text{ in.}^3$$

$$A_c = 6 \text{ times the area of one side} = 150 \text{ in.}^2$$

$$\text{Therefore, } M_c = 125/150 = 0.833 \text{ in.}$$

2) Next, consider a 10 in. x 10 in. square plate, 2.5 in. thick:

$$V_c = \text{length} \times \text{width} \times \text{thickness} = 250 \text{ in.}^3$$

$$A_c = \text{area of top and bottom} + \text{area of 4 edges} = 300 \text{ in.}^2$$

$$\text{In this case also, } M_c = 250/300 = 0.833 \text{ in.}$$

It can be seen that the second casting has twice the volume of the first, and can therefore be expected to require considerably more feed metal from the riser. Such differences depend on shape factors. These can be determined experimentally where necessary; however, it is much easier (though less precise) to utilize data of the type shown in Table 8-3. The numbers listed in the table indicate the minimum values for the ratio between riser volume and casting volume (as percentages) to assure that the riser can supply the necessary amount of feed metal to the casting. Five general classes of castings are shown, ranging from "very chunky" to "rangy." Notice that risers having a height-to-diameter (H/D) ratio of 1:1 are more efficient than when H/D is 2:1. More importantly, it can be seen that insulated risers are far more efficient than those formed directly in the sand mold.

A sample calculation follows for a simple casting shape, showing how the modulus method can be used for designing a riser:

Example

A manganese bronze casting in the shape of a square bar, 2 in. x 2 in. and 9 in. in length is to be cast in a sand mold, preferably using a cylindrical open riser connected to the end of the bar. Can such risering be used and, if so, what is the optimum riser height and diameter?

Step 1

Evaluate the riser location in terms of the feeding range of the alloy. Earlier in this chapter it is noted that the feeding distance for manganese bronze bars varies from 4 T upward, depending on the value of T. Since we are dealing here with a value of 2 in. for thickness (T = 2 in.), we can probably safely assume that a single end riser will feed the entire 9 in. length of the bar. If we wish to assure ourselves of this, we can add an external chill against the free end of the bar to give a higher thermal gradient during solidification.

Step 2

Calculate the volume (V_c), effective area (A_c) and modulus (M_c) of the casting.

$$V_c = 2 \text{ in.} \times 2 \text{ in.} \times 9 \text{ in.} = 36 \text{ in.}^3$$

The effective casting area (the area from which heat is extracted during freezing) will be the sum of the areas of the four lateral sides plus that of the free end. *Note that the area in contact with the riser is not included.*

Therefore: $A_c = 4 (2 \text{ in.} \times 9 \text{ in.}) + (2 \text{ in.} \times 2 \text{ in.})$

$$A_c = 76 \text{ in.}^2$$

$$M_c = V_c/A_c = 36/76$$

$$M_c = 0.474 \text{ in.}$$

Step 3

Multiply M_c by 1.3 (the F factor for manganese bronze) to obtain M_r :

$$M_r = 1.3 M_c = 1.3 \times 0.474$$

$$M_r = 0.616 \text{ in.}$$

Step 4

Consider an open (top insulated with a cover) end riser having a height-to-diameter (H/D) ratio of 1:1. Calculate the values of H and D for such a riser, having a modulus value (M_r) of 0.616 in.

$$V_r = H \times \pi D^2/4; \text{ since } H = D, \quad V_r = \pi D^3/4$$

$$A_r = H \times \pi D + \pi D^2/4, \text{ or } A_r = \pi D(D + D/4)$$

$$M_r = \frac{\pi D^3 / 4}{\pi D(D + D/4)}$$

$$M_r = D/5$$

Therefore $D/5 = 0.616 \text{ in.}$, and $D = 3.08 \text{ in.}$, $H = 3.08 \text{ in.}$ Note that, for ease in calculation, we did not deduct the neck area connecting the riser to the casting when calculating effective riser area. This introduces a small error, tending to make the riser a bit larger than necessary. *Note also that our effective riser area includes that of the cylindrical sidewall and bottom, but not that of the riser top, which is insulated.*

Step 5

Assuming a riser having a diameter and height of 3 in., calculate its volume and determine whether it is large enough to provide feed metal to the 2 in. x 2 in. x 9 in. bar.

$$V_r = \pi D^3/4 = 0.785 \times 27 = 21.2 \text{ in.}^3$$

The ratio of the riser volume (V_r) to the casting volume (V_c) is:

$$V_r/V_c = 21.2/36 = 0.59$$

Thus, the riser volume, as calculated, is 59% of the casting volume. Referring to Table 8-3, note that the bar casting in question may be considered as "average" in its configuration classification. Thus, for a riser cast in a sand mold and

having an H/D ratio of 1:1 its volume should be at least 58% of that of the casting. The calculated riser should therefore be adequate. Had it not been, we would have increased its volume by extending the height.

Table 8-3 Minimum Volume Requirements of Risers

Type of Casting	Minimum V_r/V_c (%)			
	Insulated Risers		Sand Risers	
	H/D = 1:1	H/D = 2:1	H/D = 1:1	H/D = 2:1
1. Very Chunky. Cubes, etc. Dimensions in ratio 1:1.33:2*	32	40	140	198
2. Chunky. Dimensions in ratio 1:2:4*	26	32	106	140
3. Average. Dimensions in ratio 1:3:9*	19	22	58	75
4. Fairly Rangy. Dimensions in ratio 1:10:10*	13	15	30	38
5. Rangy. Dimensions in ratio 1:15:30 or larger ratio*	8	9	12	14

*Ratio of thickness:width:length

The foregoing example is, of course, quite simple and is intended merely to illustrate the principles involved and the sequence of calculations. For cast sections too long or too wide to be fed with a single riser, multiple risers must be used with or without the use of intermediate chills and insulating sleeves. This gives rise to the concepts of *infinite* bars and plates as well as *feeding paths*, and brings into play the use of other factors that compensate for differences in the rate of heat transfer. Good riser design also involves consideration of the geometry of the neck that attaches it to the casting. A growing number of computer programs have been written to simplify such calculations.

GROUP II—WIDE-FREEZING-RANGE ALLOYS

The "work-horse" alloys of the copper-base group are the leaded red brasses and tin bronzes, virtually all of which have wide freezing ranges. These alloys comprise the greatest percentage of annual casting production, and find extensive application in parts used for plumbing, valves and fittings, meters and pumps, all of which require corrosion resistance in combination with pressure tightness and moderate strength. The relative ease or difficulty in attaining adequate soundness in such parts is strongly dependent on section thickness and uniformity, even more so than for Group I alloys.

The principles of risering for Group II alloys can be better understood by first recalling their solidification and shrinkage characteristics. It has already been mentioned that the wide-

freezing-range alloys normally solidify in a manner analogous to the setting of concrete, whereby the entire mass, upon cooling below the liquidus temperature, first thickens and then becomes “mushy” due to the formation of an ever-increasing amount of crystals of solid metal throughout the liquid (Fig. 8-5). This is the characteristic behavior of such alloys whenever they are allowed to solidify at a relatively slow rate.

As previously discussed, a process known as *mass feeding* occurs during the earlier stages of solidification, aided by both gravity and atmospheric pressure. This process is a natural phenomenon which occurs automatically, and compensates for about two-thirds of the solidification shrinkage exhibited by the alloy. The remaining shrinkage (amounting to about 1 or 2% of the total volume) takes place during the final stages of solidification. At this time, the structure is about 70% solidified and has become somewhat rigid. As freezing continues, the solid crystals grow laterally, eventually trapping isolated pools of liquid metal between them. When these pools freeze, they leave behind voids whose size and shape depend on the relative coarseness of the surrounding dendrites. Since the last pockets of metal to freeze are isolated, feeding from adjacent regions is virtually impossible. Consequently, under such conditions of slow freezing, the alloys of Group II can be considered as having practically no feeding range, as do those of Group I.

Experience has shown that success in achieving internal soundness with Group II alloys depends upon avoiding slow cooling rates. There are three possible means for doing this, within the limitations of casting design and available molding processes:

1. Minimize casting section thickness.
2. Reduce and/or evenly distribute the heat in the metal entering the mold cavity.
3. Use chill and mold materials of high chilling power.

The sections that follow describe practical methods (and their limitations) for producing castings of acceptable soundness and integrity. As with any parameter of quality, it must be kept in mind that soundness is a relative condition that must be defined and evaluated in terms of the service requirements to be met by the casting. For example, castings made of Group II alloys are seldom, if ever, required to meet Class I or Class II ASTM radiographic standards of soundness with regard to internal shrinkage porosity. In general, soundness is judged by pressure tightness of the casting, in combination with freedom from visible porosity on as-cast or machined surfaces, and compliance with minimum mechanical property requirements.

THIN CASTINGS

Parts having a uniform section thickness of about $\frac{3}{8}$ in. or less, even in ordinary sand molds, tend to freeze quickly enough to develop a rather dense, fine-grained layer, or “skin” of metal at surfaces in contact with the sand. They benefit from the combined effects of mass feeding and atmospheric

pressure in undergoing a uniform compaction of volume and shape during the early stages of freezing; the residual 1 or 2% internal microshrinkage is so uniformly and finely distributed as to be invisible to the naked eye. This results in parts that are pressure tight and visibly sound without any deliberate attempt at feeding. The use of simple ingates, or even “kiss gating” (see the chapter on *Gating*), so long as this does not create hot spots, is sufficient to yield sound, commercial-quality castings. When hot spots do occur in such parts they are often at or near the point of gating, at fillets, or at junctions of casting walls. These are potential areas of coarse “macroshrinkage” and leakage (Defect B 311, See the chapter on *Common Defects*). Such conditions can sometimes be improved by reducing pouring temperature or by gating directly into thin, rather than heavier, sections of the casting. Multiple gates can sometimes be used advantageously to reduce heat concentrations in the casting.

MODERATE AND HEAVY-SECTION CASTINGS

As casting section thickness increases beyond about $\frac{1}{2}$ in., or as isolated hot spots become more prevalent because of increasing complexity of design, it becomes more and more difficult to attain castings of acceptable quality. Macroshrinkage can become a serious problem, both in terms of loss of pressure-tightness as well as visible porosity on machined surfaces. There is often an inclination to correct such a condition in accessible areas such as flanges or hubs by attaching a riser to the casting to provide feed metal. However, conventional risering procedures, as they apply to narrow-freezing-range alloys cast in green sand, simply do not work. Not only does the riser not eliminate the macroshrinkage, it may even exaggerate the condition. This is because the mass of the riser further reduces the freezing rate of the heavy section and the anticipated feeding cannot take place because the “mushy” mode of freezing prevents directional solidification (Fig. 8-10).

Risering of moderate and heavy-section castings, with proper design and application, can be beneficial, however. A major use of risers for such castings is for eliminating a class of defects known as sinks, or sink marks (Defect D 141, see the chapter on *Common Defects*). These defects consist of localized depressions on the casting surface, varying in severity from shallow areas to rather deep pockets that extend into the casting interior. Sinks occur at hot spots that freeze more slowly than adjacent areas. The forces of atmospheric pressure against the surface of the casting act uniformly during freezing. So long as the casting surfaces, in turn, offer uniform resistance to compression, the compaction of the casting volume will be evenly distributed and not noticeable. Where the mushy stage of freezing is prolonged, however, such areas remain vulnerable to external pressure, which can cause their collapse. Ironically, the metal displaced by the formation of the sink often compensates for the solidification shrinkage in that area, with the result that the adjacent internal structure is quite sound.

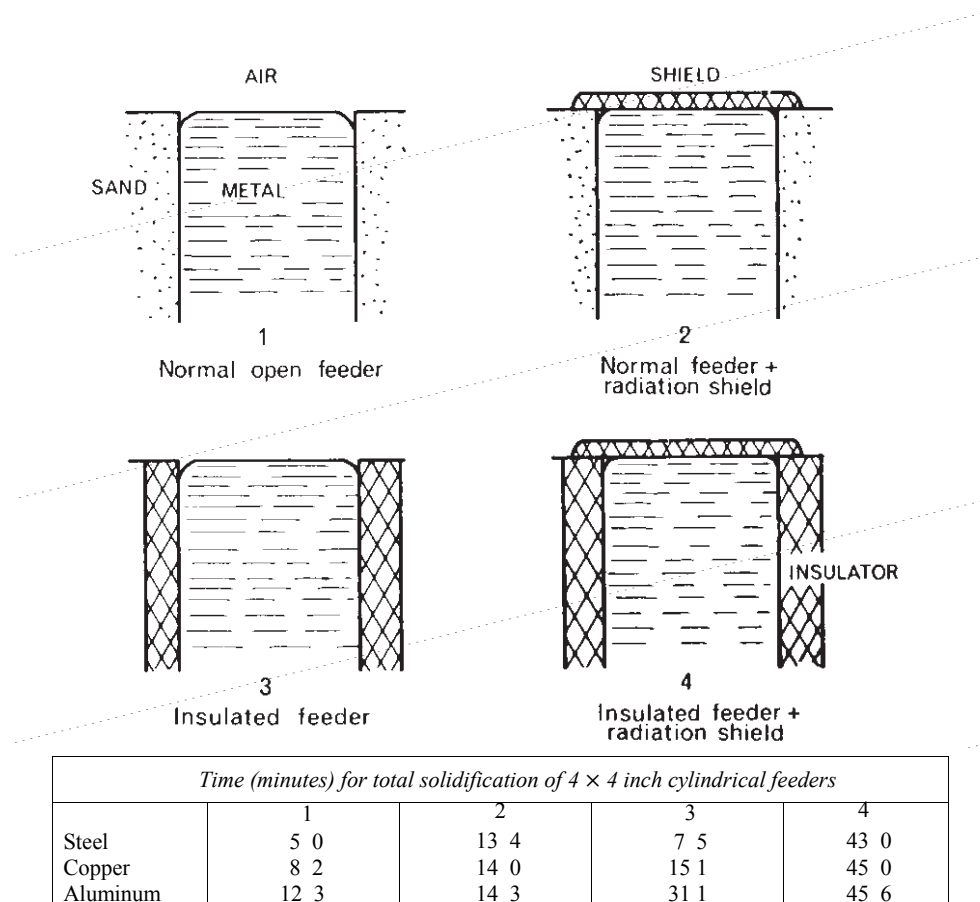


Fig. 8-18. Effect of various heat insulating techniques on the efficiency of feeders for aluminum, copper, and steel castings.

The risering technique used to avoid sinks is based not upon the principle of directional solidification, but upon that of uniform solidification. As the term implies, the purpose is to minimize the formation of any hot spots and to cause the casting to solidify at the same rate throughout. This is essentially what occurs with small, thin-walled castings of uniform section. With heavier castings, while total uniformity may not be achieved, it can be promoted. For example, isolated heavy sections such as bosses and rib junctions can be caused to cool more rapidly by the use of metal chills or molding aggregates such as zircon or chromite. In addition, by gating into thinner sections, the heavy regions will be allowed to fill last, with cooler metal. Dead risers—those appended to the last sections to fill—can be used to provide metallostatic pressure to the casting and to form an open channel to the interior of the casting so that atmospheric pressure can act from the interior as well as from the exterior of the casting. Since it is still important that these risers remain molten longer than the casting itself, it is advantageous to provide them with insulating or exothermic sleeves and top covers. (The benefits of these can be seen in Fig. 8-18.)

The design of risers for control of sink defects is not an exact science. As a rule, the risers should be as small in diameter and as tall as is practical. This means a diameter not much greater than 1.5 times the thickness of the section to which

it is attached, and a height at least three times the diameter. Actual dimensions may have to be modified, depending upon particular conditions and results attained.

For certain classes of medium- to heavy-section castings, the elimination of sink marks by risering, in conjunction with localized placement of chills to minimize internal macroshrinkage, is often adequate in producing an acceptable, commercial grade of casting. Where pressure tightness and freedom from visible shrinkage porosity is required in heavy-section castings, problems become much more severe. Flinn, Trojan et al. have summarized the results of an extensive research program, conducted under the sponsorship of the American Foundry Society, directed toward the attainment of soundness in heavy castings of wide freezing-range alloys.

Except for high-leaded tin bronzes, virtually all alloys of this family were found to exhibit varying degrees of leakage under pressure when allowed to solidify at rates comparable to those in sand molds. Regardless of riser size, heavy-section bars and plates cast of 85-5-5-5 alloy could not be fed effectively without extensive use of massive chills to produce directional solidification. Except for very short bars, end chills alone were inadequate in developing directional solidification. Thermal studies confirmed that temperature

gradients of at least 60°F (33°C) per inch were necessary, during freezing, for the alloy to develop a solidification front which would allow feeding to occur from the riser. This necessitated the use of wedge chills placed against the faces of the casting along its length, as shown in Fig. 8-19. Chilling in this manner, while effective, has obvious limitations in complex casting shapes except over short distances. Where these techniques can be applied, the design of risers can be handled as described for the Group I alloys. It cannot be stated with any certainty, however, that the freezing range is much greater than 3T to 4T, and may be even less. Insulating riser sleeves and covers can be used here to great advantage to assure pressurization and feeding, however short-range.

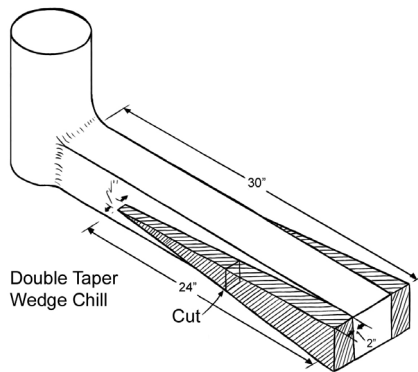


Fig. 8-19. Arrangement of wedge chills on gunmetal bar castings. This method of chilling avoids warpage.

CASTING DESIGN FOR COPPER-BASE ALLOYS

In a book of this scope, it is possible to deal only briefly with the subject of casting design. Unfortunately, this topic often receives too little attention, and the casting designer, not being familiar with foundry processes or the behavior of alloys during solidification, is concerned almost exclusively with the mechanical engineering requirements of the part in service. For this reason, the designer often develops casting configurations which are difficult, if not impossible, to produce with sound sections throughout. Additionally, due to vague casting strength and soundness requirements, the part may be over-designed with sections thicker or more massive than necessary. This can cause an otherwise potentially sound casting to be unsound.

Many poor casting designs are due to a lack of communication between foundry personnel and the casting designer. The need for consultation at an early stage in design cannot be overemphasized. The foundry is all too frequently presented with a drawing of a design that is unsatisfactory from a casting standpoint. At this late stage only minor modifications, if any, can be made to improve castability and enhance quality.

A few general rules for the design of copper-base alloy castings are as follows:

- Avoid abrupt changes in section thickness. When such changes are necessary, the thicker section should always be blended or tapered gradually into the thinner section.
- Generous radii should always be provided at internal corner fillets and edges. Large radii at these locations facilitate feeding at intersections and help prevent the formation of hot spots during freezing.
- As far as possible, avoid L, T, and X intersections. It is much better to radius inside and outside edges rather than to form a sharp-cornered L (Fig. 8-20). T sections cannot be avoided, but their adverse effects can be minimized by providing generous radii at corners and, where possible, by making the arms of unequal thickness (Fig. 8-21). X intersections have particularly adverse effects and it is nearly always possible to avoid them. For example, they can often be converted to two offset T sections. "Dimpling" can also be used to reduce the severity of hot spots at T intersections (Fig. 8-22).
- With a knowledge of the solidification behavior of the alloy, the designer should consider the likely feeding paths, riser placement, and gate locations in order to avoid isolated heat centers insofar as possible. Consultation with a foundry engineer may be required to accomplish this.
- For reasons given earlier, every effort should be made to minimize the section thicknesses of Group II alloy castings. Especially with these alloys, thicker does not necessarily mean stronger.

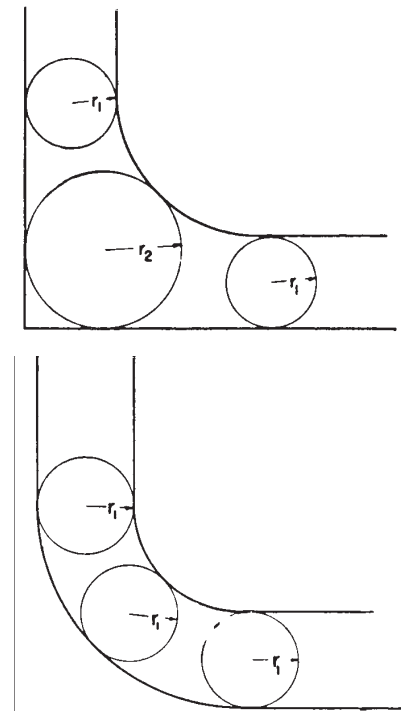


Fig. 8-20. An L-section was redesigned to eliminate hot spots.

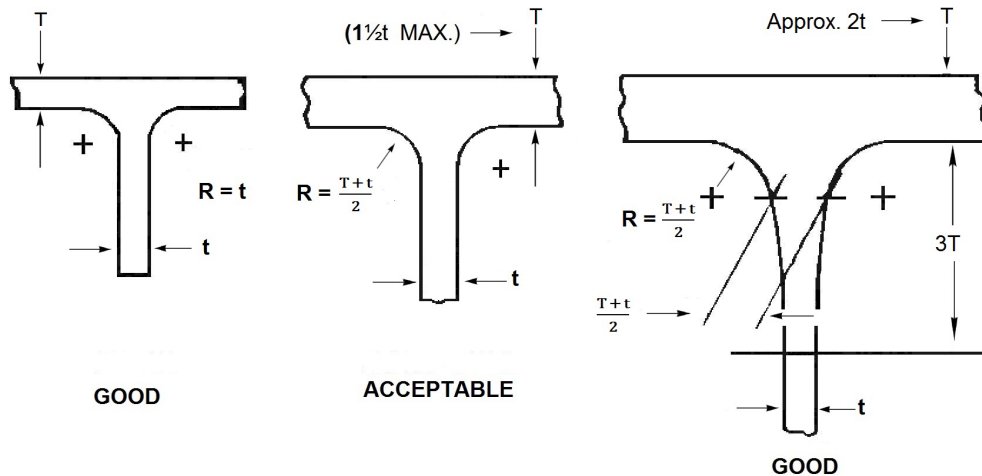


Fig. 8-21. Recommended fillet radii and blending practice for walls intersecting at 90 degrees.

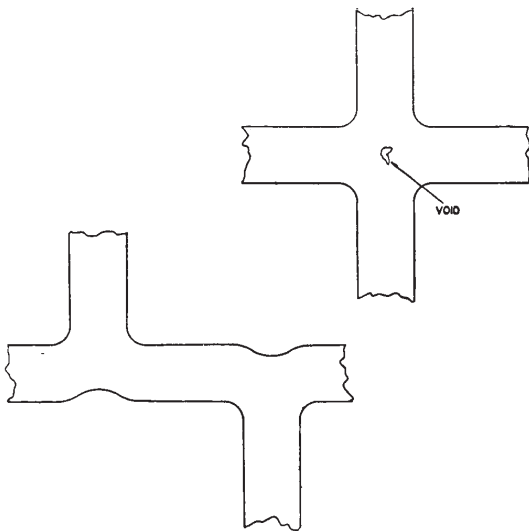


Fig. 8-22. A casting X-section was redesigned to avoid shrinkage defects.

Ideally, the design of a casting should develop as follows:

1. The designer, after first determining the required surface configurations and stresses to which the casting will be subjected, should then sketch out a preliminary design.
2. The rough design should then be discussed with a foundry consultant, who should provide advice and information regarding ease and cost of manufacture, optimum choice of alloy, predicted properties in various sections of the casting (with allowance for possible unsoundness) and optimum casting shape from the foundry viewpoint.
3. The designer should then prepare a detailed drawing, incorporating as many of the foregoing recommendations as seem practical.
4. Final review of the design should be made with the foundry consultant for purposes of verification.
5. The final drawing should then be prepared, including dimensional tolerances of the casting, machining allowances, draft requirements, and other information necessary for pattern making and foundry production.

Although such a procedure might seem to delay the design process, the potential for cost savings and quality enhancement certainly justifies these suggested steps.

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COPPER-TIN-LEAD-ZINC ALLOYS— LEADED AND UNLEADED RED BRASSES AND TIN BRONZES

INTRODUCTION

The copper-tin-lead-zinc alloys date back hundreds of years and, today, comprise the most important and most widely used compositions of all the copper-base casting alloys. In the past, most of the individual alloys included here have been designated by various commercial or colloquial names. These have now been largely superseded by the United Numbering System (UNS) designations listed in the chapter on Standard Designations. Therefore, these designations will be used throughout this chapter for reference purposes, together with a parenthetical indication of the nominal alloy composition. Composition will always be given in the following sequence: copper, tin, lead, zinc.

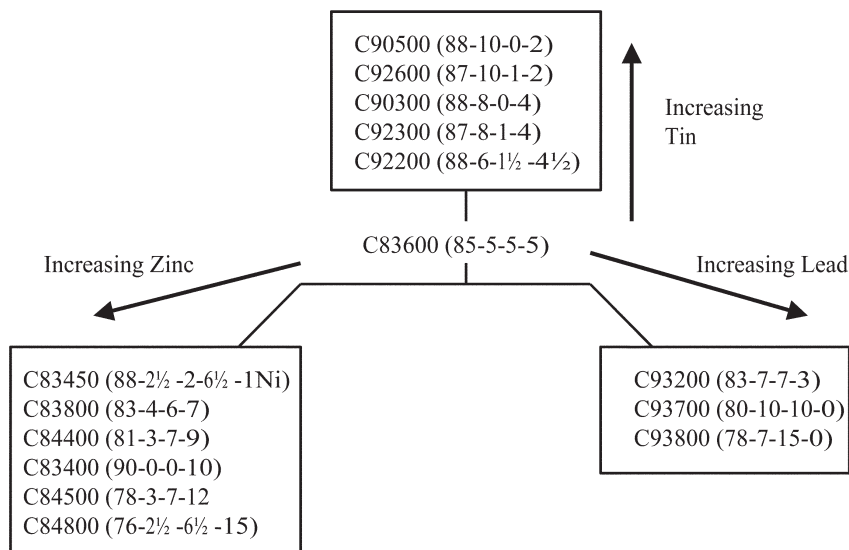
For the benefit of those persons familiar with the generally accepted alloy family names used in the past, this chapter will deal with selected members of the following families:

- Leaded red brasses
- Leaded semi-red brasses
- Tin bronzes
- Leaded tin bronzes
- High-leaded tin bronzes
- Lead-free brasses and bronzes

These alloys families are interrelated in that each alloy contains at least two, and usually three of the alloying elements tin, lead, and zinc in varying proportions. The relationships between the alloy families and their compositions can be seen in Table 9-1. Here, alloy C83600 (85Cu-5Sn-5Pb-5Zn) is considered the hub of a “wheel” since it contains equal amounts of each of the alloying elements. Historically, in fact, this alloy was once known as “ounce metal” because it could be produced by alloying one ounce of each alloying element in combination with one pound of copper.

The favorable combination of casting properties, machinability, and general utility of alloy C83600 has contributed to its popularity and usage for centuries. Over the years, however, both for economic and technical reasons the development of a wide array of other alloys based on the copper-tin-lead-zinc system has been found useful. As copper and, especially, tin have traditionally been the most expensive elements in this group of alloys, it was inevitable that attempts would be made to develop compositions having greater proportions of zinc and lead yet still possessing the necessary castability and mechanical properties required for specific applications.

Table 9-1. Families of the Copper-Tin-Lead-Zinc Alloy Group



As shown in Table 9-1 (lower left), increasing zinc levels produced alloys known as the leaded “semi-red” brass, typified by the alloys presently designated as C83400 (90-0-0-10), C84400 (81-3-7-9), C84500 (78-3-7-12), and C84800 (76-2½-6½-15). Note that alloy C83800 (83-4-6-7), C83450 (88-2½-2-6½-1Ni), as well as C83600 (85-5-5-5) were designated in the past as leaded “red” brasses. Above the 15% zinc level, the alloys fall into family “yellow” brass, which are included in the group covered in Chapter 10 on *Leaded and High-Strength Brasses*.

A second family of alloys (Table 9-1, lower right) that evolved because of certain engineering property requirements utilizes the excellent strengthening effects and load-bearing properties produced by the increased tin content in combination with the lubricity and bearing qualities imparted by the high levels of lead. These materials comprise the alloy family known as high-leaded tin bronzes, used extensively for bushings and bearings and typified by alloys C93200 (83-7-7-3), C93700 (80-10-10-0), and C93800 (78-7-15-0).

The third family of alloys included in this group utilizes the beneficial effects of increased tin contents in combination with substantially reduced levels of lead. These comprise the leaded and unleaded tin bronzes, listed in the upper portion of Table 9-1, and include such alloys as C92200 (88-6-1½-4½), C92300 (87-8-1-4), C90300 (88-8-0-4), C92600 (87-10-1-2) and C90500 (88-10-0-2).

With the 1993–1995 restrictions on lead in potable water, the most common plumbing alloys C83600 and C84400 needed to be replaced by lead-free machinable red-brass alloys. Some of these new alloys use bismuth, selenium, or sulfur along with other elements to impart free machining to the copper-tin-zinc base rather than lead. The development of these new alloys is being spurred by increasingly restrictive regulations on lead. Even after 23 years the situation is still fluid, hence an historical approach will be used in the section on Lead-Free Red Brass Replacements later in this chapter to indicate possible replacements and associated issues.

METALLURGY

As a group, the copper-tin-lead-zinc alloys exhibit very wide freezing ranges (Tables 9-2 and 9-3), varying from about 160 to 300F (90 to 170C). Consequently, all solidify in a mushy, dendritic manner (as described Chapter 8 *Solidification*) with the attendant effects of pronounced segregation, undercooling, and non-equilibrium which result from lack of adequate diffusion. These alloys do not lend themselves to heat treatment, which enhances properties by structural modification. However, grain refinement with zirconium, boron or FKM2000 was shown to be effective on some alloys in the late 1990s. These alloys are always used in the as-cast condition, and their microstructures depend essentially on alloy content (and purity) and rate of solidification. A familiarity with typical microstructural features of the various alloys, together with an understanding of possible abnormalities that can occur, can assist the metallurgist in evaluating and controlling alloy quality.

Technically, the alloys of this group are either ternary or quaternary. As will be noted, lead is nearly or entirely insoluble in the solid alloys and thus has little or no effect on alloy phase relationships within the copper-tin-zinc system. From a practical point of view, one can therefore consider the alloys of this group as binary or ternary, with or without lead being present as an insoluble additive.

Although the cast microstructures of these alloys represent non-equilibrium conditions, they can best be interpreted and understood by consideration of phase-equilibrium diagrams.

Likewise, the ternary copper-tin-zinc system is easier to understand if first the solubility limits and general phase relationships are considered in the binary Cu-Zn and Cu-Sn systems. Consideration will also be given here to the Cu-Pb system to illustrate the unique behavior of lead as an alloying element.

Copper-Zinc

Zinc is a relatively inexpensive, yet potent, alloying element in copper, imparting strength and hardness by the mechanism of solid-solution strengthening. Note that in amounts up to 15%, zinc produces only a slight lowering of liquidus temperature and the binary alloys have very narrow freezing ranges. Figure 9-1 illustrates the relatively wide range of solubility of zinc in copper in the solid state, whereby compositions containing up to 32.5% zinc solidify as single-phase “alpha” (α) solid solutions. This is to be expected for all the alloys in this group (which contain a maximum of 15% zinc). At higher zinc levels, a second, intermediate solid solution (β) is seen. (This “beta” phase will be discussed in more detail in Chapter 10, *Leaded and High-Strength Brasses* under the subhead *Yellow Brasses*).

Zinc has a higher vapor pressure than expected from Raoult’s Law in the molten alloys (which is only moderated by tin), and is readily lost by evaporation and oxidation. This explains the need to replenish the zinc lost in melting, and accounts for the presence of zinc oxide in the foundry atmosphere.

Copper-Tin

Tin is also a potent solid-solution strengthener in copper, even more so than zinc, since less tin is required for an equivalent increase in strength. Unlike zinc, tin also improves corrosion resistance. As seen in Fig. 9-2, tin produces a rather drastic effect, both on the melting temperature (liquidus) and freezing range of Cu-Sn alloys when added in amounts of up to 10% (the limiting amount for alloys in the present group). Within this range of composition, the phase-equilibrium diagram indicates that alloys should solidify as single-phase, alpha, solid solutions—which are analogous to those that form the Cu-Zn system described herein. However, due to the very wide freezing ranges of the Cu-Sn alloys, together with pronounced undercooling and slow diffusion, considerable segregation occurs during freezing. This causes high composition gradients to exist within the alpha crystals, their

Table 9-2. Solidification Ranges and Recommended Pouring Ranges for Copper-Tin-Lead-Zinc Alloys

Alloy	Freezing Range ¹		Pouring Range Classification ²
	Celsius	Fahrenheit	
C83400 *	1043—1021	1910—1870	A
C83450 *	1015—860	1860—1580	A
C83600	1010—854	1850—1570	A
C83800	1004—843	1840—1550	A
C84400	1004—843	1840—1550	A
C84500 *	977—838	1790—1540	A
C84800	954—832	1750—1530	B
C92200	988—825	1810—1518	A
C90300	1000—854	1832—1570	A
C92300	999—854	1830—1570	A
C90500	999—854	1830—1570	A
C92600	982—843	1800—1550	A
C93200	977—854	1790—1570	A
C93700	930—762	1705—1403	B
C93800	943—854	1730—1570	B

1 = Please refer to www.copper.org (the Official Website of the Copper Development Association, Inc.) and specifically to <http://www.copper.org/resources/standards/uns-standard-designations.html> for an explanation of alloy designations and to <http://www.copper.org/resources/properties/db/basic-search.php> for alloy information concerning casting alloys in detail.

2 = See Table 9-3.

* Not used very often

Table 9-3. Pouring Range Guide for Castings

	Heavy Section		Thin Section	
	Celsius	Fahrenheit	Celsius	Fahrenheit
Class A	1050—1180	1925—2150	1150—1260	2100—2300
Class B	1010—1120	1850—2050	1070—1150	1950—2100

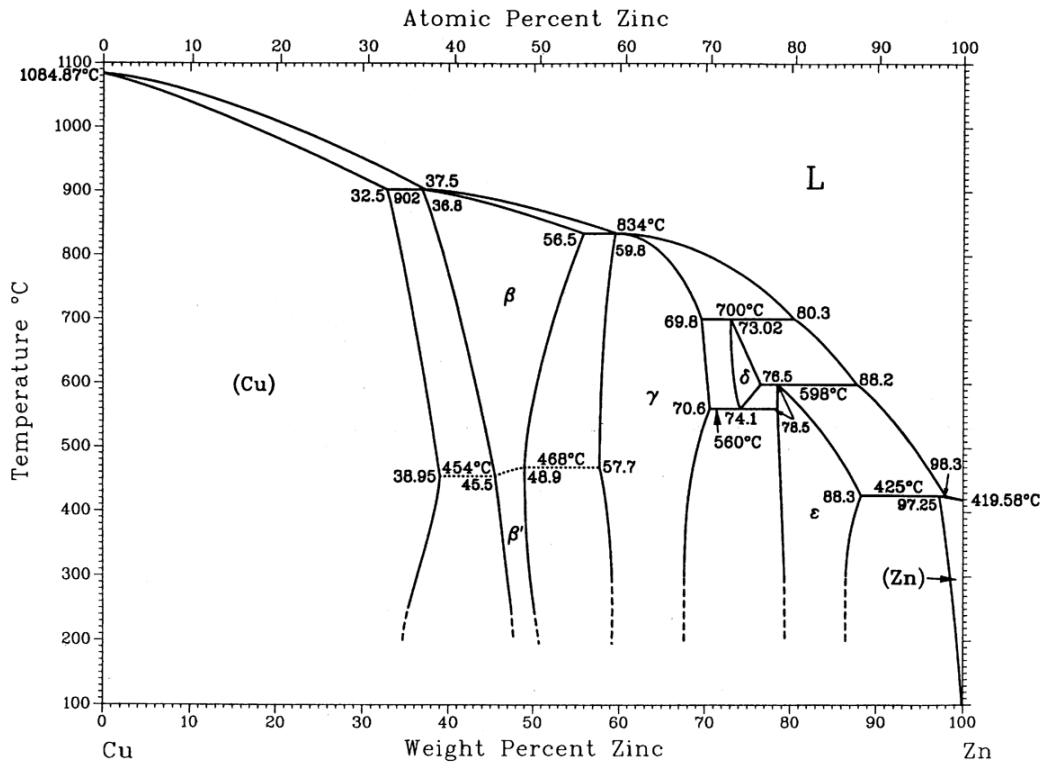


Fig. 9-1. A copper-zinc phase equilibrium diagram is shown. (Artwork courtesy of ASM Intl., Materials Park, Ohio, "Binary Alloy Phase Diagrams," T.B. Massalski, 2nd Edition [1990]).

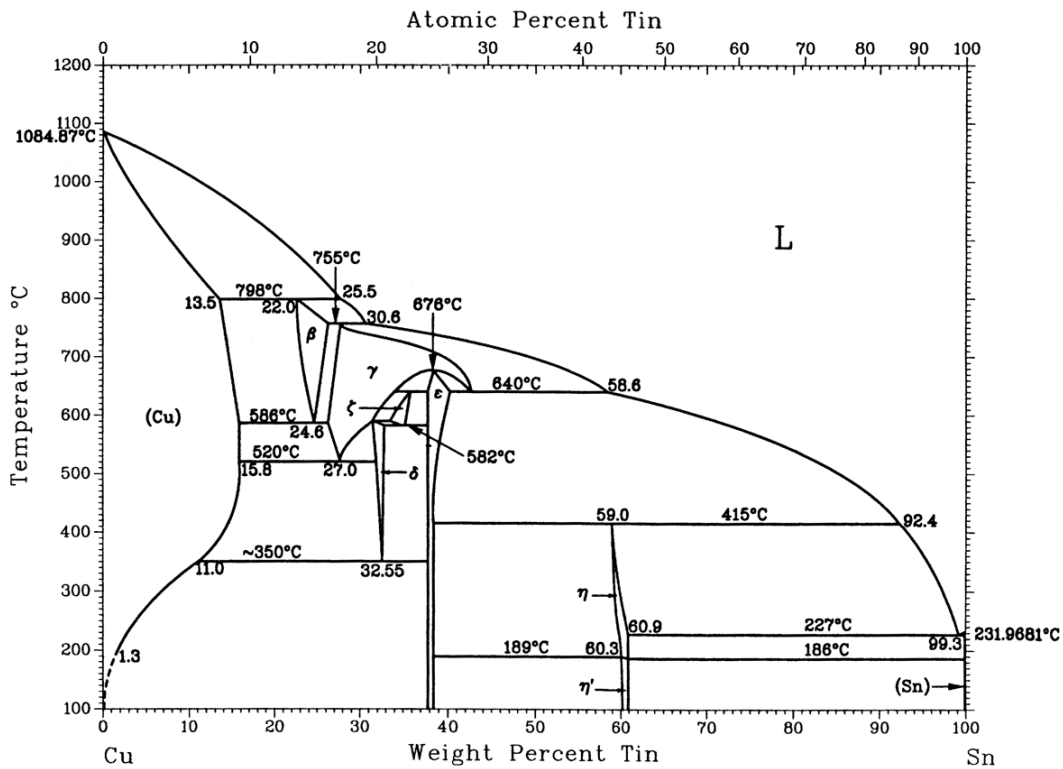


Fig. 9-2. A copper-tin phase equilibrium diagram is shown. (Artwork courtesy of ASM Intl., Materials Park, Ohio, "Binary Alloy Phase Diagrams," T.B. Massalski, 2nd Edition [1990]).

central portions being rich in copper, surrounded by zones increasingly rich in tin. This phenomenon, known as coring, commonly occurs in the as-cast structure.

Another important consequence of this non-equilibrium freezing is the fact that the last liquid present during solidification contains much higher tin than in the nominal composition of the alloy. Thus, the final solidification may actually follow the peritectic reaction shown in Fig. 9-2. This results in the eventual formation of a hard, brittle "delta" (δ) phase, occurring as bluish lakes of alpha-delta eutectoid at the alloy grain boundaries.

Authorities agree that, for practical purposes, the line on the Cu-Sn diagram showing the limiting tin solubility in the alpha phase can be drawn vertically downward at the maximum value of 15.8%, from 968F (520C) to room temperature. Also, the epsilon (ϵ) phase shown to form at ~662F (~350C) is rarely encountered due to the sluggishness of the transformation. Hence, the alpha-plus-delta field may be considered as extending to room temperature.

Copper-Lead

It may be seen from Fig. 9-3 that lead, although continuously soluble in molten copper, is virtually insoluble in the solid state (solubility < 0.007% in solid copper). At the copper-rich end of the diagram, alloy solidification begins with the crys-

tallization of essentially pure copper as the temperature falls below the liquidus. As freezing continues through the liquidus-solidus range, further growth of the copper crystals occurs while the remaining liquid increases in lead content, reaching a value of 37% at the monotectic temperature of 1751F (955C). At the monotectic temperature, precipitation of additional copper from the melt occurs isothermally until the liquid eventually attains a composition of 86% lead. Next, an extended cooling period follows with little change occurring until, at 619F (326C), the residual liquid solidifies as essentially pure lead.

It is of interest to note the effects of the mode of solidification on the shape and distribution of the lead phase in the alloys. As can be seen from the phase-equilibrium diagram, alloys low in lead content (e.g., 1 to 7% Pb) have relatively wide freezing ranges and therefore solidify in a mushy, dendritic manner. By the time the monotectic temperature is reached, solidification is about 85% complete and the residual lead is entrapped between the dendrite arms, where it eventually solidifies. A comparable situation exists with the wide freezing-range copper-tin-zinc alloys of lower lead content. This behavior is advantageous since the lead particles tend to be isolated in the same locations where microshrinkage voids occur in such alloys (see the chapter on Solidification). This explains the effectiveness of lead in promoting pressure-tightness in these alloys. Lead also disrupts the continuity of the alloy matrix structure and, thus, small

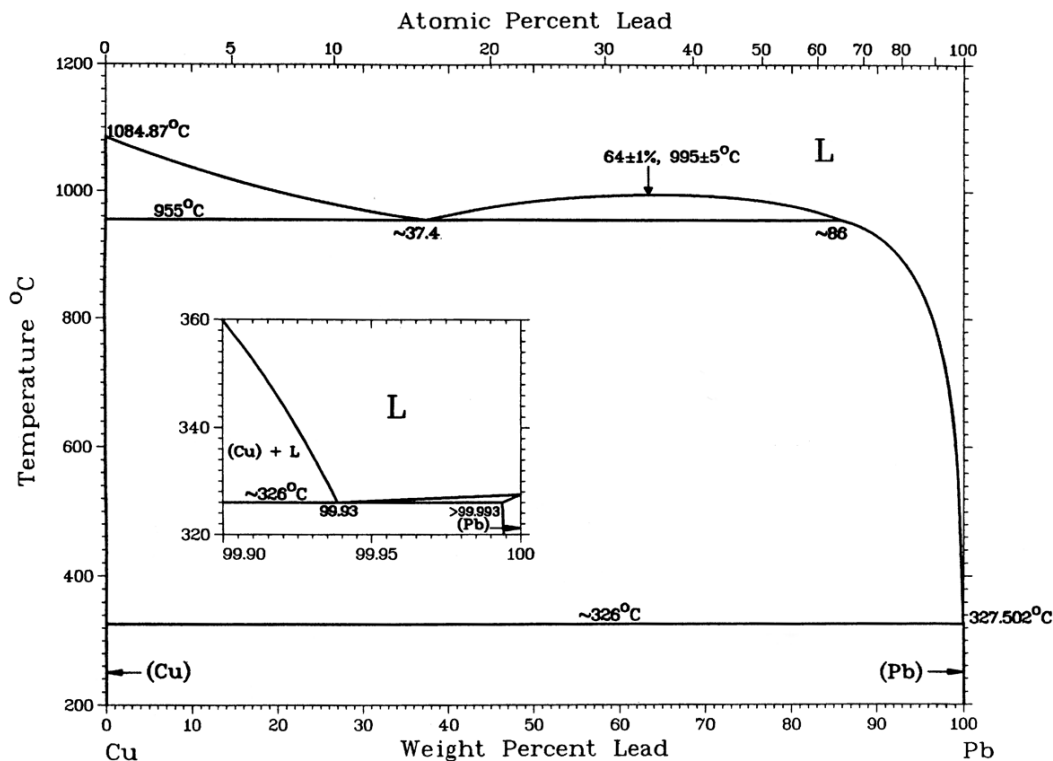


Fig. 9-3. Copper-lead phase equilibrium diagram. (Artwork courtesy of ASM Intl., Materials Park, Ohio, "Binary Alloy Phase Diagrams," T.B. Massalski, 2nd Edition [1990]).

amounts of lead when well distributed can serve both as a lubricant and as “chip breakers” in enhancing machinability.

At higher lead contents, with alloys of somewhat narrower freezing range, rather marked gravity segregation can occur, especially under slow cooling conditions.

Copper-Tin-Zinc System

Authorities agree that, for practical purposes, the 932F (500C) isothermal section of the ternary copper-tin-zinc phase equilibrium diagram (Fig. 9-4) represents the effective phase relationships existing at room temperature. The phases present, within the range of compositions of commercial interest, can be understood in terms of what has already been discussed in connection with the various binary copper alloy phase diagrams.

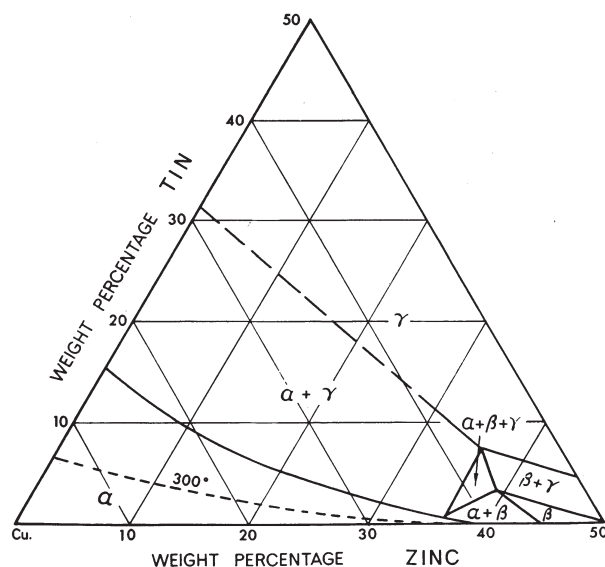


Fig. 9-4. The 932F (500C) isothermal section of the Cu-Sn-Zn ternary equilibrium diagram.

The principal phase occurring in all the commercial alloys is that designated as “alpha” (α) in Fig. 9-4. This field represents a continuous series of solid solutions analogous to the alpha phases shown in the binary Cu-Zn and Cu-Sn diagrams. When both alloying elements are present simultaneously, each reduces the other element’s solubility to some extent, and the solid curved line which bounds the alpha region in Fig. 9-4 shows the effective solubility limits. The wide freezing-ranges of the ternary alloys (Table 9-2) result in as-cast structures wherein the alpha matrix shows pronounced coring, as shown in Fig. 9-5.

The second phase that occurs consistently in all the leaded alloys is, of course, the lead itself. The quantity and distribution of the lead depends upon the amount present in the alloy, the freezing range of the alloy, and its actual rate of solidification. Chill castings, for a given lead content, tend to

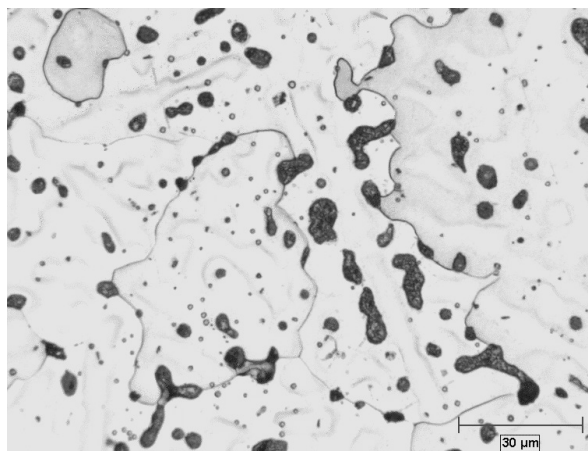


Fig. 9-5. Coring in a sand-cast red brass with a ferric chloride etch is shown.

exhibit finer grain size and, consequently, finer distribution of the lead particles than sand castings. The lead inclusions are of a dark gray color and their shapes tend to conform to the dendritic grain boundaries of the matrix, as shown in the photomicrograph of an unetched structure (Fig. 9-6). Since the lead phase is virtually insoluble in the solid condition, there is no need to consider the constitution of these alloys in terms of a quaternary Cu-Sn-Pb-Zn equilibrium diagram. Instead, we can actually ignore the lead content and recalculate the percentage composition of the alloy in terms of the copper/tin/zinc ratio. For example, alloy C83600 (85-5-5-5) would be expected to solidify as would its unleaded equivalent 89½ Cu, 5¼ Sn, 5¼ Zn.

Referring again to the ternary diagram in Fig. 9-4, note that the alpha field is bounded by a two-phased region of compositions consisting of alpha plus gamma (γ). The gamma phase in the ternary diagram, like the alpha phase, also consists of a continuous series of solid solutions of tin and zinc in copper. Metallurgically, this phase is said to be isomorphous with the gamma phase of the Cu-Zn system and the delta phase of the Cu-Sn system. When, due to non-equilibrium freezing conditions, the gamma phase appears in the solidified structures of the ternary alloys it has the identical appearance of the delta phase that constitutes the alpha-delta eutectoid in Cu-Sn alloys. For this reason, it is commonly referred to as the “delta” phase. In appearance, this phase forms a part of an alpha-delta eutectoid which occurs as bluish inclusions, often elongated, found at the grain boundaries of the matrix (see Fig.9-6).

The alpha-delta eutectoid occurs most often in the tin bronzes (8 to 10% Sn), and is more prevalent under conditions of fast freezing. It is frequently detected in leaded red brass compositions, but less often in the semi-red bronzes. Excessive amounts of alpha-delta eutectoid are considered undesirable as they reduce the elongation of the alloy. The occurrence of this phase in commercial alloys is regulated by restriction of the sum of the tin and zinc contents.

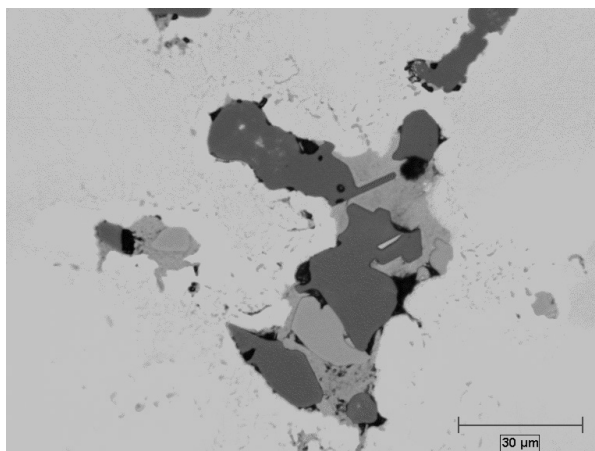


Fig. 9-6. Distribution of lead and alpha-delta eutectoid phases in sand-cast leaded red brass at 250x magnification is shown.

LEAD-FREE RED-BRASSES

Lead is now known to cause development problems in children and cause other neurological, nervous and blood disorders. Lead has long been attributed as one of the reasons for the fall of the Roman Empire, because of its extensive use in Roman aqueducts. Lead pipe was used in municipal plumbing systems until the 1950s.

In recent years, a series of federal and state laws has required lead to be essentially eliminated from plumbing. The Safe Drinking Water Act of 1974 established chemical and bacterial contaminant limits in drinking water. An amendment to the Act in 1996 regulated leaded plumbing fittings and limited lead to 11 ppb in drinking water. In 2007, a new California regulation (AB 1953) was introduced, which limited the lead content to 0.25% in all brass products coming in contact with potable water. Subsequently this act was superseded by 'The Reduction of Lead in Drinking Water Act', effective January 2014.

The role of lead in many copper alloys was due mainly to their ease of machining water tight fittings and taps. The lead is insoluble in solid copper, so it is distributed in discrete particles, usually in interdendritic areas. The lead at the α -Cu discontinuities facilitates chip ejection, thereby reducing costs, and imparts some pressure tightness. Machining also smears the lead across the surface, thereby reducing the applied force and speed needed for machining.

As leaded copper alloys for plumbing fittings constituted an important market, and the impending 1996 amendment limiting lead, the Copper Development Association (CDA), American Foundry Society (AFS), the Brass and Bronze Ingot Industries and the Canadian Materials Technology Laboratories (now CanmetMATERIALS, the largest research center in Canada dedicated to metals and materials) convened in 1992 to consider options to leaded plumbing alloys. The efforts led to the development of lead-free copper alloys. Lead-free red brasses are briefly presented and reviewed in

the following sections. Progress on other alloys is presented in Chapters 10 and 13.

Literature Review and Analysis

The results were first published by CanmetMaterials in 1993 and an abridged version in AFS Transactions in 1995. The review covered supply and demand, price, sustainability, recyclability, hazards, drinking water limits (existing and potential), properties, phase diagrams and thermodynamic properties of copper alloys with bismuth, indium, and selenium. According to ASARCO, the effects of bismuth and selenium on machinability were additive in C87600. Besides bismuth, indium and selenium, the elements that improve machinability of copper casting alloys are tin, nickel, antimony, phosphorus, sulfur, and uranium. Phosphorus and sulfur levels allowed in red brasses cast in green sand are limited by their tendency to cause casting defects from their interaction with water and oxygen.

The review also assessed the commercial availability of the elements. The 30 million faucets and other plumbing fittings for potable water supplies in the U.S. require 80,000 mt of red brasses a year. The annual world consumption of bismuth, indium and selenium are 4,000 mt, 160 mt and 2,200 mt respectively. Mine production was 2,500–4,500 mt of bismuth and 2,000 mt of selenium, stockpiling and recycling account for the differences. Hence, each percent in a new low-lead alloy would require 800 mt a year, just in the U.S. Indium was ruled out on the basis of limited supply and higher cost. Supplies of bismuth and selenium were sufficient in 1993 and enough was available to fill the North American red brass supply chain. However, consumption patterns indicated that at any time new products could quickly develop and consume 20% of the bismuth or half the selenium for a period of 15 years.

Bismuth bronzes were used in South America by the Incas due to the high levels of naturally occurring bismuth in copper ores. They were intentionally used in the 1880s by James Webster for telegraph wires. Webster developed two bismuth-tin-bronze alloys. One, described as "hard, tough, and sonorous," was used for piano wires. Another Webster alloy was "durable and bright" and used in kitchenware due to its luster and slow tarnishing. This particular alloy's ability to hold polish made it useful as a light reflector or mirror material as well, for which it was used for a number of years. In the period 1989–1991, there were patents and commercial announcements claiming copper-bismuth casting alloys without lead that were machinable.

The introduction of bismuth into copper has long been considered a contentious proposal. Bismuth coats the grain boundary and seriously reduces ductility of copper and its alloys, one of copper's key properties. Historically copper ore bodies containing bismuth were either discounted or not developed until refining techniques were developed to eliminate bismuth. The addition of bismuth to casting alloys complicates housekeeping in jobbing foundries and creates issues for recycling. Elements such as tin increase

the contact angle between a bismuth droplet and the surface of copper. This implies that bismuth rejected from freezing copper forms spherical droplets rather than wetting and spreading on grain boundaries.

Bismuth had been widely used to treat a variety of human conditions; new applications are found each year. Bismuth is not a dietary requirement, but France alone consumed more than 1,000 mt a year in 1974. It was not until 16 deaths from massive long-term doses was there any concern about the toxicity of bismuth. Bismuth subsalicylate (used as a stomach remedy) has been largely replaced. While high doses over prolonged periods do result in neurotoxic effects, bismuth is excreted within a few weeks and symptoms subside. There have been no industrial accidents, and bismuth telluride is the only compound governed by the U.S. Dept. of Labor. In 1993, EPA draft legislation was considering a limit of 0.02 mg/L for bismuth in drinking water. This limit was later raised to 0.1 mg/L.

Selenium on the other hand has critical dietary requirements, but the difference between deficient and toxic excess is a little more than an order of magnitude. Both extremes are manifested by fatigue and motor problems. Soils (plants and animals) in the U.S. Midwest are high in selenium, while some soils in China and New Zealand are deficient. Animals moving from one region to another are susceptible to motor problems (such as blind staggers from eating plants that absorb selenium (loco weed), a condition even reported by Marco Polo). Selenium can mimic sulfur and be incorporated into structural and enzymatic proteins, thereby destroying their normal functional roles. While many selenium compounds are considered toxic, their odor objectionable, death from them is extremely rare, and may be more cumulative. Environmental Protection Agency (EPA) limits for selenium in drinking water were 0.010 mg/L, while the Occupational Safety & Health Administration (OSHA) limited airborne selenium to 0.2 mg/m³. The relationship between selenium, vitamin A, electron transfer in muscles, aging, cancer, etc. is extremely complex due to some populations in the various

regions of the world having dietary intakes of selenium that are deficient or excessive.

The study recommended alloys based on the following:

- a leaded red brass similar to C84400, recommended by users with bismuth and nickel replacing lead or even C83600 with bismuth and selenium replacing lead;
- C87600 and C87800, two copper-zinc-silicon alloys as recommended by CDA/ICA (International Copper Assoc.);
- C90300 and C90500, two copper-tin alloys.

The AFS Copper Division's selection, made in February 1994, was C83600 with bismuth and selenium because C83600 was the most common green sand casting alloy.

Bismuth-Selenium Alloys

CanmetMATERIALS, with the financial support from CDA, the Brass and Bronze Ingot Manufacturers, Inc., (BBIM at that time), and AFS, investigated the properties of an alloy containing 5% tin, 5% zinc with bismuth and selenium. ASARCO provided copper selenide, which simplified making the alloys, and avoided the liberation of toxic selenium compounds. Partway through the development work, the sponsors recommended splitting the alloy in two. The bismuth was distributed as discrete globules and the selenium as copper and zinc selenides (Fig. 9-7). The alloys were initially known as SeBILOY® I and II (subsequently named EnviroBrass® I and II by the CDA). Chemistries for C89510 and C89520 are shown in the table on Copper-Bismuth and Copper-Bismuth-Selenium Alloys in Table 1-2, Designation Number and Chemical Composition of Cast Copper Alloys, in Chapter 1 and some properties in Table 9-4.

Design of Experiments (DoE) was used to cover the entire range of chemistries for submissions for American Society

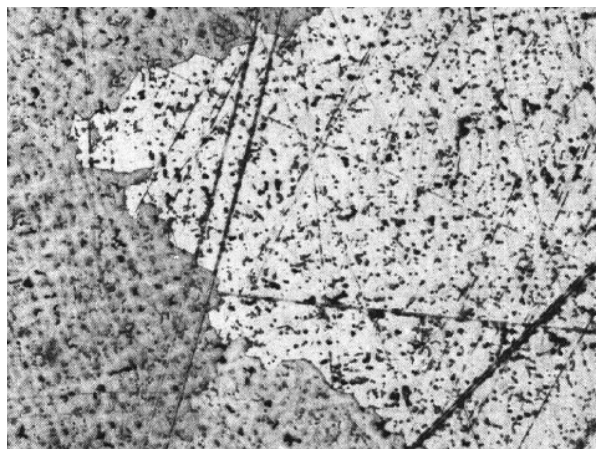


Fig. 9-7. Optical micrograph of polished and etched sand cast C89520 – 37.5X.

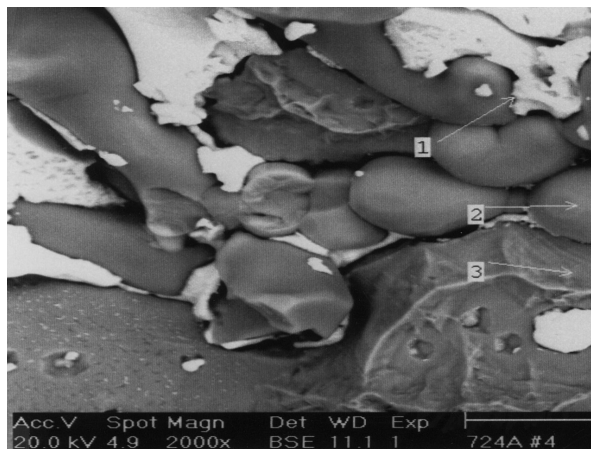


Fig. 9-8. BSE micrograph of fracture surface of C89520 pulled at 149C – 400X. Labelled areas 3 - Bi, 4 - ZnSe, 5 - Matrix Cu-Sn-Zn

Table 9-4. Casting Characteristics EnviroBrass® Alloys and Equivalent Alloys

Alloy	Liquidus °F (°C)	Freezing range deg F (deg C)	Fluidity (cm at 100 F superheat)	Relative Hot Hearing Resistance	Drossing	Soldering	Brazing	Effect of Section Size on Mech. Prop.
C83600	1850 (1010)	280 (156)	24	15-21	Low	Excellent	Good	Large
C84400	1850 (1010)	291 (162)	30	23-24	Medium	Excellent	Good	Large
C89510	1871 (1022)	371 (206)	24	14	Low	Excellent	Good	Small
C89520	1842 (1006)	353 (196)	25	8	Low	Excellent	Good	Small
C85800	1650 (899)	50 (28)	Medium	Medium	Medium	Good	Good	Medium
C89550	1638 (892)	50 (28)	Medium	Good	Medium	Good	Good	Medium

of Testing & Materials (ASTM) certification (properties of ASTM test bars with 20 compositions for each alloy). ANOVA (Analysis of Variance) analysis of 51 chemistries indicated the alloy with nominally 2% bismuth and 1% selenium would have a tighter and higher range of properties if the tin was restricted to 5 to 6%. SEM (Scanning Electron Microscopy) studies of fractured test bars showed a bismuth phase and two copper-zinc-selenium compounds (Fig. 9-8). Low tin (<5%) allowed bismuth globules to spread out along the grain boundaries, selenium may also be beneficial but nickel harmful. Further tests showed tin and phosphorus (>0.05) were beneficial to ductility. On the other hand, tin has a large effect on the solidus (drops 100C (180F) as tin increases from 4 to 6%).

In green sand molding, the elements phosphorous and sulfur are limited to 0.02 and 0.08% in the final casting due to their reaction with the water in the green sand and formation of gas defects at higher levels. There was an improvement in test bar properties cast in chemically bonded sand when phosphorous was increased to 0.05%, but higher levels were not investigated for fear of drossing reactions. A sulfur containing alloy will be discussed below.

Shrinkage measured using a Tatur test mold was similar to C83600 and C84400. Fluidities of the four alloys, determined by three methods, were similar after taking into account the higher liquidus temperatures of the Bi-Se alloys (increase pouring temperature 20C(30F). The C89520 filled 1-2 mm thick sections in the Kondic Fluidity Test further than the leaded alloys. The new alloys were less susceptible to hot tearing under constraint. Feeding distances were the same as for C83600 and further than C84400 and leak rates no worse than the red brasses. Castings produced at a commercial foundry in C89520 had a better surface finish than C83600 castings. Melting losses of zinc and phosphorus were similar to the red brasses. Corrosion was similar to the leaded alloys. Because the bulk of the solid is 89Cu-5½Sn-5½Zn, the casting characteristics of C89510 and C89520 are essentially the same as C83600 and can be cast using the same patterns, gating and risers.

The machinability indexes are 84, 75, and 85 for C83600, C89510 and C89520 respectively. Grain refinement with zirconium, FKM2000, or boron does not affect mechanical properties or fluidity, but can improve machinability. During machining lead acts as an internal lubricant and provides

discontinuities to act as a chip breaker. Bismuth can replace lead in some of these roles, but tool sharpness, feed rate, and more rigid machines are critical. Due to the low melting point of the bismuth phase, the strength of the bismuth-selenium alloys drops quickly when heated (Fig. 9-9), therefore, machining is best performed under lubricant to avoid cracking the parts. On the advice of ingot makers, the lead limit of C89510 and C89520 were set at 0.25%, although later copper-bismuth alloys limited lead to 0.09%. The lead-bismuth phase diagram (Fig. 9-10) suggests that for each 0.1% of lead impurity in a Cu-Bi alloy would decrease the liquidus by 25C (45F) at the 1% Bi level and 13C (23F) at the 2% Bi level. Consequently the low bismuth alloys are likely to be more sensitive to lead impurities at higher temperatures.

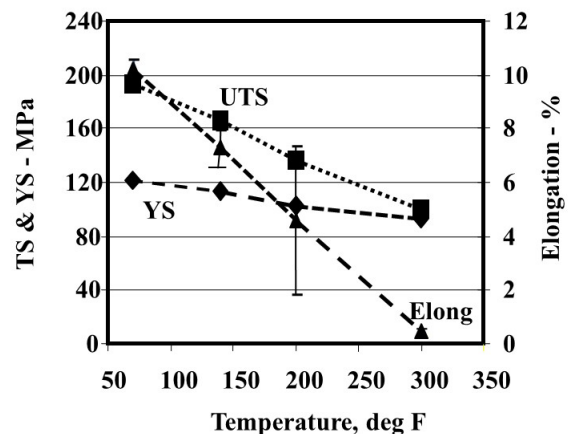


Fig. 9-9 Properties of C89520 at selected temperatures.

CANMET also successfully pursued the development of a lead-free yellow brass for permanent mold casting of plumbing fittings, which was called EnviroBrass® III or C89550. See Chapter 10 for more information about that alloy.

Other Lead-Free Cu-Sn-Zn Alloys

During the same period, Federal Metal conducted independent research and applied for a number of patents. Their first US Patent 5,487,867 was granted in 1996 which covered the addition of 0.1 to 7% bismuth and 0.1 to 2% mischmetal to replace lead in most copper alloys. Currently, the company

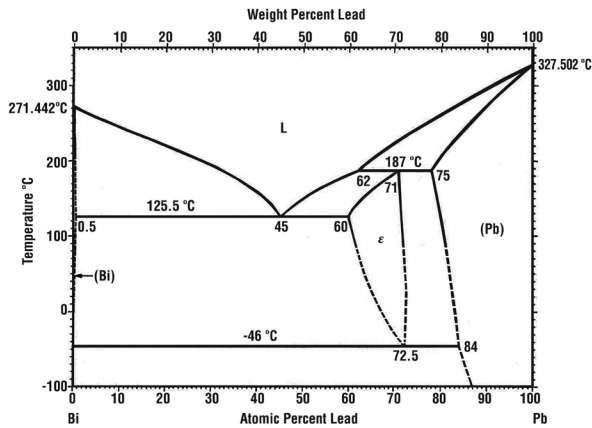


Fig. 9-10. Lead-bismuth phase equilibrium diagram. Artwork courtesy of ASM Intl., Materials Park, Ohio, "Binary Alloy Phase Diagrams," T.B. Massalski, 2nd Edition (1990).

markets four alloys C89833 and C89844 as Federalloy I-836 and I-844, to replace C83600 and C84400 respectively, and C89835 and C89325 as Federalloy III-932 and III-937 to replace C93200 and C93700 respectively. Mischmetal was first produced in 1903, and consists of the reactive rare earth metals: cerium 50%, lanthanum 25% and neodymium 10%. Their reactivity is exploited for use as flints. The amount of mischmetal in each of the alloys is proprietary, and not indicated in the alloy specifications, but the patent claims rare earths disperse the bismuth more completely.

Chinese demand for selenium to reduce over-voltage potential in the electrodeposition of manganese and to produce the bright red ceramic tiles used in traditional buildings reduced the availability and increased selenium prices from a range of \$3.50–\$10.00 to \$60 per lb. Electrolyte additives (for reducing over-voltage) usually get incorporated into the deposited metal, and are consumed. Hence, these two uses disperse selenium into non-recoverable end uses.

Japanese industry was concerned that the low strength of EnviroBrass® II, particularly in hot water systems, was inadequate to withstand earthquakes, and sought another solution. Kurimoto Bronze supplies C89845 which has extra zinc and 2% nickel.

Industry response to these issues was a plethora of new alloys containing bismuth to replace C84400 and C83600 for green sand casting; see Table 9-5 and the section on Copper-Bismuth and Copper-Bismuth-Selenium Alloys in Table 1-2 in Chapter 1. Except for the two alloys C89320 and C89325 that substitute for 88-10-2-0, the properties of the remaining alloys are similar (Table 9-6). As most alloys are ASTM accredited (20 compositions), it is surprising that only tin levels had to be limited to the upper range in EnviroBrass® II, C89835 and C89836 in order to maintain properties. The Nibco C89844 alloy has higher zinc but in C89836 zinc levels were limited by the Yorkshire Fittings patent, as follows. It is likely most of the alloys have lower properties as temperatures approach bismuth melting point of 520F (271C)(Fig 9-11).

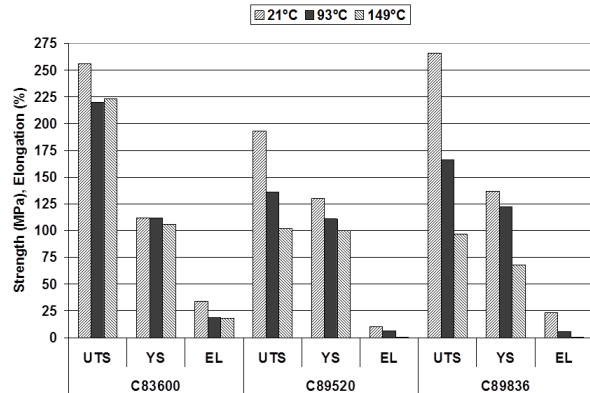


Fig. 9-11. Properties of C83600, C89520 and C89836 alloys at selected temperatures.

Environmental issues with lead have seen the development of a lead-free bismuthized bearing alloy C89320. The properties of the new alloy have been compared with C93200 and C93600. The mechanical properties indicated that phosphorus levels should exceed 0.05% to meet the ASTM minimum ductility. Strength of the bismuth alloy fell below those of C93700 above 150C (302F). The coefficients of friction were 0.27 for C93200 and 93600, 0.32, for C89320 and bismuthized alloy, and 0.45 for 20% nickel silvers with no sign of galling. Results of static friction tests, machinability rating & finish, four corrosive solution rates were similar to the leaded alloys.

AFS Copper Lead No Lead Consortium 2010

In 2007, pending a new California regulation (AB 1953) limiting lead content to 0.25% in all brass products coming in contact with potable water (superseded by 'Reduction of Lead in Drinking Water Act', effective January 2014), selenium price had risen to \$60 a pound and bismuth to \$15–\$19 per lb, the AFS formed another 'No Lead Consortium' to examine the issues. They found:

- Corrosion and pitting of alloys C89520 and C89836 were similar to C84400 and C83600.
- Gating systems and leaker formation rates for EnviroBrass® II were similar to those with C83600. For C89836, leakers were a common issue that often responded to gating system changes, increasing zinc and nickel, just zinc, or lower or tighter control of pouring temperatures. Increasing the zinc level during the development of alloy C89836 was limited by the 1987/1988 Yorkshire Fittings patents.
- Bi and Bi-Se slags lower furnace and crucible lining life by about 20%.
- Cu-Bi alloys are more difficult to machine than their leaded-red brass equivalents. One reason is their rapid loss of strength as part temperatures approach the melting point of bismuth. Cracking during machining can be reduced by wet machining. There

Table 9-5. Families of the Copper-Tin-Zinc-Bismuth-Selenium Alloy Group

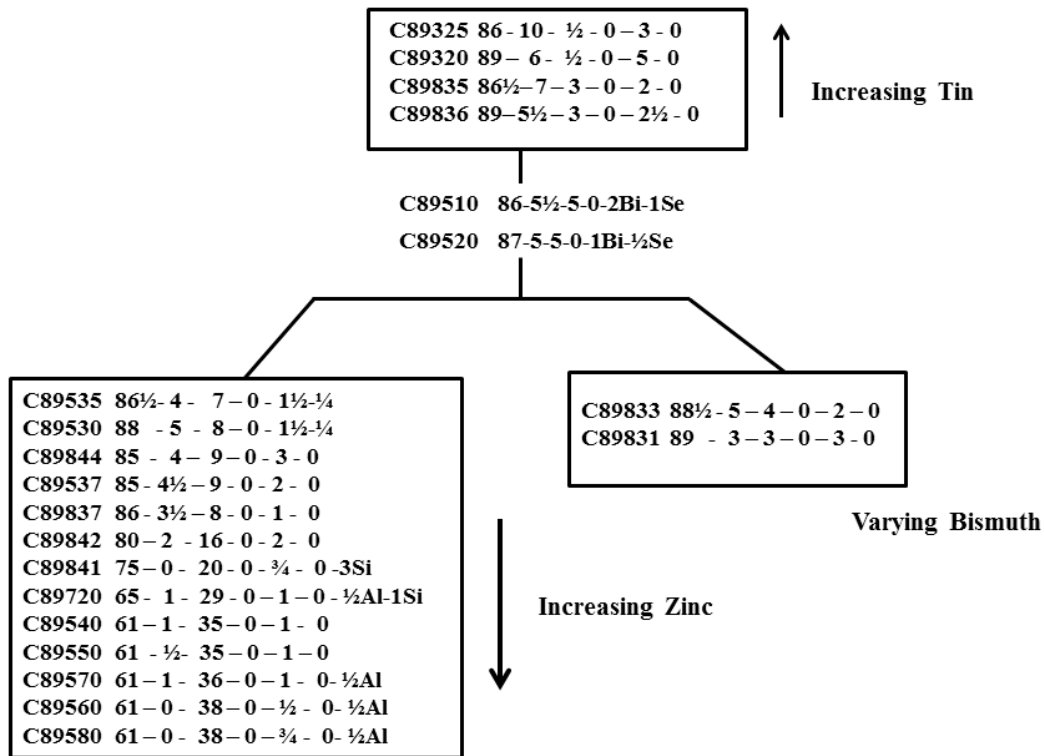


Table 9-6. Casting Characteristics of Copper-Tin-Zinc-Bismuth Alloys

Alloy	Mold	Typical Mechanical Properties				Casting yield	Effect of sect. size on mech. prop.	Fluidity	Shrinkage or pattern makers'	Solder-ability	Brazing	Mach. Index
		Tensile ksi	YS ¹ ksi	Elong %	Brinell Hard-ness							
C89320	PM	40	20	30	70	H	M	M	L	E	G	80
C89325	Sand	35	18	20	73	H	L	M	3/32	G	G	80
C89510	Sand *	30	20	12	37	H	L	M	M	E	G	75
C89520	Sand *	31	21	10	54	H	L	M	M	E	G	85
C89530	Sand *	33	15 ²	15	52					E	E	84
C89535	Sand *	38	19 ²	15	55R					E	Fair	75
C89537	Sand	45	21	25								
C89831	Sand	34	15	20	55	H	L	M	5/32	E	G	85
C89833	Sand *	37	17	28	60	H	L	M	11/64	E	G	81
C89835	Sand *	35	18	20	65	H	L	M	2/16	E	G	70
C89836	Sand *	33	19	30	65					E	G	85
C89837	Sand	37	17	32	60	H	L	H	7/32	E	G	66
C89844	Sand *	34	15	30	55	H	H	M	3/16	E	G	70
C89845	rod/bar	32	16 ²	15	67	H	H	M	3/16	E	E	76

Yield strength¹ mostly 0.5% Ext, except ² 0.2% offset
H=high L=low M=medium E=excellent G=good

* ASTM B585 certified

is some concern that high speed dry machining can cause work hardening, which leads to cracking. High tin or phosphorous levels have also been tried.

- Soldering C89836 was successful. The lower melting solders require reduced gaps, lower temperatures and longer, slower cooling if cracking is to be avoided.

- The production numbers of the by-product bismuth (lead, copper and tungsten) were unreliable and the future availability of bismuth was uncertain. Lead leachate levels in drinking water have been lowered, while those of bismuth were raised. They are now lead 5 ppm, bismuth 0.1 mg/L, selenium 0.05 mg/L.

Based on the extensive investigations on C89510 and C89520, and all the information on other Cu-Sn-Zn-Bi alloys collected on the CDA website (www.copper.org), it is apparent that the foundry characteristics of these alloys can be compared to the equivalent Cu-Sn-Zn-Pb alloy simply by deducting the Pb, Bi and Se compositions and recalculating the Cu-Sn-Zn percentages to determine the equivalency.

Sulfur Containing Alloys

An alloy containing 2.7–3.3%Sn, 2.1–3.5%Zn, 1%Ni, 0.02–0.1%Fe and 0.2–0.8% sulfur was patented in 2006. The alloy was cast in furan resin. Iron and nickel were added to decrease the activity of sulfur. Thermal analysis indicated that the sulfides formed an interdendritic liquid during the solidification of the alpha-Cu phase. Sulfur dioxide was not liberated during solidification. Mechanical properties exceeded those of C83600 (tensile >195MPa and elongation >15%) for sulfur below 0.7%. Machinability approached that of C83600 as sulfur was increased to 0.6–0.8%. Machinability decreased with increasing zinc content and Rockwell B Hardness increases (from 35 to 43 RHB). In pure copper sulfur forms Cu₂S at grain boundaries and inter-dendritic areas. In copper alloys, sulfur forms sulfides with copper, zinc and manganese in complex sulfide structures, and their volume increases with the sulfur content. The shape of sulfide particles changes from spherical to irregular at 4% zinc in the new furan cast alloy. The spherical particles are formed from the monotectic reaction and the irregular zinc sulfide particles from the eutectic reaction (consult the Cu-Cu₂S phase diagram). Tin (less than 4%) and nickel have no effect on the formation or amount of zinc sulfide.

In this new alloy, the role of lead is played by copper and zinc sulfides. Zinc sulfide is harder and less desirable, so zinc level is constrained. While the formation of Cu₂S and ZnS magnifies the effect of sulfur, copper and zinc are consumed and the calculated equivalency to a Cu-Sn-0%Pb-Zn (95-4-0-1) alloy is not helpful in predicting casting properties.

Since 2010, most of the AFS Copper Division activity has been focused on the sulfur containing alloy. The new alloy, now known as Biwalite, is a registered as C83470 by CDA and ASTM with the chemical composition 3–5%Sn, 1–3%Zn, 0.1–1%Ni, 0.5%Fe, and 0.2–0.6% sulfur. The melting behavior of this alloy is reported to be similar to bronzes and held in the furnace at up to 1220C (2230F) and poured at 1150C (2100F). The alloy is deoxidized with phosphorous by the addition of Cu-P master alloy. The alloy has a narrow freezing range of the order of 50C (80F).

Two foundries that cast the new alloy in parallel with C89833 (2% Bi) into green sand made panel presentations during the 2014 AFS Casting Congress. Ford Meter Box preferred higher sulfur contents for easier machining. The pressurized gating systems were those in use at A.Y. McDonald for the C89833 alloy but with additional parting line venting. Ford Meter Box used wider ingates. Sulfur was not lost during furnace holding, and odor was not noticeable. One foundry reported marginally more leakers, gas defects and shrinkage

at the centerline. Issues with pouring temperature, phosphorus level, gating systems, or additional parting line venting, etc. to reduce cold shuts and misruns were not resolved. Both foundries found chips were large and did not break up during machining, and one was expecting to do further trials with different conditions and tool bits. Soldering was also acceptable. To date, there is no word on the acceptability of C83470 for green sand casting of plumbing components, although further trials were more successful.

MICROSTRUCTURAL VARIATIONS

All of the alloys of this group exhibit microstructures with a strongly cored alpha matrix, with or without intergranular inclusions of lead or alpha-delta eutectoid; it is often difficult to distinguish one composition from another on the basis of microstructure alone. The greatest value of metallographic examination is for purposes of comparison and for determining whether known alloys exhibit abnormal amounts or distributions of the expected phases or foreign inclusions. Microscopic examination is likewise useful as a means of diagnosing causes of unsoundness or lack of pressure-tightness, as described in Chapter 16 on *Quality Control*.

The dendritic freezing behavior of this group of alloys renders them susceptible to microshrinkage porosity, which usually ranges from about 1 to 3% by volume. Larger degrees of microshrinkage, if well distributed, can be tolerated without adverse effects on mechanical properties or pressure-tightness. When the voids resulting from microshrinkage tend to concentrate, they often become sufficiently interconnected to extend through the wall of a casting or close enough that machining of both cast surfaces allows leakage to occur. These two types of microshrinkage are illustrated in Figs. 9-12 and 9-13. In these photomicrographs, the voids appear as black areas that are located interdendritically, or at grain boundaries. As a word of caution, care must be taken when dealing with leaded alloys so as not to mistake microshrinkage voids for those caused by the removal of lead particles during polishing of the specimen.

FOUNDRY CHARACTERISTICS

Throughout various chapters of this book, the unique characteristics of the copper-tin-lead-zinc alloys have been discussed in detail with regard to melt control, gating, solidification, risering, and control of casting soundness. These topics will be highlighted and summarized here, with referrals to appropriate chapters for more detailed information.

Melt Control

The susceptibility of the copper-tin-lead-zinc alloys to contamination by gas absorption (hydrogen alone, or in combination with oxygen) is a primary cause of casting unsoundness and rejection. Low-gas melts are achieved most consistently by the use of coreless induction melting furnaces. When fuel-fired furnaces are used, close atmosphere control (slightly oxidizing conditions) must be maintained, followed

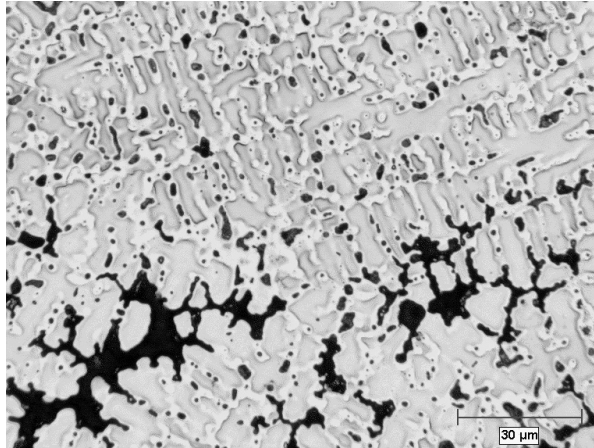


Fig. 9-12. Evenly distributed microshrinkage in red brass is shown above.

by proper deoxidation. Modern gas-fired furnaces tend to separate the flue gases from the metal to avoid this problem. Nitrogen bubbling is generally not required. Channel induction furnaces require melting under a graphite cover to reduce oxide inclusions in the melt that can rapidly tear out the channel. Evaluation of the level of dissolved gases is best made by the Reduced Pressure Test (RPT) described in Chapter 5 on Melt Control. Alternatively, one can use the fracture test comparison discussed in Chapter 16 on Quality Control, although this is a much less sensitive method.

The proper degree of deoxidation with phosphorus-copper must be established by each foundry, according to its melting practice and product mix. Residual phosphorus levels must be monitored to prevent wide variations, and should normally be targeted and held in the range of about 0.015 to 0.030% (for the reasons explained in the chapters on *Melt Control and Quality Control*).

Scrap returns should be of known composition in order to avoid contamination with undesired elements during melting. Excessive amounts of iron in the melt (from shot blasting, skimming and stirring tools, wire, etc.) will cause hard inclusions that damage cutting tools. Iron in excess of 0.3% reduces the ductility, but not the susceptibility to hot tearing, grain size, porosity, pressure tightness or fluidity. Antimony in excess of 0.25% has similar affects, and because of deleterious effects should perhaps be less than the 0.25% specified. Small amounts of either silicon or aluminum (about 0.010% of either) are known to cause serious leaking problems. 0.005% aluminum can reduce the ductility of C83600 by 5–40%. Aluminum can be picked up from pouring brass and aluminum into the same sands. It is not clear whether these elements do damage by forming entrapped oxide films in the melt or by permitting the absorption of hydrogen. Manganese is not detrimental to strength and the ductility will not be affected up to 0.2%, although it has been suggested that manganese should be limited to 0.1% in C83600. Carbon absorbed from graphite crucibles or graphite covers is typically 0.002 to 0.015%, but should be limited to 0.005%

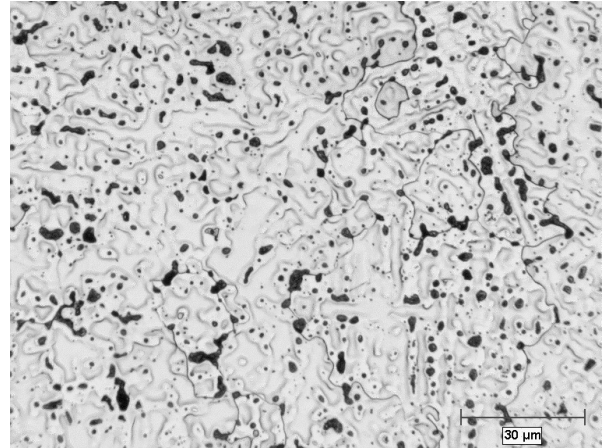


Fig 9-13. Localized, interconnected microshrinkage in red brass is illustrated.

so as not to cause porosity with oxygen and sulphur. Arsenic tends to dissolve in the lead phase, but should be limited to 0.25% in C83600. Excessive superheating and prolonged holding in the melting furnace should be avoided as both lead to excessive zinc loss and gas adsorption.

The introduction of bismuth-modified red brasses to replace leaded red and semi-red brasses in plumbing products and other applications has resulted in leaded and bismuth-containing scrap being mixed either at the foundry, during scrap collection or ingot manufacturing. Bismuth and lead are miscible as liquids and bismuth is soluble in solid lead up to at least 18%. AFS funded research found that in alloys C83600, bismuth concentrations of up to 0.3% have a negligible effect on properties, and the data suggests that up to 0.7% or sometimes 1% bismuth alone can meet ambient temperature mechanical property specifications. However, the presence of 0.1–0.15% selenium further reduces the mechanical properties of C83600. High temperature properties of the alloy are adversely affected, particularly by selenium. Bismuth alone up to 1.2% had no effect on the room temperature mechanical properties of C84400. Selenium up to 0.26% had little effect on yield strength of C84400, but decreases ultimate tensile, elongation, and impact properties. For the latter reason, selenium should probably be limited to 0.1% in C84400.

The lead-bismuth phase diagram, Fig. 9-10, indicates that when the liquid lead is rejected from the freezing copper matrix, and bismuth reaches the 12% level in the lead, the freezing point has dropped to that of bismuth (271C, 520F). In C83600, that translates to 0.5 to 0.7% Bi in a 4–6% lead alloy and 1–1.2% Bi in C84400. Figure 9-14 shows the effect of temperature on mechanical properties (500F [260C] was selected as C83600 is used for steam lines).

In the Cu-Sn-Zn-Bi alloys the lead levels are required to be extremely low to comply with new legislation on leachate levels. However, as the Pb-Bi phase diagram, shows lead to be insoluble in bismuth (Fig. 9-10), not only could lead

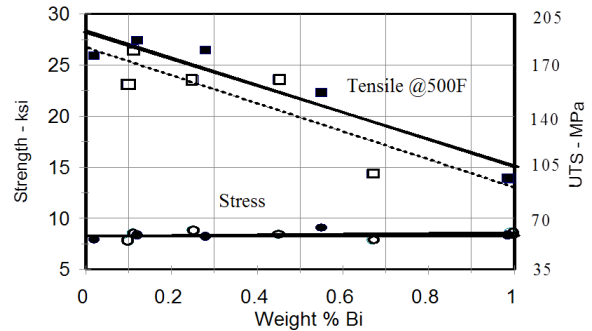
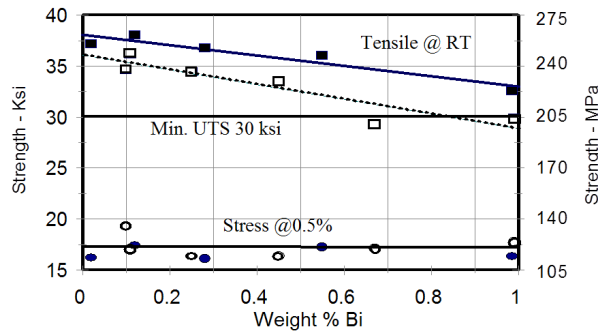


Fig. 9-14. The effect of bismuth and selenium on the properties of leaded-red brass C83600 at room temperature and 260C (500F). Note: Solid markers just Bi. Open markers Bi with Se.

whiskers occur, but lead lowers the liquidus temperature, so the low bismuth alloys are likely to be more sensitive to lead impurities at higher temperatures.

Gating and Riser

Small castings of uniform section thickness (about $\frac{1}{4}$ inch or less) can be kiss-gated successfully, using the techniques described in the chapter *Gating*. For larger parts, the unpressurized gating system involving drag runners and cope gates is advised. Where maximum soundness is required for these wide-freezing-range alloys, massive chilling is essential, as discussed in the chapter *Solidification, Feeding & Design*. Feeding from risers is extremely limited and directional solidification can be achieved only by conditions that produce thermal gradients of 60F (33C)/in. or more in the mold.

For commercial grade castings in which 1 to 3% of well-distributed microshrinkage is acceptable, the role of risers is to avoid “sink marks” at casting hot spots, caused by collapse of the casting under atmospheric pressure. The technique of approaching uniform solidification in such castings by the proper design and placement of gates and insulated risers is also detailed in the chapter on Solidification. An important factor in attaining uniform solidification is the practice of pouring at the lowest practical temperature, even if this means reducing the number of molds poured per ladle. Guidelines for the selection of pouring temperatures for these alloys are given in Table 9-2. Pouring practices for these alloys, both manual and automatic, are described in Chapter 6, Pouring.

GENERAL APPLICATIONS

Castings of the various families included in the copper-tin-lead-zinc alloy group constitute more than three-fourths of the annual production of cast copper-base alloys.

Alloy C83600, the constitutional “hub” of the entire group, was used for valves, pipe fittings, water pump and meter housings and impellers, small gears, high-quality plumbing goods, statuary and plaques. C83600 no longer meets lead leachate requirements for potable water supplies (valves,

faucets, water meter, or any part in contact with water). C83600 is still used for steam lines. The use of C83600 is due to its corrosion resistance, machinability, strength, bearing properties, color, and excellent castability of the alloy.

Leaded Red and Semi-Red Brasses

Alloy C83800 (83-4-6-7) finds application where somewhat lower mechanical strength is acceptable (lower pressure-rating valves, fittings and pump components).

Alloys C84400 (81-3-7-9) and C84800 (76-2½-6½-15) were also the “workhorse” alloys, once comprising the major tonnage of commercial plumbing fixtures, cocks, faucets and certain low-pressure valves.

High-Leaded Tin Bronzes

Alloy C93200 (83-7-7-3) is the general-utility alloy of this family and finds use in general bearing and bushing applications. It is the alloy most widely used for bushings made by continuous casting.

Alloy C93700 (80-10-10-0) because of its higher tin and lead contents, is suitable for bearings involving high speed and heavy pressures, as well as pump and impeller parts requiring corrosion resistance and strength.

Alloy C93800 (78-7-15-0) is likewise used for larger bearings, but for less demanding service involving only moderate pressures. The material is also commonly used for pump parts in acid mine waters.

Tin Bronzes (Unleaded and Leaded)

Alloy C92200 (88-6-1½-4½) is commonly used for high-quality valves, fittings, gears, and pressure vessel applications with operating temperatures of up to 550F (290C).

The remaining four alloys of this family have excellent resistance to both wear and corrosion and are usually specified for use as special bearings, pump parts, gears and steam fittings. Of these, alloys C92300 (87-8-1-4) and C90300 (88-

8-0-4) differ only in lead content, the former having better machinability. The same difference in analysis distinguishes alloys C92600 (87-10-1-2) and C90500 (88-10-0-2), with the leaded material being the easier to machine.

Copper-Zinc-Tin-Bismuth Alloys

Alloys for bearing alloys and bushings are: Alloys C89320, C89 325, C89831, and 89940.

Alloys for potable water are: those with numbers from C89510 to 89550, C89570 to 89720, C89833 and C89836 to 89845.

Alloys C89831 and C89833 can be used for pressure-tight castings, impellers, and pumps.

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LEADED AND HIGH-STRENGTH YELLOW BRASSES

INTRODUCTION

All of the leaded and high-strength yellow brass alloys contain zinc as the principal alloying element. These alloys comprise two families: the low-strength, leaded yellow brasses; and the high-strength yellow brasses.

As leaded copper alloys freeze, the lead segregates as microscopic liquid pools, which fill and seal the interdendritic microporosity produced when the higher melting constituents have solidified. The lead seals these pores and renders the casting pressure-tight. Lead also makes the alloys free cutting by promoting the formation of small, easily cleared turnings during machining. Unless present in high concentrations, lead does not have a strong effect on strength, but it does degrade ductility. Copper alloys containing lead cannot be welded, although they can be brazed and soldered.

The family of leaded yellow brasses has been defined by the American Society for Testing and Materials (ASTM) as: “copper-base alloys which contain over 17% zinc, less than 6% tin, under 2% total of aluminum, nickel, iron or silicon, and more than 0.05% lead.” These alloys are used primarily because of their relatively low cost and good corrosion resistance, and when a distinct yellow color is desired. They are readily cast in metal, gypsum, and ceramic molds as well as in green or dry sand. Their excellent machinability, buffing and polishing characteristics, and low cost make them an attractive choice for a wide array of general hardware and plumbing castings.

The most popular members of this family are alloys C85200, C85400, C85500, C85700 and C85800, whose nominal compositions and typical properties are listed in Table 10-1. The nominal compositions for alloys C85700 and C85800 are similar, except that up to 1% of Ni (incl. Co) is allowed in alloy C85700 in the Copper Development Association (CDA) composition range compared to 0.5% in alloy C85800. Alloy C85800 is also a popular high-pressure and gravity die casting alloy, and the cost of diecasting can be reduced by the use of expendable resin bonded sand cores.

The second family in this group is the high-strength yellow brasses, formerly called manganese bronzes, because of the presence of manganese. The alloys in this group have much higher tensile strengths and are, in fact, the strongest of all the copper-base alloys in the as-cast condition. These alloys

find application where relatively high strength is required in combination with good corrosion resistance and moderate cost. Significant amount of information from earlier studies and handbooks on the processing and properties of these groups of alloys are available in the literature. In this chapter, we will be concerned with four representative alloys of this family.

As shown in Table 10-2, alloys C86200 and C86300 contain significant amounts of aluminum, iron, and manganese as alloying elements. Consequently, they are considerably stronger than alloys C86400 or C86500 that are lower in the above elements but higher in zinc content. The actual chemical composition limits for these four alloys, as listed in the relevant specifications, are rather wide. Minimum mechanical properties, however, can be achieved only within restricted composition ranges.

METALLURGY

Leaded Yellow Brasses

Figure 9-1 in the previous chapter shows that zinc is soluble in copper up to 32.5% at the solidus temperature and that alloys within this composition range solidify as single-phase, alpha (α) solid solutions. The alpha phase is relatively soft and ductile, deriving its hardness from the effect of solid-solution strengthening, in proportion to its zinc content.

The leaded yellow brass compositions listed in Table 10-1 consists essentially of single-phase (α) structures with the insoluble lead dispersed as intergranular inclusions. In view of the relatively narrow freezing ranges of these alloys, there is a minimum tendency toward microsegregation during solidification, and, hence, little evidence of “coring” in the microstructure. Casting of these alloys in permanent mold and/or high-pressure diecasting can further reduce microporosity defects because of the relatively high solidification rates.

Addition of aluminum changes the dendrite morphology from the conventional interlocking dendrites to feathery dendrites and leads to improved casting fluidity during permanent mold casting. Typical microstructures from ¼ inch thick fluidity plate castings poured in a metal mold showing the dendrite morphology before and after aluminum addition are presented in Fig. 10-1 (a) and (b) respectively.

Table 10-1. Nominal Composition and Properties of Leaded Yellow Brasses *

Elements/Properties	Nominal Composition (wt. %)				
	C85200	C85400	C85500	C85700	C85800
Copper	72	67	61	61	61.5
Tin	1.4	1	-	1	1
Lead	3	3	-	1	1
Zinc	23.5	29	39	36	36
Typical Mechanical Properties **					
Tensile Str. ksi	38/30	34/-	60/54	50/-	55/48**
Yield Str. ksi	13/14	12/-	23/23	18/-	30/28**
% Elongation	35/15	35/-	40/34	40/-	15/9**
Freezing Range					
Fahrenheit	1725-1700	1725-1700	1652-1634	1725-1675	1650-1600
Celsius	941-927	941-927	900-890	941-913	899-871

* CDA Standards Handbook, Part 7 Alloy Data (Cast Products, 4th Edition, 1996).(www.copper.org)

** Mechanical properties = sand / permanent mold, except for alloy C85800 that is high pressure die cast / permanent mold cast properties.

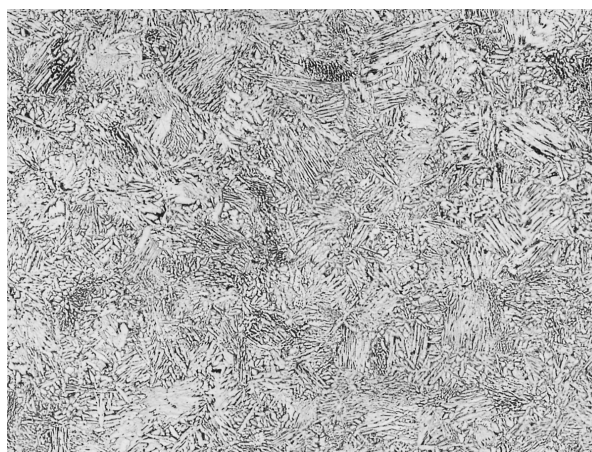


Fig 10-1. Microstructures from alloy C58500 cast in permanent mold showing the dendrite morphology (left) before, and (right) after 0.3 % Al addition (100x). (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada.)

Table 10-2. Nominal Composition and Properties of High-Strength Yellow Brasses *

	Nominal Composition			
	C86200	C86300	C86400	C86500
Copper	63	63	59	58
Aluminum	4	6.2	1	1
Iron	3	3	1.2	1.2
Manganese	3.7	3.7	0.8	0.8
Lead	-	-	1	-
Sn	-		1	0.5
Zinc	25	25	38	39
Mechanical Properties (Typical)				
Tensile Str., ksi	95	119	65	71
Yield Str., ksi	48	67	25	29
% Elongation	20	18	20	30
Freezing Range				
Fahrenheit	1725 – 1650	1693 – 1625	1616 – 1583	1616 – 1583
Celsius	941 – 899	923 - 885	880 – 862	880 - 862
* CDA Standards Handbook, Part 7 Alloy Data (Cast Products, 4th Edition, 1996) (www.copper.org)				

High-Strength Yellow Brasses

As the zinc content of Cu-Zn alloys is increased significantly beyond 32.5% (as in alloys C86400 and C86500), the microstructures of the alloys begin to show increasing amounts of a second, “beta” (β) phase. The beta phase has significantly greater hardness and strength (and lower ductility) than the alpha phase, and hence, it has a marked strengthening effect on the alloys. The beta phase or, more precisely, the “beta-prime” (β') phase, first appears in the alloy microstructure at room temperature at a zinc content of about 39%. At 40% zinc, as shown in Table 10-3, the presence of this phase is manifested by a sudden increase in alloy strength. The rate of cooling after solidification can also influence the beta content, slower cooling rate could result in the precipitating of more alpha phase.

Other alloying elements, such as aluminum, have an even stronger tendency to promote the formation of the beta phase when added to Cu-Zn alloys. For example, an addition of 1%

Table 10-3. Tensile Strengths of Annealed Cu-Zn Binary Alloys

% Zn	Nominal Tensile Strength (ksi)
0	32
15	40
20	44
30	47
35	48
40	54

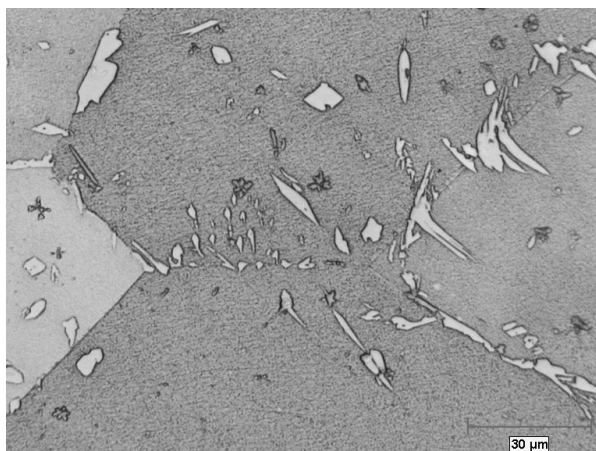


Fig 10-2. As cast (sand) microstructure of (a) alloy C86500 (58%Cu, 0.5%Sn, 39.5% Zn, 1%Al) showing a light, acicular alpha phase in beta matrix (500x). (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada.)

aluminum has the same effect as an addition of 6% zinc. Thus, aluminum is said to have a *zinc equivalent* of six. In the case of alloys C86400 and C86500 (which differ basically only in the absence or presence of lead), we can therefore expect the microstructure to reflect the alpha-beta proportion to be found in a binary 55% Cu-45% Zn alloy. This may be seen in the sand cast microstructure of alloy C86500 shown in Fig. 10-2. Note here that the alpha phase, which appears as an acicular structure, has formed by precipitation from a single, beta phase that appears as the matrix structure at room temperature. Lead, when present, occurs as insoluble particles within the matrix structure. Alloys C86400 and C86500, having two-phase structures, may be considered as moderate-strength alloys.

In spite of their relatively low zinc contents, alloys C86200 and C86300 show microstructures that contain little or no alpha phase. This is because of the high zinc-equivalence of the 4 to 6% additions of aluminum, resulting in an effective zinc content of 50 to 55%. Typical microstructure of alloy C86300 poured in sand mold is shown in Fig. 10-3. The high beta content of the alloy accounts for its unusually high mechanical strength. The small, black inclusions seen in the microstructure are particles of a complex, iron-rich intermetallic. Iron is essentially insoluble in these alloys and is added primarily for grain refinement. This is particularly important for castings containing both thin and thick sections. In the absence of iron additions, heavy sections that cool slowly tend to develop coarse grain size with consequent reduction in mechanical strength. Normally, these iron-rich inclusions are small and well distributed, forming round to rosette-shaped particles similar to that shown in Fig. 10-4. Under certain conditions, including when excessive amounts of iron are present, these particles may form as large inclusions or “hard spots” which adversely affect machinability and cosmetic appearance of these alloys.

The role of manganese in the high-strength yellow brasses remains obscure. Although it has a low zinc equivalent

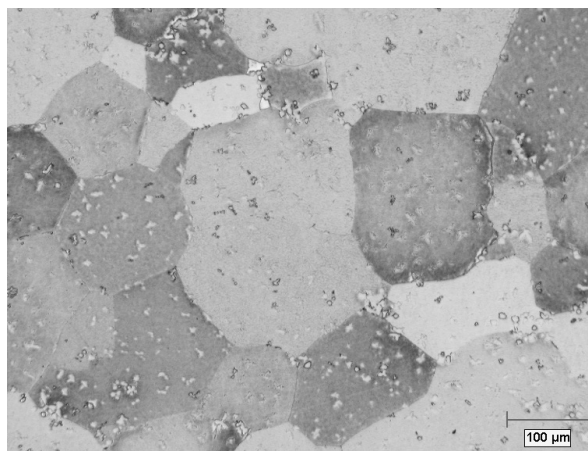


Fig 10-3. As cast (sand) microstructure of alloy C86300 showing matrix structure of beta phase with relatively small, acicular particles of alpha phase at grain boundaries and within grains. The black specks are iron-rich particles of intermetallic phase (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada.)

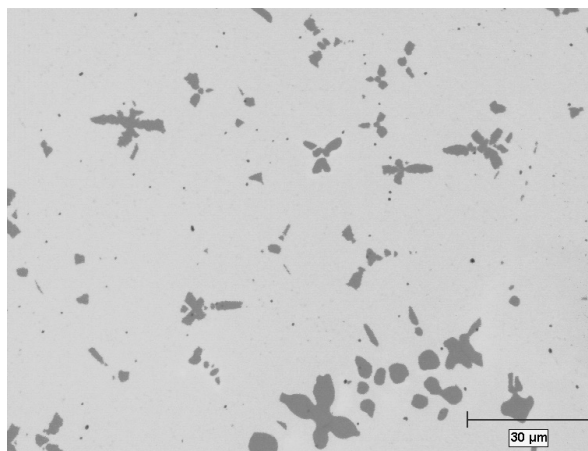


Fig 10-4. Unetched microstructure of alloy C86300 showing rounded and rosette-shaped inclusions of iron-rich intermetallic phase precipitated along grain boundaries and within grains (500x). (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada.)

(0.5), it increases strength slightly without reducing ductility. Manganese is also thought to have some benefit as a mild deoxidizer and in improving foundry characteristics of the alloys.

The mechanical properties of the high-strength yellow brasses are strongly influenced by the proportion of beta phase in the microstructure; this, in turn, is markedly affected by the percentage of zinc and other alloying elements present in the alloy. For this reason, despite the latitude in composition limits permitted by specifications, actual composition must be controlled within narrow limits and carefully balanced to achieve reproducible, desired properties. For critical applications it is not uncommon to specify microstructural requirements as well as composition and mechanical proper-

ties, for purposes of corrosion resistance. In the case of the "all-beta" alloys (C86200 and C86300), severe composition imbalance may actually result in the formation of small amounts of "gamma" (γ) phase at the grain boundaries, resulting in severe brittleness of the castings.

The most important metallurgical effect of the beta phase is that it significantly raises ductility at high temperatures. This extra ductility improves the alloy's resistance to hot cracking in highly restrained molds and allows some yellow brasses to be cast by the pressure die cast and/or permanent mold processes. The "all-beta" alloys have a reputation for being "hot short" at about 400C (752F) and require care during shakeout.

Cooling rate in the mold also has a marked effect on the identity, size, and shape of microstructural constituents. Thus, there will be differences in both microstructure and properties of thick and thin sections, and between chill-cast and sand-cast parts. The beta-alpha transformation cannot be suppressed, even with rapid chilling. For this reason, property enhancement by heat treatment is not possible, although stress relief annealing at 600F (316C) is sometimes performed, especially after welding.

EFFECTS OF IMPURITIES

Leaded Yellow Brasses

Iron, within the limits permitted by specifications, can act as a grain refiner in leaded yellow brasses and increases strength and hardness somewhat. If grain refiner additives (e.g., boron or zirconium) are present in the melt, then intermetallic inclusions can form with free iron, creating "hard spots" which create comet tails during polishing and buffing.

Like iron, nickel refines grain size and increases strength, but can adversely affect machinability at levels above 0.3%. Aluminum is sometimes added in small amounts to control flaring and to produce smooth casting surfaces in sand

castings. No more than 0.2% aluminum should be used for this purpose, and aluminum should be avoided entirely for castings that must be pressure-tight. To attain better fluidity in thin wall sections, sometimes up to 0.1% phosphorus (as 15% phosphorus-copper) is added to the melt. This practice is not recommended. It is especially important to avoid the addition of phosphorus in combination with aluminum. However, for castings poured in metal mold, up to 0.3% aluminum can be added to improve casting fluidity and surface finish. This level of aluminum addition has also been shown to also improve the corrosion resistance of alloy C85800 poured in metal and sand molds.

Although tin increases corrosion resistance, it can also contribute to hot shortness tendencies and must be kept below 0.8%. For thin-wall castings made with metallic cores, the presence of as little as 0.2% tin can create cracking problems. Addition of boron as grain refiner can reduce the hot cracking tendency in some of these alloys. Silicon improves castability, but is damaging to pressure tightness. Moreover, if the alloy contains manganese, silicon can contribute to the formation of hard spots (intermetallic compounds of Fe-Si-Al-Mn). Arsenic and antimony strongly reduce the dezincification tendency of the alpha phase.

The addition of boron as a Cu-2%B master alloy or boron containing fluxes is known to be very effective as grain refiner for the high-zinc yellow brass alloy C85800 poured in a metal mold. Examples of microstructures from alloy C85800 cast in permanent mold before and after grain refinement with Cu-2% B master alloy are shown in Figs 10-5(a) and (b) respectively. However, there is concern that in the presence of free iron, iron boride might form that would act as hard spots on the plumbing fittings that could have an adverse effect on polishing, buffing and plating qualities. It is suggested to maintain the Fe and B contents below 0.06 % and 12 ppm respectively to prevent the formation of iron boride. It is noted that the specification for yellow brass calls for 0.5 % Fe maximum. For this reason, the iron content in the ingot should be less than about 0.06% to prevent the formation of iron boride inclusions.

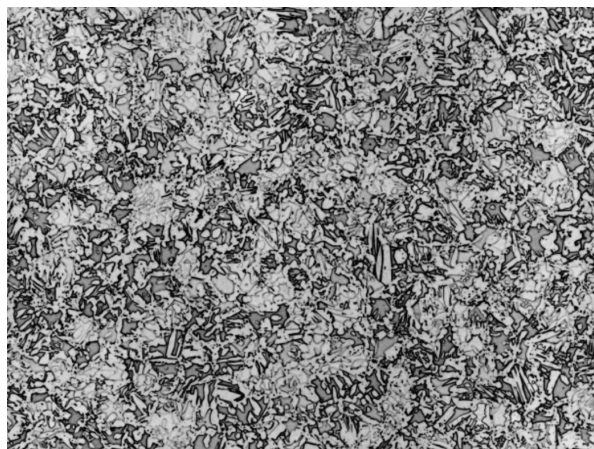


Fig 10-5. Microstructures from alloy C85800 cast in permanent mold showing the dendrite morphology (left) before, and (right) after grain refinement with boron (100x). (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada.)

High-Strength Yellow Brasses

In order to assure that proper ratios of the alpha and beta phases are maintained in the microstructures of these alloys, particular attention must be paid to the dangers of contamination from other alloys during melting. This pertains to any metallics intentionally charged to the furnace as well as residual metal adhering to furnace linings or to the interiors of crucibles or pouring ladles.

Lead and tin are two common elements that may inadvertently be introduced into heats of high-strength yellow brasses. In the case of alloys C86400 and C86500, Table 10-2 indicates that the presence of as little as 1% lead (added for machinability purposes) is sufficient to reduce the tensile and yield strengths by 5000 psi and elongation by 5%. Similar effects may occur by the unintentional lead contamination of alloys C86200 and C86300. In the latter two alloys, when tin is maintained at a level below 0.20% it is possible to attain the minimum mechanical properties. For alloys C86400 and C86500, the permissible limits for tin content are somewhat higher, being 1.5 and 1.0% respectively. Tin, in fact, is sometimes added to these alloys in order to reduce their tendency toward dezincification in marine environments.

When present, nickel acts in a manner similar to copper and thus promotes the stability of the alpha phase in the microstructure. It has a zinc equivalent of -1.3.

MELTING AND POURING

Both families of the yellow brasses are commonly melted in either fuel-fired or electric induction furnaces. Although the yellow brasses are not as susceptible to gas pickup as other alloys, it is recommended that melting be carried out under a slightly oxidizing atmosphere. To add iron, it must be dissolved in the alloy, not present as oxides or as inter-metallic inclusions. In addition, the sum of the iron and tin contents must be kept below 0.8%. The rapid solidification of permanent molded brass castings may contain a certain percentage of impurities. This tolerance for impurities results in structural modifications, which strongly affect the mechanical properties of the castings. It is necessary to pay close attention to the fluctuations in the "effective titer" (T_e) of the alloy, knowledge of whose value permits prediction of the alloy properties and dezincification resistance. The properties are dependent on the amounts of alpha and beta phases (see figures) present in the alloy. Effective copper titer (T_e) can be calculated using Guillet's formula:

$$T_e (\text{in \% Cu}) = \frac{\text{Cu} \times 100}{(\text{Cu} + \text{Zn} + 2\text{Sn} + 2\text{Mg} + 0.9\text{Fe} - 1.3\text{Ni} + 0.5\text{Mn} + 6\text{Al} + 10\text{Si})}$$

The effective titer of brass for permanent mold casting must fall between 58 and 61%, with 60% being the optimum. The bend test (cross-section of 1 cm²) and Tatur shrinkage cones are other indicators of effective titer.

The high zinc content of the alloys poses the problem of extensive zinc losses during melting. This adds to the difficulty of alloy composition control as well as creates environmental control problems in the ventilation of the foundry. Flaring of zinc is worse with the ordinary leaded yellow brasses in which there is little or no aluminum present to increase the surface tension of the bath. In addition, for a given alloy, flaring is worse with the use of open-flame furnaces, particularly those of the reverberatory type. When it is necessary to use fuel-fired furnaces in melting the yellow brasses, fluxes may be found useful in reducing zinc losses when added as protective covers. Fluxes are ordinarily found less necessary when melting is done in electric induction furnaces.

A good rule to follow is to melt these alloys rapidly, to minimize the degree of superheating, and then pour promptly to avoid long holding times in the furnace. Before pouring, it will be necessary to replenish the zinc lost by vaporization. In the case of the leaded yellow brasses, the amount of zinc to be added should be established by experience, according to the melting practice of the particular foundry. For these alloys, small variations in zinc level from heat to heat are less critical than they would be for the high-strength yellow brasses.

For the high-strength alloys it is important to maintain the zinc level within rather narrow limits. Ordinarily, zinc additions in the range of 0.5 to 1.5% will be necessary, depending on melting and pouring practice. To obtain a measure of the zinc addition required one technique is the chill-cast finger bar (~ 1/2 x 1/2 x 8 in.) that can be rapidly cooled by compressed air. Brinell hardness readings obtained from such a test bar can be correlated with zinc content of the alloy being cast. With a little experimentation, this rapid-hardness test procedure can be used as a measure of the zinc content of the melt.

It has also been shown that some of the grain refiners that can be used for the leaded yellow brasses are boron, zirconium, and FKM200 (a proprietary refiner). Historically, boron-containing fluxes had been used as grain refiner for high zinc yellow brasses with very good results. In recent studies, addition of boron as Cu-2%B master alloy has been found to be a very effective method of refining the grain structure of yellow brass alloy C85800. Zirconium alone is partially effective. Addition of boron increases the effectiveness of zirconium as a grain refiner in yellow brass. Addition of FKM 2000 (at the supplier's recommended level of 50 g / 550 lb) is also effective as a grain refiner in yellow brass. In addition, grain refinement is effective in increasing the hot tear resistance of yellow brass. In unrefined yellow brass, a combination of about 1% Sn and 1.4% Pb is detrimental to the hot tear resistance of the alloy when poured in a permanent mold.

When making decorative castings that require a highly reflective surface finish, a finer grain size is desired. For this reason, permanent mold casting is the preferred casting method for faucet manufacturers. Some casters use grain refined metal to produce a really "tight grained structure" under the chill surface. As mentioned before, grain refining

methods typically use boron or zirconium additives. Due to cost, boron is the more prevalent grain refiner used with the leaded yellow brasses. Regardless of which grain refiner is used, extreme care must be taken during the inoculation process. The grain refiner must be added in small doses, with sufficient time allowed after each dose. If these precautions are not taken, the grain refiner can react with free iron and/or chromium to form hard spot inclusions in the casting. As discussed before, about 0.3% Al should be added during melting to improve the casting fluidity. In addition, iron and boron levels should be maintained below 0.06 and 12 ppm respectively to avoid formation of hard spots.

Good temperature control must be maintained to avoid overheating of the metal in the furnace and to assure proper pouring temperatures. In general, for the leaded yellow brasses the pouring temperature range for thin castings should be 2050 to 2180F (1120 to 1195C) and, for heavy castings, 1900 to 2050F (1040 to 1120C). When pouring these alloys, the metal surface should be kept well skimmed. Molds should be poured as rapidly as possible, keeping the sprue filled at all times. In no case should pouring be interrupted, since this will allow time for zinc vapors to oxidize and condense on the surface of the mold. These pockets of zinc oxide cause pitted surfaces on the casting, a defect known as “zinc worms” which is unique to this class of alloys (see Defect G 121, chapter on *Common Defects*).

The proper tapping temperature for the high-strength yellow brass alloys is that at which the zinc first begins to flare from the surface of the melt. For the lower-strength alloys C86400 and C86500, this temperature will be about 1850F (1010C), while for the high-strength alloys C86200 and C86300 it will be closer to 1950F (1065C). As with all alloys, pouring temperature is a function of many factors related to casting size and design. In general, the usual pouring range for these alloys is about 1750 to 2050F (955 to 1120C). Although the ideal pouring temperature is just below the point where zinc flaring occurs, good judgement should be exercised by taking into account the size and quantity of castings to be poured from the ladle. The aluminum content of these alloys, as well as their narrow freezing ranges, place them in the Group I classification of alloys described in the chapter on *Gating*. The aluminum oxide skin, which forms on the surface of the molten alloys, makes them quite sensitive to turbulence during transfer and pouring. (Details regarding the gating and pouring of such alloys are given in the chapters on *Gating* and *Pouring*.)

PROPERTIES AND APPLICATIONS

The greatest attractions of the leaded yellow brasses are their low cost, excellent castability, machinability, and ease of finishing, combined with an attractive yellow color and relatively good corrosion resistance. These alloys are used extensively in the plumbing industry for many small cocks and fittings, ornamental castings, small gears, and a multitude of machine parts. While not as corrosion-resistant as the red and semi-red brasses in many environments, their

resistance is actually greater in contact with gasoline, fuel oils, and other hydrocarbons.

Plumbing fittings are usually produced in yellow brass (C85800) by the permanent mold casting in Europe. Historically, majority of the leaded and high-strength yellow brasses in North America are poured in sand molds. In recent years, many North American foundries are turning to permanent mold casting of copper-base alloys because of the better surface finish, precise and consistent dimensional control and improved mechanical properties, compared to sand cast parts. In addition, environmental problems associated with sand disposal and working conditions in the foundries are favoring the casting of copper-base alloys in permanent mold. A broad R&D initiative was undertaken at CANMET-MTL (Canada Centre for Energy and Mineral Technology-Materials Technology Laboratory, now called CanmetMATERIALS) with financial support from American Foundry Society (AFS), Copper Development Association (CDA) and other R&D establishments to develop the permanent mold casting technology for copper base alloys and also to find ways to reduce or eliminate the use of lead from brasses in plumbing fitting applications. Because of this work, the lead content in some of brass alloys can be reduced to about 0.5% without significant reduction in the machinability or pressure tightness. Some new processing data on the permanent mold casting of the high-zinc yellow brass (C85800), containing about 0.3% Al and 0.5%Pb and relatively low tin levels, show that pressure tight faucets similar to that shown in Fig. 10-6 can be produced successfully. In addition, some new lead free alloys containing bismuth and selenium are now available for plumbing fitting applications.

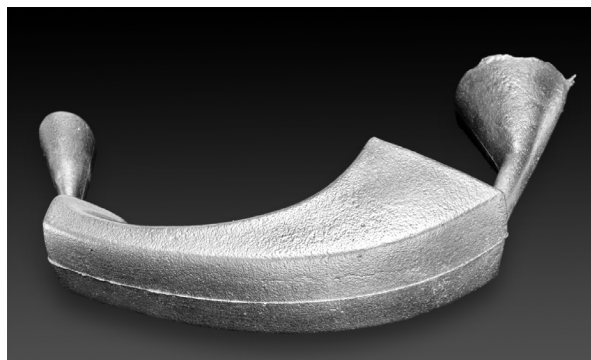


Fig 10-6. Photograph of as-cast faucet of alloy C85800 in metal mold with the gating system (0.4x). (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada.)

Outstanding strength, in combination with corrosion resistance and moderate cost are the principal attributes of the high-strength yellow brasses. As discussed, the strength and hardness of the alloys increase with the percentage of the beta phase in the microstructure, however, increased amounts of beta diminish both the ductility and corrosion resistance of the alloy.

The high-beta alloys C86200 and C86300 are fairly weldable, because of their low levels of tin and lead, are not recommended. Alloys C86400 and C86500 are not weldable. When welding is done the casting should be stress-relief annealed as described in the sub-section of this chapter on Metallurgy.

Applications for the all-beta alloys include structural castings, heavy-duty bearings, hold-down nuts, gears, etc. The use of these alloys in such corrosive environments as seawater, ammonia, acids, and contact with molten metals (mercury, solder, etc.) should be avoided. This is because these alloys are subject to failure by stress-corrosion cracking in these environments.

The lower-strength alpha-beta alloys have marginally better corrosion resistance and find applications as gears, valve stems, and some marine fittings. Their resistance to dezincification in seawater can be improved by small additions of tin, although their previously popular use in ship propellers has diminished in favor of certain grades of aluminum bronzes.

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ALUMINUM BRONZE ALLOYS

INTRODUCTION

Aluminum bronzes are copper-base alloys containing about 6% to 12% aluminum and varying amounts of iron, nickel, manganese and/or silicon alloying additions that provide a broad range of mechanical properties—from high ductility (as in the tin-bronzes) to the high-strength levels of high-tensile manganese bronze. As dramatically different properties can be brought about by comparatively small changes in chemical composition, it is important that producers fully understand that the consistency and reliability of aluminum bronze products can be maintained only by close control of chemical composition and manufacturing methods. This chapter will present an overview of the significant metallurgical characteristics as well as the processing and foundry practices related to the casting alloys included in ASTM specification B148. The alloys listed in Table 11-1 include aluminum bronzes, nickel-aluminum bronzes, silicon-aluminum bronze, and manganese-nickel aluminum bronze.

The aluminum bronzes, C95200, C95300, C95400 and C95900, contain aluminum and iron as the major alloying additions. For more detailed information on specific alloys and processes, refer to the references at the end of this chapter. The silicon aluminum bronze (C95600) as the name implies contain silicon as the alloying element other than aluminum and iron. In the case of nickel aluminum bronzes (NAB), C95500 and C95800, nickel is added to aluminum bronzes. Most of these alloys also contain small amounts of manganese but one alloy C95700, is purposefully alloyed with very high amounts of manganese (11% – 14%) known as manganese aluminum bronze (MAB).

APPLICATIONS

The aluminum bronzes are widely used in applications where good strength, hardness, ductility and corrosion resistance are required. Their bearing and wear-resistant properties, when adequately lubricated, make them useful in applications including gears, slides, gibs, cams, bushings, bearings, molds, and dies. The nickel-aluminum bronzes are used widely in salt water or oxidizing media applications. Marine propellers are manufactured using nickel aluminum bronze alloys produced to the government specification MIL-B-21230A, Alloy 1. Manganese-nickel-aluminum bronze was originally developed for marine propellers. The good

casting characteristics, high strength and ductility and good resistance to cavitation erosion make these alloys suitable for turbine castings, impellers, and hydrofoil components. Other applications for aluminum bronze alloys include combustion engine components, steam and chemical apparatus requiring elevated temperature service 600 to 750F (316 to 399C), valve components, spark-resistant tools, forming dies, rolls and shoes used in metal shaping.

METALLURGY

The metallurgy of the aluminum bronzes is complex, as these alloys often contain four or more major alloying elements. In addition, the structures obtained are dependent on the cooling rate from the casting temperature, and the alloys are heat-treatable. There is probably more information published on the metallurgy of these alloys than on any other copper alloy system, and the reader is referred to the bibliography at the end of this chapter for additional reading. What follows is a simplified treatment. The details of aluminum and nickel-aluminum bronzes are treated first whereas the manganese-aluminum bronzes are dealt separately

Aluminum and Nickel-Aluminum Bronzes

The Copper-aluminum equilibrium diagram shown in Fig. 11-1 (a) indicates that alloys containing up to about 9.4% aluminum should exhibit a single phase alpha (α) structure at room temperature. However, at higher temperatures alloys containing more than 8% aluminum always solidify as a two phase material consisting of alpha + beta ($\alpha + \beta$). The equilibrium diagram shows that the high temperature β phase will transform to α but the transformation rate is so slow, alloys containing more than 8% aluminum will eventually end up as two-phase materials. In alloys containing more than 9.4% Al, the β phase undergoes a eutectoid transformation, if cooled slowly in the region of 1640-105F (900-565C), and forms a mixture of alpha + gamma2 ($\alpha + \gamma_2$).

The most common alloying element added to Cu-Al alloys is iron which is added as a grain refiner to improve the toughness as well as reduce the formation of the γ_2 phase during solidification. The equilibrium phase diagram of Cu-Al-Fe alloy containing 5% iron is presented in Fig. 11-1 (b). The room temperature microstructure consists of α and β phases with precipitates of Fe(δ) based on Fe₃Al. The other

Table 11-1. Composition and Mechanical Properties of Aluminum Bronzes

Alloy	C95200	C95300 A	C95400 A	C95410 A	C95500 A	C95520 A,B	C95600	C95700	C95800 C	C95820 D	C95900 E
	Aluminum Bronze				Nickel Aluminum Bronze		Silicon Aluminum Bronze	Manganese Nickel Aluminum Bronze	Nickel Aluminum Bronze		Aluminum Bronze
Copper	86.0 (min) 88.0	86.0 (min) 89.0	83.0 (min) 85.0	83.0 (min) 84.0	78.0 (min) 81.0	74.5 (min) 78.5	88.0 (min) 91.0	71.0 (min)0 75.0	79.0 (min) 81.3	77.5 (min) 79.0	Rem 87.5
Aluminum	8.5 – 9.5 9.0	9.0 – 11.0 10.0	10.0 – 11.5 11.0	10.0 – 11.5 10.0	10.0 – 11.5 11.0	10.5 – 11.5 11.0	6.0 – 8.0 7.0	7.0 – 8.5 8.0	8.5 – 9.5 9.0	9.0 – 10.0 9.5	12.0 – 13.5 13.0
Iron	2.5 – 4.0 3.0	0.8 – 1.5 1.0	3.0 – 5.0 4.0	3.0 – 5.0 4.0	3.0 – 5.0 4.0	4.0 – 5.5 5.0	-	2.0 – 4.0 3.0	3.5 – 4.5 4.0	4.0 – 5.0 4.5	3.0 – 5.0 4.5
Manganese	-	-	0.5 (max.)	0.5 (max.)	3.5 (max.)	1.5 (max.)	-	11.0 – 14.0 12.0	0.8 – 1.5 1.2	1.5 (max.) 1.0	-
Nickel (including cobalt)	-	-	1.5 (max.)	1.5 – 2.5 2.0	3.0 – 5.5 4.0	4.2 – 6.0 5.5	0.25 (max.)	1.5 – 3.0 2.0	4.0 – 5.0 4.5	4.5 – 5.8 5.2	-
Silicon	-	-	-	-	-	0.15 (max.)	1.8 – 3.2 2.0	0.1 (max.)	0.1 (max.)	0.1 (max.)	-
Lead	-	-	-	-	-	0.03 (max.)	-	0.03 (max.)	0.03 (max.)	0.02 (max.)	-
As-cast properties											
Tensile strength, ksi (MPa)	65 (450)	65 (450)	75 (515)		90 (620)		60 (415)	90 (620)	85 (585)	94 (650)	
Yield strength, Ksi (MPa)	25 (170)	25 (170)	30 (205)		40 (275)		28(195)	40 (2750)	35 (240)	39 (270)	
Elongation, %	20	20	12		6		10	20	15	13	
Brinell hardness No (3000-kg load)	110	110	150		190						
Heat-treated properties											
Tensile strength, ksi (MPa)		80 (550)	90 (620)		110 (760)		125 (862)				
Yield strength, Ksi (MPa)		40 (275)	45 (310)		60 (415)		95 (655)				
Elongation, %		12	6		5		2				
Brinell hardness No (3000-kg load)		160	190		200		255				241 min
Note:	A B C D E	These grades respond to heat treatment Chromium shall be 0.05 max. cobalt 0.20 max. tin 0.25 max. and zinc 0.30 max. ; used only in heat treated condition ; the yield strength is measured at 0.2% offset; Nickel content should be higher than iron Zinc shall be 0.2 max. and tin 0.02 max. Normally supplied annealed between 1100 and 1300 F for 4 h followed by air cooling									

common alloying element, though not added alone in aluminum bronzes, is nickel. Nickel forms NiAl when the alloy is cooled slowly. The phase diagram for an alloy with 6% Ni is shown in Fig. 11-1(c).

In the case of nickel-aluminum bronzes, containing nickel, iron and manganese as alloying elements, the microstructure always consists of various nickel- or iron-rich kappa (K) phases in an alpha matrix. The phase diagram for alloys containing aluminum and 5% each of iron and nickel are shown as the pseudo-binary equilibrium diagram of Fig. 11-

1(d). In addition, because of non-equilibrium solidification and cooling, which is characteristic of the casting process, the alloys with more than about 8.5% aluminum contain substantial β phase at higher temperatures. This transforms to $\alpha + \gamma_2$ as the casting cools to room temperature as explained earlier and additional κ phases also formed in this reaction. The κ phases, depending upon the morphology and compositions, are identified as κ_I , κ_{II} , κ_{III} and κ_{IV} . The schematic diagram indicating these various phases in nickel aluminum bronzes is shown in Fig. 11-2 (a) and a typical micrograph is presented in Fig. 11-2(b).

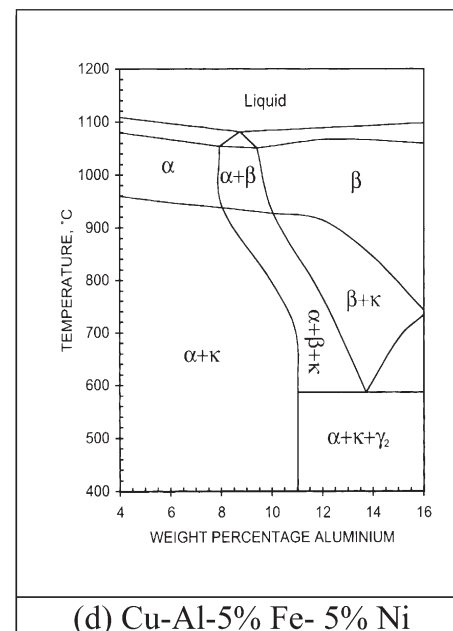
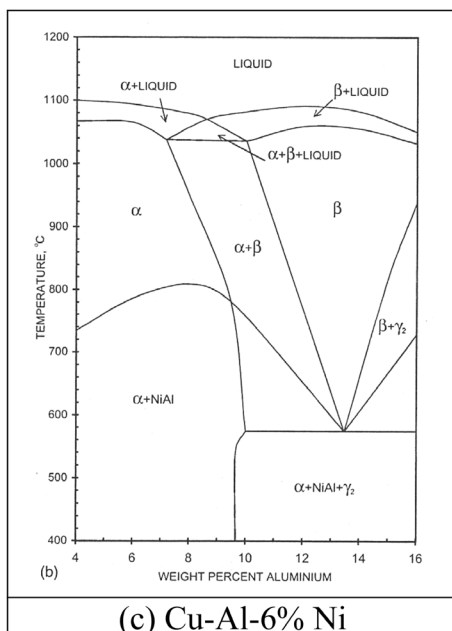
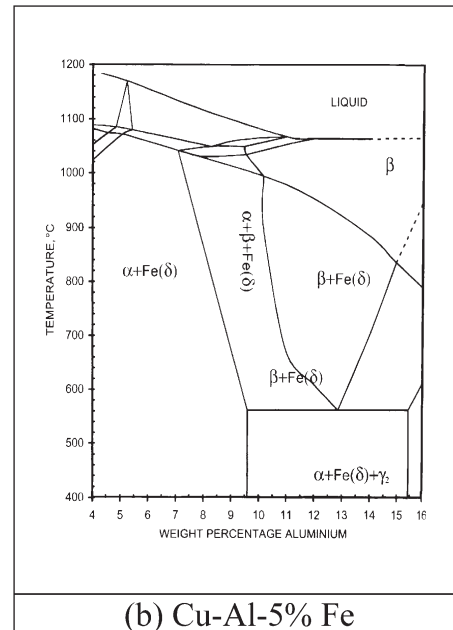
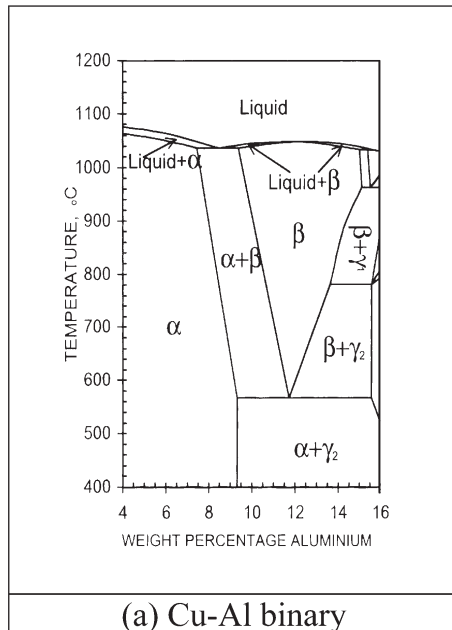


Fig. 11-1. Phase diagrams of Cu-Al, Cu-Al-Fe, Cu-Al-Ni and Cu-Al-Fe-Ni alloy systems are shown. (Artwork courtesy of the Copper Development Assn., UK, "Cast and Wrought Aluminum Bronzes-Properties, Processes and Structure," Harry Meigh.)

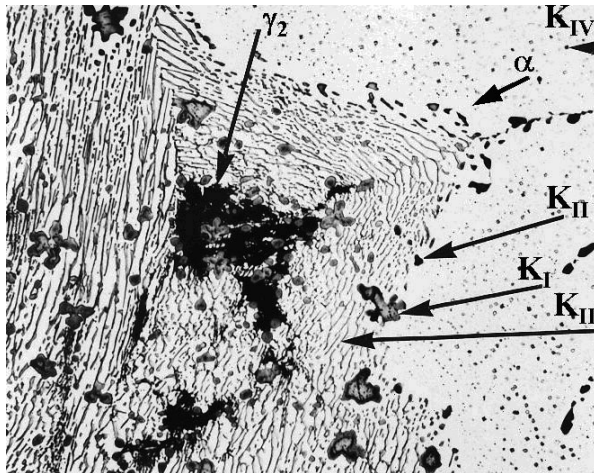
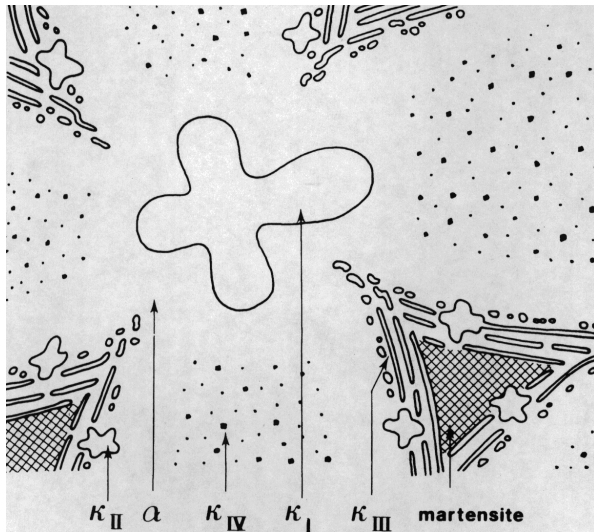


Fig. 11-2. The different phases in (C95800) Ni-Al-bronze are shown. (Artwork previously published in AFS Transactions #80-125.)

The γ_2 phase is detrimental to both ductility and corrosion resistance. The amount of this phase in the microstructure increases with the aluminum content; therefore, the higher-strength, higher-aluminum-content aluminum bronzes C95300, C95400, and C95500 generally rely on heat treatment and/or alloying with nickel and manganese to prevent formation of excessive γ_2 phase in the microstructure. Both nickel and iron combine with the aluminum to form complex κ phases and thus increase the amount of aluminum necessary to introduce the γ_2 phase. The addition of manganese to the aluminum-bronze is also reported to slow the transformation of β phase to the $\alpha + \gamma_2$ eutectoid.

Alloy C95600, the silicon aluminum bronze, is reported to take advantage of the finding that silicon, like manganese, has a positive aluminum equivalent (1 % Si equals 1.6% Al) and has the advantage of reducing the difficulties associated with the breakdown of β phase to the $\alpha + \gamma_2$ eutectoid at slow cooling rates. This alloy is claimed to have improved

machinability and enhanced bearing properties. Up to 1 % iron may be added as a grain refiner.

Microstructure

It is evident from the above discussion that the microstructure of aluminum bronze alloy will be very complex depending upon the composition and thermal history. A typical microstructure of an alloy containing aluminum and iron (C95200) and consisting of α , mixture of $\alpha + \gamma_2$ and particles of Fe_3Al is shown in Fig. 11-3 (a). The more complex Cu-Al-Fe-Ni-Mn alloys such as C95800 contain an α matrix embedded with particles of kappa, and an intimate mixture of $\alpha + \kappa + \gamma_2$ in the areas formerly occupied by the high-temperature β phase as shown in Fig. 11-3 (b). At relatively higher aluminum contents (C95500), the volume fraction of $\alpha + \kappa + \gamma_2$ increases significantly which is illustrated in Fig. 11-3(c).

Effect of Impurity Elements

The specified chemical composition requirements of ASTM B148 for the aluminum bronzes are presented in Table 11-1. In addition to the elements listed, impurity elements can significantly alter properties.

The addition of lead, which is virtually insoluble and forms isolated interdendritic particles, has a beneficial influence on machinability. Addition over 1% is necessary to achieve significant improvements in machinability. Lead is also added to improve bearing properties, but such aluminum bronze alloys have reduced strength and ductility. For castings to be welded or heat-treated, the lead content should be below 0.03 % and preferably lower to reduce the tendency for the heat-affected zone cracking or quench-cracking. For example, in continuously cast alloy C95800, the lead permitted in ASTM B505 is 0.03% maximum.

Zinc is perhaps the most common impurity in aluminum bronze and may, on rare occasions, increase to 1%. Zinc is not considered to have any effect on either mechanical properties or corrosion resistance unless amounts greater than 1% are present. Generally, small amounts of tin up to approximately 0.1% are not considered harmful. However, addition of tin beyond this level could reduce the ductility. Magnesium has been recommended as a deoxidant, but even 0.01 % is said to have detrimental effect on ductility. The high aluminum content of this family of alloys makes them self de-oxidizing and additions for this purpose are not usually needed. Phosphorus is reputed to cause hot shortness during welding at levels as low as 0.01 %, but does not alter the usual mechanical properties until more than 0.08% is present. Cobalt has been reported to improve the mechanical properties. Chromium, in low levels, up to 0.1% has no effect on properties. However, higher amounts were reported to improve the hardness and wear resistance of the alloy. Beryllium and selenium were also reported to have no effect on properties until a level of 0.05%.

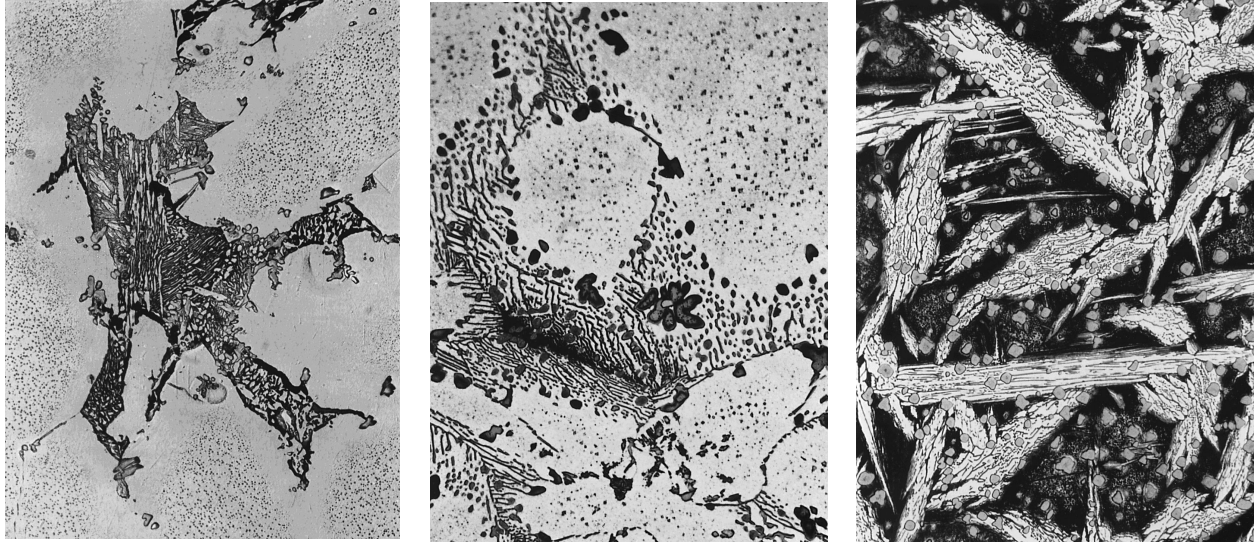


Fig. 11-3. Typical microstructures of sand cast Cu-Al-Fe and Cu-Al-Fe-Ni alloys. (Artwork previously published in AFS Transactions #86-22.)

Silicon, even though is being used as an alloying element in C95600, is considered as an impurity in nickel aluminum bronze and manganese aluminum bronze. It is reported to promote embrittlement in manganese aluminum bronzes and reduces the ductility in nickel aluminum bronzes when present in excess of 0.1%. The other element known for its detrimental effect on properties is bismuth. It reduces the ductility both at room as well as high temperatures (hot ductility). Bismuth also causes embrittlement in the heat-affected zone during welding. The maximum permissible amount quoted in the literature is as low as 0.005%, however, it should be surely restricted below to 0.03% to achieve high ductility.

Heat Treatment

With regard to heat treatment, alloy C95200 is non heat-treatable. Alloys C95300, C95400 and C95500 can be heat-treated to higher strength levels. These alloys are normally subjected to two-step thermal treatments: a solution treatment in the range of 1600 to 1675F (880 to 915C) followed by water quenching plus a temper treatment in the range of 1150 to 1225F (620 to 650C) followed by air cooling. Both alloy composition and anticipated service requirements must be considered in the selection of a heat-treatment cycle. The increased strength after heat treatment is accompanied by reduced tensile ductility, as shown in Table 11-1.

The nickel aluminum bronzes, especially in large sections, suffer from selective dealloying in seawater known as dealuminification. This has been attributed to the formation of eutectoid ($\alpha + \gamma_2$ phases) irrespective of high nickel content which is thought to be enough to reduce the eutectoid transformation in aluminum bronzes. It is suggested that this alloy be given a temper anneal heat-treatment (known as corrosion inhibiting treatment) at 1200 to 1300F (650

to 700C) for six to eight hours, followed by air cooling to eliminate or reduce the volume fractions of γ_2 phase, and is still required to meet the minimum tensile properties specified in Table 11-1 for non-heat-treated material. The effect of this treatment in reducing the eutectoid phase is shown in Fig. 11-4. On the other hand, for alloys containing low aluminum contents ($\sim 8.5\%$) where dealuminification is not a concern, it has been reported that this temper-anneal treatment could be used to improve the strength through precipitation hardening.

Effect of cooling rates

The structure of the aluminum bronzes is affected by the cooling rates encountered in the castings. In the case of nickel aluminum bronzes, which are commonly used for very large castings such as propellers, cool at very slow rates, in some cases as low as 20F (12C)/hr as compared rates of $\sim 750\text{F}$ (400C)/hr experienced by the sand cast keel blocks which are used for mechanical property evaluation. This slow cooling promotes the undesirable eutectoid transformation and coarsening of kappa precipitates which will reduce the properties and reduce the corrosion resistance.

Manganese-Nickel Aluminum Bronze

The C95700 alloys are reported to solidify with an all- β structure, but below approximately 1560F (850C) some β phase transforms to α phase resulting in an $\alpha + \beta$ microstructure in which are embedded a number of iron-manganese, and nickel-rich intermetallic compounds (Fig. 11-5). Aluminum has the greatest effect on mechanical properties by increasing strength and reducing ductility. Manganese has similar but less significant effects on properties. Iron is added to refine the grain size and produces fine to coarse particles in the microstructure. Nickel is added mainly to improve corrosion

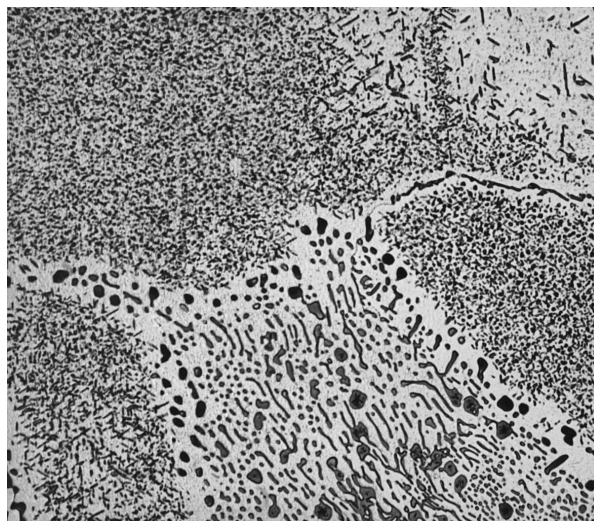
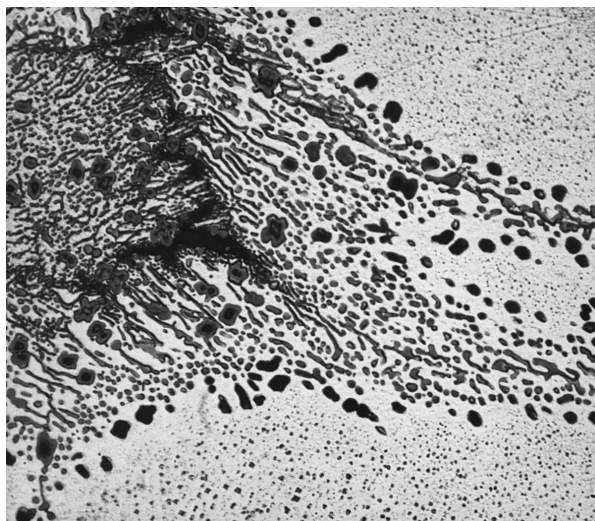


Fig. 11-4. Effect of corrosion inhibition heat treatment is shown. Left view) sand-cast, mold shakeout at less than 750F (400C) and Right view) an additional 700C for six hours, air cooled. (Artwork previously published in AFS Transactions #80-125.)

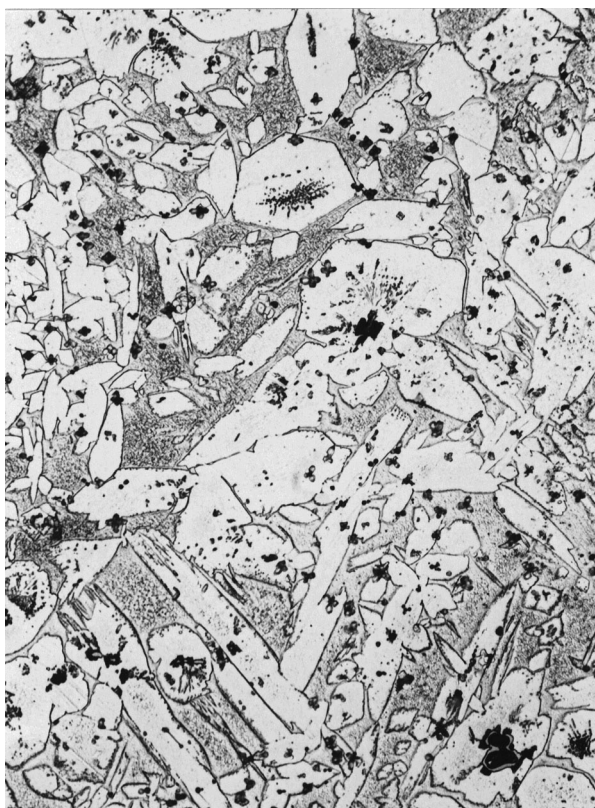


Fig. 11-5. The microstructure of manganese aluminum bronze is shown. (Artwork previously published in AFS Transactions #87-92.)

resistance but has little effect on tensile properties. Tin addition of about 0.25% reportedly improves general seawater corrosion resistance.

Impurity elements including carbon, silicon, and phosphorus introduce embrittling phases in this material. Excessive carbon results in “sparkle” on fracture surfaces or thin or needle-like particles in the microstructure. Phosphorus in excess of about 0.05 % can also produce a “sparkle-like” defect. Zinc levels should be kept below 0.5 % since zinc impairs corrosion resistance and causes porosity in weldments.

Although alloy C95700 is not normally heat-treated, quenching from 1520F (825C) followed by tempering can impart a useful increase in strength at the expense of ductility. Stress relief annealing at 600 F (350C) has been reported to improve the seawater corrosion resistance of weldments. Slow cooling below about 1000F (550C) increases magnetic permeability and reduces ductility and impact resistance due to low-temperature precipitation of manganese-rich compounds. It has been shown that the toughness of such castings could be improved by annealing at 1330F (720C) followed by air cooling at a rate of 80F/hr (25C/hr).

MECHANICAL PROPERTIES

The minimum tensile and hardness properties as specified in ASTM B 148 are listed in Table 11-1. For additional information on the physical and/or mechanical properties of these copper-base casting alloys, the reader should consult the references at the end of this chapter, and refer to the chapter, *Properties of Cast Copper-Base Alloys*. Some general observations regarding aluminum bronzes could be made as follows:

Aluminum is the most significant element that affects the mechanical properties (Fig. 11-6). The strength and ductility

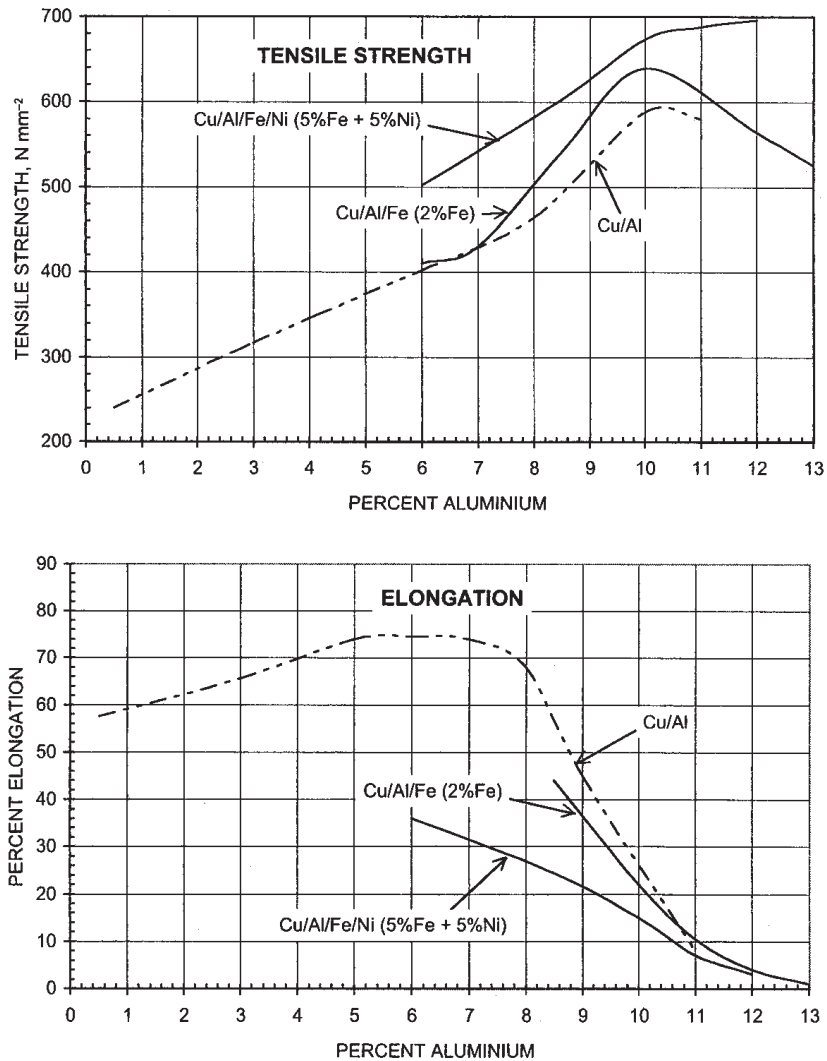


Fig. 11-6. The effect of aluminum content on properties is shown. (Artwork courtesy of the Copper Development Assn., UK, "Cast and Wrought Aluminum Bronzes-Properties, Processes and Structure," Harry Meigh.)

increase with increasing aluminum contents. The strength peaks around 10% aluminum. Ductility is the highest (~ 75% elongation) when the aluminum content is between 5 and 7% which drops to nearly zero at higher aluminum content of 13%. Nickel and iron improves the strength but reduces ductility marginally. Manganese and silicon act similar to aluminum, but on a smaller scale, in improving strength.

Another factor to be considered in mechanical properties is the effective cooling rate of the casting. The large castings such as propellers cool very slowly at a rate of 20F (12C)/hr. It had been shown that the properties of these slow cooled castings will be always lower, sometimes up to 25% less than test bar castings. This is shown in Fig. 11-7 where test specimens from actual nickel-aluminum bronze propellers are compared with specimens from sand cast test bars and continuous cast rods. However, the effect of slow cooling is minimal if the aluminum content is less than 9.3%. The alloys

with high aluminum content, more than 10.4%, are affected by the cooling rate in the temperature range of 1830-1050F (1000-560C) and ductility is the most affected property while strength remains unaffected. Even smaller castings, such as keel blocks, show higher properties when shakeout from the mold occurs earlier and are air cooled.

FOUNDRY PRACTICES

Aluminum bronzes represent one of the most versatile families of copper-base alloys from the standpoint of molding and casting processes. Parts are regularly cast in a wide range of sizes using both synthetic green sand and dry sand molds. A large tonnage of marine propellers is cast in cement-bonded or chemically-bonded dry sand molds. (Factors to be considered in the selection and use of mold and core sands for aluminum bronzes are discussed in the chapter, *Casting Processes and Materials*.)

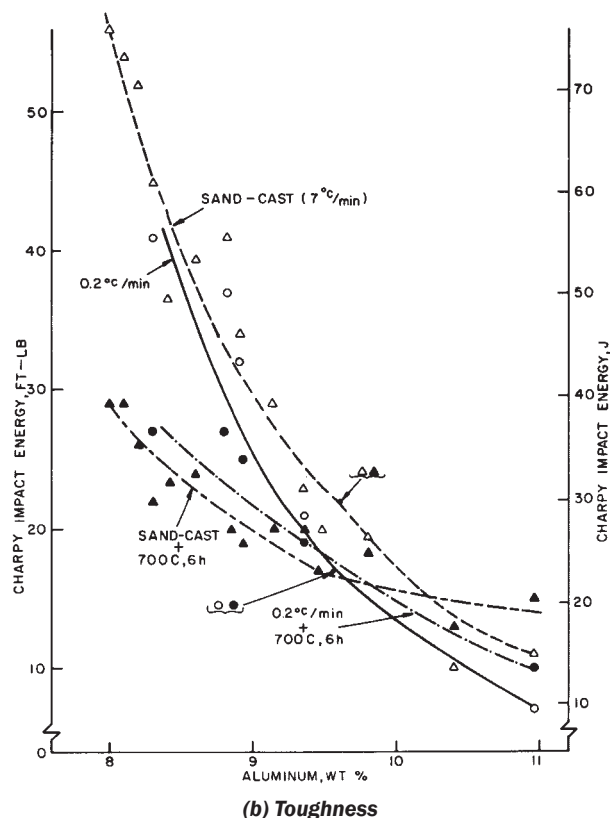
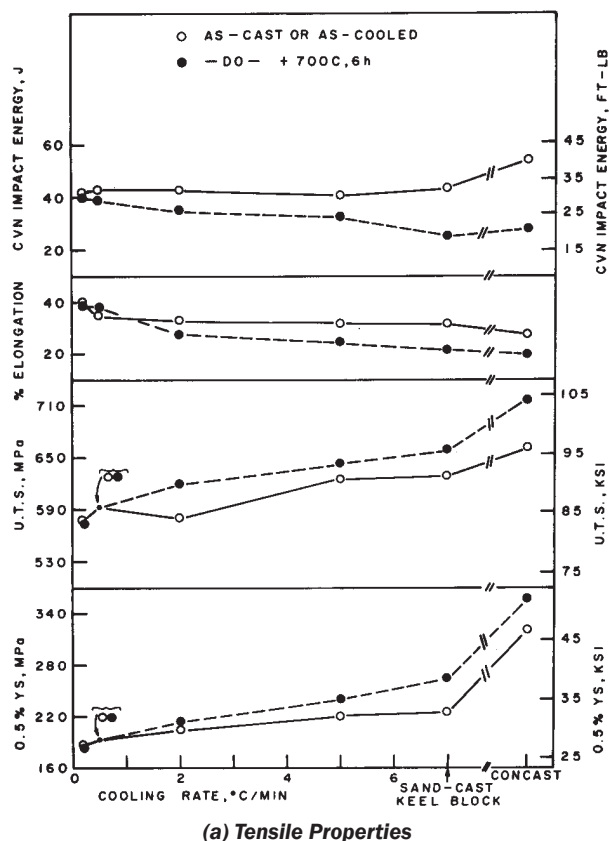


Fig. 11-7. The effect of cooling rate on properties is shown above. (Artwork previously published in AFS Transactions #82-113.)

Gating and Riser

The production of sound aluminum bronze castings necessitates the use of techniques that are different from those used in casting tin bronze alloys. Since the alloy has high drossing tendencies, it is imperative that the metal be introduced into the mold in such a manner that agitation is avoided. Gates that introduce the metal into the lowest part of the casting are recommended. Some small castings are shown in Fig. 11-8 with typical gating systems.

In most cases, for light castings of non-uniform section thickness it is advantageous to gate into thick sections so that the metal in the gate will act as a feeder. Where possible, the gate should be as far from the cores as possible to reduce the likelihood of turbulence.

The general practice of using several small gates should be avoided, as should the practice of double pouring. This is because the oxide films of separate metal streams may not unite, and thus may cause cold shuts or laps.

It is again emphasized here that runners should be placed in the drag, with gates in the cope. Runners should extend beyond the furthest gates in an effort to entrap dross, and a minimum distance of 5-6 inches between the bottom of the sprue and the first gate is advised. This helps trap dross on the top of the runner. In many cases, it is advisable to

use backup gates that are angled in the direction of the sprue. Sharp corners should be avoided. In the case of large castings, skimming can be done through open risers during pouring.

The basic principle to follow when designing gating systems for aluminum bronze is to avoid conditions which result in the formation of oxides, and to trap, skim, or otherwise prevent unavoidable oxides from entering into the casting proper. Recently developed porous ceramic filters, when correctly incorporated into the runner, may provide significant improvement. However, in large castings where the filter is exposed to high temperatures and flow rates for longer periods, the filter may disintegrate (which introduces inclusions from this secondary source).

The high shrinkage and short freezing-range of aluminum bronze dictates the provision of large feeding heads, or risers. In accordance with the general rules of shrinkage control, the risers are placed to feed the portions of the casting that solidify last.

Typical gating and riser systems are shown in Figs. 11-9 through 11-12, and modern practice is described in the chapter on *Gating*. Molds are often tilted to ensure progressive solidification. Tilting machines similar to those used for large aluminum permanent molds are sometimes used.

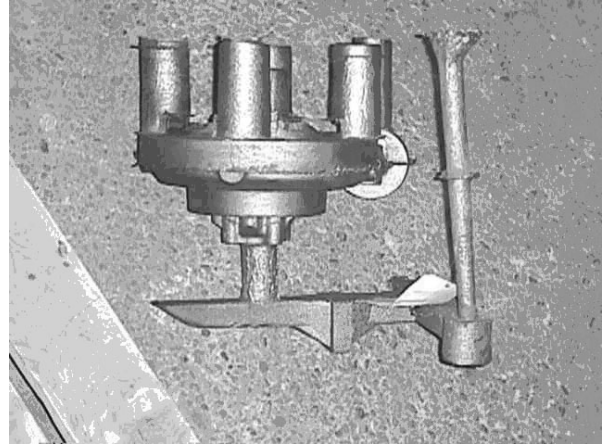
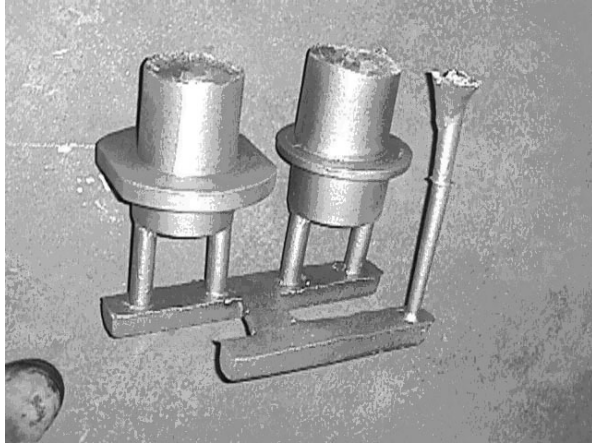


Fig. 11-8. A typical gating system used for aluminum bronze castings is shown. (Artwork courtesy of Gamma Foundry, Richmond Hill, Ontario.)

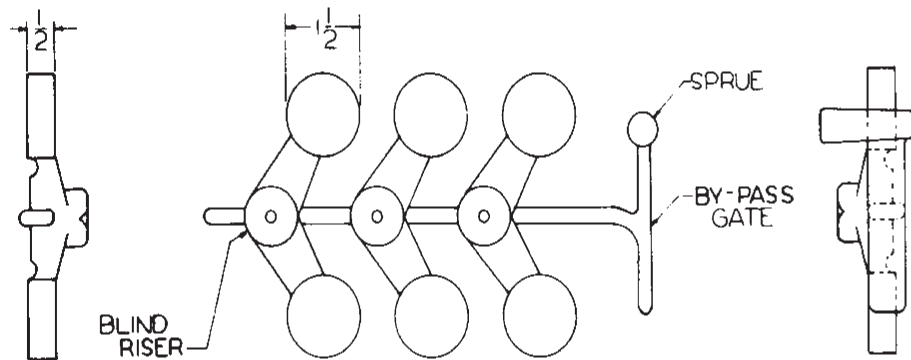


Fig. 11-9. A typical gating and risering system for a matchplate casting is illustrated above.

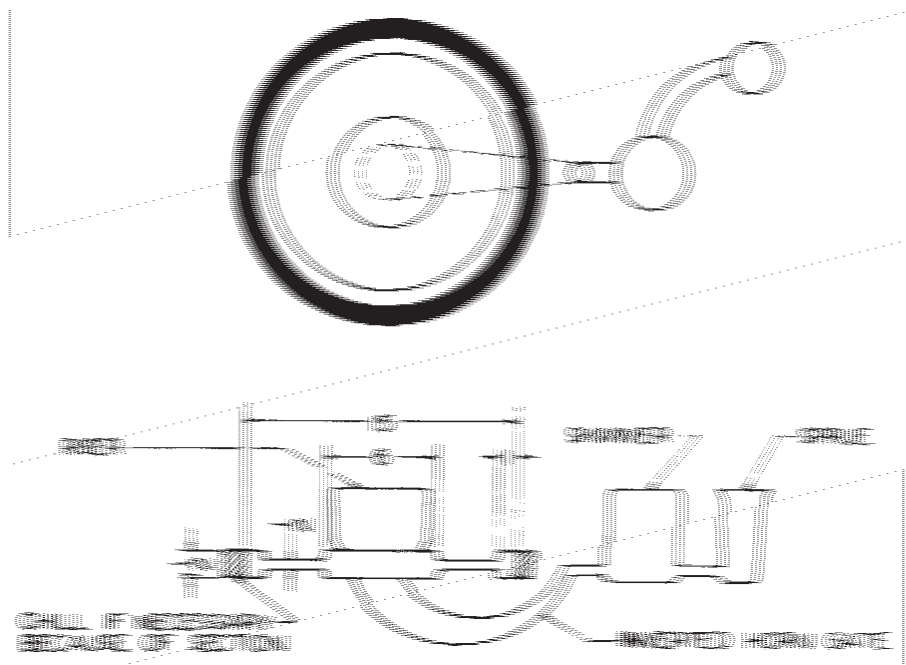


Fig. 11-10. An example of conventional chilling, gating, and risering techniques.

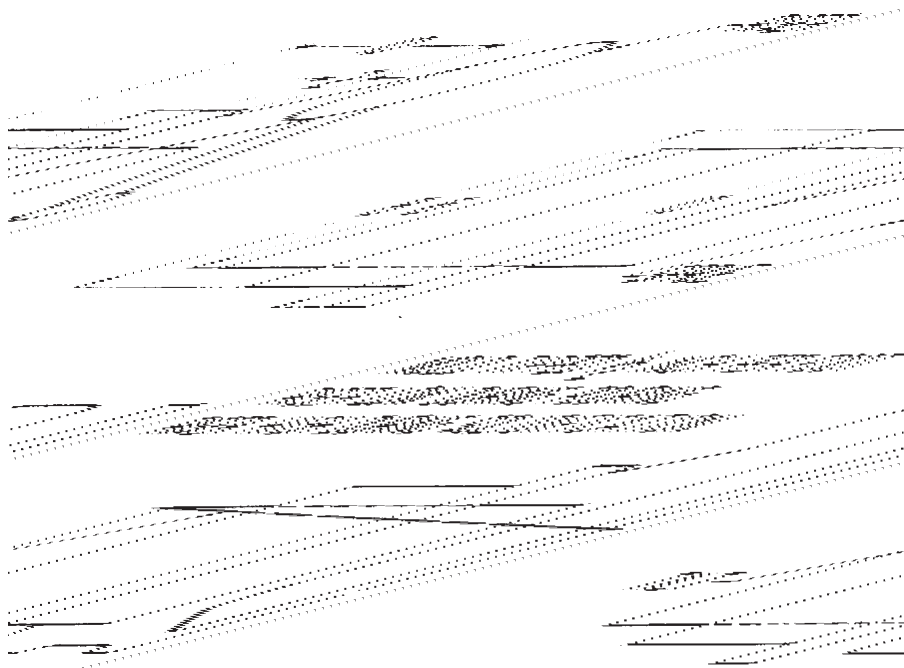


Fig. 11-11. An example of tilt pouring and feeding.

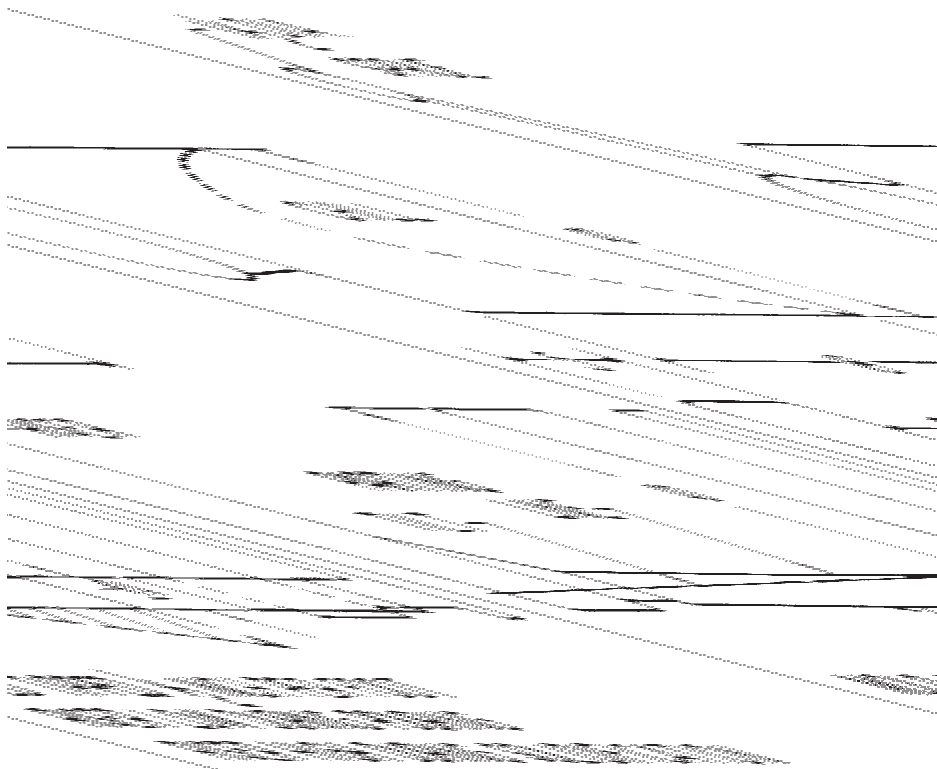


Fig. 11-12. Another example of tilt pouring and feeding.

It is very common, in the casting of aluminum bronze, for the weight of the heads and risers to exceed the weight of the casting being poured. In fact, it is rare to find casting yields of more than 50%.

Many devices such as chills, insulating materials, exothermics, and so forth, are used to assist the risers in serving their function. The use of chills on heavy sections also aids in overcoming the tendency to form coarse and brittle structures due to slow cooling.

Permanent Mold Casting

The narrow freezing ranges and relatively high hot-strength of aluminum bronzes (along with the absence of lead as an alloy constituent) enables these materials to be cast in permanent molds, either by gravity or by low-pressure diecasting. Aluminum bronzes could also be produced by continuous casting. In Europe, select compositions of aluminum bronze are widely used in permanent mold casting. The composition

and range of properties available from permanent mold cast aluminum bronzes are presented in Table 11-2.

Melting and Pouring

Practically all equipment suitable for other bronzes and bronzes can be satisfactorily used for melting aluminum bronze. The most important factor, regardless of the method, is that the heat or charge should be brought to the pouring temperature as rapidly as possible. For this reason, the furnace should have ample heat input. Excessive stirring of the molten metal bath should be avoided.

Fluxes can be used advantageously with aluminum bronze for providing a cover over the molten metal and thereby preventing gas absorption, and for preventing the formation of oxides. In addition, fluxes can be used for the removal of oxides already present. Since aluminum oxide is highly refractory, only certain fluoride-based fluxes possess sufficiently strong solvent action to serve these purposes. In

Table 11-2. Composition and Properties for Permanent Mold Cast Aluminum Bronzes

Alloy	C95300	C95400	C95410	C95500	C95800
Copper	86.0 (min)	83.0 (min)	83.0 (min)	78.0 (min)	79.0 (min)
Nominal	89.0	85.0	84.0	81.0	81.3
Aluminum	9.0 – 11.0	10.0 – 11.5	10.0 – 11.5	10.0 – 11.5	8.5 – 9.5
Nominal	10.0	11.0	10.0	11.0	9.0
Iron	0.8 – 1.5	3.0 – 5.0	3.0 – 5.0	3.0 – 5.0	3.5 – 4.5
Nominal	1.0	4.0	4.0	4.0	4.0
Manganese	-	0.5 (max.)	0.5 (max.)	3.5 (max.)	0.8 – 1.5
Nominal					1.2
Nickel (including cobalt)	-	1.5 (max.)	1.5 – 2.5	3.0 – 5.5	4.0 – 5.0
Nominal			2.0	4.0	4.5
Silicon	-	-	-	-	0.1 (max.)
Lead	-	-	-	-	0.03 (max.)
Mechanical Properties					
Tensile Strength, ksi (MPa)	80 (550)	100 (690)	100 (690)	110 (760)	90 (620)
Yield Strength at 0.5% elongation, ksi (MPa)	30 (205)	40 (275)	40 (275)	60 (415)	40 (275)
Elongation in 2" (50.8 mm) min, %	20	10	10	5	15

actual practice, fluxes should be used with caution, as the slag that is formed may be difficult to remove and can attack crucibles and furnace linings.

The following paragraphs give practical guidelines important to the production of clean, low-gas heats of aluminum bronze.

Unless the foundry has much alloying experience, as well as laboratory facilities to check chemical analysis, it will probably be advantageous to purchase properly prepared ingot. In the use of prepared ingot, certain precautions and procedures are advisable. For purposes of discussion, we will assume that gas-fired crucible furnaces are being used. The procedures would be as follows:

- Preheat a clean crucible to normal operating temperature.
- Charge the furnace, keeping the charge below the top edge of the crucible. If both new ingot and backscrap are being used, the ingot should be on the bottom. Backscrap should not exceed 30% of the charge unless it is in very large sections.
- The remainder of any metal to be charged into the crucible should first be preheated by the exhaust gases leaving the furnace.
- Add the balance of the charge while the metal in the crucible is still in the semi-solid state.
- The flame should be slightly oxidizing and should be adjusted to a rich green color with a slight tinge of yellow. Check for proper pouring temperature with an immersion-type pyrometer.
- Before pouring, make a gas-check determination using the shrink bar or, preferably, the reduced pressure test. If the presence of gas is indicated, purge with dry nitrogen or with commercial degassing tablets developed for aluminum bronzes. Continue purging until all indications of gas disappear. If the metal is gassed to the extent that purging is not completely successful the metal should be cast into ingot and used in subsequent heats. The cause of the excessive gas should be determined and corrected.
- Skim dross from the surface of the melt. Pour without any further delay.

If the alloy is being made in the foundry, it is advisable to start with purchased hardener containing approximately 70% aluminum and 30% iron. Nickel, when needed, should be added in the form of 50-50 nickel copper shot. Manganese is usually added in the form of copper manganese master alloy of 30% manganese content. When preparing an alloy it is important that the iron is dissolved and the melt is homogeneous in all respects.

The procedure for induction melting will not be much different from the gas melting. The charge should be well packed and later additions should be preheated to prevent moisture pick-up. Induction melting is satisfactory provided the power input is reduced after meltdown to avoid turbulence and thus prevent the surface oxide skin from being broken and

stirred into the melt. In addition, use of fluxes and covers should be discouraged for the same reasons. If aluminum is to be added to the alloy care should be taken to switch off the induction furnace as the reaction is exothermic which produces significant increase in the temperature of the melt.

Castings should be poured within the range 2050–2300F (1121–1260C). Although the exact temperature varies with casting size and shape, pouring should always be done at as low a temperature as practical. Superheat temperature is generally 50–100F (10–38C) above pouring temperature to allow for heat loss during degassing, transfer, and so forth. Minimum disturbance of the metal during pouring is important. The lip of the crucible or ladle should be held as close to the mold as possible and the molten metal should be delivered in a continuous, smooth stream. Splashing should be avoided so as not to entrap air.

Shakeout Time

Tests have shown that shakeout temperature has little effect on the properties of test bars in alloys containing low aluminum contents, preferably less than 9.3%. However, for alloys with more than 10.5% Al, such as C95400, it has been reported that the shakeout time has significant effect on ductility. The test bar casting should be shaken out after 10 minutes for the test bars meet the ASTM specification on ductility. This is due to the fact that rapid cooling from 1100F (593C) to room temperature inhibits κ and $\alpha + \gamma_2$ transformation. In addition, early shakeout of larger castings may enhance corrosion resistance. However, large, thin, complicated sections should not be shaken out too soon because of possible warpage.

Due to high iron content, the highly alloyed aluminum bronzes are not susceptible to the phenomenon known as self-annealing, and shakeout time is not critical.

FINISHING

Aluminum bronze alloys are tough and hard; as such, best finishing results are usually obtained with abrasive cut-off tools and grinding. However, because some special high-aluminum alloys are very brittle, it is best to cut off gates and risers while the castings are at red heat.

Repair and Salvage

The aluminum bronzes can be joined by most welding processes and can be brazed and soldered using special fluxes. Many of the earlier welding problems with aluminum bronzes have been overcome, and the best results are obtained with inert gas metal arc-welding (GMAW) and gas tungsten arc-welding (GTAW). Coated electrodes for the shielded metal arc-welding (SMAW) process are also available. The most significant characteristics of aluminum bronze are as follows:

Oxide films—the high-melting-point oxide makes welding difficult unless inert gas arc-welding processes or active fluxes

containing chlorides and fluorides are employed. Fluxes for oxyacetylene or SMA welding are hygroscopic and must be dried to prevent porosity. Wire brushing before each weld run is the preferred method for removing oxides.

Thermal expansion—the coefficient of thermal expansion (averaging 0.000018 cm/°C) is higher than for many metals and high residual stresses or distortions are likely to occur in weldments. The high thermal conductivity results in a wide heat-affected zone and can affect corrosion resistance or other properties.

High temperature ductility—strict control of lead (0.03 max) and tin (0.1 max) content is essential to maintain maximum elevated temperature ductility and to prevent sub-solidus cracking. Configurations of weld patterns should be so arranged as to minimize restraint during welding.

In regard to arc cutting of aluminum bronzes, tungsten arc-cutting provides the best edge and is preferred over carbon-arc, oxy-arc, and iron powder cutting. It is reported that oxy-gas cutting of aluminum bronze is not satisfactory. Post-weld stress relief heat-treatments may be required for certain seawater corrosion applications.

Cladding of aluminum bronze components using lasers or other electron beam instruments is being promoted as a useful tool for repair and extending the life. These claddings could be highly resistant to corrosion, erosion and cavitation.

DEFECTS

Defects in aluminum bronze with a few exceptions will follow the general pattern of cause-and-remedy typical for other copper-base materials, which are covered in the chapter, *Common Defects in Sand Cast Copper-Base Alloys*. Aluminum bronze is usually free from microporosity, but the tendency to form gross shrinkage cavities due to inadequate feeding is greater than that encountered in most other alloys. Aluminum bronzes are highly prone to dross formation. Cold shuts or laps will result both from too low a pouring temperature and from the quiet meeting of two streams of oxidized molten material.

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COPPER-SILICON ALLOYS

INTRODUCTION

This chapter covers two families of copper alloys containing silicon, the silicon bronzes and the silicon brasses. By definition, the distinction between the two families is a matter of zinc content—the bronzes containing less than 5% zinc, and the brasses containing more than 5% zinc.

The silicon bronzes were first introduced, circa 1920, as wrought alloys produced by two different well-known brass mills. These alloys were designated by the respective trade names “Herculoy” and “Everdur.” The second alloy is free of zinc. Later, the cast versions of these two alloys were both encompassed in a single UNS designation number (C87200) and constituted the only member of this family. The specification mentioned only silicon nominal composition and zinc is optional. However, today, silicon bronze containing zinc is listed in standards with two different UNS specifications, C87600 and C87610.

The silicon brasses, developed later, possess the good fluidity and castability of the silicon bronzes, and also have the

advantage of lower melting points because of their higher zinc contents. This makes the silicon brasses particularly well-suited for both pressure die casting and permanent-mold casting. Common alloys in this group are given the UNS classification as C87400, C87500 and C87800.

The popular usage of silicon bronzes peaked during World War II, at a time when the world supply of tin was severely curtailed. These alloys were accepted as adequate substitutes for tin bronzes in certain applications. Today, however, these alloys comprise a relatively small percentage of the copper-alloy foundry industry’s annual tonnage. Although experienced metallurgists recognize the excellent casting properties of copper-silicon alloys, their silicon content makes them incompatible with the more popular copper-tin-zinc-lead alloys, causing many foundrymen to be hesitant about introducing them into the foundry. The future may see a reversal of this trend, since the copper-silicon alloys offer a means of eliminating the lead contamination problems in the foundry atmosphere and in the foundry’s solid wastes.

Table 12-1. Nominal Composition of Silicon Bronzes

	Nominal Compositions		
	C87600	C87610	Range for C87200
Cu	89	92	89 min.
Si	4.5	4.0	1-5
Zn	5.5	4.0	5 max
UTS, ksi	60	45	45
0.5% YS, ksi	30	18	18
Elongation, %	16	20	20
Solidification range, F	1780 – 1580	1780 – 1580	1780 – 1580
Solidification range, C	971 – 860	971 – 860	971 – 860

Table 12-2. Nominal Composition of Silicon Brasses

	Nominal Composition		
	C87400	C87500	C87800
Cu	81	82	82
Si	3.2	4	4
Zn	14	14	14
Tensile strength, ksi	50	60 min.	85
Yield strength, ksi	21	24 min.	50
Elongation, %	18	16 min.	25
Freezing range	1680 – 1510F (916 – 821 C)	1680 – 1510F (916 – 821 C)	1680 – 1510F (916 – 821 C)

PROPERTIES AND APPLICATIONS

Silicon Bronze

As mentioned earlier, two alloys, C87600 and C87610 can qualify as silicon bronzes, by virtue of the limitation on zinc content (5% max.). Their nominal composition, solidification range and minimum mechanical properties are listed in Table 12-1.

It can be seen that both alloys fall within the chemical composition limits of old alloy C87200. Both likewise exhibit mechanical properties which meet or exceed the minimum values listed. In fact, mechanical properties can vary considerably, depending on silicon content; higher levels of silicon produce greater strength and hardness with less ductility as shown above for alloy C87600.

Many have observed that the presence of zinc makes the alloy less prone to gas pick-up during melting, being less temperature-sensitive in this regard. Conversely, the zinc-free composition has better corrosion resistance in certain environments. In general, the alloy, with or without zinc, is recognized as having good to excellent corrosion resistance in a wide range of chemical environments, and this accounts for one of their major uses (see the chapter on *Properties of Cast Copper-Base Alloys*).

Typical applications for the silicon bronze compositions are pump and valve parts, impellers, bearings, gears, marine fittings and bells. Their combined properties of good fluidity, atmospheric corrosion resistance and weldability have likewise made these alloys popular for art casting work.

Silicon Brasses

Several different alloy compositions exist within the family of silicon brasses as shown in Table 12-2 together with mechanical properties and solidification range. Even though the nominal compositions are similar each alloy can tolerate different amounts of other 'trace' elements. Alloy C87400 is a sand cast alloy and has a higher limit for lead (1.0%) where as the allowable lead content in C87500 (0.5%) and C87800 (0.15%) are relatively low. The ingot alloy C87800 can accommodate more impurity elements such as tin, manganese, antimony etc.

The mechanical properties of the alloys can vary widely, depending on the actual levels of silicon and zinc within the specification limits as well as the other alloying elements; close control of composition must therefore be exercised to achieve the desired properties. The low melting point and good fluidity of this alloy contribute to its versatility in casting parts in sand, plaster, ceramic, or permanent molds, as well as in the production of centrifugal castings and pressure die castings. Typical applications are bearings, gears, impellers, rocker arms and valve stems.

METALLURGY & EFFECTS OF IMPURITIES

The copper-silicon phase diagram shown in Fig. 12-1 indicates that binary alloys containing less than 4% silicon should solidify as single-phase, "alpha" (α) solid solutions. This would have been essentially the case for the low-zinc (Everdur) version of C87200 which is not of current interest. The presence of other elements within the permissible limits, and particularly iron and manganese, causes the formation

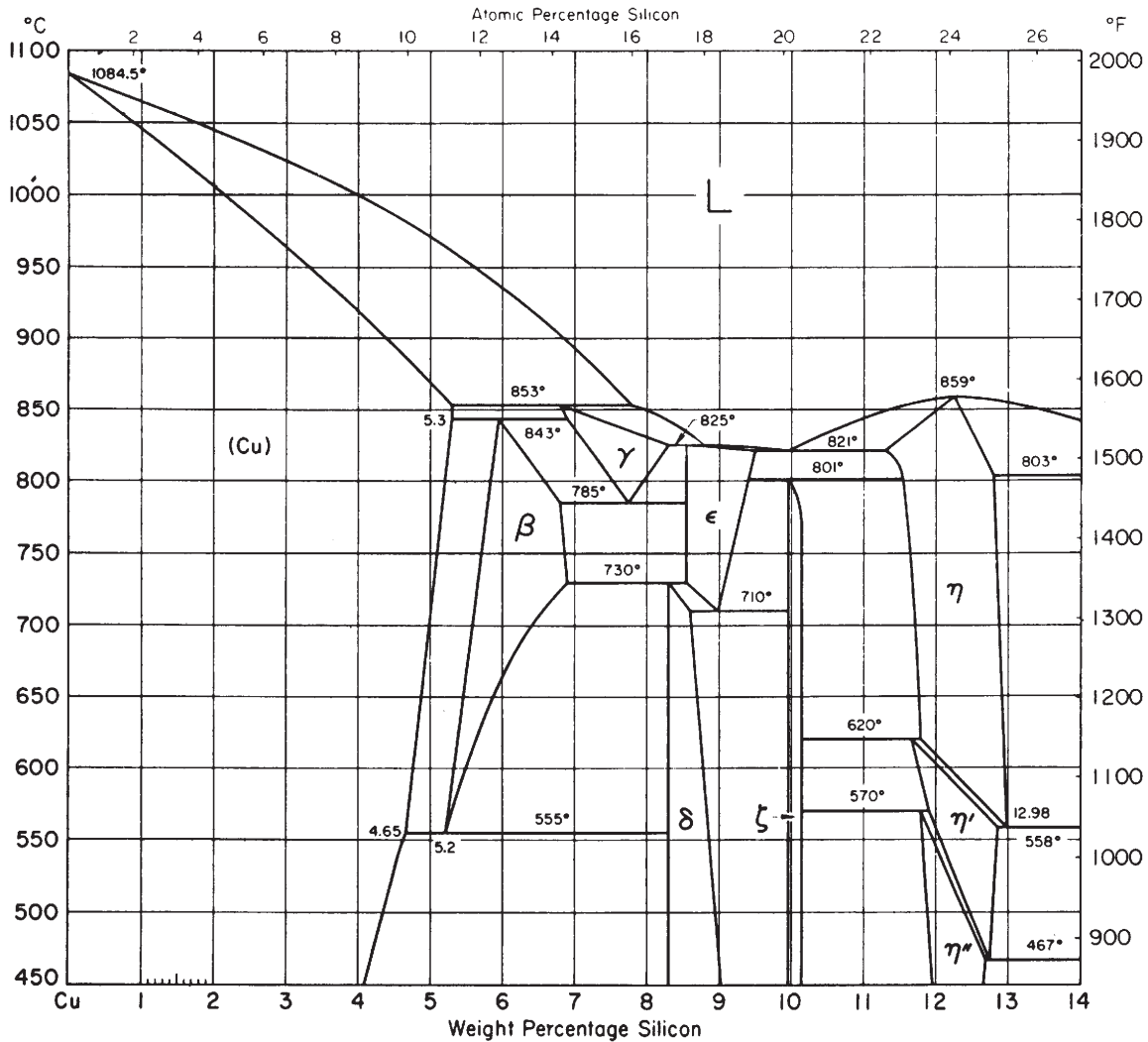


Fig. 12-1. A copper-silicon phase-equilibrium diagram is illustrated above.

of intermetallic compounds containing silicon. These occur at grain boundaries or as fine precipitates within the alpha grains, and have a substantial strengthening effect on the alloy. The lack of adequate diffusion during solidification, which causes the coring effect, may also cause the last remaining liquid to freeze by a peritectic reaction, resulting in the formation of small amounts of a second "beta" (β) phase at the grain boundaries of the alpha matrix.

As significant amounts of zinc are added to an alloy containing 4% silicon, the presence of the beta phase becomes much more evident in the microstructure. This phase is a ternary Cu-Si-Zn solid solution which is isomorphous with the beta phases appearing in the Cu-Si and Cu-Zn phase-equilibrium diagrams, respectively. This duplex alpha-beta structure is typical of the silicon bronze with 4% Zn and also of silicon brass, which contains 14% zinc. The strength of these alloys is enhanced by the presence of the harder (although less ductile) beta phase. These alloys have relatively wide freezing ranges and, hence, solidify in a dendritic manner. For this

reason, as shown in Fig. 12-2, the beta phase occurs within the interdendritic areas of the alpha matrix. As the zinc content increases, the silicon brass contain more amount of beta phase as shown in Figure 12-2a, compared to the silicon bronze which contain less beta phase in inter dendritic areas (Fig. 12-2b). At higher magnification (Fig. 12-3) it may be seen that the beta particles are frequently surrounded by parallel striations, extending into the alpha phase. Also, the beta phase sometimes contains acicular particles of the silicon-rich delta phase.

It should be pointed out that alloy C87500 has a total impurity limit (all elements) of 0.5%. This is because the alloy contains high percentages of the beta phase and is sensitive to embrittlement. It is obviously necessary, therefore, to exert close control on alloy composition limits and impurities in order to achieve consistent mechanical properties for silicon bronze. Even with such control, one can experience considerable variation in properties with section size because of the effects of coring (micro-segregation). It has been report-

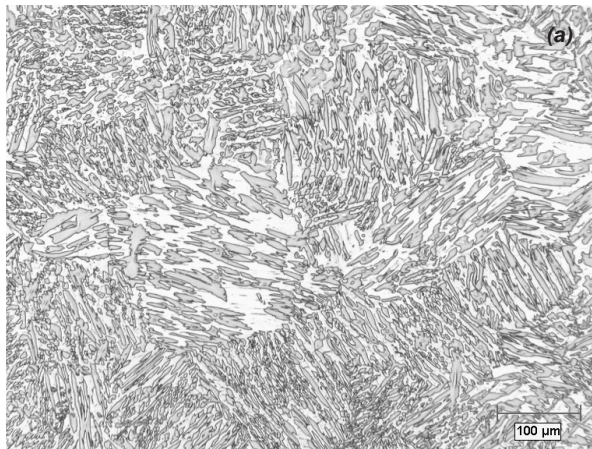


Fig. 12-2 (a and b). Microstructure of Cu-Si alloys. (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada)

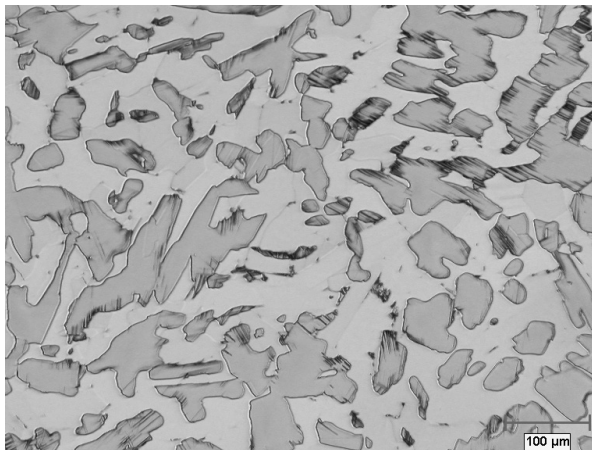


Fig. 12-3. Same microstructure as 12-2, at higher magnifications; observe the slip lines running along the β phase. (Artwork courtesy of CanmetMATERIALS, Hamilton, ON, Canada)

ed that homogenization of a cored structure by soaking 8 hours at 1292F(700C) has shown improvement in ductility; however, it is questionable whether such heat treatment is cost-effective in any but special cases.

MELTING AND POURING

Overheating of these alloys during melting may seriously damage mechanical properties. This effect is often attributed to the strong tendency of these alloys toward gas absorption. Actually, these alloys give anomalous results when subjected to the reduced-pressure solidification test for gas content, as described in the chapter, *Melt Control*. Tests with these alloys indicate relatively little tendency toward gas pickup, yet industrial experience has shown frequent cases of gas porosity in castings. Hydrogen is the gas involved, and there appears to be the possibility that hydrogen absorbed by the melt may actually react with silicon to form a relatively stable hydride. Whereas certain proprietary degassing agents may be useful for gas control, the best procedure is to melt

the alloys as rapidly as possible, superheat to the pouring temperature without overheating, and then pour promptly with minimum turbulence.

In general, these alloys are poured with somewhat less superheat than are those of the copper-tin-lead-zinc family. This practice is possible because of the lower drossing tendencies of the silicon brasses and bronzes, together with their greater fluidity. This greater fluidity may, in fact, be attributed to the effect of silicon in lowering the surface tension of the molten alloy.

These copper silicon alloys (both brass and bronze) are classified as having drossing and shrinkage characteristics which are intermediate between those of the red brasses and those of the high-strength yellow brasses and aluminum bronzes. Their tendency toward oxide-skin formation makes it advisable to use the non-turbulent gating techniques advocated for aluminum bronzes (see Chapter 7, *Gating*). The intermediate freezing ranges of these alloys, as explained in Chapter 8 (*Solidification, Feeding & Design*), require feeding techniques which utilize high thermal gradients in the mold in order to achieve directional solidification and subsequent freedom from shrinkage porosity.

PERMANENT MOLD CASTING

As mentioned in the introduction the silicon brasses are suitable for permanent mold casting and die casting due to the low melting temperature and medium freezing range. The ASTM standards on Copper-Alloy Die Castings (B176) and Copper Alloy Permanent Mold Castings (B806) mentions the alloy C87800. This alloy, can tolerate higher levels of impurities. Recent studies have shown that, silicon bronze can also be effectively produced by permanent mold casting. The presence of aluminum has been found to be quite beneficial in improving the casting fluidity and surface finish of Cu-Si alloys. The problem of lead contamination in drinking water may make this lead-free alloy suitable for plumbing applications.

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COPPER-BASE ALLOYS WITH NICKEL AND MONEL METAL

INTRODUCTION

Nickel-bearing copper-base casting alloys are of three general classes: 1) cupronickel alloys, 2) leaded nickel brasses and bronzes, commonly known as nickel silvers, and 3) nickel-tin type age-hardenable bronzes.

Monel is a nickel-copper alloy.

Cupronickel Alloys

Two alloys in the cupronickel family are covered by ASTM International (previously American Society for Testing & Materials) and military specifications, commonly known as 90/10 and 70/30 cupronickel alloys. Their casting characteristics and mechanical properties have been studied and are listed in the Bibliography at the end of this chapter. Table 13-1 gives the chemical composition and tensile properties for these two alloys in ASTM B 369 "Standard Specification for Copper-Nickel Alloy Castings." Conforming specifications and additional properties can be found in Chapter 1, *Standard Designations for Copper and Copper Alloys*.

A considerable amount of work has been done on a chromium-modified 70/30 cupronickel alloy (IN-768) and on beryllium and silicon-beryllium modifications of the same alloy.

The cupronickel alloys have good corrosion resistance for marine service and are superior to the copper-tin bronzes,

such as C90500 (1A or Navy "G") or C92200 (2A or Navy "M"), for this application. Cupronickels can be cast in heavy sections to greater soundness than the tin bronzes. The 964 cupronickels are readily weldable, which is an important attribute in casting alloys. The copper-tin bronze alloys are not readily weldable. The tensile properties of these alloys, especially those of the 70/30 cupronickel alloys, are superior to those of the copper-tin-bronze alloys.

The basic mechanical properties as well as the corrosion- and heat-resistance of copper are progressively improved with increasing nickel content. Nickel also has a strong effect on the color, as the 90/10 cupronickel alloy is pinkish in color while the 70/30 cupronickel alloy has a silvery-white color.

The 70/30 cupronickel alloy can be hardened and strengthened significantly with additions of silicon, niobium, aluminum, beryllium, and chromium. Although a number of alloy systems have evolved to strengthen the alloy, the niobium-silicon modified 70/30 cupronickel is the most commonly used and is covered by ASTM B369 (C96400). Proper balancing of these alloying elements produces an alloy having a good combination of castability, weldability, and mechanical properties.

The 90/10 cupronickel alloy is also covered by specification ASTM B369 (C96200). It, too, is a weldable alloy, but its tensile properties are considerably less than those of the 70/30 alloy. However, the 90/10 alloy does have tensile properties equivalent to C90500 (1A - Navy "G"), and better

Table 13-1. Chemical Composition and Tensile Properties for 70/30 and 90/10 Cupronickel Alloys

Copper Alloy UNS No.	ASTM Spec.		Cu	Ni	Fe	Si	Mn	Pb*	Nb	C	Yield Strength ksi	Tensile strength ksi	Elong. % in 2 in.
C96200	B369	Min.	84.5	9.0	1.0	-	-	-	-	-	25	45	20
		Max.		11.0	1.8	0.3	1.5	0.03	1.0	0.1			
C96400	B369	Min.	65.0	28.0	0.3	-	-	-	0.5	-	32	60	20
		Max.		32.0	1.5	0.5	1.5	0.03	1.5	0.15			

* Weldability test requirements may not be attained if the lead content exceeds 0.01%.

than C92200 (2A - Navy “M”), and can be cast in heavy sections to greater soundness than these copper-tin bronzes. The corrosion rates in seawater are considerably lower than for tin bronze but are somewhat greater than for the 70/30 alloy, especially at higher velocities and temperatures.

Nickel Silvers-Leaded Nickel-Brasses and Bronzes

These alloys are popularly known as “Dairy Metals” perhaps because of their initial use in milk processing around 1930. They are also known as “Dairy Brasses,” “Dairy Bronzes” and “German Silvers.” These alloys are characterized by a pleasing white appearance similar to that of stainless steel and used in corrosion-resisting applications such as dairy and food machinery parts, restaurant kitchen equipment, steam fittings, hardware for marine and building applications, etc. and compete with stainless steel in these areas. Chemistry of these alloys varies widely depending on strength, hardness, gall-resistance and corrosion-resistance requirements. One essential feature is the high nickel content, ranging from 12 to 30%. This imparts required corrosion resistance and gives its white appearance. These alloys may also contain up to 9% lead, which enhances machinability and anti-galling characteristics. During the 1980s it was conclusively established that ingestion of lead causes severe health problems in humans even when present as only a few parts per billion in food. This led to replacement of lead with bismuth and selenium in 1990s. Bismuth and Se do impart enhanced machinability and anti-galling characteristics to the alloys. However, on a relative basis, leaded alloys are more ma-

chinalable than their bismuthized counterparts. Nominal compositions and properties of the leaded and lead-free alloys are listed in Table 13-2.

Nickel-Tin Bronzes

The nickel-tin bronzes provide a useful combination of high strength, corrosion-resistance, and good wear properties. ASTM B584 covers three leaded nickel-tin bronze alloys and the age hardening nickel-tin type. The nominal chemical compositions and minimum tensile properties are listed in Table 13-3.

Monel Metal

Commercial Monel castings usually fall into the following composition range: nickel 62–65%, copper 29–32%, silicon 1.25–4%, iron 1.5–2.0%, manganese 0.5–1% and carbon 0.05–0.20%. Table 13-4 lists the compositions of Monel castings; the most widely used alloy is specified in ASTM A494 (“Standard Specification for Castings, Nickel and Nickel Alloy”), and additional data are given in the *ASM Handbook, Volume 15, Casting*.

Federal Specification QQ-N-288 is obsolete and has been replaced by ASTM A494. Composition E of QQ-N-288 or M30C of ASTM A494 is similar to alloy 411 specified by INCO. Their mechanical properties are given in Table 13-5.

Table 13-2. Nominal Chemical Composition and Typical Tensile Properties of Nickel Silver Alloys-ASTM B584 (“Standard Specification for Copper Alloy Sand Castings for General Applications”)

Copper Alloy UNS No.	Commercial Designation	Cu	Sn	Pb	Zn	Ni	Bi/Se	Mn	Yield Strength ksi (Mpa)	Tensile Strength ksi (Mpa)	Elongation % in 2 in. (50 mm) ksi (Mpa)
C97300	12% leaded nickel silver (nickel bronze)	57	2	9	20	12			17 (117)	35 (241)	20
C97600	20% leaded nickel silver (nickel bronze)	64	4	4	8	20			24 (165)	45 (310)	20
C97800	25% leaded nickel silver (nickel bronze)	66	5	2	2	25			30 (207)	55 (380)	15
C89940	Lead-free nickel silver	Bal	4.	0.1	4	22	Bi = 4		-	25 (172)	2.5
Vitalloy I*	Se-bearing nickel silver	Bal	4	0.1	4	22	Se = 2		30 (207)	45 (310)	8
Waukesha Alloy 126*	Modified lead-free nickel silver	Bal	-	-	20	20	Bi = 3	20	38 (262)	50 (345)	4.0

* No CDA number

Table 13-3. Nominal Chemical Composition and Minimum Tensile Properties of Nickel-Tin Bronze and Leaded Nickel-Tin Bronze (ASTM B584)

Copper Alloy USN No.	Commercial Designation	Composition					Minimum Mechanical Properties		
		Cu	Sn	Pb	Zn	Ni	Tensile Strength, ksi (Mpa)	Yield Strength, ksi (Mpa)	Elongation % in 2 in.
C94700	Nickel-Tin Bronze Gr A	88	5	-	2	5	45 (310)	20 (138)	25
C94700 H.T.	Age-hardened						75 (517)	50 (345)	5
C94800	Leaded Nickel-Tin Bronze Gr B	87	5	1	2	5	40 (276)	20 (138)	20
C94900	Leaded Nickel-Tin Bronze Gr C	80	5	5	5	5	38 (262)	15 (103)	15
C96800	Spinodal Cu-Ni-Sn Alloy	82	8			10	18 (125)	14.5 (100)	3

Table 13-4. Composition * Specifications for High-strength Monel Castings as in ASTM A494/A494M

Specification	Ni	Cu	Si	Fe	Mn	C	S	P	Nb
M-35-1	Bal	26-33	1.25	3.5	1.50	0.35	0.03	0.03	0.50
M-35-2	Bal	26-33	2.0	3.5	1.50	0.35	0.03	0.03	0.50
M-30H	Bal	27-33	2.7-3.7	3.5	1.50	0.30	0.03	0.03	-
M-25S	Bal	27-33	3.5-4.5	3.5	1.50	0.25	0.03	0.03	-
M-30C	Bal	26-33	1.0-2.0	3.5	1.50	0.30	0.03	0.03	1.0-3.0

*Values are maximum unless otherwise indicated

Table 13-5. Mechanical Properties of Monel Castings as in ASTM A494/A494M

Specification	UTS, Min, ksi (MPa)	YS, Min, ksi (MPa)	% Elongation, Min in 2 in. (50 mm)	Hardness,BHN
M-35-1	65 (450)	25 (170)	25.0	-
M-35-2	65 (450)	30 (205)	25.0	-
M-30H	100 (690)	60 (415)	10.0	243-294
M-25S	-	-	-	-
M-30C	65 (450)	32.5 (225)	25.0	125-150

Although Monel is a nickel-base alloy, to some extent it is an extension of the cupronickel series; since it is often melted in bronze foundries, it is included in this chapter. Silicon has a marked strengthening effect and alloys of up to 4% Si (S Monel) have excellent resistance to corrosion and galling, and are widely used for valve seats, trim and sliding applications. The low-silicon alloys have lower strength and hardness, but better ductility, and are used in a variety of corrosive media, particularly at higher temperatures.

The increasing availability of stainless steel and special alloyed iron castings is providing competition to Monel in some applications.

METALLURGY

Cupronickel Alloys

Nickel forms a single-phase alpha solid solution with copper, at all proportions. The basic mechanical properties as well as the corrosion-resistance of copper are progressively improved as nickel content increases. The addition of alloying elements such as silicon, niobium, beryllium, and chromium are utilized for significant improvements in tensile properties in the 70/30 cupronickel alloy. Additions of these alloying elements in proper amounts cause precipitation hardening. Slow cooling can cause precipitation of intermetallic compounds (usually silicides) which will strengthen the alloy but reduce ductility. Fast cooling produces a relatively soft and ductile alloy. Subjecting the alloy in this condition to intermediate elevated temperatures for a given time will precipitate intermetallic compounds that create a strengthening effect (age hardening or precipitation hardening).

Effect of Silicon and Niobium on 70/30 Cupronickel

In the early production stages of the 70/30 cupronickel alloy, silicon was utilized to increase strength. With more than 0.40% silicon, tensile properties of MIL C-20159 could be met; however, visible weld cracks occurred in the heat-affected zone of the base metal on the required weldability test, even without bending. Adding niobium obviated the detrimental effects of the higher silicon, so that crack-free welds were obtained. Figure 13-1 illustrates the influence of silicon and niobium on the tensile properties. The amount of silicon and niobium required is dependent upon the strength-ductility level desired. Completely weldable castings can be produced if the niobium content is equal to or greater than the silicon content.

ASTM B369 and MIL-C-20159 limit the silicon to a maximum of 0.50% and the niobium to a range of 0.50 to 1.50%. It has been found that by keeping the silicon slightly above the mid-range (0.25–0.40%) and the niobium also about mid-range or slightly below (0.80–1.00%), an excellent combination of tensile properties and weldability can be obtained. Table 13-6 shows that if the silicon and niobium are on the low side of the specification, low yield strength may result. However, if the silicon and niobium are high, there will be a significant

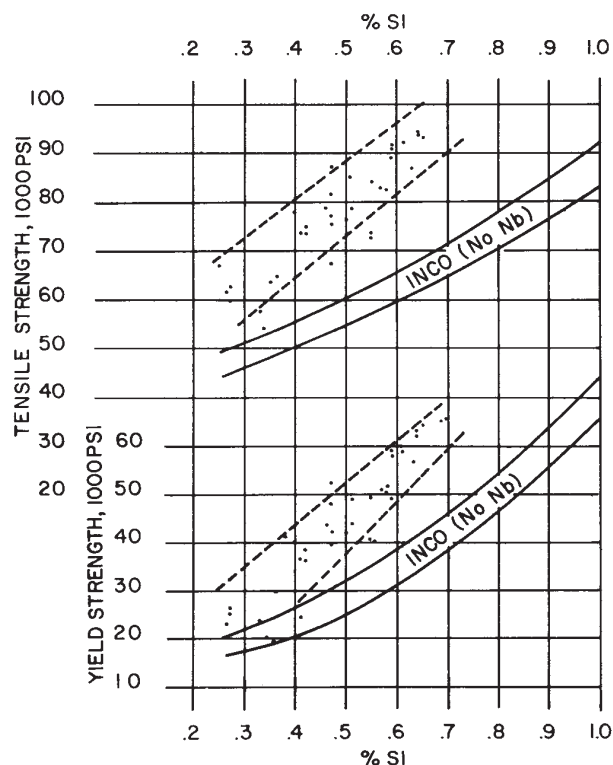


Fig. 13-1. The influence of Si and Nb on the strength of 70/30 cupronickel. Heats contain major elements within the percent range of: Cu 65.7-68.4; Ni 28.8-31.6; Mn 0.83-1.41; Fe 0.50-0.94 (except one with 1.07% designated by dot inside box); Nb 0.33-0.83.

increase in yield strength but low elongation may result. While the niobium and silicon contents have a major effect on the tensile properties, cooling rate and test-bar type are critical also in this respect.

Effect of Cooling Rate and Heat Treatment on Properties of 70/30 Cupronickel

As noted, the addition of silicon and niobium greatly increases the strength of 70/30 cupronickel alloys by causing the precipitation of complex nickel-niobium-silicon compounds within the alpha matrix as the casting cools from the pouring temperature. The amount and size of the precipitate is a function of the composition and the time the casting spends in the critical temperature zone of about 1250–1050F (675–550C) during cooling. Thus, small castings which cool rapidly through this zone, or castings which are shaken out early, have little time to develop fully the precipitates; consequently, the tensile and yield strengths are lower than in larger, slowly cooled castings.

Similarly, castings which are oil-quenched from high temperatures show low strength and high ductility, but subsequent reheating to 1050–1250F (550–675C) causes precipitation, and consequent increase in strength and hardness. This is shown in Table 13-7. In simulated slow cooled conditions,

Table 13-6. Effect of Si and Nb Content on Mechanical Properties of Specimens Machined from the Modified Keel Blocks

Melt No.	Si Wt %	Nb Wt %	Si + Nb Wt %	UTS, ksi	YS, ksi	El, %
10910*	0.10	0.70	0.80	58.0	29.2	33.6
1727*	0.12	0.95	1.07	54.1	20.4	44.8
1767	0.22	0.78	1.00	74.6	39.5	28.3
1778	0.22	0.79	1.01	78.8	45.5	26.1
1793	0.24	0.66	0.90	71.8	33.9	30.8
1800	0.27	0.70	0.97	77.3	41.2	29.9
1802	0.28	0.60	0.88	73.1	38.0	28.9
1787*	0.30	0.94	1.24	82.1	48.1	19.5
1790	0.30	0.69	0.99	77.4	42.1	26.1
1729	0.31	0.85	1.16	74.7	37.2	33.0
1764	0.31	0.82	1.13	79.3	44.1	25.8
1774	0.32	1.08	1.40	88.9	51.0	20.3
1788	0.32	0.75	1.07	79.4	43.7	24.4
1749	0.35	0.66	1.01	70.3	34.0	31.6
1762*	0.41	0.78	1.19	81.4	50.7	17.9
1746*	0.42	0.39	0.81	63.2	30.3	34.1
1756	0.42	1.27	1.69	83.6	45.5	23.0
1759	0.43	0.64	1.07	77.9	46.9	20.6
1738	0.44	0.72	1.16	70.5	37.0	32.9
1742	0.49	0.69	1.18	79.0	46.1	26.9
1734	0.50	0.47	0.97	68.6	35.6	28.5
1732	0.51	0.93	1.44	77.3	42.2	27.4
1753*	0.61	1.71	2.32	87.9	55.1	11.3
ASTM B369-72						
	0.7 max	1.5 max		60 min	32 min	20 min
*Do not meet ASTM B369-72 mechanical property requirement						

where keel blocks were homogenized at 1832F (1000C) for 2 hr in an argon atmosphere and then cooled at 54F(12C)/hr to 752F(400C) followed by air cooling, tensile properties and CVN impact toughness decreased for both Nb- and Cr-modified 70/30 Cu-Ni alloys.

The cooling rate effects discussed above explain the results given in Table 13-8, which show the influence of test-bar design and early shakeout. Clearly, slower cooling yields higher strength and lower ductility.

The strength of small castings usually can be improved by a so-called homogenization heat treatment. (This involves heating to 1200F (650C), holding for 1 hour at temperature, and furnace cooling to 500F (260C). The effect of this treatment is illustrated in Table 13-9 for separately cast test bars (small castings) as well as for those removed from a large casting. Figure 13-2 illustrates the type of casting and location of test bars. The casting shown in the figure weighed 3950 lbs (cleaned weight). The homogenization treatment

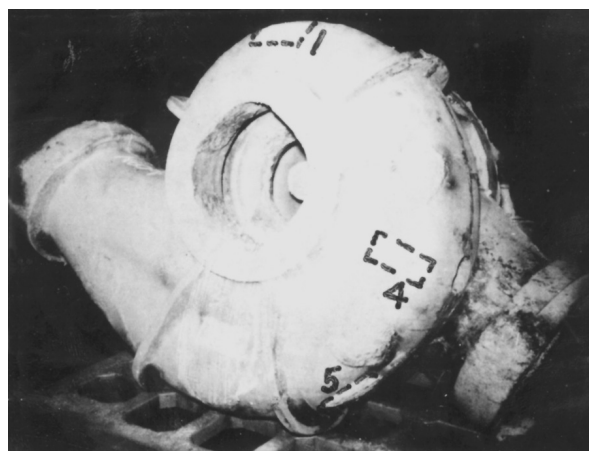


Fig. 13-2. A 70/30 cupronickel alloy. Note the location of test bars removed from the casting. Cleaned casting weight is 3,950 lbs. See Table 13-9 for tensile properties of specimens.

Table 13-7. Tensile Properties and Hardness of 70/30 Cupronickel with Various Cooling and Aging Conditions

Condition	Y.S. 0.5% EUL ksi	Tensile Strength ksi	% Elong.	Bhn (3000 kg)
As-cast/mold cooled	55.0	90.5	16	179
Heat to 1600F-air cooled. (simulates early shakeout)	-	-	-	114
Heat to 1600F-air quench (O.Q.)	-	-	-	86/103 range of 4 samples
1600F-O.Q. + 1050F A (1 hour)	42.0	78.0	19	133
1600E-O.Q. + 1100E A (1 hour)	46.5	79.5	20	130
1600F-O.Q. + 1200F A (2 hours)	-	-	-	148
1600F-O.Q. + 1200F A (5 hours)	-	-	-	159
1600F-O.Q. + 1200E A (15 hours)	-	-	-	185
ASTM B369 (C96400 alloy min.)	32.0	60.0	20	-

Chemistry

C	Mn	P	S	Nb	Si	Ni	Cu	Pb	Fe
0.01	1.23	<0.005	0.01	1.33	0.48	29.40	66.8	0.005	0.7

O.Q. – Oil Quench

A – Aging Temperature. Furnace cooled to 500F after aging

Table 13-8. Effect of Test-Bar Type on Tensile Properties, Vertically Cast in 1 in. Keel Block vs. 1 in. Full Web-Webbert. (Refer to ASTM Standard B208 for Preparing Test Specimens)

Nb	Si	Y.S. 0.5% EUL Ksi		Tensile Strength Ksi		% Elong.		Bhn (3000kg)	
		W	K	W	K	W	K	W	K
0.64	0.23	29.3	32.5	67.8	70.5	37	33	116	133
0.65	0.23	27.0	33.0	67.5	74.0	34	30	105	132
0.78	0.27	31.3	37.3	71.8	76.8	36	29	139	136
0.93	0.39	45.5	48.0*	83.8	84.0*	25	20*	-	-
0.97	0.41	47.5**	50.3	85.1**	86.8	25**	20	177**	177

W = 1 in. full Web-Webbert
K = 1 in. keel block

All test results were obtained on specimens cooled in a dry oil sand mold for two hours before shakeout.

Early shakeout tests on some of the above compositions:

*10-15 min. (shakeout)	37.0	78.0	30	
**10-15 min. (shakeout)	38.0	78.3	36	146

Table 13-9. Influence of Homogenization (Aging) Heat Treatment on Tensile Properties

Type of Test Bar*	0.5% Yield Strength ksi		Tensile Strength ksi		Elongation %		Bhn (3000 Kg)				
	As-cast	Treated**	As-cast	Treated	As-cast	Treated	As-cast	Treated			
Webbert	51	61.5	83.0	89.5	28	22.5	143	163			
1 in. Y	55.5	61.0	83.5	87.0	24	20	163	167			
3 in. Y Corner	49.5	61.5	78.0	87.5	26	21	149	167			
Center	43.0	57.0	74.0	83.0	30	20	140	159			
From casting, see Fig. 13-2											
Location 1	46.5	46.5	75.5	78.0	19	19	156	156			
Location 4	49.5	43.0	77.5	72.5	21	23	149	156			
Location 5	46.0	45.5	76.0	73.5	17	15	152	149			
* All separately cast test bars cast in dry sand molds.											
** Homogenized (aged) at 1200F, 1 hour at temperature. Furnace-cooled to 500F.											
Chemistry											
Cu	Mn	Fe	Nb	Si	Ni	C	S	P	Pb	Al	Ti
68.3	0.99	0.55	0.41	0.57	30.15	0.01	0.003	0.02	0.016	0.005	0.05

Table 13-10. Tensile Properties of Test Bars in 90/10 Cu-Ni Alloys

Wt % Si	Wt % Nb	UTS		0.5% yield strength		Elong. %
		ksi	(MPa)	ksi	(MPa)	in 2 in. (51 mm)
0.16	0.18	51.1	(352)	29	(200)	22
0.17	0.18	54.9	(378)	32.6	(225)	24
0.3 max.*	1.0 max.*	45*	(310)*	25*	(170)*	20*

*ASTM B369 specifications for alloy C96200

did not benefit the properties of the test bars cut from the casting because their cooling rate after heat treatment was little different from their original cooling rate as part of the large casting. Thus, no further precipitation of second phases such as Ni_3Nb , Ni_3Si , or $\text{Nb}_2\text{Ni}_3\text{Si}$ occurred. Because of these self-age-hardening characteristics, the drop-off in tensile strength due to mass is considerably less for the niobium-modified 70/30 than for the tin bronze alloys.

90/10 Cupronickel

For 90/10 cupronickel, the basic metallurgy is the same as that of the 70/30 alloy, and the control of silicon content is critical. As the silicon content increases, yield strength increases, while elongation and weldability decrease. Niobium improves the weldability of the 90/10 alloy just as it does with the 70/30 alloy, but it also can have a detrimental effect on ductility. Low silicon (in the range 0.10 to 0.15%) and niobium

in the range of 0.50 to 0.70% produce an alloy with good weldability and meeting the ductility requirements of ASTM B369 and MIL-C-21059, Type II. Typical tensile properties of test bars cast in 90/10 cupronickels are given in Table 13-10.

Beryllium-Modified 70/30 Cupronickel Alloy

The addition of beryllium to cupronickel induces age-hardening effects due to the precipitation of copper-nickel-beryllium compounds. These act in the same way as the silicides precipitated in "normal" cupronickel, but the strengthening effect is greater and a good level of ductility is maintained. Two beryllium-modified 70/30 alloys were developed which showed very attractive properties and foundry characteristics. However, environmental constraints and potential health hazards when dealing with beryllium have prevented these alloys from becoming popular.

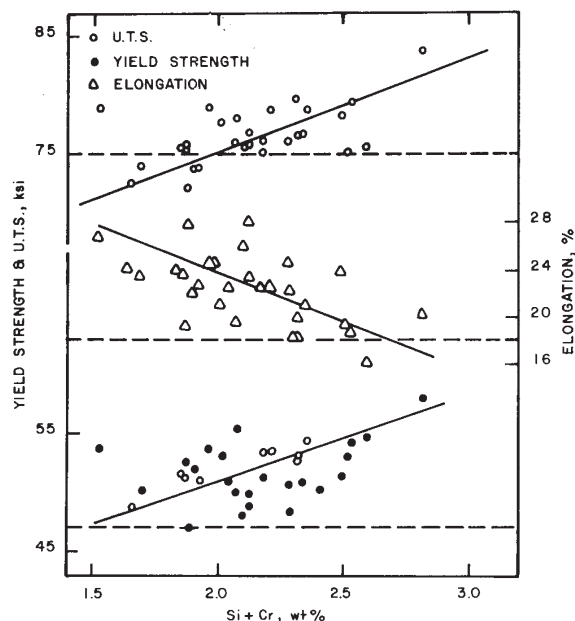


Fig. 13-3. The cumulative effect of Si plus Cr on Ultimate Tensile Strength (UTS), yield strength, and elongation of Cu-Ni casting alloys is shown.

Chromium-Silicon Modified 70/30 Cupronickel Alloy

Additions of chromium from 1.4 to 2.0%, and silicon additions from 0.3 to 0.6% to the 70/30 cupronickel alloy produce an alloy with a yield strength of at least 45,000 psi, coupled with good toughness and weldability. The as-cast tensile properties are relatively uniform over section size ranging from ¼ in. to 4 in. thick. Zirconium in the range of 0.05 to 0.15% was found to be necessary for acceptable weldability (which is impaired at higher levels of chromium and silicon). The zirconium, together with 0.05% titanium, is utilized as de-oxidant prior to pouring. Figure 13-3 shows the effect of Si and Cr content on tensile properties. The cumulative effect of increasing the (Si + Cr) results in increases in yield and tensile strength, but a reduction in elongation. This effect is similar to the cumulative effect of (Si + Nb).

Silicon strengthens the matrix by the formation of silicides, as with the "normal" alloys. The effect of chromium is more complex; in addition to forming silicides, it may also strengthen the matrix by spinoidal decomposition. This type of strengthening occurs as the casting cools to room temperature. Since spinoidal decomposition is insensitive to cooling rates, it is this factor which gives the alloy remarkably uniform properties over a wide range of section thickness. It also ensures that the properties of the weld metal and the heat-affected zone remain about the same as the base metal without the need for additional heat treatment.

The microstructure resembles the Nb-modified 70/30 alloy in that both coring and vein-like, nickel-silicide precipitate form in the copper-rich interdendritic regions. In addition, as shown in Fig. 13-4, the Cr-Si hardened 70/30 alloy contains a fine Cr silicide precipitate in the interdendritic regions.

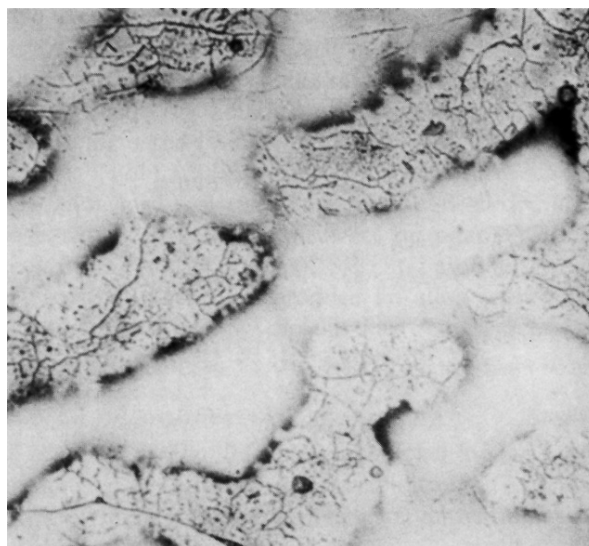


Fig. 13-4. The microstructure of a 70/30 Cu-Ni alloy containing 0.26% Si and 1.4% Cr shows nickel-rich primary dendrites (white). Vein-like nickel silicides and particles of chromium silicide are precipitated in the interdendritic regions. Etched in alcoholic ferric chloride (500x).

In addition to the good mechanical properties and unique retention of properties after welding, the alloy also has exceptional impingement-resistance to flowing seawater.

Nickel Silvers-Leaded Nickel Brasses and Bronzes

Nickel silver alloys are strengthened by the nickel addition through solid solution strengthening of an alpha matrix. They are not heat-treatable. Nickel is the most important element in developing whiteness in these alloys. Part of nickel can be replaced by manganese for developing whiteness. It has been established that nickel plus manganese content must be 16% for developing complete whiteness. However, corrosion resistance is mainly dependent on nickel. Mechanical properties are also improved as the nickel content increases (Table 13-2). Zinc, in the presence of nickel/manganese also exerts a definite though less effective influence on whiteness. Tin helps to improve corrosion resistance and castability and in even distribution of lead and bismuth. Tin also increases hardness and strength by the formation of intermetallic compound but decreases ductility. Lead and bismuth are insoluble in Cu-Ni-Zn or Cu-Ni-Zn-Mn matrix. Lead improves pressure-tightness, machinability and gall resistance. Bismuth also imparts anti-galling properties, but its effect on pressure-tightness and machinability is questionable.

A silvery alloy *paktong* (a cupronickel) appeared in Europe in the 17th century imported from China. Unable to duplicate the alloy, German metallurgists made an alloy containing 20% nickel and 20% zinc with the appearance of silver between 1800 and 1830. It became known as German silver, and was used for decorative wear and utensils. The 20th century casting alloys contain up to 9% lead to enhance machinability and anti-galling characteristics. These alloys were popularly

known as “dairy metals” perhaps because of their initial use in milk processing around 1930. They are also known as “dairy brasses,” “dairy bronzes” and “German silvers.” These alloys are characterized by a pleasing white appearance imparted by the nickel similar to that of stainless steel and used in corrosion-resistant applications such as dairy and food machinery parts (valves, pump impellers, mixing blades, etc.), restaurant and kitchen equipment, steam fittings, hardware for marine and building applications, etc. and compete with stainless steel in these areas. The chemistry of these alloys varies widely depending on strength, hardness, gall-resistance and corrosion-resistance requirements. The three older casting alloys are “dairy metal” (C97600 which is also known as 20% Ni silver), 12% leaded nickel bronze (C97300), and 25% leaded nickel bronze (97800). While standard alloy compositions, testing, and properties are governed by ASTM B369, B494 and other standards (see Chapter 2), there are National Sanitary Foundation or NSF/ANSI (American National Standards Institute) 61 and 372 standards governing material properties in food and potable water use and their testing methods.

After the removal of the anti-knock lead tetraethyl additive from gasoline in the late 1970s which caused lead dusting along roadways, the 1990s saw further efforts to control lead in humans by limiting lead uptake in potable water supplies (Chapter 9), dairy and food. A number of 20% nickel silvers have been patented in which bismuth, bismuth and selenium, or silicon are used instead of lead to produce machinable, gall resistant castings. The nominal chemistries of the four new alloys are a) C89940 (20% Ni, 4% Sn, 4% Zn, 5% Bi), b) 22% Ni, 4% Sn, 4% Zn 2% Se, c) C99780 or 20% Ni, 20% Mn, 20% Zn, 1% Al, 4% Bi, and d) 20% Ni, 5% Mn, 2.5% Fe, 1.5% Si. Bismuth and selenium do impart enhanced machinability and anti-galling characteristics to the alloys. However, on a relative basis, selenium containing alloys have better machinability than leaded alloys, which in turn are more machinable than their bismuth containing counterparts. Nominal compositions and typical properties of the leaded and lead-free alloys a and c are included in Table 13.2. A white manganese bronze and a white copper bronze (C99780) have been developed with anti-microbial properties for food processing equipment with bismuth rather than up to 2% lead as in C99700. Mn, Sn, Pb and Bi additions lower the melting point and promote fluidity. Zinc also lowers the melting point and tends to minimize gas porosity.

Nickel-Tin Bronzes

The simple 5% nickel, 5% tin bronze alloy C94700 responds to age-hardening. A copper-nickel-tin compound precipitates during slow cooling or upon aging at 500–600F (260–316C), with or without prior solution heat treatment. However, heat treatment does substantially enhance the response to the aging treatment (Table 13-3). If contaminants such as silicon or aluminum are present in very small amounts (i.e. over 0.01%), the alloy reacts very slowly, or not at all, to heat treatment. Therefore, these impurities must be critically controlled when heat treatment for improved strength is

required. An amount as low as 0.05% Pb retards response to age-hardening and renders the alloy very susceptible to hot cracking on quenching from the solution temperature 1400F (760C). If the alloy is to be used in the as-cast condition, the control of impurities is apparently no more critical than for the standard nickel-free tin bronze casting alloys. The leaded varieties of the nickel-tin bronzes have a quite uniform distribution of lead particles through the matrix, improving machinability as well as resistance to wear and galling. As noted above, these alloys are not heat-treatable.

Monel Metal

As noted earlier, copper-nickel alloys form a continuous alpha solid solution, regardless of the proportion of copper or nickel present. Hence, it is not surprising that the basic metallurgy and strengthening mechanisms are the same for 65 Ni/30 Cu Monel as they are for 70 Cu/30 Ni cupronickel. Thus, silicon strengthens the matrix by the formation of silicide precipitates, whose volume fraction increases with the silicon content of the alloy. Increasing copper reduces the silicon solubility in the matrix. This, in turn, increases the volume of silicide precipitates and, thus, increases the strength and hardness of the alloy. Both of these effects are shown in Fig. 13-5.

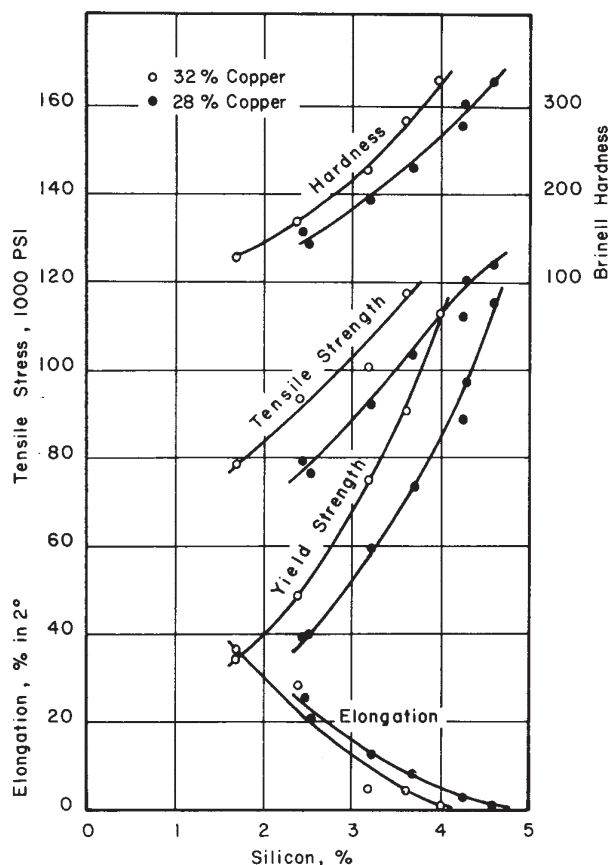


Fig. 13-5. The effect of copper and silicon on the properties of cast Monel induction furnace heats.

Table 13-11. Effect of Carbon Content on the Mechanical Properties of 28% Copper, 1.25% Silicon Monel Metal. Data Courtesy of Victor T. Popp, Union Carbide Corp.

%C	0.05	0.10	0.15	0.20	0.25	0.30
T.S. psi	62,000	70,000	78,000	80,000	89,000	82,000
Y.S. psi	25,000	30,000	32,000	35,000	38,000	38,000
El. %	35	40	40	39	38	35
Charpy Ft. lbs.	90	70	63	58	58	50
Bhn	118	125	140	148	150	149

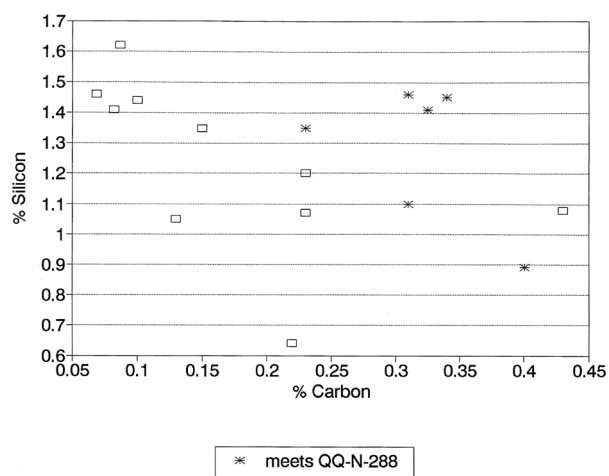


Fig. 13-6. This plot (and Fig. 13-7) were created from the data in Tables 13-5, 13-6, 13-12 and 13-13 to show the relationship between C and Si and C and Si + Nb respectively.

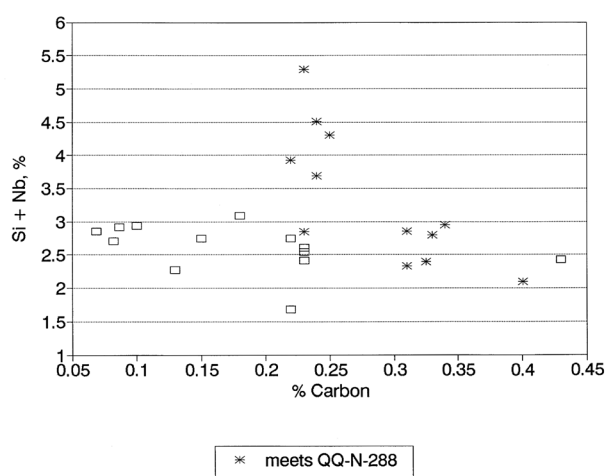


Fig. 13-7. This plot (and Fig. 13-6) were created from the data in Tables 13-5, 13-6, 13-12 and 13-13 to show the relationship between C and Si and C and Si + Nb respectively.

Manganese and magnesium are added as deoxidizers and desulfurizers. Both have little effect on strength, although manganese is said to improve the casting characteristics. Iron is traditionally present in amounts of ~2%, and slightly increases strength by reducing silicon solubility. Iron may also have a beneficial effect on grain size. Carbon is added to produce a carbon boil, which reduces the carbon content as will be explained in the next section. Carbon deliberately or accidentally retained affects the mechanical properties, increasing the strength and hardness and reducing the impact properties as shown in Table 13-11. For the normal 1.5% Si Monel, a carbon content in the range of 0.15–0.20% is usually preferred.

Niobium is added intentionally to some Monels because of certain beneficial effects. Niobium increases the ability of silicon to increase yield strength and ultimate tensile strength (UTS) by forming fine precipitates and inducing precipitation hardening. Niobium also improves weldability by achieving

desired mechanical properties at low silicon levels and by offsetting the detrimental effects of impurities such as lead, tin, sulfur and phosphorus. The addition of niobium reduces the tendency toward hot cracking of the metal adjacent to the weld. However, niobium reduces ductility.

The critical C, Si and Nb contents to meet the ASTM A494 (Grade M35-1& M30C) and US Federal (QQ-N-288, composition E) specifications for the mechanical properties have been defined. Tables 13-12 and 13-13 show the mechanical properties in the absence and presence of Nb respectively. These data together with those from Tables 13-5 and 13-6 have been plotted in Figs 13-6 and 13-7 to show the relationships between C and Si and C and Si+Nb respectively. All these results show that the C content should be between 0.2 and 0.35%, and the Si and Nb contents should exceed 1.1 and 1.4% respectively to obtain the minimum of 450 MPa UTS, 224 MPa yield strength and 25% elongation. In the presence of Nb, the C and Si+Nb contents should exceed

Table 13-12. Effect of C and Si Contents (no Nb) on Mechanical Properties of Monels

C (wt %)	Si (wt %)	UTS (MPa)	YS 0.2% (MPa)	YS 0.5% (MPa)	Elong. %	RA %	Impact	Hardness* Brinell
0.054	1.08	481	193	205	50	57	177	114
0.11	1.15	539	213	222	50	61	268	103
0.12	1.58	563	237	251	46	49	193	170
0.13	2.06	663	317	335	42	42	162	188
0.11	2.64	737	378	387	35	34	191	158
0.15	2.95	854	475	545	19	23	104	232
0.17	2.68	726	393	413	27	30	89	182
0.24	1.06	395	208	221	32	32	122	97.6
0.24	1.68	537	233	247	42	34	98	103
0.24	2.26	456	264	278	22	22	45	116.5
0.20	2.47	555	333	350	21	21	33	151
0.21	3.12	676	496	498	11	13	19	207
0.20	3.17	759	561	549	10	12	22	257
0.35	1.22	380	197	208	22	20	53	98.3
0.35	1.73	386	224	235	18	17	28	111
0.44	2.67	587	374	387	12	14	13	176
0.38	2.66	584	368	383	13	15	15	170
0.37	3.14	651	477	476	8	9	11	212.5
0.02	1.65	507	203	214	47	55	210	93.6
0.16	0.14	528	176	189	48	51	212	96.4

Legend

UTS = 398-635 (% C) + 150 (% Si)	% el = 70-78 (% C) - 11 (% Si)
R-sq = 79.2%	R-sq = 88.6%
** or UTS = 400-600 (% C) + 150 (% Si)	** or 70-78 (% C + % Si/7)
= 400 + 600 (-% C + % Si/4)	
YS (0.2% offset) = 205-100 (% C) + 11 (% Si) ³	YS (0.5% el) = 225-130 (% C) + 11 (% Si) ³
R-sq = 97.5%	R-sq = 95.5%

Table 13-13 Effect of Si and Nb on Mechanical Properties of Monels

C wt %	Si wt %	Nb wt %	UTS (MPa)	YS 0.2% (MPa)	YS 0.5% (MPa)	Elong. %	RA %	Impact (J)	Harness* Brinell
0.22	0.64	1.04	461	182	193	23	23	60	127
0.23	0.54	1.87	461	180	195	24	25	61	112.5
0.22	0.85	1.90	471	190	204	25	27	72	113.5
0.23	1.07	1.47	518	198	212	32	27	62	113
0.22	1.53	2.39	504	218	233	29	28	58	135
0.24	1.57	2.12	504	207	222	30	28	51	114
0.25	1.71	2.59	512	220	235	29	27	54	114
0.24	2.10	2.41	565	283	302	23	26	44	142
0.23	1.94	3.35	575	261	278	31	28	-	182

*10 mm ball diameter, 1500 kg load, 15 s duration

0.2 and 2.5% respectively. Thus, the alloy should contain a minimum of 0.2% C, 1.1% Si and 1.4% Nb to meet the ASTM and QQ-N-288 specified mechanical properties.

MELTING PRACTICE

The general casting characteristics of the copper-nickel alloys are given in Table 13-14. Increasing nickel content increases the pouring temperature. Hence, for the high nickel alloys, electric melting is desirable in order to keep the melting times short. The stirring action of induction melting is also useful for ensuring that high-melting-point components such as nickel and iron are completely dissolved and the alloy composition is homogeneous.

Leaded Nickel Brasses and Bronzes (Nickel Silvers) and Nickel-Tin Bronzes

The melting and pouring practices for nickel silvers and nickel-tin bronzes are similar to those for the corresponding nickel-free brasses and bronzes (see the following chapters on *Melt Control*, *Pouring*, *Copper-Tin-Lead-Zinc Alloys* and *Leaded and High-Strength Yellow Brasses*). Additional care is necessary due to the fact that nickel increases the hydrogen solubility (as do the higher melting and pouring temperatures required for these alloys). In addition, alloys containing about 10% or more nickel can dissolve carbon, which can generate gas porosity through the evolution of carbon monoxide if the alloys are not thoroughly deoxidized (also see the chapter on *Melt Control*). For this reason, carbon base melt covers are not used on high nickel alloys, and it is good practice to coat graphite crucibles, stirring rods, etc. with a refractory wash before use. The age hardening nickel-tin bronzes are

particularly sensitive to contamination by lead or silicon. Because of this, great care must be exercised in the choice of raw materials.

Monel, Cupronickel, and High-Ni Nickel Silvers

Again, the melting and pouring practices for these alloys are based on the principles outlined in the chapter on *Melt Control* and the chapter on *Pouring*. If the furnace charge is comprised of pure copper and nickel it is common practice to melt under strongly oxidizing conditions to reduce the hydrogen content, and then deoxidize (usually with silicon and manganese). Other alloying elements are then dissolved in the melt, under a protective cover (not carbon), in order to limit gas absorption and prevent oxidation loss of valuable alloying elements.

In the case of Monel, a “carbon boil” may be induced in the nickel (as in steel-melting practice) to achieve a low initial hydrogen content. In this practice, carbon is deliberately dissolved in the nickel and then the melt is oxidized (by lancing or adding nickel-oxide). This removes the carbon by forming carbon monoxide bubbles, which purge away the hydrogen as the bubbles rise through the melt.

Where it is required to remelt a substantial amount of scrap (the use of foundry revert should be limited to 60%), the melt cannot be made to dissolve oxygen because of the high alloy content (silicon, zinc, niobium chromium, manganese, etc.) of the charge. All of these elements have a strong affinity for oxygen. In this case, the metal is melted as rapidly as possible under mildly oxidizing conditions, with or without flux covers to limit hydrogen absorption, and then thoroughly deoxidized

Table 13-14. Casting Characteristics

Alloy Designation	Drossing	Gassing	Fluidity	Shrinkage	Casting Yield	Effect of Section Size on Soundness and	Melting Range °F
Cupronickel Alloys							
70-30 (C96400)	Medium	High	High	High	Low	Small	2140/2260 (120)
Be Mod. 70-30 (C96600)	High	High	High	High	Low	Small	2010/2160 (150)
Cu-Ni-Si-Be 70-30	-	-	High	High	Low	Small	1940/2110 (170)
Cr-Si Mod. 70-30	-		High	High	Low	Small	2156/2246 (90)
90-10 (C96200)	Low	High	High	High	Low	Small	2010/2100 (90)
Monel	Low	High	High	-	Medium	Small	2228/2368 (140)
Nickel Silvers							
12% leaded Ni alloy (C97300)	High	Medium	High	Medium	Medium	Medium	1856/1904 (54)
20% leaded Ni alloy (C97600)	Medium To High	Medium to High	High	Medium	Medium	Medium	2027/2089 (62)
25% leaded Ni alloy (C97800)	Medium to High	Medium to High	High	Medium	Medium	Medium	2084/2156 (72)
22% bismuth Ni alloy (C89940)	Medium	High	High	Medium	Medium	Medium	1980/2150 (170)
Ni-Sn Bronzes							
Ni-Sn Bronze Gr. A (C94700)	Low	Medium	Medium	Medium	Medium	Medium	1660/1880 (220)
Pb-Ni-Sn Bronze Gr. B (C94800)	Low	Medium	Medium	Medium	Medium	Medium	1660/1880 (220)

to prevent any possibility of steam-reaction porosity. If the hydrogen content of the melt is very high, it may be necessary to flush the melt with an inert gas, such as nitrogen-lancing.

Induction melting is most commonly practiced, although arc furnaces have been used for the higher nickel alloys. In this case, carbon contamination is possible. To remove carbon, the melts may be blown with dry air or oxygen after meltdown, using nickel or iron tubes depending on the iron content of the melt.

Besides the effect of carbon as a gas generator, hard carbide inclusions may occur with alloys containing chromium, niobium, titanium, etc. These have a disastrous effect on ductility and machinability and, hence, must be avoided. Borax fluxes are not used with Monel as the metal may pick up boron, which, if carbon is present, forms hard carbide inclusions with the deleterious effects noted above.

A typical induction practice for Nb-Si modified 70/30 cupronickel is as follows:

1. Place electrolytic copper in the bottom of the furnace and pack revert around it to create a high density charge; add nickel.
2. During meltdown, add electrolytic manganese and silicon (Mn to 1.2% and Si to 0.25%).
3. When the charge is completely melted and the temperature reaches 1425–1455C (2600–2650F), pour a gas test coupon to note shrinkage characteristics (2 in. dia x 3 in. specimen in green sand mold).
4. If gas test shows proper shrinkage, pour sample for chemical analysis and determine C, Mn, Si, Ni, Nb, Pb, Fe, and S.
5. If the shrink test is unsatisfactory, add additional silicon and/or magnesium, or flush the melt with nitrogen until a satisfactory shrink is observed.

6. Adjust Mn to 1.10%. Adjust Si to 0.32%. (Niobium alloy and silicon should be mixed together before adding.) Adjust Nb to 0.92% (use ferro-niobium or nickel-niobium, depending on Fe content).
7. Stick Mg (0.10%) should be plunged into bath before adding Si and Nb.
8. After the niobium and silicon are added, several minutes should be allowed for thorough mixing before the heat is tapped.
9. The tapping temperature depends on types and size of castings to be poured. A typical pouring temperature range is 1370–1455C (2500–2650F).

Because nickel increases the melting point, there is a tendency to pour these alloys too hot. Therefore, some of the temperatures given in the Bibliography should be viewed with caution. Besides potentially increasing gas content, mold erosion, and mold reaction problems, a high pouring temperature increases the rate of oxidation and volatilization of the alloying additions. Thus, with niobium or chromium alloys high in zinc, the increased oxide film thickness may counter the expected increase in fluidity from the high pouring temperature. For these (and many other) alloys, attention must be given to careful (non-turbulent flow) gating and running practice rather than to overheated metal.

A typical melting practice for weldable grade Monel is as follows:

1. Charge the crucible with Ni, returns (if used), graphite and Fe with Cu on top.
2. Heat the charge until molten and maintain temperature at 2552F (1400C).
3. Deoxidize the melt with 95% Si-Fe master alloy.
4. De-gas for 5 minutes with dry argon to remove nitrogen and hydrogen (Note: a carbon boil will also reduce nitrogen and hydrogen contents, but higher temperatures are required, roughly 3002F [1650C])
5. Stir in Mn (deoxidizer) and Nb-Fe master alloy.
6. Plunge Mg and stir to desulfurize
7. Plunge Ti to fix nitrogen.
8. Stir in balance of 95% Si-Fe master alloy.
9. Skim the melt and tap at 2588F (1420C).

DEOXIDATION PRACTICE

The nickel-tin alloys require an addition of 2 ounces of 15% phosphor copper per 100 lbs of melt, just prior to pouring. An addition of cuprous oxide (up to 3 ounces/100 lbs of melt) during melting is recommended when melting the age-hardening alloy. When this is practiced, the phosphor copper addition before pouring should be increased to 3 or 4 ounces/100 lbs of melt. This procedure enhances the properties of this alloy by reducing the dissolved hydrogen content of the melt.

The nickel silver alloys require the following deoxidation practice for each 100 lbs of melt:

- 5 oz of 70/30 copper manganese shot, added about 3 minutes before pouring.
- 1 oz of stick magnesium after treating with the manganese alloy.
- 3 oz of 15% phosphor copper, just before pouring.

There are proprietary alloys available for deoxidizing and degassing purposes. These are usually all-purpose blends made up for a single alloy addition and provide less chance for error during this important phase of the melting procedure.

Deoxidation of 70/30 cupronickel has been described in the previous section on melting practice. The usual silicon addition of approximately 0.3% used to strengthen the alloy also acts effectively as a deoxidizer. This is also true for the manganese and magnesium additions, which serve as effective desulfurizers as well, forming globular, high-melting-point sulfides as opposed to grain boundary films (typical of copper and nickel sulfides) which have a disastrous effect on ductility and strength. Desulfurization is an important consideration when using these alloys, since sulfur can be picked up by the melt from refractories or certain grades of copper used as charge material.

In Monel metal, boron present in the melt can form brittle carbides. For this reason, deoxidation with master alloys containing boron should be avoided. Deoxidation practices, in general, are similar to those for 70/30 cupronickel and were described in the previous section.

MOLDING

Sands

Since nickel-containing alloys are poured over a temperature range from 2050–2850F (1121–1565C), they require good refractory sands. Synthetic sands based on washed silica, bonded with either low-sulfur fire clay or low-sulfur bentonite, have been found to produce good quality castings. Olivine sand is increasingly being used.

Shell molds and cores bonded with various resins have been used successfully with all of the alloys.

The CO₂-silicate process has been quite successful in small to very large molds for all of the alloys. However, some trouble has been encountered with CO₂-silicate cores in the form of gas porosity from core moisture reaction gases.

Facings

Facings are not generally used with these alloys, nor are they recommended since most have a tendency to reduce permeability. Facings of chill-type materials (zircon, chill shot, etc.) have been used successfully in helping to control directional solidification in heavy-section castings.

Certain organic and inorganic noka sand binders can be utilized for casting production with these alloys as discussed in the chapter, *Casting Processes and Materials*.

GATING

As pouring temperatures for this family of alloys are higher than usual, factors in the gating system which will minimize sand wash, mold erosion, and metal penetration are more critical than they are for casting the lower-melting point alloys. Thus, sharp edges, loose ramming, and sharp bends in the gating system should be avoided, and low metal velocities should be maintained through the use of properly proportioned sprue, runner and gating systems.

The cupronickel and Monel families are often produced under very stringent quality control standards, requiring radiography, liquid penetrant inspection, etc. Thus, gating systems for these alloys must reduce turbulence, eliminate air aspiration and oxide inclusions, and assist in achieving directional solidification from the risers. This becomes even more critical where such castings must be welded, as inclusions and porosity seriously impair weldability.

Nickel-Tin Bronzes

Nickel-tin bronze alloys respond to the same type of gating systems used with red brasses and tin bronzes and are not critical with regard to gating practice. Knife, kiss, pressurized and non-pressurized gating systems are all used, depending on the design and size of the casting.

Leaded Nickel Silvers

Alloy C97300, with 12% Ni and 20% Zn, has a relatively low melting point and a fairly high potential for oxidation due to the high zinc content (which is volatile and readily oxidized). Hence, non-turbulent, non-pressurized systems are recommended, similar to those used for yellow brass and manganese bronze.

The C97600, 20% Ni silver and C97800, 25% Ni silver contain 8 and 2% Zn, respectively. Hence, these alloys have a higher melting point and a lower oxidation potential, although there is increasing volatilization of zinc as the pouring temperature increases. The gating systems are not as critical as for C97300; nevertheless, non-pressurized systems are recommended.

Cupronickel

The silicon content of cupronickels tends to act like phosphorus in forming a fluid slag; thus, the alloys are not particularly susceptible to oxide inclusion problems. There may be slag inclusions, however, with poor gating practice. As the niobium content increases, or with the beryllium-containing alloys, oxidation becomes more of a problem and gating practice should be similar to that used for aluminum bronze.

This is also true for the chromium-containing alloys, which cross readily at the high pouring temperatures. It is desirable to use the lowest possible pouring temperature with a non-pressurized gating system, ingates, etc., for non-turbulent filling. This may require the use of a relatively large number of gates in order to avoid misruns. This approach is preferable to increasing the casting temperature, which causes more cross formation.

Monels

The Monel alloys have the highest casting temperature (2650–2800F [1455–1540C]) and, hence, require the greatest care in terms of mold erosion. With these alloys, the greatest variable is the silicon content (Table 13-4); the high-silicon alloys are “self-slugging” and are not particularly prone to oxide inclusions. However, because of the high pouring temperature, non-pressurized, non-turbulent systems are recommended, particularly for larger castings.

RISERING

Nickel-Tin Bronzes and Nickel Silvers

The nickel-tin bronze and nickel silver alloys have a relatively long freezing range, about 260°F (127°C), which tends to increase slightly as the tin and nickel contents increase and to diminish as the zinc content increases. These alloys, therefore, are prone to interdendritic microshrinkage and are difficult to feed. Riser techniques are similar to those used for leaded red brass, and extensive chilling is required to establish steep thermal gradients where maximum soundness is required. Figure 13-8 shows typical rigging/gating for a small casting.

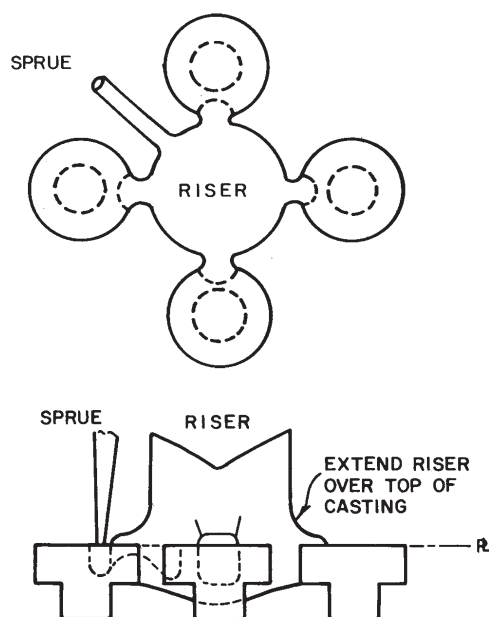


Fig. 13-8. A method of gating small gears and similar castings is illustrated above.

Cupronickels and Monels

While the cupronickel and Monel alloys are classified as having a narrow solidification range, the literature indicates that some researchers have found the cupronickels to be intermediate when compared to narrow-freezing-range alloys such as aluminum bronzes ($6-30^{\circ}\text{F}$ [$3-16^{\circ}\text{C}$]) and manganese bronzes ($30-75^{\circ}\text{F}$ [$16-46^{\circ}\text{C}$]). For example, the solidification range of Cu-Ni-Si-Be is reported to be 170°F (96°C). Therefore, the cupronickel alloys exhibit two types of shrinkage, which are normally referred to as the “piping” type and interdendritic microshrinkage porosity. Both of these are illustrated in Fig. 13-9.

The “piping” type of shrinkage is associated with the narrow-freezing alloys; interdendritic shrinkage porosity is associated with wide-freezing-range (mushy) alloys.

The cupronickel and Monel alloys require special risering and chilling techniques to achieve the directional solidification pattern so important to the production of high-quality castings. Adequate riser height and insulating or exothermic riser sleeves are needed to ensure that the riser pipe does not extend into the casting; strongly directional chilling toward the risers establishes the steep thermal gradients necessary to eliminate micro shrinkage. Figure 13-10 is an example of a successful practice. The Monel alloys, having a narrower freezing range (50°F [30°C]), are somewhat easier to feed.

Table 13-14, cited previously, illustrates the general casting characteristics of the cupronickel alloys and should be referred to regarding gating and risering requirements.

CASTING DEFECTS

The alloys discussed here may be subject to any or all of the casting defects described in the chapter on Common Defects in Sand-Cast Copper-Base Alloys. However, because of the particular characteristics of these alloys, special care is needed in the following areas:

- Nickel increases the hydrogen solubility in all alloys and, when coupled with a higher pouring temperature, gives rise to gas porosity defects unless special attention is paid to melting, deoxidation, degassing procedures, pouring temperature, and mold conditions such as moisture content, permeability and venting. Dissolved carbon can be an additional source of gas porosity in the high-nickel alloys by forming carbon monoxide bubbles.
- The high pouring temperatures for Monel, $\sim 2700^{\circ}\text{F}$ (1482°C) generate sand defects such as wash, scab, buckle and metal-mold reaction defects.
- The high-nickel alloys are sensitive to certain impurities that may cause hot cracking or tearing in the molds unless there is adequate collapsibility.
- The chromium-containing cupronickels are prone to oxide inclusions and require carefully designed pouring systems.



Fig. 13-9 Two types of shrinkage characteristics of the cupronickel alloys are illustrated above: piping and interdendritic.

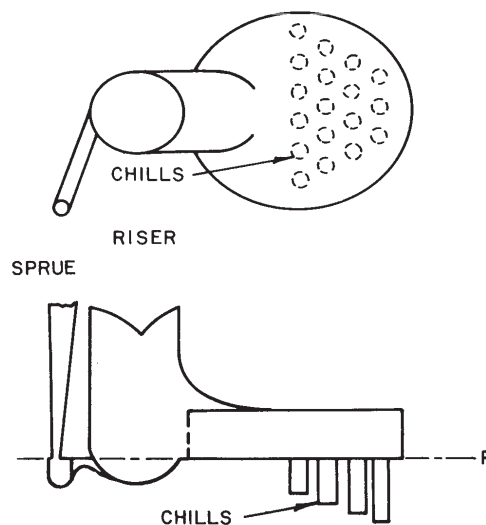


Fig. 13-10. A method of gating and risering disk castings is shown above. Note the use of chills to promote directional solidification.

FINISHING

The nickel-containing alloys produce good dense structures when properly handled, and attain a high finish after grinding and polishing.

All of these alloys can be readily machined, with the exception of the high-silicon Monel which may require a prior anneal. The leaded alloys have excellent machinability and hence can be used for very intricate parts.

WELDING

The weldability of a material is a relative term. Many metals are readily weldable by a variety of methods. Others are weldable only by the use of special techniques. Within the recommended chemistry ranges, the cupronickel alloys are

Table 13-15. All Weld Metal Deposit Tensile Properties (AWS A5.6 ECuNi)

Condition		Y.S. 0.5% Offset, ksi	Tensile Strength Ksi			Elong. % in 2 in.		Bhn		
As-welded		25.5	51.5			49.0		85.5		
Chemical Analysis of Weld Deposit										
Cu	Ni	Mn	Fe	Pb	Si	Al	Cr	Ti	Nb	S
66.94	Bal.	0.81	0.57	0.007	0.16	0.0006	0.003	0.044	0.05	0.009

freely weldable by all methods. These alloys may be welded by shielded metallic arc (SMA), gas metal arc (GMA) or gas tungsten arc (GTA) methods. The shielded-arc metal process is most often used, mainly due to the more convenient interpass temperature control and the ready availability of suitable filler metal. AWS (American Welding Society) Class 5.6 ECuNi filler metals are available for welding these alloys.

Effect of Composition

While the cupronickels are considered easily weldable, close control of the basic elements (especially the silicon content) is necessary to prevent heat-affected-zone cracking. In the niobium-modified 70/30 cupronickel, weldability is improved and strength increased for any given silicon content by the addition of niobium. It is desirable to restrict the silicon level to about 0.40% maximum, with niobium over 0.50% (preferably in the range of about 0.75% to 1.00%), for the necessary combination of strength with weldability.

The weld metal deposit of AWS A5.6 (ECuNi) does not produce strength levels that meet the minimum specification requirements of the cast 70/30 cupronickel specification ASTM B369 (copper alloy C96400). All weld metal deposit tensile properties are shown in Table 13-15. It is clear that use of such materials for “through-section” welds reduces the strength in these sections, and such welds should be made only with due regard for this feature. The low strength and high ductility of the weld metal is due to the low silicon content (0.16%).

In the niobium-modified 90/10 cupronickel alloy, increases in both silicon and niobium decrease the ductility. Substandard ductility and weldability will occur if these two elements are on the high side of the specification. Silicon in the range of 0.10 to 0.15%, and niobium in the range of 0.30 to 0.40% (silicon plus niobium in the range of 0.40 to 0.60%), will produce an alloy that will meet all the tensile requirements and weldability tests. Filler metal to AWS Class A5.6 ECuNi will produce properties approximately equivalent to the 90/10 composition, but with a poor color match.

In the chromium-modified 70/30 alloy, it is desirable to limit the silicon content between 0.30 and 0.50% to enhance weldability. Filler metals have been developed to produce

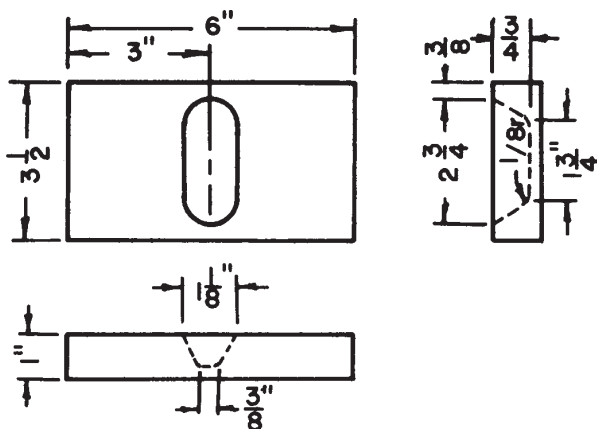
tensile and yield strengths that equal or exceed those of the parent casting, and these welds have been successfully bend-tested in accordance with the ASTM B369 standard.

In the beryllium-modified 70/30 cupronickel alloy, sound welds with no post-heat treatment have at least 70% of the strength of the heat-treated base metal. This has been done with matching filler-metal chemistry, utilizing the tungsten-inert-gas (TIG) method. With post-heat treatment on unmachined castings, the weld hardness is virtually equal to that of the base metal.

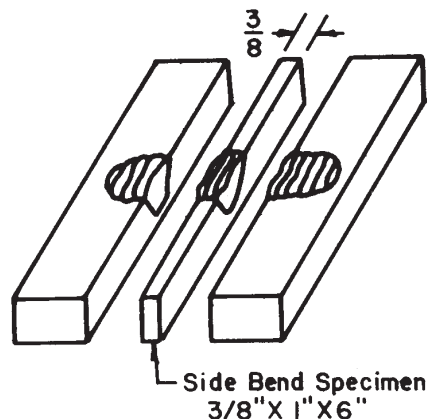
Of the cast Monels, only the lowest silicon alloy is readily weldable, and niobium may be added to improve weldability as with cupronickel. Electrodes of the same composition are used, and impurities must be limited to avoid cracking.

Effect of Impurities

The presence of certain impurities can cause serious degradation of the welding characteristics of the cupronickel and Monel alloys. The amount of the impurity present can be quite small, in fact, often too small to be readily detected or measured by conventional analytical methods. Consequently, standard industry chemical specifications alone are not adequate to ensure weldability. Therefore, some specifications (ASTM B369 and MIL-C-20159) require test plates to be cast from every heat, and weldability tests performed. The type of test utilized for these two specifications is shown in Fig. 13-11. The test requirements are for the groove to be welded, a bend bar removed, bent 180°, and examined for heat-affected zone (HAZ) cracks. No HAZ cracks over 1/8 in. long are permitted on the convex surface. Variations in HAZ cracking-susceptibility of metal from different heats is due mainly to low-melting-point constituents which segregate along grain boundaries during solidification of the casting. During welding, these low-melting constituents remelt and remain liquid while the weld metal shrinks. The HAZ grains, with weak liquid films between them, shrink later and separate, thus forming cracks. Of the common impurities, lead, sulfur, and phosphorus are probably the most detrimental. Weldability test requirements may not be attained if the lead content exceeds 0.01%. Bismuth, selenium, antimony, boron, and possibly certain other elements may also contribute to poor weldability.



**Cast Block for
Weldability Test**



Weldability Test Block

Fig. 13-11. A cast block for a weldability test (left), and a weldability test block (right).

Interpass-temperature control is also important and should not exceed about 250F (120C). Peening the base metal before deposition of weld passes, depositing weld metal in small passes, and peening all passes of the first two layers of weld metal soon after deposition will lessen or eliminate HAZ cracking. Preheat treatment is not recommended, as it is more apt to be harmful than helpful with these alloys. All welding materials and excavations should be clean and dry before welding.

While the literature covers a considerable amount of experimental work on the welding of the cupronickels, there are no industry standards except those required by ASTM and military specifications. The nickel and nickel-tin bronzes are difficult to weld.

HEAT TREATMENT

The lead-free nickel-tin bronzes can be heat-treated by solution treating for five hours at 1400F (760C), followed by oil- or water-quenching. This is followed by an aging treatment of 5 hours at 600F (316C) and air cooling. The combination of solution treatment, quenching, and aging provides maximum mechanical properties.

All of the nickel-tin alloys, including the leaded compositions, respond to a temper or aging treatment of 5 hours at a maximum of 575F (302C) applied in the as-cast condition; both strength and hardness are enhanced considerably by this. The leaded alloys should not be solution-treated and quenched, as they are likely to crack on quenching.

The silicon- or silicon-niobium-bearing 70/30 cupronickels respond to heat treatment. However, most foundries prefer to attain hardness and strength through alloy composition control rather than incur the extra expense of heat treatment.

The beryllium-modified 70/30 cupronickel is age-hardenable, as discussed earlier under the metallurgy section.

The chromium-silicon modified 70/30 cupronickel alloy will respond to aging, and the properties obtainable with a Cu-30% Ni-0.46% Si-1.73% Cr alloy are illustrated in Fig. 13-12. If the castings are not to be heat-treated, they should be allowed to cool in the molds for 1-2 hours to ensure that the temperature has dropped below 932F (500C) before the castings are shaken out. This procedure will develop optimum properties as maximum strength is achieved with the slowest cooling (spinoidal hardening coupled with silicide precipitation).

The high-silicon Monels can be softened by annealing for 1 hour at 1600F (870C), furnace cooling to 1200F (650C), and then quenching to suppress the precipitation of silicides. Rapidly cooled material can be hardened by aging at 1100 F (590C) for 4 to 6 hours, followed by air or furnace cooling.

EFFECT OF IMPURITIES

The effect of impurities on the specific properties of each alloy has been discussed. What is considered a tramp element or impurity in one alloy may be beneficial in another. For example, lead is detrimental to the weldability and mechanical properties of the cupronickel alloys and, in small amounts, will decrease the age-hardening characteristics and cause quench cracking of the nickel-tin bronzes. Lead is added in alloying quantities, however, to the nickel silver alloys for improved machinability and soundness. Other impurities that are detrimental to the cupronickel alloys which should be kept at low levels are carbon, sulfur, phosphorus, selenium, tellurium, boron and bismuth. When these elements are present singly or combined in very small amounts they can cause weld-cracking problems.

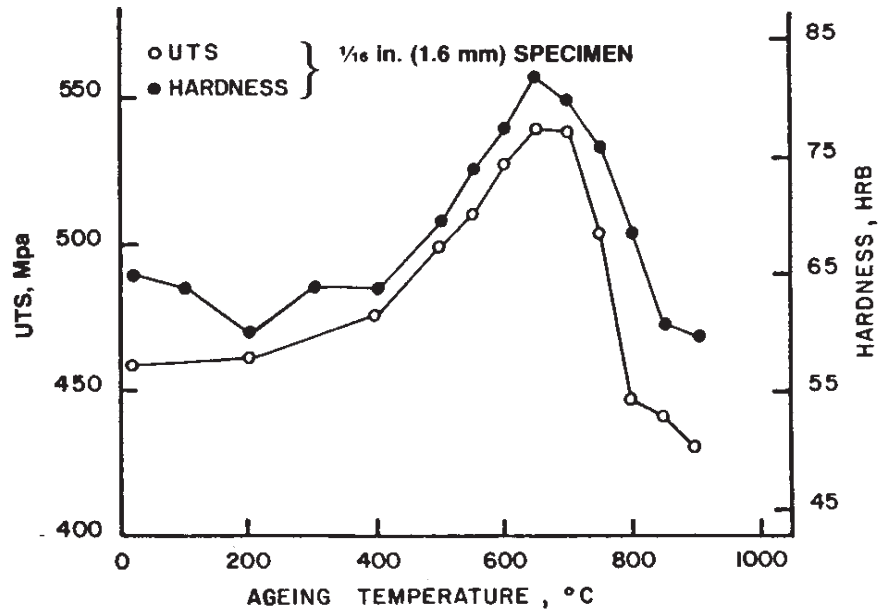


Fig. 13-12. The effect of aging temperature on UTS and hardness of 1.6 mm thick Cu 30%, Ni 0.46%, Si 1.73% Cr (water-quenched after 1 hour at 975C [1787F]).

The nickel silvers deoxidized with the proper amounts of manganese, magnesium, or phosphorus offer few problems in obtaining high-quality castings. However, manganese above 0.50% has been found to cause black inclusions on the cope surfaces of castings.

Silicon, in specified amounts, is necessary to control the mechanical properties of the Monel and cupronickel alloys, but is a harmful impurity in most of the other nickel-bearing copper-base alloys-especially those containing lead.

The influence of the various elements, whether in alloying quantities or as impurities, must be known and controlled to achieve consistent production of high quality castings.

PROPERTIES AND APPLICATIONS

The corrosion/erosion resistance of the alloys has been well established by tests in a number of media, ranging from fresh water through various petrochemicals. Seawater corrosion-resistance data have been determined over a number of years for the alloys, and their usefulness in marine applications, petroleum refineries, and seaboard power stations is well defined. The nickel-tin alloys are known for their freedom from dezincification in chlorinated and softened fresh water systems. The nickel silvers are noted for their corrosion resistance, good finish, and ability to hold fine detail in ornamental castings. They are frequently used with wrought metal forms in the construction of machinery, architectural trim and hardware.

The cupronickel alloys are found quite useful at cryogenic temperatures (-423F [-253C]), since they increase in both

strength and toughness as the temperature is lowered. Their excellent behavior in resisting the corrosive/erosive effects of seawater has placed these castings in demand for use on shipboard, power plants in coastal areas, and in air-conditioning and saline-water conversion installations. The useful degree of wear-resistance possessed by the cupronickels is becoming better appreciated as more applications are tested.

The Monels extend the strength, corrosion- and wear resistance, and service temperature range of the cupronickel applications.

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HIGH-CONDUCTIVITY COPPER AND HIGH-COPPER ALLOYS

INTRODUCTION

Cast commercially, pure copper and high-copper alloys have been used for many years in applications requiring high electrical and thermal conductivity, such as resistance welding electrodes, structural elements carrying electrical current, blast furnace tuyeres, and cooler plates. In the past, most nonferrous foundries were not familiar with or had little experience with these alloys, because great skill was required to produce the castings made from them and there was limited demand for them in comparison with other copper-base alloys. However, the advent of the age of energy conservation has increased the demand for components with the highest possible electrical and thermal conductivity. To satisfy this need, most nonferrous foundries have made significant progress in casting techniques and have instituted reliable quality-control programs.

Much of the difficulty in producing pure copper castings has been caused by unsoundness due to gas porosity, as well as the effect of very small percentages of tramp elements

entering into solid solution with copper and reducing its electrical conductivity. In order to obtain maximum electrical conductivity, pure copper must be relatively free from impurities. Figure 14-1 shows how impurities reduce electrical conductivity.

Pure copper, because of its inherent softness, is limited to applications that do not require high strength or hardness. Several copper alloys, particularly those containing beryllium and chromium, are available for use in applications where high electrical conductivity, high strength, and high temperature properties are desired. However, addition of these constituents to the copper will somewhat reduce conductivity, and the alloys must be heat treated to develop optimum strength and electrical properties.

Cast coppers, as listed in the appropriate ASTM standards, contain a minimum of 99.70% copper, plus silver. Those defined as "high-copper alloys" may contain as little as 94.2% copper in combination with specified elements, such as 2% beryllium, 1% cobalt, etc.

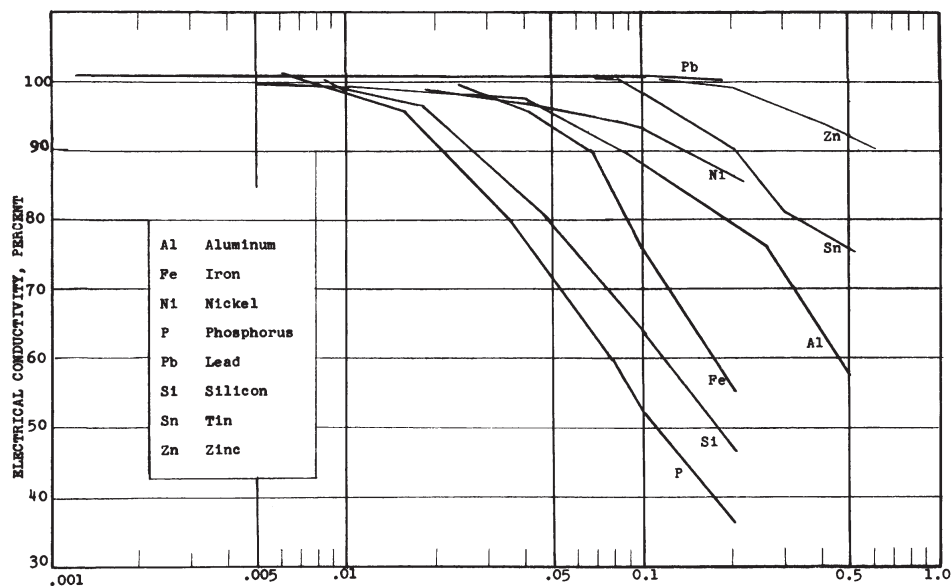


Fig. 14-1. The effect on electrical conductivity of small percentages of elements entering into solid solution with copper are illustrated above.

FUNDAMENTAL METALLURGY

The strength and high-conductivity of high-copper alloys is due to the fact that elements such as beryllium, chromium, and cobalt can be taken into solution in the alloys at high temperatures and will precipitate on cooling from the casting temperature or in separate heat treatments. This precipitation greatly increases the strength of the alloy through precipitation-hardening or age-hardening. The fact that the alloying elements are no longer in solution allows the copper matrix to approach the conductivity of pure copper.

In the “classical” binary alloys, chromium precipitates as blue-gray particles of almost pure chromium, whereas beryllium precipitates as very small particles of a copper-beryllium compound. Commercial alloys often contain additional elements such as cobalt, nickel, and silicon, so that the precipitated compounds are complexes of these elements also. Because of the potential health hazard of beryllium, new alloys such as those based on copper, nickel, and tin, are being developed as supplements to beryllium copper. As yet, these are not widely used as casting alloys; since they consist of much more than 5% alloying elements, they will not be treated in this chapter.

All of the above alloys can be heat treated. This involves solution heat-treating (heating to a temperature high enough to dissolve the beryllium or chromium in the alpha phase), followed by immediate quenching to preserve the alloy as a supersaturated, alpha solid solution. Subsequent heating, or aging, at a lower temperature will cause precipitation of the unstable phase, accompanied by a marked increase in mechanical strength and electrical conductivity.

MOLDING

Sands that are suitable for other brass and bronze alloys may be used in casting copper and high-copper alloys. Moisture content is important and should be closely controlled to prevent formation of rough surfaces and gas cavities. Synthetic sands may be used in casting copper and high-copper alloys, provided that the proper equipment is available to assure thorough conditioning of the sand mixture and to maintain control of sand properties.

Facings are seldom required in casting copper or chromium- and beryllium-copper alloys, since a relatively good finish can be obtained from a molding sand of 100 to 150 AFS gfn (grain fineness number). However, a graphite wash may be used on the runner and gate areas of large copper and chromium copper castings to prevent metal penetration, which can occur because of the high pouring temperatures and the large volume of metal, which passes through these sections of the molds.

Investment shell mold or plaster-bonded molds are often used for high conductivity copper castings. High conductivity copper castings are also cast in permanent mold. The per-

manent mold castings have finer grain structure, improved mechanical properties and exceptional surface finish.

Cores. High-conductivity copper is notorious for cracking either at hot spots on freezing (hot tearing), or while cooling in the mold (hot cracking). It is essential, therefore, that both molds and cores be formulated and rammed with this in mind. The use of silica sand bonded with a quality grade of phenolic resin or oil is suggested for copper and chromium copper alloys. Oil-bonded cores are recommended for the beryllium copper alloys. All cores should be thoroughly baked and free from gas forming materials. Cores should be well vented. Coating with a suitable core wash will reduce metal penetration and will help minimize gas formation at the core/metal interface.

CO₂ silicate-bonded cores are not recommended in certain copper castings because the increased hardness and decreased collapsibility of these cores may produce hot tears in the castings as indicated above. However, they may be used satisfactorily in some applications where the cored area is small in comparison to the surrounding mass of metal. Core knockout may be improved through the addition of one of the various commercial additives that increase collapsibility of the cores. Furan binders have also been used successfully with pure copper.

MELTING AND POURING

Equipment

Either induction or fuel-fired crucible furnaces may be used in melting copper and high-copper alloys. Induction melting is preferred, particularly for the chromium and beryllium alloys, since the fast melting rate provided by this equipment minimizes alloy losses and permits close control of metal quality. Satisfactory results can also be obtained from gas- or oil-fired crucible furnaces if absorption of combustion products is minimized.

Silicon carbide crucibles are recommended for the higher-melting-point copper and chromium copper alloys, but clay-graphite crucibles can be used for the beryllium copper alloys. When melting beryllium copper in silicon carbide crucibles, it is recommended that a wash heat be melted in each new silicon carbide crucible and that the metal be pigged or poured into a non-critical casting.

Fluxing and Deoxidizing

Fluxes or slag covers are generally unnecessary when melting copper and beryllium copper alloys. In melting copper, a layer of dry charcoal or granular graphite may be used to cover the molten metal, and it should be placed on top of the furnace so that it heats up with the metal.

In melting chromium copper, a flux cover is recommended to minimize oxidation of chromium. A thin cover of lead-free

glass or a liquid salt cover consisting of two parts sodium fluoride to one part calcium fluoride will provide satisfactory protection. Sparing use of fluxes is advisable, since these materials can harm the crucibles.

Because beryllium and chromium are strong deoxidizers, no deoxidation treatment is required for these alloys. However, deoxidation is required in melting pure copper, and this will be discussed later.

Melting Practice

High-Conductivity Copper

In the recommended melting practice for high-conductivity copper, high oxygen content is deliberately induced into the melt to limit the pickup of hydrogen and to oxidize impurities that may be deleterious to conductivity. The melt is then deoxidized, and only enough excess deoxidant is left to prevent steam reaction from oxygen picked up during the pour. (A detailed explanation of this process is given in the chapter on *Melt Control*.) The oxygen content depends not only on the melting conditions, but also on the charge material used.

Electrolytic or fire-refined, tough-pitch copper is the standard commercial copper ingot. It already contains 0.03% oxygen (as does most wrought electrical copper scrap, e.g., wire, bus bar, connectors, etc.); therefore, it needs some, but relatively little, deoxidation. Cut cathode squares (an alternative virgin raw material) contain no oxygen; however, since they may contain considerable hydrogen, strong oxidation is needed to remove the hydrogen. In-process scrap should contain neither oxygen nor hydrogen but should contain residual deoxidant in amounts depending on the efficiency of deoxidation control in the foundry. Return scrap is oxidized at least back to zero residual deoxidant to maintain control over the process and prevent progressive build-up of deoxidant to levels which affect conductivity.

In casting high-conductivity copper, furnace charges should consist of electrolytic or fire-refined copper ingot, plus some gates, risers, and other foundry scrap. All charged material should be clean and dry and of known quality. To prevent contamination, the material should be charged into a new crucible, which has been set aside for the specific purpose of melting pure copper. If fuel-fired furnaces are employed, a slightly oxidizing flame is used to heat the metal as rapidly possible to 2200–2250F (1200–1230C). During melting, a 1 to 1.5 in. layer of flake graphite should cover the copper. When using a coreless electric induction furnace, the meniscus effect at full power may cause the graphite cover to slide to the edge; therefore, it may be necessary to reduce the power input in order to keep this from occurring. After the molten copper has reached 2300F (1260C), the furnace should be turned off and a graphite rod should be used to skim back the carbon cover. If the carbon cover remains separated and the metal is still, the copper is properly deoxidized. If the carbon cover tends to spread back over the surface and the metal surface appears agitated, the copper

is not fully deoxidized and must be held for a longer period under the carbon cover, which is an effective but relatively slow deoxidant.

An alternative test is to preheat a carbon rod by pushing it into the melt and to watch the melt surface for gas bubbles. The initial bubbles result from air which was absorbed by the rod; however, once these have been driven off (approx. 1 min), further bubbles may be caused by dissolved oxygen in the melt reacting with the carbon of the rod to form carbon monoxide, and this indicates that the melt is incompletely deoxidized. If no bubbles are observed, then the oxygen content of the melt is zero (less than 0.01%), and the correct amount of deoxidant can be calculated and added to give the desired residual deoxidant.

At this point, the copper must be deoxidized by plunging calcium boride, or one of the various deoxidants available commercially in tube or capsule form, to the bottom of the melt. In a tilting furnace, the deoxidant can be placed in the bottom of the transfer crucible and the metal poured on top of it. Regardless of the type of deoxidant used, only enough should be added to ensure complete deoxidation of the metal, with a slight excess provided to protect the metal during pouring. Excessive deoxidation should be avoided, since residual deoxidant will result in low electrical conductivity in the finished castings. Excessive calcium is found to be detrimental to both electrical conductivity and mechanical properties. In addition, it has tendency to give rise to dross inclusions in the surface of the castings.

A relatively simple procedure for evaluating the degree of deoxidation consists of pouring a 3 in. X 3 in. diameter deep test plug. A shrinkage cavity indicates that the metal is thoroughly deoxidized and ready to pour. A puffed-out riser indicates that deoxidation is incomplete and that more deoxidant is needed. Since molten copper oxidizes very rapidly, care and promptness in pouring the test plug are important in order to obtain a truly representative sample by normal dipping. Otherwise, the metal poured in the shrink test may not have the same oxygen content as the bulk metal in the crucible. It is likewise necessary to cover the risers (and the top of the shrink bar) immediately after pouring with material which will both insulate (to promote feeding) and generate a reducing atmosphere (to prevent oxygen pickup). Vermiculite-graphite mixtures have been used for this purpose.

As shown in Fig. 14-1, common impurities such as phosphorus, silicon, and iron have a disastrous effect on conductivity. These are oxidized from the melt to form slags during the oxidizing melting cycle. If a high level of contamination in the charge is suspected, such slag should be removed before the carbon cover is added since the carbon can reduce these elements from the slag and cause them to go back into solution in the copper. The best practice is to use only contaminant-free raw materials and to use graphite (rather than iron) skimmers, stirrers, and so forth.

Finally, all deoxidants must be added to the furnace or pouring ladle in such a manner that they thoroughly mix with

the molten metal. Also, a period of at least one minute is recommended between deoxidant addition and pouring to allow time for reaction and for the reaction products to float to the surface of the melt.

It should be noted that deoxidants (with the possible exception of lithium) react with oxygen only, not with hydrogen. Hence, if the melt has become high in hydrogen, it must be degassed by flushing with dry nitrogen, preferably before final deoxidation. This procedure is discussed in the chapter on *Melt Control*.

High-Copper Alloys

When a charge of copper ingot or scrap is used to begin melting high-copper alloys, the copper is first oxidation melted and deoxidized, as explained above. Then, usually after some final skimming or degassing treatment, alloy additions are dissolved and the melt is poured.

When using ingot or scrap that is prealloyed, any excess oxidation simply wastes valuable elements such as chromium and beryllium, since these elements oxidize preferentially. Thus, a residual dissolved oxygen content to protect from hydrogen pick-up cannot be established (see the chapter on *Melt Control*). Instead, these materials are melted either under a slightly oxidizing or inert gas atmosphere or under a melt cover of fluxes or glass in order to limit alloy loss. The metal is melted as rapidly as possible at the minimum temperature necessary to dissolve the alloying elements or pour the melt. Deoxidation is not necessary, as the melt already contains a strong deoxidant (chromium or beryllium). An unsatisfactory shrink test indicates the presence of hydrogen, and this makes it necessary to degas the melt by flushing with dry nitrogen.

Chromium Copper

Because very poor crucible life is obtained in melting chromium copper in the lift-out or push-up type of induction melting furnaces, the use of fuel-fired crucible furnaces is recommended for this material. Maximum crucible life is obtained only through the use of silicon carbide crucibles.

Chromium copper castings can be produced by adding a master alloy to molten, pure copper or by melting commercially prepared ingot. The first technique involves melting and deoxidizing the copper under a protective graphite cover, as described previously for high-conductivity copper. The graphite cover is then skimmed off (hard chromium carbide inclusions can be formed) and replaced by a cover consisting of an inert gas, salt, or flux. Finally, a prepared master alloy containing 5% chromium is added.

The preferred melting technique for chromium copper in the average foundry is to use a charge consisting of 50% commercially prepared ingot (containing about 1.2% chromium) and 50% foundry returns. The charge should be melted under a cover of flux, inert gas, or plain glass and slightly oxidizing

flame should be used. The addition of some master alloy containing 5% chromium is necessary to compensate for the lower chromium content of the gates and risers in the charge. The amount of master alloy to be added will depend upon the melting equipment, pouring temperature, and length of holding time in the furnace, and, it must be determined by a chemical analysis of the returns in the charge. The preferred chromium content in the finished casting is approximately 0.8%. The master alloy should be pushed through the protective cover with a carbon rod. After the master alloy has been added, 10 to 20 min will generally be required to dissolve the chromium and to raise the metal to the pouring temperature. Because chromium is easily oxidized, approximately 20 to 30% of the original addition will be lost in melting.

Satisfactory results can also be obtained by melting a commercially prepared ingot containing excess chromium to compensate for melting losses. The best practice is to add the ingot to a molten heel of risers, gates, and foundry scrap that has been melted under a protective cover, in a slightly oxidizing furnace atmosphere. The excess chromium in the ingot will compensate for the melting losses, while the balance of the material acts as a diluent for some of the impurity increase invariably obtained in remelting foundry scrap.

Regardless of the casting procedure used, regular composition checks are recommended in order to exercise control over the properties of the cast material. Another process control technique is to cast a separate test coupon with each heat of metal. This coupon may be promptly heat-treated and tested for hardness to verify that the heat contains the required level of chromium for response to age-hardening treatment.

Beryllium Copper

Caution should be observed in the melting, casting, and finishing of beryllium copper alloys since handling these alloys under improperly controlled conditions might create a health hazard. Appropriate environmental control agencies should be contacted for specific regulations and for guidance in establishing proper procedures. (See also the chapter on *Health and Safety Aspects of Copper-Base Alloy Foundry Practice*.)

Beryllium copper may be formulated from pure copper and master alloys, but use of prealloyed ingot and carefully segregated foundry returns is more economical unless a chemical analysis service is available and the composition of all components is accurately known.

The recommended melting practice for beryllium copper alloys is first to charge the foundry returns to the furnace. These returns should be melted, under a slightly oxidizing atmosphere, as rapidly as possible to minimize loss of beryllium and absorption of gas. The prealloyed ingot (preheated) should then be added and the melt temperature raised to the pouring temperature. The excess beryllium in the ingot serves to compensate for any losses during melting, usually averaging about 5% of the contained beryllium.

For the highest quality work, the metal should be degassed with dry nitrogen just prior to pouring, since beryllium copper is prone to hydrogen absorption.

POURING PRACTICE

Pouring practice for copper and high-copper alloys is similar to that used with the bronze alloys. The only exception is the need for an inert cover over the molten metal from the time it melts until it is poured into the mold. Without this cover it is impossible to control the deoxidation process in pure copper, because it quickly reabsorbs oxygen in the furnace or ladle. Covers on the alloys provide a mechanical barrier which helps prevent hydrogen pickup from reaction with the water vapor in the air; however, they are primarily used to prevent the oxidation of valuable alloying elements and to reduce oxide inclusions in the casting. Care must be taken to see that the cover is retained in the ladle during pouring; otherwise, it too may cause inclusions in the casting. Recommended pouring temperature ranges for the alloys are shown in Table 14-1. Superheating should be avoided, as this increases drossing, gas absorption, and the loss of alloy constituents.

FINISHING

Gates and risers usually are removed by band saws with skip-tooth blades, although an abrasive cut-off wheel may be used for the beryllium alloys. Final grinding and trimming should be performed after heat-treated castings have been shot-blasted to remove the surface oxide film produced in heat-treating.

HEAT TREATMENT

Heat treatment has little or no effect on the properties of cast copper, but the beryllium- and chromium-copper alloys can be heat-treated to develop optimum strength and electrical conductivity. As previously described, this consists of solution heat-treating at a relatively high temperature, quenching in water, and then aging (or precipitation hardening) at a lower temperature. Table 14-2 lists the approximate time and temperature cycles for each alloy.

Solution annealing may be performed in any suitable furnace where the temperature can be maintained within $\pm 15^{\circ}\text{F}$ ($\pm 9^{\circ}\text{C}$). All castings, except those of alloys C82000 and C81800, may be annealed in an air atmosphere, followed by a water quench immediately upon removal from the furnace. The C82000 and C81800 alloys must be bright annealed in a protective atmosphere such as cracked ammonia or city gas. However, beryllium copper alloys should not be solution heat-treated in salt baths.

Solution annealing time will vary, depending upon section size. Solution heat-treating times given in Table 14-2 are satisfactory for light castings. For heavy section castings, a general rule is to hold the part at the solution heat-treating temperature one hour per inch of section thickness.

Castings in the solution-heat-treated or as-quenched condition are soft and must be precipitation hardened if they are to develop optimum strength and electrical conductivity. Standard air-circulating furnaces are satisfactory for pre-

Table 14-1. Recommended Pouring Ranges

Material	Pouring Temperature Range	
	$^{\circ}\text{F}$	$^{\circ}\text{C}$
Copper C81100	2100-2350	1149-1288
Chromium Copper C81500	2200-2300	1204-1260
Beryllium Copper C82000 (10 C)	2050-2250	1121-1232
Beryllium Copper C82500 (20 C)	1850-2050	1010-1121
Beryllium Copper C81800 (50 C)	2050-2250	1121-1232
Beryllium Copper C81400 (70 C)	2150-2300	1177-1260
Beryllium Copper C82400 (165 C)	1900-2050	1038-1121
Beryllium Copper C82600 (245 C)	1895-2000	1035-1093
Beryllium Copper C82800 (275 C)	1850-1975	1010-1082

Table 14-2. Heat Treating Cycles for Beryllium Copper and Chromium Copper Alloys

Alloy	Solution Annealing		Precipitation Hardening	
	Time*	Temperature	Time*	Temperature
	hr	°F (°C)	Hr	°F (°C)
Beryllium Copper Alloys				
C82000 (10C)				
C81800 (50C)	1	1675-1700F (913-927C)	3	900F (482C)
C82400 (165C)				
C82500 (20C)				
C82600 (245C)				
C82800 (275C)	1	1475-1700F(802-816C)	3	650F (343C)
C81400 (70C)	1	1800-1850F(982-1010C)	2	900F (482C)
Chromium Copper				
C81500	1	1800-1850F(982-1010C)	2	900F (482C)

**All times shown refer to time at temperature and may vary depending on section thickness and casting configuration.*

Table 14-3. Typical Properties of Several Beryllium Copper Alloys in the Cast-and-Aged Condition

precipitation hardening or aging. Time and temperature are important, since over-aging results in higher electrical conductivity and some loss in strength and hardness. Therefore, a trial run should precede any deviation from the standard time-temperature cycle in order to determine its effect on the properties of the material. Castings may be air-cooled to room temperature after precipitation hardening.

In some applications where high strength is not an important criterion, the cast-and-aged condition may be satisfactory. This condition is achieved by bypassing the solution heat-treatment and aging the castings in the cast condition. Typical properties of several alloys in the cast-and-aged condition are shown in Table 14-3.

Oxide films formed during heat treatment may be removed by blasting, tumbling, or by chemical pickling.

Chromium copper, when cast and cooled in sand molds, has rather poor mechanical strength and low conductivity. Optimum strength and conductivity are obtained only through the use of the standard solution treatment and aging process.

Very high conductivities (over 90%) and moderate strength can be achieved by solution treating in a protective atmosphere and then slow cooling in the furnace.

It should also be noted that heat treating chromium copper alloys without the use of a protective atmosphere would

Table 14-4. Composition and Typical Properties of Heat-Treated Copper Casting Alloys of High Strength and Conductivity

UNS Number	Nominal Composition	Tensile Strength		Yield Strength		Elongation, %	Hardness	Electrical conductivity, %IACS
		Mpa	Ksi	Mpa	Ksi			
C81400	99Cu-0.8Cr-0.06Be	365	53	250	36	11	69 HRB	70
C81500	99Cu-1Cr	350	51	275	40	17	105 HB	85
C81800	97Cu-1.5Co-1Ag-0.4Be	705	102	515	75	8	96 HRB	48
C82000	97Cu-2.5Co-0.5Be	660	96	515	75	6	96 HRB	48
C82200	98Cu-1.5Ni-0.5Be	655	95	515	75	7	96 HRB	48
C82500	97Cu-2Be-0.5Co-0.3Si	1105	160	1035	150	1	43 HRC	20
C82800	96.6Cu-2.6Be-0.5Co-0.3Si	1140	165	1070	155	1	46 HRC	18

promote the formation of a soft skin on the surface of the castings. The thickness of this oxidized zone on the casting surface is approximately twelve mils (0.012 in.). Thus, castings which are heat treated in air furnaces must be machined after the treatment to remove this soft layer, in order to obtain accurate conductivity and hardness measurements so that maximum properties are present on load-bearing and other important surfaces.

DEFECTS

Defects in high-copper alloys follow the same general patterns and have the same causes as the defects noted in the chapter on *Defects* for other copper-base alloys.

The most common defects found in high-copper alloys are as follows:

- Gas porosity in cast copper due to lack of proper deoxidation.
- Low electrical conductivity and loss of mechanical properties due to excessive impurities. Impurities may result from the use of contaminated scrap or from the use of a crucible in which other alloys were previously melted. Impurities may also result from excessive use of de-oxidants.
- Excessive drossing due to turbulence caused by improper gating or excessive agitation during melting.
- Shrinkage cracks and cavities due to lack of proper filtering and feeding.
- Low physical and mechanical properties resulting from improper alloying and/or heat treatment.

EFFECTS OF IMPURITIES

Beryllium Copper Alloy—excessive quantities of aluminum, iron, tin, zinc, and chromium may cause loss of hardness or

electrical conductivity following heat treatment. Excess lead results in hot shortness and discoloration during pickling.

Chromium Copper—excess phosphorus, aluminum, iron, tin, lead, zinc, and silica may result in loss of mechanical properties or electrical conductivity following heat treatment.

Cast Copper—very small quantities of impurities, particularly phosphorus, silicon, iron, arsenic, aluminum, and beryllium, have a serious effect on the electrical conductivity of cast copper. Impurities also contribute to the hot tearing and hot cracking problems mentioned in the discussion of cores.

PROPERTIES

Typical properties of sand-cast and aged, and fully heat-treated alloys are listed in Tables 14-3 and 14-4. Nominal compositions are also given in Table 14-4. More detailed information on properties, heat treatment, and chemical composition can be found in the *ASM Metals Handbook* and the Beryllium Corporation's *Bulletin* (see Bibliography). Rigid control of the principal alloy constituents as well the impurity limits must be maintained in order to obtain the highest possible electrical conductivity and the required physical and mechanical properties.

APPLICATIONS

Cast copper is used mainly in terminals and in other components that require high electrical conductivity; however, it is also widely used for heat transfer purposes. Its use is limited to applications that do not require high strength or hardness.

One of the advantages of the chromium copper alloy is that it possesses moderate strength and hardness as well as good electrical conductivity. These properties permit the use

Table 14-5 Typical Properties of Sand and Permanent Mold Cast High Conductivity Copper

Casting process	Nominal Composition	Tensile Strength		Yield Strength		Elongation, %	Hardness	Electrical conductivity, % IACS
		Mpa	Ksi	Mpa	Ksi			
Sand Cast	99.96 Cu	172		62		40		
Permanent Mold	99.96 Cu	187		48		52	56 HRF	

of this alloy in contacts, clamps, and similar current-carrying components, such as welding electrodes, where strength is an important consideration.

The beryllium copper alloys are widely used where maximum strength, resistance to wear and corrosion, and good thermal and electrical conductivity are required. Specific applications of the several alloys are listed below.

C82000 (10C) Alloy

This alloy meets the requirements of Resistance Welders Manufacturers Association Class 3 and is used extensively in cast parts for resistance welders such as electrode holders, tips, seam wheels, jaws, and dies because of its good conductivity, strength, and resistance to mushrooming and sticking.

C82500 (20C) Alloy

This alloy possesses high strength, wear, and corrosion resistance, and it is suitable for use in critical mechanical parts including cams, bushings, bearings, gears, sleeves, and pump and valve parts.

C82800 (275C) Alloy

This material is a special-purpose alloy and is designed for use in plastic molds and in other applications that require maximum strength and wear resistance.

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COMMON DEFECTS IN SAND-CAST COPPER-BASE ALLOYS

INTRODUCTION

Defect analysis and control should have the following goals:

- identify defects which result in rejection of castings or unnecessary rework,
- eliminate the causes of the defects, and
- continually improve quality and reduce production costs.

The term “defect” describes not only a nonconformity in a casting that results in its rejection, either by the metalcasting facility’s quality inspector or the customer, but any nonconformity that increases the processing cost of the casting, such as surface roughness, hardness or additional padding. Identifying defects is more important and more difficult than it might initially appear.

Defective castings occur in the normal day-to-day operation of any sand foundry. These defects result in scrap or extensive rework, which unless steps are made to reduce their frequency, will seriously impact the metalcaster’s bottom line and competitive position. To reduce defects, the foundry must correctly identify the defect and the conditions that cause the defect. A detailed, precise statement of the problem is needed, identifying the specific casting, the defect, the pattern (i.e., the position on the pattern and whether present in more than one location), the alloy and typical pouring conditions, and the sand and mold conditions that produced the defect. Ideally, the statistical probability of this and other defects should be included. When foundries try to determine the source of casting defects they need to compile all of the necessary background information; data on metallurgy, pouring, molding and sand conditions, etc.

Normally, when foundries seek solutions to casting defects the failed casting or part of the casting containing the defect is sent to the lab with little or no information on the pouring, molding or sand conditions. Metal data is often the only information that is supplied. One industry study noted that sand and molding contribute to 80% of casting defects. This data was found as a result of a mobile foundry lab gathering data on metal analysis, temperature and sand practices at 76 Canadian foundries. (“Mobile Lab Measures Canadian Foundry Technology,” *Modern Casting*, Vol. 78 (12) pp. 22-23 (Dec 1988)). This study was done to investigate typical

problems encountered during metalcasting focusing on defects and their causes. The areas found to affect casting quality were: sand control, metal composition, temperature control and gating design.

Statistical methods are important in the identification of conditions that lead to casting defects. It has been often shown that foundries comply with the appropriate average sand properties or metal conditions, but frequently the range does not fall within acceptable limits. For example, a metalcaster’s green sand has a moisture content of 3.5% plus or minus 1%, see Fig. 15-1, this implies that the moisture level is between 2.5 and 4.5%, 95% of the time. As the compactibility of a specific sand changes by 3-4 points for every 0.1% change in moisture, one could expect the compactibility to vary by plus or minus 25-30 points, and green strengths to vary from 10-30 psi.

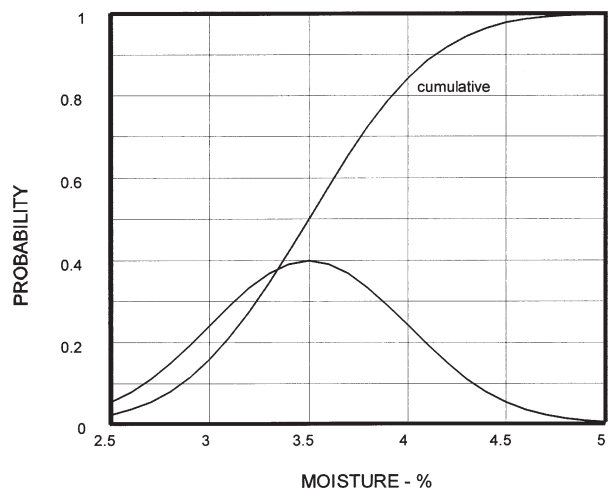


Fig. 15-1. Understanding the relationship of probability and moisture content can help reduce casting defects.

Suppose a defect, such as blowholes, can occur at moisture contents above 4%. This doesn’t mean that blowholes occur with 100% probability above 4% moisture and 0% probability at moisture levels below 4%, but the probability rises quickly as the moisture levels approach and exceed 4%. In this example, the moisture exceeds 4%, 16% of the time. If the compactibility were reduced by 6-8 points and

the moisture by 0.2% without changing the range, then this is equivalent to shifting the distribution centered at 3.5 to one centered around 3.3 % moisture. Moisture levels would still exceed 4%, 10% of the time. If testing was conducted by making molds from only a few batches of sand, the defect might still occur and one could infer that decreasing the moisture is not the solution to the problem. Elimination of causes requires that during normal production both defects and processing variables have been measured correctly and defined statistically. When both the defects and the causes are determined, then cause and effect relationships can be established and critical causes eliminated.

Figure 15-2 shows the effect that compactibility can have on many castings prone to certain defects. Defects induced by high compactibility and high moisture are mold wall movement, shrinkage, blows, pinholing, surface roughness, gas tracks, scabbing, rattails and shakeout problems. Defects caused by sand with low compactibility and low moisture are cuts and washes, broken edges, dropped copes, crushes, penetration, burn-on and difficult draws. Hot sand further complicates the issue. Thus, changing the average sand moisture will move the range of compactibilities and change the frequency of the various defects and their relative costs. The solution should not be to change the average compactibility, but to tighten the process and thus the range, hopefully reducing the occurrence of all defects. Management must

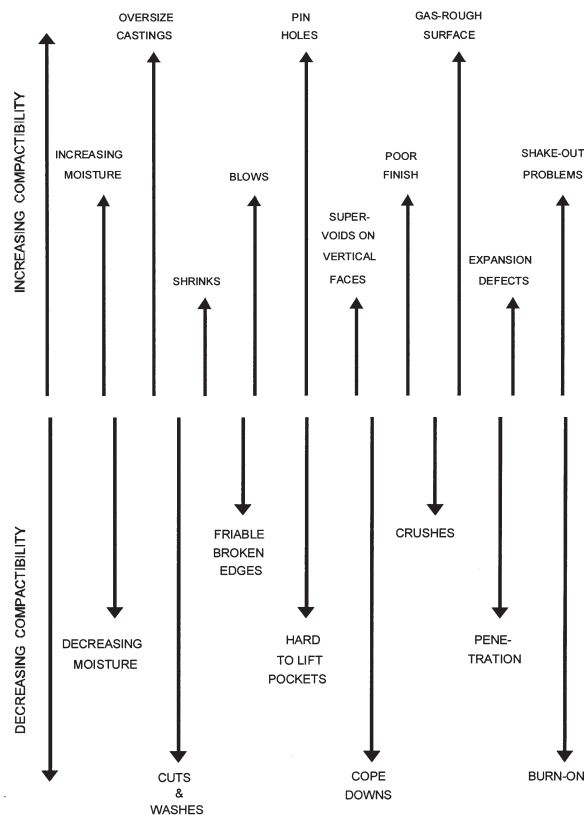


Fig. 15-2. The effect of moisture content on compactibility and the type of defects is shown.

know the control limits on various properties of the system sand, and have some idea of the process specification limits. The range is as important as the average.

Tools such as Pareto analysis help deal with defects that occur concurrently and help select the most common or most costly defect. Figure 15-2 shows how compactibility and moisture can alter the frequency of many defects in castings that are prone, but perhaps not all of the defects shown here. In the past, foundries assumed that working on one defect at a time would solve the problem. They should work towards minimizing all of the major defects and not just blindly exchange one defect for another. Pareto analysis ensures that focus is 80% on the important issues and not on the trivial issues. Figure 15-3 shows a histogram of important defects identified by CANMET's (now CanmetMATERIALS) first Mobile Foundry Laboratory Project. In this case, only the most common defects are shown.

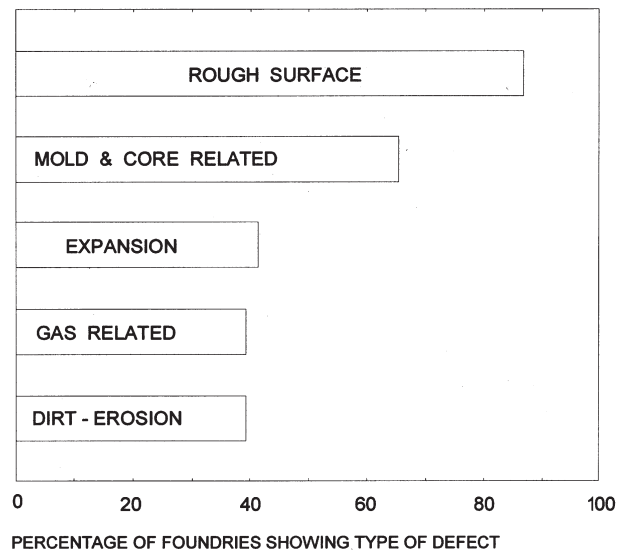


Fig. 15-3. This histogram depicts the more common casting defects.

The remainder of this chapter deals first with defect identification, and then cause and effect. While it is important that defects be identified correctly, it is critical when dealing with cause and effect diagrams.

DEFECT IDENTIFICATION

The American Foundry Society (AFS) has adopted an 'International System' that classifies defects by their visual appearance, nature, size and location on or within the casting. This system recognizes seven categories of defects:

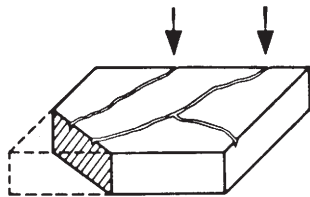
- A. Metallic projections
- B. Cavities
- C. Discontinuities
- D. Defective surfaces
- E. Incomplete casting

- F. Incorrect dimension or shape
- G. Inclusions or structural anomalies

Each category is further divided into subgroups that are designated by numerals. Any defect may thus be identified by a letter, followed by three digits. Detailed listings of defects according to this system are given in the *International Atlas of Casting Defects*. This defect listing system of designation will be used in this chapter for listing several of the more common defects encountered with copper-base alloy castings; possible causes and remedies will be noted. Reference should also be made to other publications dealing with causes and cures of defective castings. The chapters on *Casting Processes*, *Melt Control* and *Quality* within this book contain valuable, detailed information on quality and process control in the brass foundry.

Special attention has been given to the problems of structural unsoundness and leakage under pressure that occurs in several families of copper-base alloys having wide freezing ranges (Defect B 311). These problems may result from solidification shrinkage or, more commonly, from the interaction of such shrinkage and the release of dissolved gas during solidification. Such interaction is critical, as relatively small variations in production conditions can cause problems to appear and disappear quite suddenly without apparent reason. (This is discussed in detail in the *Melt Control* and the *Solidification, Feeding and Design* chapters.)

DEFECT A 112—VEINING OR FINNING



This defect occurs as projections in the form of veins that are generally perpendicular to the casting surface, occurring either singly or in networks, and not situated along parting lines (Fig. 15-4). In green sand molding, these projections often appear at fillets in conjunction with defects D 230 (scabs) or A 211 (swells).

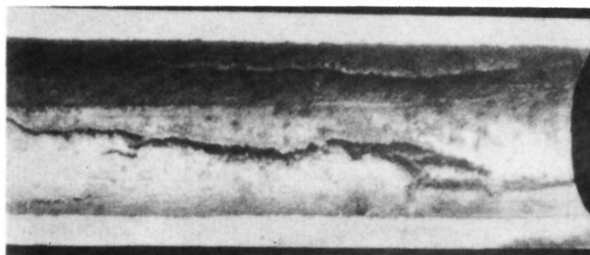


Fig. 15-4. A cross-section of a bronze bushing shows veins from core cracks, caused by improper curing of the cores. This defect was eliminated when the cores were properly cured.

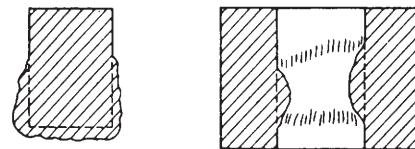
Possible Causes

Defect A 112 may be caused by mold surface cracks occurring during drying when the sand has a tendency towards excessive shrinkage, due to: a) too rapid heating, b) too high a baking temperature, or c) too much sand binder or moisture. This defect can also be caused by surface cracking occurring at the time of pouring in a sand which is too dense or too high in silica, initiation of the formation of scabs (see defect D 230), or by mold fissures accompanying swells (defect A 211).

Remedies

Although cures depend on the assumed cause, remedies may include: a) regulating sand composition and baking, and sealing mold cracks; b) taking measures for avoiding scabs (defect D 230); c) increasing mold rigidity and reducing metallostatic pressure.

DEFECT A 211—SWELLS



Swells occur as massive and irregular projections on the interior and exterior surfaces and corners of the casting (Fig. 15-5), generally rough and extended, and often in combination with defects D 121 (roughness), D 122 (penetration), and A 112 (veins and fins).

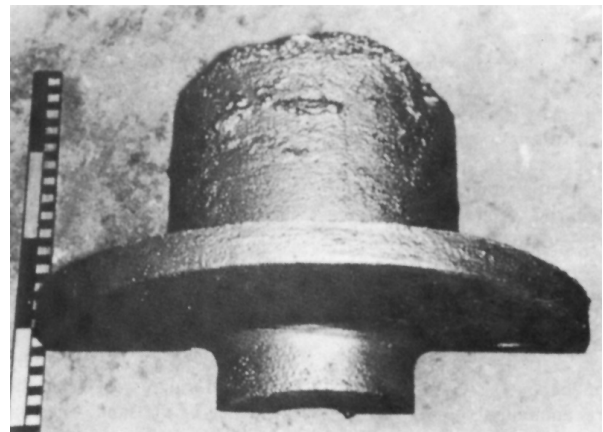


Fig. 15-5. This flanged bushing shows swells that resulted from a soft-rammed mold.

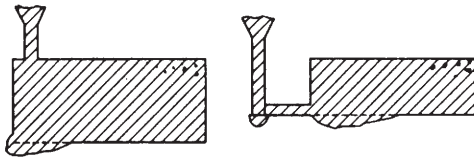
Possible Causes

Causes of defect A 211 may include: a) insufficient sand ramming; b) incomplete drying; and c) excessive or dynamic pressure of the liquid metal.

Remedies

Swells may be avoided by: a) increasing the ramming density in areas of the mold subject to the defect, or increasing the binder content of the sand; b) substituting dried or chemically bonded sand for the green sand; and c) modifying the location of the casting in the mold together with the gating and risering system in order to reduce the pressure of the liquid metal.

DEFECT A 212—EROSION, CUT, OR WASH



Defect A 212 occurs as irregular, generally rough projections on the surfaces of a casting, usually in the vicinity of gates or on the drag surface in line with a gate or extending along the course of metal flow into the mold cavity (Fig. 15-6). Sand inclusions are often found in other regions of the casting.

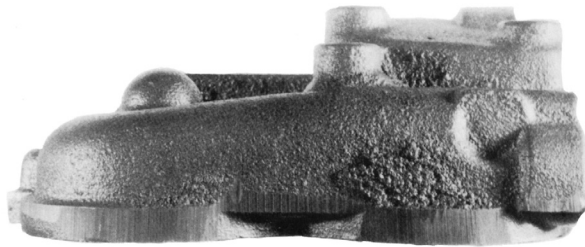


Fig. 15-6. A typical wash or cut that is located in the gate area.

Possible Causes

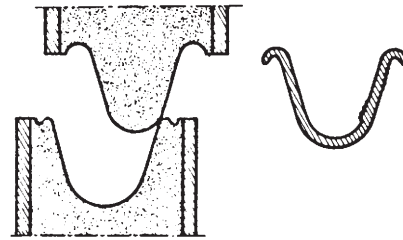
Causes of defect A 212 may include: a) sand of insufficient cohesion strength; b) defective drying of mold or cores; and c) poor gating system in which the metal enters the mold at too great a speed or impinges for too long a time on one portion of the mold or core.

Remedies

Defects may be avoided by: a) selecting a binder having higher hot strength; b) increasing dry compression strength of sand; c) harder, more uniform mold ramming; d) controlling the baking of the mold and cores; e) studying the gating system to avoid excessively rapid or localized entry of liquid metal into the cavity and extended impingement upon the same area of the mold or core, and preventing the stream of liquid metal from impinging directly upon corners of the sand

or on vertical walls in the mold cavity; f) using ceramic gates and/or strainer cores; g) reinforcing the affected zones of the mold cavity walls by making them of refractory material or by protecting them with resistant coating.

DEFECT A 213—CRUSH



This defect occurs as non-geometric projections on the vertical or oblique surfaces of the casting in the direction in which the mold is closed or in which a core is placed. Generally, the defect can be found in numerous areas of the same casting, often combined with sand inclusions.

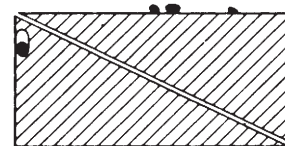
Possible Causes

Defect A 213 may be caused during mold closing, particularly when there are high mold projections when corners or surfaces of the mold rub against each other causing a tearing away of sand (see sketch). This defect can also occur upon closing the mold after the setting of the core.

Remedies

This defect may be prevented by: a) improving the design of the casting, if possible, in order to provide greater draft or increased wall thickness; b) using adequate alignment pins or positioning devices such as chaplets during the closing of the mold; and c) using caution in closing the mold to verify that rubbing has not occurred.

DEFECT A 311—TIN SWEAT AND LEAD SWEAT



With tin or lead sweat, the surface of the casting is more or less covered by a thin layer of white metal. In the case of lead, the sweat often occurs in localized areas, sometimes of considerable thickness, or in beads, some pea size (Fig. 15-7). This is usually encountered only with tin bronzes and high-lead tin bronzes.

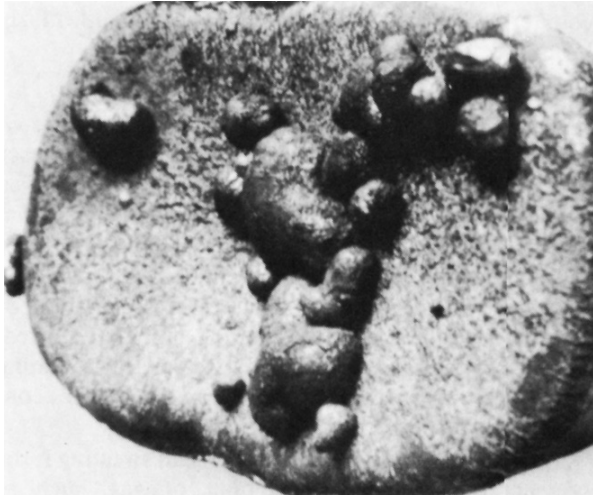


Fig. 15-7. This sprue shows defect A 311-Tin Sweat from a leaded tin bronze casting. A casting analysis showed: 85% Cu, 13.79% Sn, 0.17% Pb, 1.04% Zn. An exuded material analysis showed: 74.2% Cu, 22.85% Sn, 0.34% Pb, 1.2% Zn. During solidification, a part of the residual liquid of the alloy was exuded by the forces of contraction and the pressure of released gases. This defect is accompanied by microporosity.

Possible Causes

It is generally the pressure caused by the release of dissolved gasses which gives rise to this defect; hence, macroporosity may also exist. Contraction of solidified portions of the casting can also play a role in the formation of the defect.

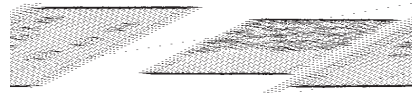
Remedies

Silicon and/or aluminum contamination of metal can also cause tin or lead sweat. Careful segregation of material being charged into melting units is required. Alloy composition should be adjusted, as lead sweating is likely to occur with those high-lead tin bronzes containing 10-25% lead, and tin below 5%.

The most probable cause of tin or lead sweating is the presence of an excessive amount of gas, such as hydrogen, dissolved in the molten metal. The dissolved gas forces the tin or lead to the surface during solidification. Castings showing tin or lead sweats usually have discolored or open fractures. To prevent this defect from occurring melting should be accomplished under an oxidizing atmosphere followed by appropriate deoxidation with P-Cu.

As well as gas dissolved in the metal, gas that is picked up by the molten metal in the mold may cause the tin and lead to sweat. Sand should be relatively dry and of high permeability and molds should be vented.

DEFECT B 111—BLOWHOLES AND PINHOLES



Defect B 111 consists of smooth-walled cavities, essentially spherical, often not contacting the external casting surface (blowholes). The largest cavities are most often isolated; the smallest (pinholes) appear in groups of varying dimensions. In specific cases, the casting section can be strewn with blowholes or pinholes. The interior walls of blowholes and pinholes can be shiny or more or less oxidized. These defects can appear in all regions of the casting (Figs. 15-8, 15-9 and 15-10).

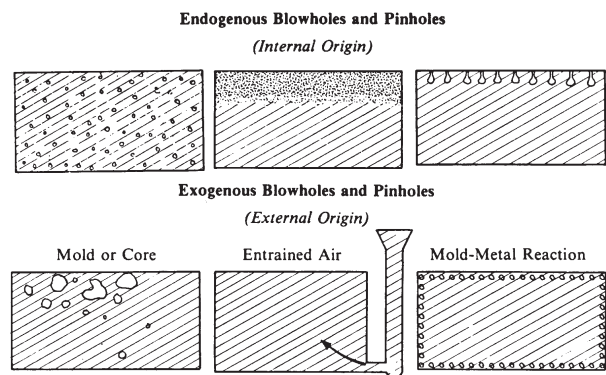


Fig. 15-8. Endogenous and exogenous blowholes and pinholes are shown.

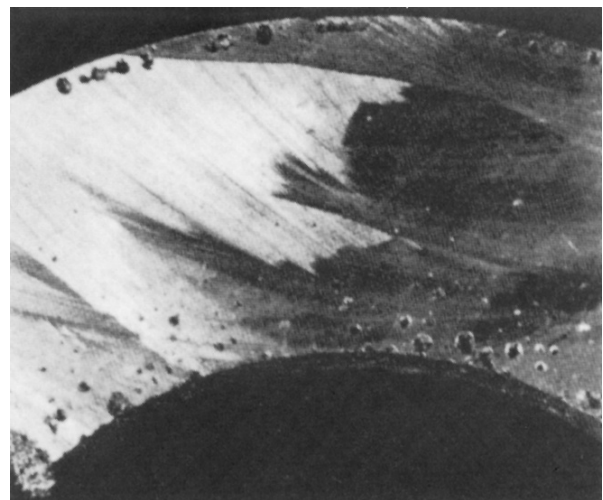


Fig. 15-9. Gas porosity is marked by small, spherical, bright-walled cavities usually segregated near the surface but underneath the skin of heavy sections of the casting.

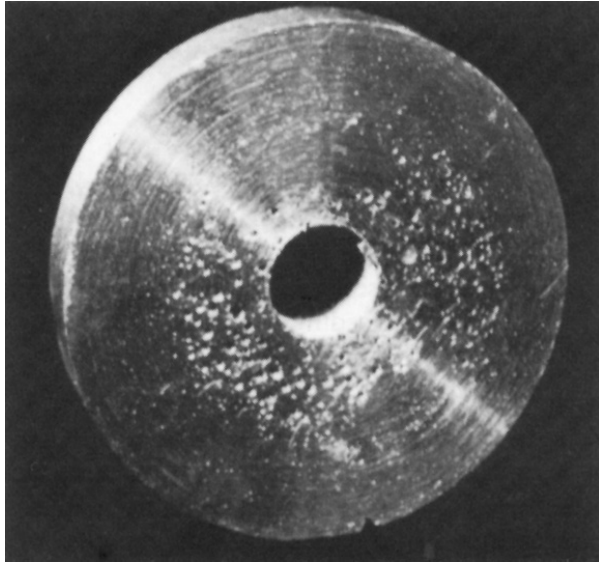


Fig. 15-10. A 180 mm (7.2 in.) diameter nozzle cast in a 10%-tin bronze. Blowholes are due to gas absorbed during melting.

Possible Causes

Blowholes and pinholes are produced because of gas entrapped in the metal during the course of solidification. Such gases, however, can also cause defects other than defect B 111.

Blowholes or pinholes may be of metallurgical origin (endogenous gas holes), caused by excessive gas content in the metal bath (due to such factors as charge materials, melting method, atmosphere, etc.). Dissolved gases are released during solidification.

Gas arising from mold or core materials (exogenous gas holes) may also cause these defects. This can be from: a) excessive moisture in molds or cores; b) large amounts of gas liberated by core binders; c) excessive amounts of additives containing hydrocarbons; or d) blacking and washes which tend to liberate too much gas.

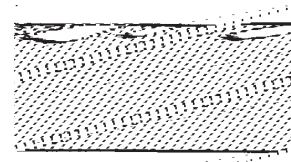
These defects may also be caused by mechanical entrapment of gas (exogenous gas holes) due to: a) insufficient evacuation of air and gas from the mold cavity; b) insufficient mold and core permeability; or c) entrainment of air due to turbulence in the sprue and runner system.

Remedies

The formation of blowholes and pinholes may be prevented by: a) making adequate provision for evacuation of air and gas from the mold cavity (whistlers, vents); b) improving either the uniformity and/or the permeability of mold and cores; c) avoiding improper gating systems; d) assuring adequate baking of dry sand molds; e) controlling moisture levels in green sand molding; f) reducing amounts of binders and additives used or change to other types; g) using

blackings and washes which provide a reducing atmosphere; h) keeping the sprue filled and reducing pouring height; i) increasing static pressure by enlarging runner and sprue height; and j) avoiding excessive melting temperatures and using care in proper melting, deoxidation, and degassing. (Defects due to dissolved gas are especially troublesome in copper-base alloys.)

DEFECT B 121—BLOW



The casting with a blow shows a smooth depression on outer or inner surfaces, or gas pockets just under the cast surface or in heavy sections above a cored cavity. The depressions or holes will be discolored, sometimes black, gold or reddish brown (Fig. 15-11).

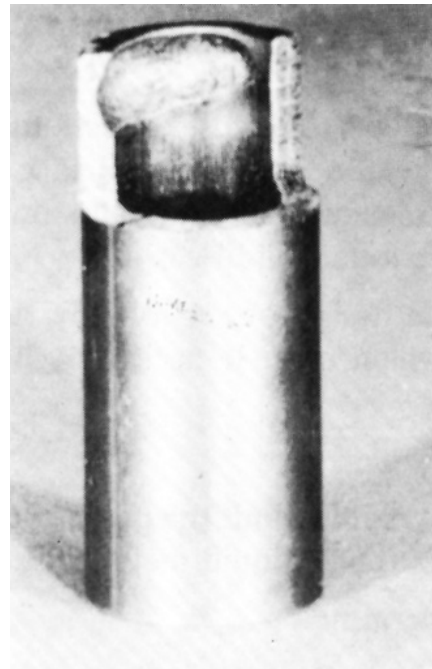


Fig. 15-11. A small bushing is sectioned in half to show a blow defect.

Possible Causes

Blows may be caused by: a) sand properties, b) core practice, e) molding techniques, or d) the use of chills.

Remedies

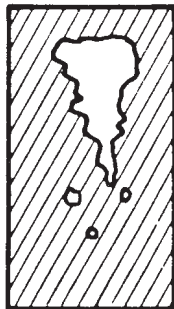
Wet sand in localized areas or sand with too low a permeability is likely to cause blows. To avoid this, the permeability of sand should be checked and maintained at the desired level. Sand should be mixed properly to ensure that all ingredients are uniformly distributed.

Insufficient baking and improper selection of core ingredients may cause blows. Cores with too low permeability and lack of adequate venting may also cause blows. Cores should be thoroughly dried after assembly and after applying core washes.

Hard and uneven ramming of sand adjacent to the pattern may also cause blows. Although sand has relatively high permeability, venting the mold at the parting line and above high portions of the casting in the cope will help to reduce the tendency to blow.

To avoid the formation of blows from chills, chills should be warm and dry. Alternatively, a dry wash coating may be applied.

DEFECT B 221—INTERNAL OR BLIND SHRINKAGE



Defect B 221 consists of internal cavities, generally with rough, often dendritic walls (but smooth for certain short-freezing-range alloys). These cavities are either isolated or dispersed, but localized in zones which are the last to solidify or are in contact with re-entrant angles of the casting, cores, gates or risers. This defect is most pronounced with alloys of narrow freezing range, such as yellow brasses, manganese bronzes, aluminum bronzes, and pure copper (Fig. 15-12).

Possible Causes

The principal cause of this shrinkage is the volume contraction of the metal in the liquid state as it cools in the mold to its solidification temperature, or as it changes from the liquid to the solid state. Solidification contraction and insufficient feeding in thick sections can also cause this defect.

Other auxiliary factors can also affect the size, appearance, and location of the defect. These are: a) gases evolved by the

mold; and b) mold wall movement or deformation caused by expansion due to elevated mold temperature, metal pressure (static pressure or solidification expansion), or poor compaction in areas difficult to compress.

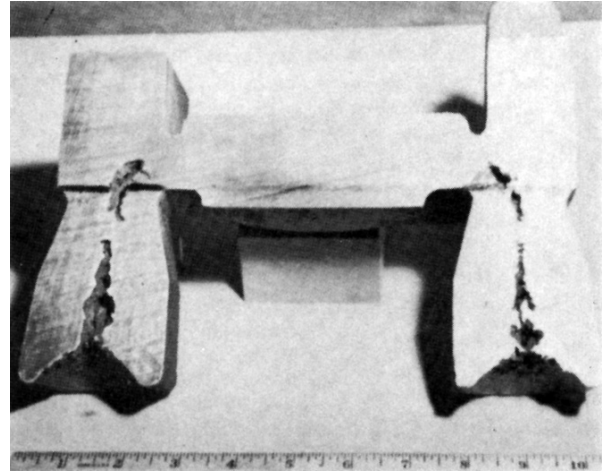


Fig. 15-12. Insufficient cope height prevented adequate riser height to feed the sections involved. Sectioning through both the risers and the casting demonstrates the need for additional feed metal height.

Remedies

Increased control in the following areas may help to prevent the occurrence of defect B 221.

Design Factors

Confine designs to the use of sections having essentially the same modulus (surface area/volume ratio) or which increase gradually toward riser locations (directional solidification).

Modify the design of sections by the addition of padding that may be removed by machining if necessary. Padding may be the only solution in heavy-sections cast in long-freezing range alloys.

Pouring

So far as possible, limit the pouring temperature in order to minimize liquid metal contraction.

Gating and Riser

Use risers having a sufficient reserve of liquid feed metal, located so as to feed sections which are slow to freeze and with due consideration of effective feeding distances.

Use exothermic or insulating riser sleeves and covers.

Use an adequate number of risers, taking into account the feeding characteristics of the metal poured and the degree of

soundness required. Consider the feeding distance between risers into thin plates as risers in close proximity may feed the other leaving the casting unfed.

Utilize internal or external chills to create end-feeding effects or to modify the effective section modulus. Employ cooling fins.

DEFECT B 222—CENTERLINE OR AXIAL SHRINKAGE



Defect B 222 consists of a cavity or porous region along the centerline of casting sections that are plate-like in shape (Fig. 15-13).

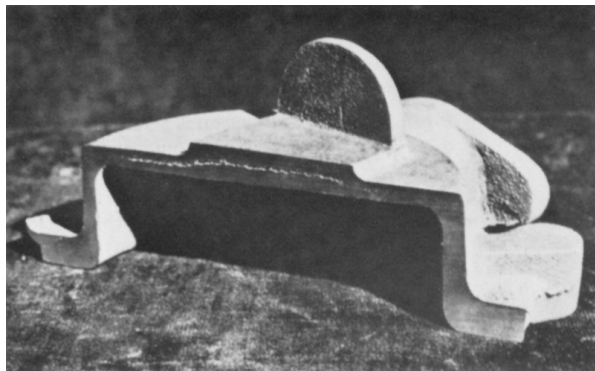


Fig. 15-13. A brass sand casting, 150 mm (6 in.) diameter is shown with a centerline shrinkage crack (B 222) that is located in a zone of porous metal. The defect disappears after lowering the iron and tin content, increasing riser size, and pouring at a lower temperature.

Possible Causes

Centerline or axial shrinkage may be caused by the layer of metal in contact with the mold rapidly solidifying, especially in the case of green sand or a metal mold, with the metal at the centerline of the casting taking somewhat longer to freeze. The metal at the centerline is subject to the effects of liquid contraction and solidification shrinkage.

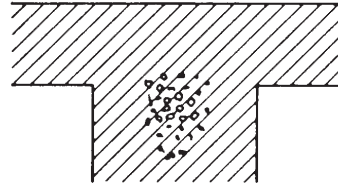
This effect is noticed especially where the alloy has been poured at a temperature too high for the section thickness in question.

Remedies

Defect B 222 may be avoided by: a) lowering the pouring temperature; b) not pouring into a permanent mold which is

insufficiently heated; c) tilting the mold and pouring slowly, or tilt-casting; d) observing rules governing location and size of risers, or e) using an alloy containing fewer impurities.

DEFECT B 311—MACROSHRINKAGE, MICROSHRINKAGE, SHRINKAGE POROSITY, AND LEAKERS



Defect B 311 can be revealed by a pressure-leakage test of the casting walls or by visual examination, with or without a magnifying glass, of fractured or machined casting sections. On fractured surfaces, the defect has a spongy appearance, either dendritic or in the form of small, superimposed cavities showing orange-brown discoloration. On machined surfaces, minute, closely spaced openings are apparent. This defect occurs typically with the wide-freezing-range alloys, and particularly with the red and semi-red brasses and tin bronzes (Figs. 15-14, 15-15) which have 1.5% porosity and only a few mm. of sound metal at the metal-mold interface.

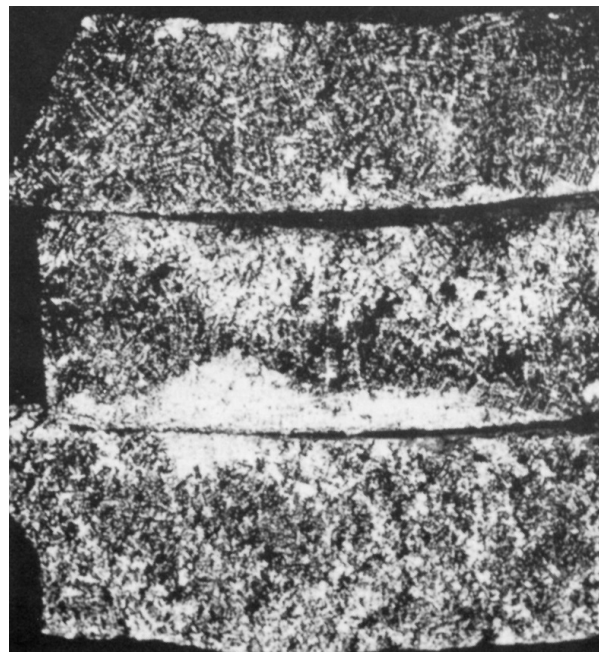


Fig. 15-14. Weak, discontinuous or open structures, as shown by these fractures, are caused by the presence of aluminum or silicon in the alloy, excessive pouring temperatures, or small amounts of gases such as hydrogen.

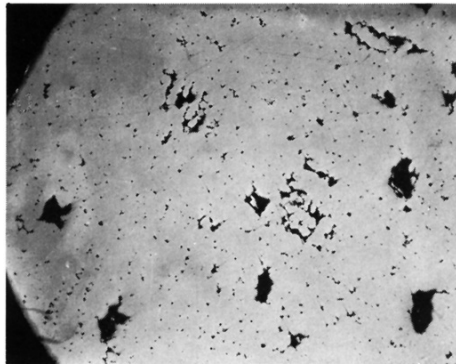
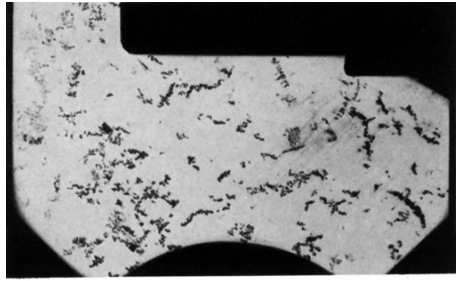


Fig. 15-15. Macroporosity is shown in an unetched bronze casting.

Possible Causes

Defect B 311 may be caused by a volume change during solidification, resulting from solidification shrinkage and lack of feeding in defective areas (microshrinkage).

Release of gas during solidification may also cause this defect, from gases dissolved in the metal or formed as internal reaction products. It should be noted that this gas has the effect of enlarging the size and/or extent of shrinkage porosity and does not have the characteristics of gas evolved without accompanying shrinkage (see B 111). In practice, most B 311-type porosity is a combination of gas and unfed solidification shrinkage.

Gases evolved from molding materials by the thermal or chemical effects of the liquid metal may also cause this defect.

Remedies

Since this porosity is usually caused by the interaction of both dissolved gas and solidification shrinkage, it is difficult to make specific recommendations for general cases. Among the variables which should be investigated in seeking a remedy are the following:

The presence of as little as 0.007% aluminum and/or silicon in the leaded bronzes causes a coarse, dendritic, discolored fracture often associated with leakers. Careful segregation of charge material is required. The presence of small amounts of deleterious gases in the melt, such as hydrogen alone or

hydrogen plus oxygen, is a major cause of weak, discontinuous or open structures.

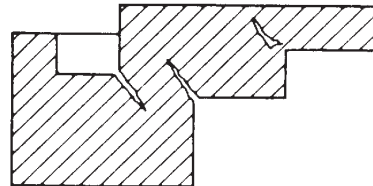
Melting should be accomplished under an oxidizing atmosphere (see the chapter on *Melt Quality*) and both the de-oxidation and degassing treatments should be controlled to achieve a known level of residual gas. In general, the heavier the casting section thickness to be produced, the lower the optimum residual gas content.

As a general rule, pouring temperatures for the wide-freezing-range alloys should be as low as possible without encountering serious problems of misruns and cold shut (E 121 and C 311). Excessive pouring temperatures not only delay casting solidification rate but may also result in gas pick-up from mold and core materials during pouring.

Gas-producing materials in ladle linings, fluxes and molding sands and binders (especially moisture) should be minimized to avoid gas contamination of the melt during pouring. Melting practice is important as gas pick-up increases with temperature. Returns should be free of wet sand and oily swarf.

When open, porous structures persist in cast sections known to be produced from metal of low gas content, the problem is more likely due to solidification shrinkage. Such defects can be minimized by the placement of heavy external chills against the casting wall in the affected sections in order to develop high thermal gradients during freezing (see the chapter on *Solidification*).

DEFECT C 221—HOT TEARING



Defect C 221 consists of more or less deep inter-crystalline fissures of irregular outline (Fig. 15-16) The cracks often show a fine dendritic structure with an oxidized surface. This defect most often appears in the last sections of the casting to solidify in which constraints are present (section changes and reentrant angles, for example).

Possible Causes

A solidifying alloy, upon reaching a temperature close to the solidus, is subjected to constraint or deformation. The resulting stresses, acting upon the semi-solid casting section, result in formation of a strain, or hot tear.

In general, contraction may be hindered due to faults in design such as: a) large differences in section thickness; b) abrupt transition from one thickness to another, or c) too

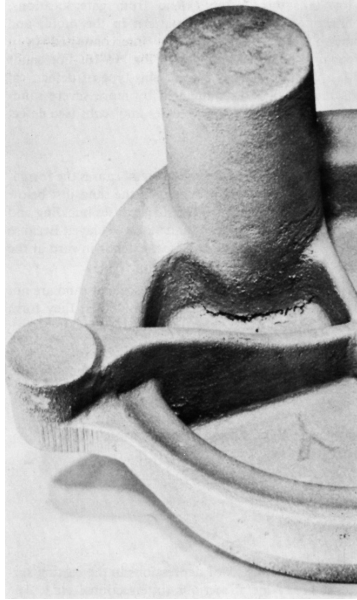


Fig. 15-16. A casting of 85-5-5 bronze is shown above. The 50 mm (2 in.) diameter boss results in delayed cooling, restraint and serious internal shrinkage which extends to the surface as a hot tear. The part was cast in dry sand in the reverse position from that shown in the photo.

many branching, connected sections in which contraction is constrained or hindered by excessively rigid mold and cores, or by rough mold surfaces (metal molds). Elongation or deformation of the mold from heated sand or metal mold components may result in hot tearing as well.

In permanent molding or die casting, this defect may be due to a) excessive cooling time prior to knockout; b) hindered contraction due to insufficient taper; c) mold being opened

too soon and the casting damaged by extraction; d) extraction of cores which are improperly aligned or guided; e) poor ejector locations, causing bending stresses; f) hot spots due to excessive pouring temperature or thin corners of sand (cores); g) insufficient flow of liquid metal.

Metallurgical causes of hot-tearing may include that: a) the alloy being poured has an excessively wide freezing range, which prevents the development of adequate strength in stressed areas; or b) the alloy contains lead or another low-melting phase which remains liquid at grain boundaries.

Remedies

Hot tearing may be prevented by correcting the various causes listed previously.

Cooling fins or external chills may be placed at locations subject to tensile stresses and where delayed freezing can be expected to occur (Fig. 15-17).

DEFECT C 311—COLD SHUT OR COLD LAP



Defect C 311 consists of a linear discontinuity with rounded edges (Fig. 15-18). This defect has a characteristic appearance and may vary in depth, extending either partially or entirely through the section of the casting. In the mildest case, the defect may consist merely of a shallow groove with rounded edges.

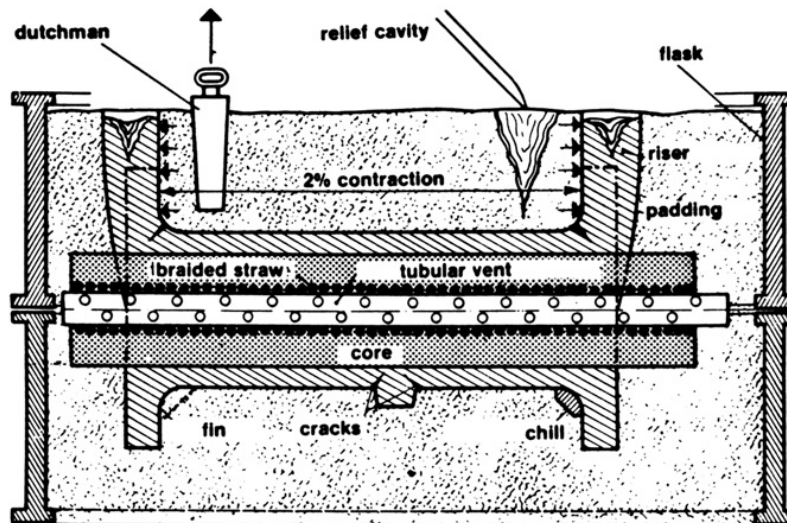


Fig 15-17. A schematic representation of the formation of hot tears and of various corrective measures possible in the case of a flanged, cast tube.

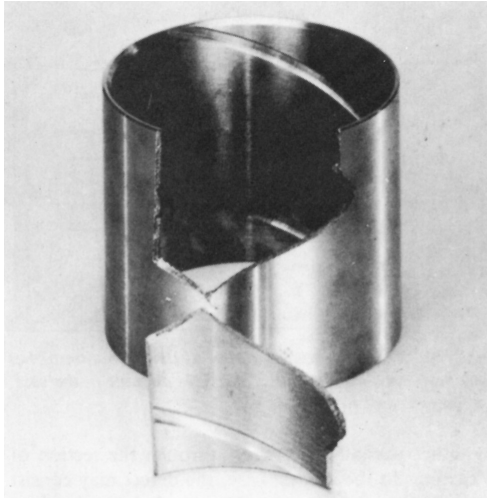


Fig. 15-18. A crack in a bushing from a cold shut is shown.

Cold shut often occurs on castings with wide or rangy surfaces with thin sections that are difficult to fill, or where two streams of metal converge in the mold because of the filling sequence.

Possible Causes

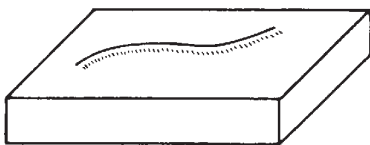
Cold shuts or laps may be caused by: a) insufficient fluidity and oxidized metal; b) slow or interrupted pouring; c) insufficient venting; or d) incomplete fusion of two streams of metal in die casting (the two often showing different structures due to differences in cooling rates).

Remedies

To avoid defect C 311 the following steps may be taken: a) pour at higher temperatures; b) increase the fluidity of the alloy, c) increase mold filling rate by changes in gating, or d) improve venting of the mold.

For metallic molds, the mold and metal temperatures may be adjusted (usually increased). Also, the mold wall may be heated selectively or temperature control of the mold may be improved at the defect location. Refining the gating system may also help to prevent these defects. The mold wash should be checked in terms of insulating qualities.

DEFECT D 132—RATTAIL



Defect D 132 consists of a shallow, groove-like defect that usually appears only on horizontal drag surfaces of the casting. Usually an irregular depression up to 5 mm (0.2 in.)

deep occurs, with a sharp-angled edge below which sand may be lodged.

Rattails most often extend from gate locations, delineating the metal flow pattern in the mold, and somewhat less frequently are interconnected in a branching pattern as shown in Fig. 15-19. For sands with a strong tendency toward this type of defect, rattails may also be accompanied by more severe sand-expansion defects such as buckles and scabs (see defect D 231).

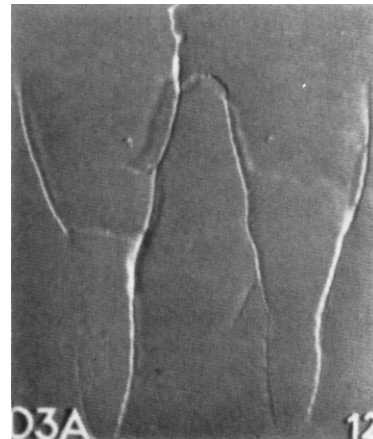


Fig. 15-19. These grooves, known as rattails, are formed from the edges of projecting sand scale that are not flattened by the metal after mold filling.

Possible Causes

Heat from the stream of molten metal causes the formation of a wet condensation zone in the sand just below the surface. The expansion of the silica causes buckling and detachment of the crust of sand at the wet layer. Because of its increased volume, the crust extends inward at the edges of the stream (1 and 2 of Fig. 15-20).

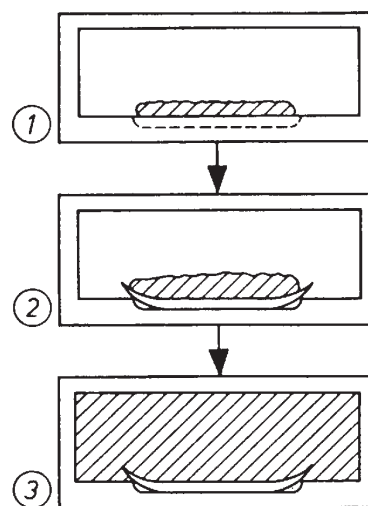


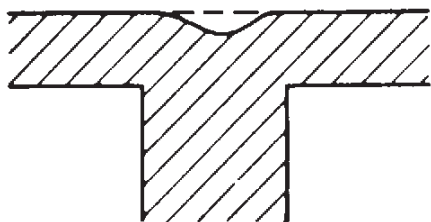
Fig. 15-20. The progressive formation of a rattail is shown.

Since the edges of the projecting scale of sand are not flattened by the metal after the mold fills, they form grooves known as rattails (Figs. 15-19, 15-20).

Remedies

To avoid the formation of rattails, the same remedies may be used as for avoiding scabs (defect D 231).

DEFECT D 141—SINK MARKS, DRAW, AND SUCK-IN



Defect D 141 consists of depressions in the casting surface at heavy metal sections (intersections, etc.). The surface of these depressions is generally not different from that of other areas (Fig. 15-21).

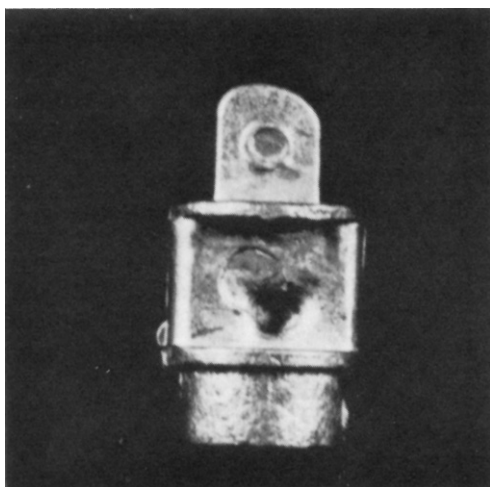


Fig. 15-21. Defect D 141C- sink marks are shown in this casting.

These depressions most often appear at thickened sections of the casting and sometimes at the bottom of an internal shrinkage cavity or porous area. In extreme cases, they appear as shrinkage defects.

Possible Causes

Solidification contraction (surface collapse) at locations such as heavy sections that are slow to freeze may be a cause of defect D 141.

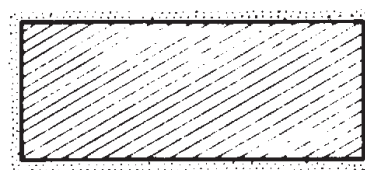
These defects occur most frequently with alloys of wide freezing range, where atmospheric pressure collapses the mushy surface prior to complete solidification.

In die casting, defect D 141 may occur as a result of low metal and/or mold temperature together with insufficient metal pressure.

Remedies

The formation of sink marks, draw, and suck-in may be prevented by: a) modifying the casting design and avoiding abrupt changes in sections; b) tapering adjacent sections to obtain directional solidification; c) adding risers, supplementary gates or chills to assure the proper sequence of freezing and feeding; d) lower pouring temperature; or e) in diecasting, checking metal and mold temperature as well as injection velocity and pressure.

DEFECT D 221—BURN-ON



Defect D 221 consists of a strongly adherent crust of sand on the casting which cannot be removed by a normal cycle of blast cleaning, but which requires grinding away. This defect is localized at the hottest locations of the casting. Parts, or the entire cast surface, of the casting will have an extremely rough surface as if the metal had penetrated freely between the sand grains, some of which are completely surrounded and enclosed in the wall of the casting (Fig. 15-22).

Possible Causes

Burn-on may be caused by: a) inadequate ramming, b) excessive metallostatic (head) pressure, c) excessive pouring temperature, d) coarseness of the sand (high gfn), or e) high metal fluidity (excessive residual phosphorus).

Remedies

The formation of burn-on may be prevented by: a) assuring adequate and uniform rammed density of sands; b) considering the use of mold and core washes when excessive head pressure or sand coarseness exists (high-lead alloys are most troublesome in this respect); c) adjusting pouring temperature to minimize superheat; d) maintaining residual phosphorus at the minimum level to avoid reaction unsoundness in the castings (0.03% for lighter castings and less for heavy castings). In some cases, the metallostatic head on fixed height molding machines can be decreased by increasing the size of the pouring cup and pouring short.

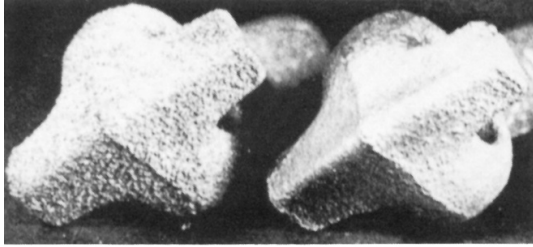
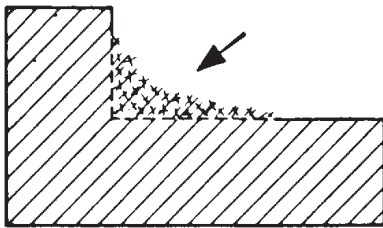


Fig 15-22. These castings are shown with burn-on.

DEFECT D 223—METAL PENETRATION



Defect D 223 consists of a projection of no particular geometric shape, comprised of an intimate mixture of sand and metal having a spongy appearance and strongly adhering to the casting (Fig 15-23). This generally occurs at locations where the sand is the hottest (cores, concave sections) and is of lowest density.

Possible Causes

In general, the factors causing metal penetration are the same as those causing burn-on (defect D221). Metal penetration represents extreme conditions and often results in parts that cannot be economically salvaged, if at all. Metal penetration is most prevalent with alloys high in lead and/or phosphorous, cast in heavier sections (Fig. 15-24).

Remedies

To prevent metal penetration from occurring, use the same remedies as those used for the prevention of defect D 221.

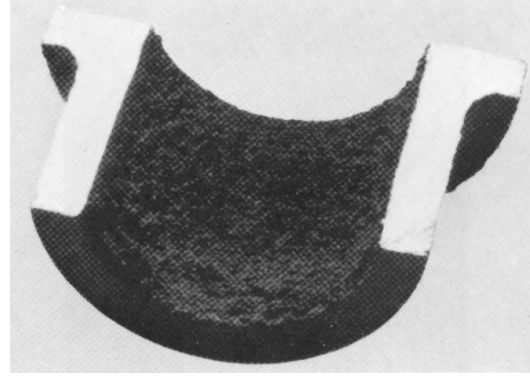


Fig. 15-23. A sand-cast bronze half-bearing shows defect D 223—Penetration. Low surface tension of the liquid metal was directly responsible for this defect. To avoid this defect a graphite wash should be used on the core. Normal precautions should be taken when casting phosphor bronze. A more dense sand having good thermal conductivity (iron oxide addition to the sand) should be used.

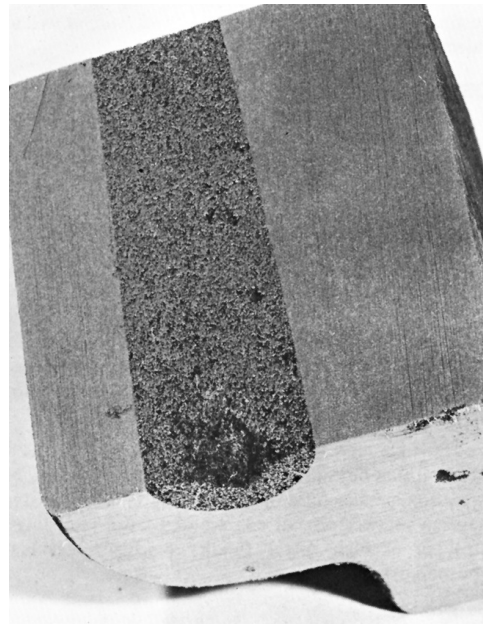
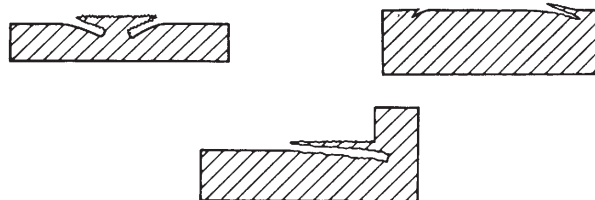


Fig. 15-24. A cross-section of a bronze pillow block with a 20 mm (0.8 in.) diameter cast hole formed by a silicate/ CO_2 core. Total penetration of the core by the liquid metal has occurred. The use of an alumina core wash reduced, but did not prevent penetration. Elimination of the core is a costly solution since it involves increased risering as well as extra machining. The corrective action taken here was to use a shell core. This not only eliminated penetration but also permitted reduction of finish stock to 0.5 mm.

DEFECT D 231—SCAB AND EXPANSION SCAB



Defect D 231 consists of irregular metallic projections of several mm thickness, generally with sharp edges, parallel to the surface of the casting, and having very rough surfaces. They are generally attached to the casting only at a few points. The surface of the casting beneath the defect shows a depression that is of the shape and thickness of the scab. True scabs can be detached by means of a chisel; however, the areas of attachment to the casting remain evident and the underlying depressions persist.

A true scab usually forms on the upper horizontal mold surface (cope scab), or on the lower horizontal mold surface (drag scab). Scabs occur less often on lateral walls.

Possible Causes

Cope Scab

The formation of a cope scab can involve the appearance of a low-strength wet condensation zone (Fig. 15-25 sketch 1), followed by formation of a crust of dry sand whose expansion

is restrained by compression stresses in the mold wall (Fig. 15-25 sketch 2). The pressure forcing this crust against the backup sand, caused by the arrival of the liquid metal, causes the crust to break (sketch 3). The liquid metal infiltrates the space behind the crust forming a thin layer of metal that comprises the scab (Fig. 15-26). If such infiltration does not occur, the defect will instead be a buckle.

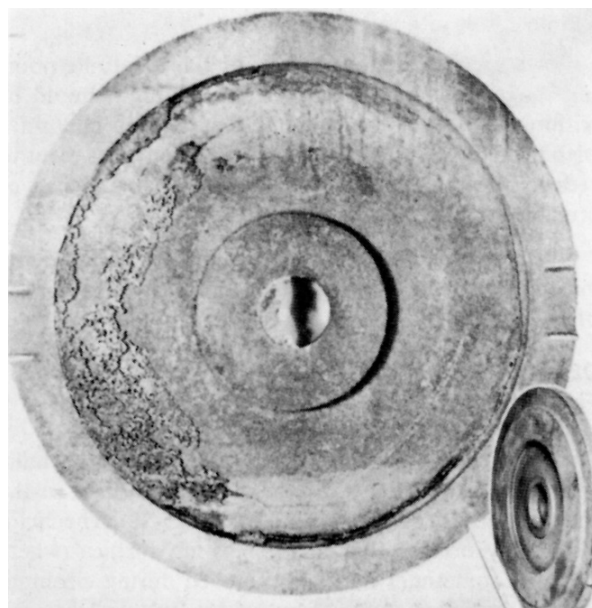
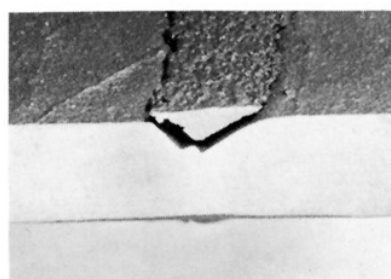
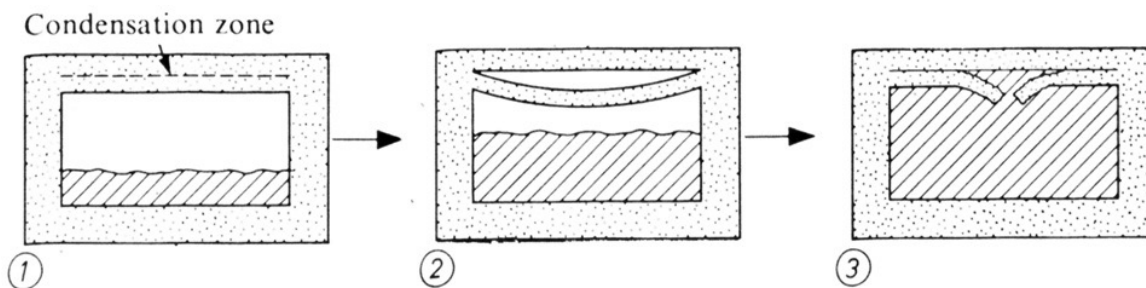
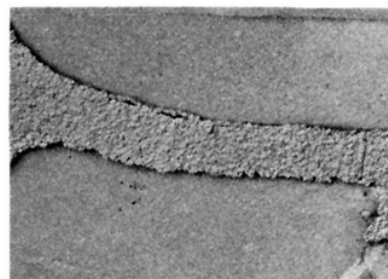


Fig 15-26. A typical expansion defect (scab) on a cope surface is shown.



Cross-section of a scab



Top view

Fig. 15-25. The formation of a scab is shown in the schematic diagram and photos.

A fillet scab may also form by the appearance of a low-strength condensation zone (Fig. 15-27 sketch 1), followed by the formation of a crust of dry sand whose expansion is unrestrained by compressive stress in the mold wall (sketch 2). The crust does not break, but separates as it expands and projects into the mold cavity at one edge. The metal infiltrates the cavity behind the crust (sketch 3) causing flat projections extending from the corner (fillet scab).

Drag Scab

A drag scab can be formed when a stream of metal entering the mold cavity causes the rapid formation of a low-strength wet condensation zone (Fig. 15-28 sketch 1). Then, with sufficiently high restraint in the mold wall due to compressive stresses, a crust of dry sand is produced whose formation is confined to the regions along the length of this zone.

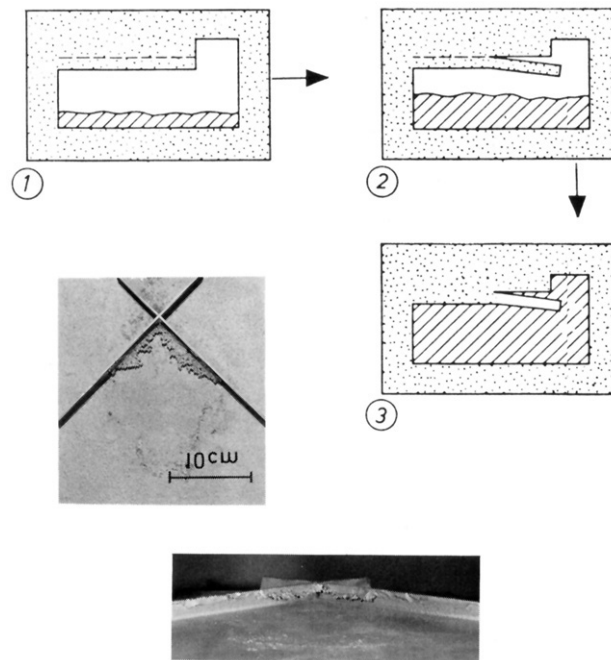


Fig. 15-27. The formation of a fillet scab is shown in the schematic diagram and photos.

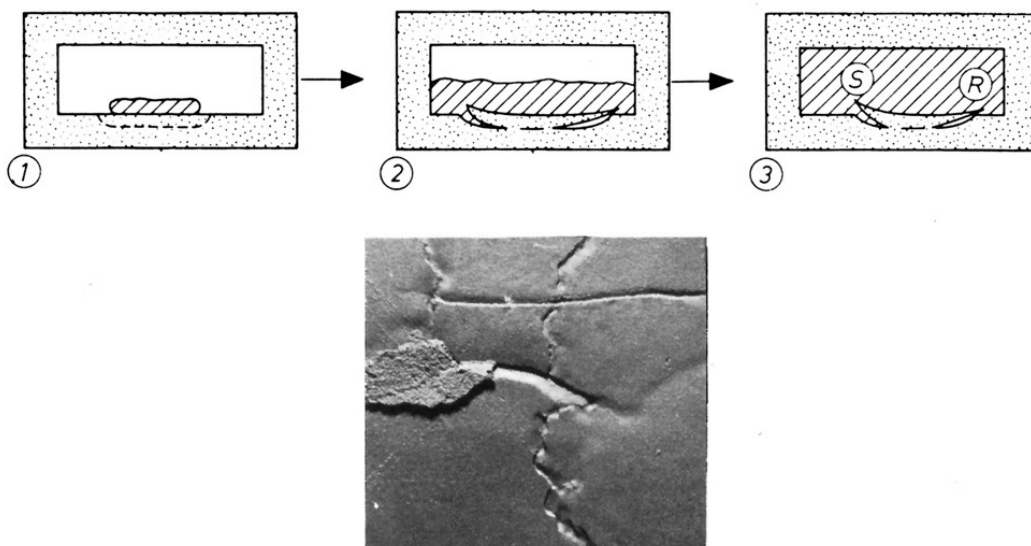


Fig. 15-28. One type of drag scab is shown in the schematic diagram and photo.

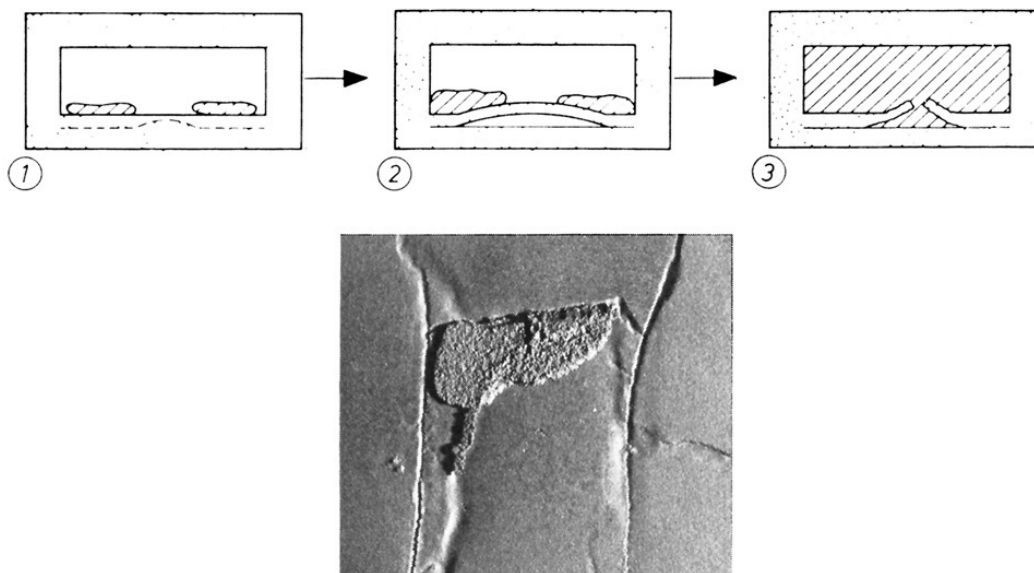


Fig. 15-29. Another form of drag scab is shown in the schematic diagram and photo.

One possibility is that the crust does not separate completely from the backing sand. Because of the expansion of the silica, the crust shears toward the region adjacent to the mold wall (Fig. 15-28 sketch 2). The edges of the crust are raised, causing the formation of rattails (R) or, if the edges are raised sufficiently to permit metal infiltration beneath the crust, the formation of scabs (S).

Another possibility is that the crust forms and raises between two parallel streams of liquid metal (Fig. 15-29 sketches 1 & 2), and then becomes compressed by the continued flow of metal into the mold. If the crust does not break, there will merely be a slight surface depression on the casting. If the crust breaks without metal penetration, the defect will be a buckle (D 131); if penetration does occur, a scab will form (sketch 3).

Remedies

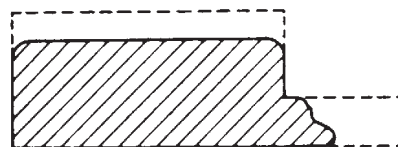
To inhibit the formation of scabs, the following procedures may be followed.

Minimize the formation of weak condensation zones by: a) increasing the binder (clay) level of green sand; b) replacing natural or southern (calcium) bentonite clays with a greater proportion of western (sodium) bentonite having better hot-strength; c) reducing the moisture level of the sand; d) reducing the temperature of the system sand; or e) improving the mulling of the sand.

Reduce the compression stresses at the mold surfaces by: a) gating to achieve more uniform, rapid filling of the mold; b) removing excessive fines from the sand, increasing permeability; c) using additives or cushioning agents in the sand to offset the effects of silica expansion; d) substituting sand minerals (olivine, zircon) having lower coefficients of expansion than does silica; and e) where possible, suggest-

ing design changes which minimize the presence of sharp fillets or wide, flat surfaces on the cope or drag.

DEFECT E 121—MISRUN



When a misrun occurs, a portion of the casting will be missing, usually on the cope surface or at a location remote from the gate area (Fig. 15-30). The edges surrounding the missing portion are rounded. Adjacent surfaces are generally shiny.

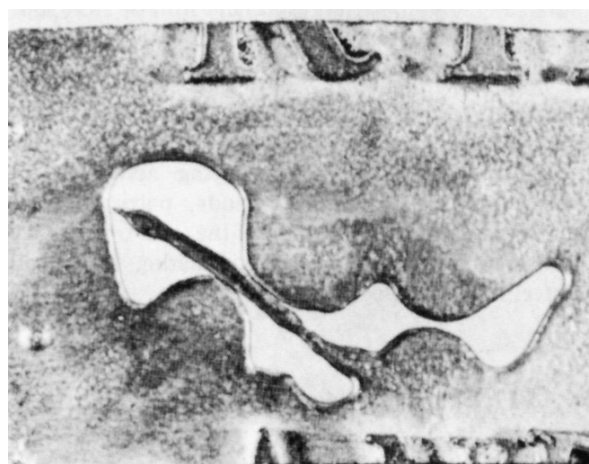


Fig. 15-30 An illustration of a misrun in a marker is shown.

Possible Causes

Misruns may be caused by: a) gating practice; b) sand properties (high moisture, low permeability); c) metal (oxidized, low fluidity); d) improper pouring temperature; e) bad pouring technique; and f) core practice (gas backpressure).

Remedies

To inhibit the occurrence of misruns, the height of cope should be increased so that the metal in the sprue will be substantially above the highest level of the castings in the mold. The gating system, sprue-runner-gates, should permit the free and smooth flow of metal into the mold cavities.

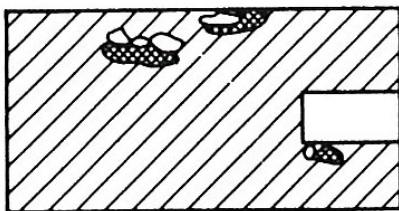
High moisture in molding sand has a tendency to chill the liquid metal preventing flow to the extremities of mold cavity. Low permeability sands and/or hard ramming will prevent the exit of the gases generated, thereby causing a back pressure which would prevent the metal from completely filling the mold.

Proper segregation of raw material will prevent the pick up of any harmful impurities that would cause sluggishness. Proper deoxidation and skimming practice should result in a more fluid metal.

For a specific casting, each alloy has a definite pouring range. The first and last molds poured should be within this temperature range. If the last molds poured contain a high percentage of misruns, it would be advantageous to reduce the number of molds poured per ladle or crucible.

The sprue should be kept full at all times during pouring to ensure that gating system is controlling the flow of metal. It is difficult to pour the first mold, if the ladle is too full.

DEFECT G 121—INCLUSIONS OF SLAG, DROSS, FLUX, OR OXIDE



Defect G 121 consists of irregularly shaped nonmetallic inclusions resembling the slag or dross formed in the melting furnace or pouring ladle (Fig. 15-28). The inclusions may occur either on the casting surface (where they are sometimes partially removed during cleaning, leaving irregular cavities), or within the walls of the casting (detectable only by fracture, radiography, or machining). In special cases (wormy surface, zinc worms) the surface of the casting, usually in the vicinity of the gate, shows irregular depressions, shallow but elongated, and similar in appearance to worm tracks in mud. Upon

shakeout, these depressions are often seem to be filled with a deposit of zinc oxide and are sometimes associated with a poor fracture structure. Such wormy surfaces are usually associated with red and semi-red brasses or yellow brasses.



Fig. 15-31. A brass disc, 200 mm (8 in.) in diameter, containing dross inclusions is shown.

Possible Causes

The origin of such nonmetallic inclusions may be the slag or dross formed in the melting furnace or crucible by metal oxidation, with or without reaction with siliceous material present in the charge or the furnace wall. Other sources may include fluxes or cover materials used in melting, or the products of deoxidation with phosphor-copper, etc.

Such materials, unless carefully removed before pouring, become entrained in the metal stream during pouring. If they are not trapped within the sprue or runner system they may enter the mold cavity, as a rule lodging at or below the cope surfaces, in re-entrant corners or against cores, where they become entrapped by the freezing metal.

Wormy surfaces (or zinc worms) may be caused by: a) gating systems causing metal turbulence; b) contaminated metal; or c) poor pouring practice.

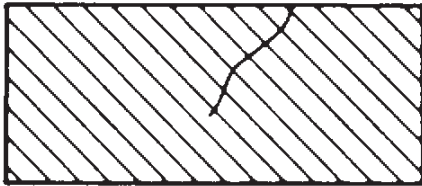
Remedies

The formation of defect G 121 may be inhibited by: a) avoiding entrainment of slag or dross from the furnace while filling the pouring ladle; b) keeping ladles clean, and thickening

the slag for ease in skimming by the addition of clean, dry silica sand or other coagulant; e) minimizing the use of fluxes wherever possible, and using dry graphite on the bath surface of induction furnaces to control excessive oxidation of melt; d) assuring that slag and dross are retained in the ladle or crucible during pouring, preferably by the use of “teapot” pouring spouts; e) keeping pouring basins and sprues filled during pouring; f) using nonpressurized gating systems with suitable chokes; and g) locating machined surfaces in the drag half of the mold.

Wormy surfaces (zinc worms) may be avoided by: a) adhering to gating and pouring practices listed above; b) avoiding interrupted or intermittent pouring (this is a major cause); c) avoiding high pouring temperatures which cause excessive flaring of zinc; d) preventing even trace contamination of leaded alloys by silicon and/or aluminum; and e) avoiding excessive residual phosphorus in red and semi-red brasses.

DEFECT G 142—OXIDE SEAMS OR SKINS



Oxide seams or skins are non-metallic inclusions in the form of skins which cause localized discontinuities in the casting. (Fig. 15-32).



Fig 15-32. This casting is shown exhibiting oxide film inclusions. The metal entered the mold with turbulence and aluminum oxide skins were trapped in the casting wall.

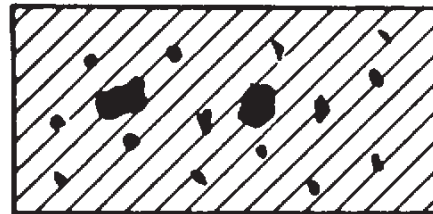
Possible Cause

Formation of oxide skins may occur during the filling of the ladle or pouring the mold. These skins remain trapped in the liquid metal because of the effects of metal turbulence. Alloys containing aluminum, silicon or chromium in substantial amounts are particularly prone to the formation of insoluble oxide films during melting and pouring, and hence are prone to this type of inclusion (see discussion of Group I alloys in the chapter on *Gating*).

Remedies

The formation of oxide seams or skins may be inhibited by: a) observing the gating and pouring practices recommended for avoiding defect G 121 (oxide, dross and slag inclusions); and b) absolutely minimizing turbulence in transfer and pouring.

DEFECT G 144—HARD SPOTS



Defect G 144 consists of hard inclusions, finely dispersed or sometimes rather large. The occurrence of hard spots is more common in the high tensile yellow brasses, but may also be encountered in red and semi-red brasses. Hard spots are usually detected during machining, finishing, or surface treatment.

Possible Causes

High-Strength Yellow Brasses

Hard spots in high-strength yellow brasses may be caused by improperly dissolved alloying or metal-treatment agents, particularly iron.

Intermetallic compounds rich in iron, also containing silicon, zinc, copper, boron and manganese formed by holding the molten metal for long periods at temperatures close to the melting point of the alloy may also cause the formation of hard spots. Formation is promoted by pickup of silicon from sand and refractories, particularly in the presence of active flux covers such as those containing boron.

In other copper-base alloys, iron arising from contaminated charge material, especially iron or steel shot from blast-cleaning operations or iron core wires, may cause hard spots to form.

Remedies

The formation of hard spots may be inhibited by: a) using greater care in making alloying additions; b) avoiding prolonged holding periods, particularly at lower temperatures; c) avoiding the use of reactive fluxes containing boron; and d) eliminating tramp iron and steel from furnace charges.

CASTING DEFECT ANALYSIS

Having identified a defect, the next step is to establish the cause or causes of the defect, and prove a cause and effect relationship exists so that the probability of the defect's occurrence can be reduced. There are a number of tools, such as Pareto Charts, Scatter Diagrams, Control Charts, Ishikawa Diagrams, Failure Mode Effects Analysis (FMEA) and Design of Experiment (DoE). Each has its place. It is important that management is sold on the process, employees are involved, and the cost of the defect and effort are known, so there will be a commitment to undertaking further steps in establishing a cause and effect and in implementing the solution.

Whatever the next step, it is assumed that as much data on the defect, its cost, frequency, and all process flow charts and variables documented are available for a brainstorming session to use the creative thinking of a team to critically examine the data and explore potential cause and effect relationships (which are not necessarily confined to the data collected). Agreement should then be sought on the next course of action, which might be:

- to collect more information on the defect,
- to measure other process variables,
- to recommend suitable actions to management, which might include changes or to conduct a designed experiment,
- to test potential solutions, and
- if successful, implement and communicate results to all involved.

The team uses a facilitator to brainstorm and insure that all team members understand each possible cause. It is important to stay on task and not to be delayed by specifics. At the conclusion, the facilitator reviews and records the causes. To assist the process, the remainder of this chapter will discuss the use of cause and effect diagrams and how they can be used to explore the causes of a specific defect, and prove a cause and effect relationship exists.

Ishikawa (Cause and Effect) Diagrams

The metalcasting process can be regarded as an organized series of causes that produce a desired defect-free casting. The prevention of defects involves several steps, identifying the defect, identifying the sources of variation that cause them, and eliminating the controllable cause of variation. One effective way of identifying potential causes of defects is the use of cause and effect diagrams. These are also known

by several names: Ishikawa Diagram, Fishbone Diagram, or Brainstorming Diagram. This diagnostic tool provides a geometric correlation between an effect and all possible causes. As such the diagram helps aid brainstorming sessions enumerate and consider most of the probable causes of a specific defect. While a Cause and Effect Diagram is effective in correlating effects with potential causes, it does not prove cause. Proof of cause, or multiple causes, requires further investigation of the process or even designed experiments conducted on- or off-line.

A Cause and Effect Diagram has the following structure:

- The name of the effect (defect) is put in a box on the right-hand side of a sheet of paper.
- A horizontal line is drawn across the paper with an arrow ending at the box.
- The names of the main family of causes: methods, equipment, materials, measurements, data and information systems, environment, money, management, and people, are placed in boxes and joined by slanting arrows to form a fishbone geometrical form.
- Branches and sub-branches are placed on each main branch to identify all possible causes and sub-causes that belong to each family.

Cause and effect diagrams for each defect follow at the end of this chapter in the Appendices. These diagrams are designed to assist participants in a brainstorming session to quickly identify many issues that need to be examined in the session. They are not exhaustive, but are provided to expedite the process and indicate the various statistical studies that might be done in advance of the brainstorming session and subsequent cause elimination session. The brainstorming session should encourage problem solving by pursuing the following rules:

- encourage free-thinking and discourage criticism of any suggestion,
- create a list of ideas first, discuss and organize them later,
- put ideas on the diagram, and
- use further brain-storming to revise the diagram until all causes and sub-causes have been identified,
- later, as more information is gathered, further refinements can be made to the cause and effect diagram.

Upon completion of the cause and effect diagram for the defect in question, statistical methods such as control charts on the various processes should be used to encourage open discussion on the various process parameters and access measurements of identified causes and show the statistical distribution of the cause. Process upper and lower control limits need to be determined from the statistical data. The customer might also specify an acceptable range. Process capabilities need to be determined. If the actual control limits are well within the process capabilities, then the variable

can be adequately controlled to avoid producing defects. While this might not be the actual cause of the defect, it might need to be further explored. If a cause and effect relationship is proven, the metalcaster might need to change processes or equipment if the existing process cannot meet the required limits.

At the end of the brainstorming sessions, a consensus must be reached on which process variables need to be investigated. Ideally, the number should be small, between 3 and 5. The least effective way to solve the problem is to change one variable at a time while holding the others fixed. While a full factorial investigation reveals all inter-relations. However, depending on the number, it might be cheaper to use design of experiments to investigate a partial factorial design. It is important that a budget be established before proceeding, as this may limit what can be accomplished. In any event, each suspect process needs to be related to a parameter that can be controlled. For example, suppose the group wants to investigate surface roughness, and they identify metallosstatic head, mold hardness, sand grain size, and metal fluidity (penetration) as likely to exacerbate the problem. Metallosstatic pressure can be varied by altering cope height, mold hardness by squeeze pressure and sand compactibility, grain size by using several different sized sands (one could be the existing system sand), and metal fluidity by varying the pouring temperature. As this translates into five process parameters, it would require 2^5 or 32 experiments to fully investigate the whole matrix using just a high and low value of each variable. Ideally, a quantitative measure of surface finish would improve the result. A statistical DOE package could be used to generate a random set of 8 experiments and later calculate the correlation and prove cause and effect. Provided no further experiments were required, the new process parameters should be tested, and process changes made.

Job shops present difficult options for balancing job planning and scheduling, multiple standards and specifications, short production runs of varying size often involving repeat and new tasks. Nevertheless, feedback and corrective actions must be swift and simple during short production runs. Action plans delayed are in danger of being distorted or lost by the time the order is repeated. However, a repeat order should trigger the former corrective action. Special warning or caution slips should be attached to blueprints or job cards. Although history is useful, production runs of a few hours can generate sufficient statistical data to determine process capabilities, etc. Repeated small lots and historical records coupled with patience will furnish the data, analyses and solutions. Sometimes the data can be organized by machine center or part type, rather than the defect type to improve the analyses.

A full discussion of these and other techniques is beyond the space allocated for this chapter. The reader is referred to numerous texts on quality control and statistical techniques. No one procedure works, but sometimes the information has to be recast, i.e., rather than type of defect, perhaps

the cause of defect (material, machine, specification, all jobs, lines, etc.).

SUMMARY

The following procedures can be followed to help determine the cause of a casting defect. They can be stopped at any stage once the cause is found and corrective action successfully implemented. Document all information on each defect, as you will probably need it again.

- Identify the casting, the number of castings on the pattern and the time or times the casting was poured.
- Record the sand and metal parameters at the time the castings were poured, and if cores were used, their age, coating history, temperature and humidity conditions during their storage. It should be recalled that sand systems change rapidly, and changes can be dramatic depending on the foundry's product mix.
- Location on the pattern is important if there is more than one casting on a pattern, as the defect may be specific to one position. Check whether the defect occurs on the first two or last molds poured from each ladle. A time-indexed history of scrap and sand parameters is a rich database that can be used to analyze foundry processes.
- Classify the parameters of the defect, surface finish, color, appearance, and particularly the location, whether at the bottom of deep draws, near re-entrant angles, in-gates, chaplets, chills, risers, the cross-section of adjacent pieces, dimensions relative to the pattern, more importantly relative to the drawing, etc.
- Record the mold surface appearance, hardness, and permeability in the area of the defect and at the parting line, when the defect is specific to a given location, and is not near any of the problem areas in 4. Perimeters now come with an attachment to measure the permeability of a mold or core. The fitting needs a square inch of flat surface. If the values vary significantly, try to determine the reason for the difference.
- Identify the defect and any others that occur concurrently. Use an illustrated atlas of defects.
- Use the appropriate cause and effect diagram to determine which conditions and parameters could cause the defect. Be sure to include parameters that may occur with significant frequency (consult histograms of greensand properties). Make a list of all potentially relevant causes.
- Calculate the cost of the defect in addition to using Pareto analysis, correlation analysis, and regression analysis. Costs include all work up to the time it is detected (molding, metal processing costs, cleaning, and inspection) and an estimate of the cost if the customer finds any castings your inspection process misses. You will be surprised how often it pays to do designed experiments to reduce defects.

- Determine the size of the matrix to be used for designed experiments once you know the potential payoff of solving your defect problem.

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DEFECT CLASSIFICATION CHARTS

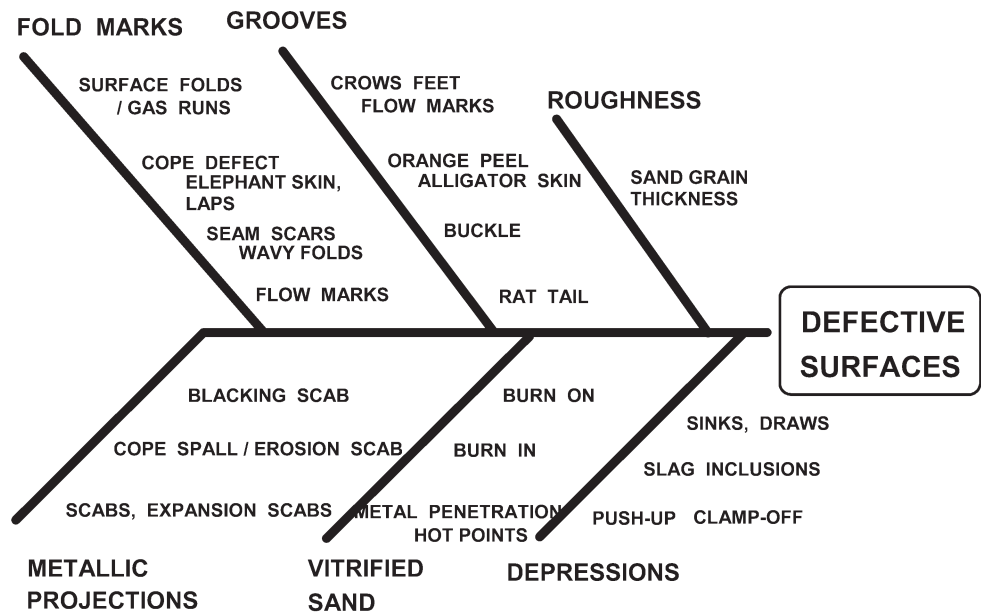


Fig. 15A-1. Defect classification chart for defective casting surfaces.

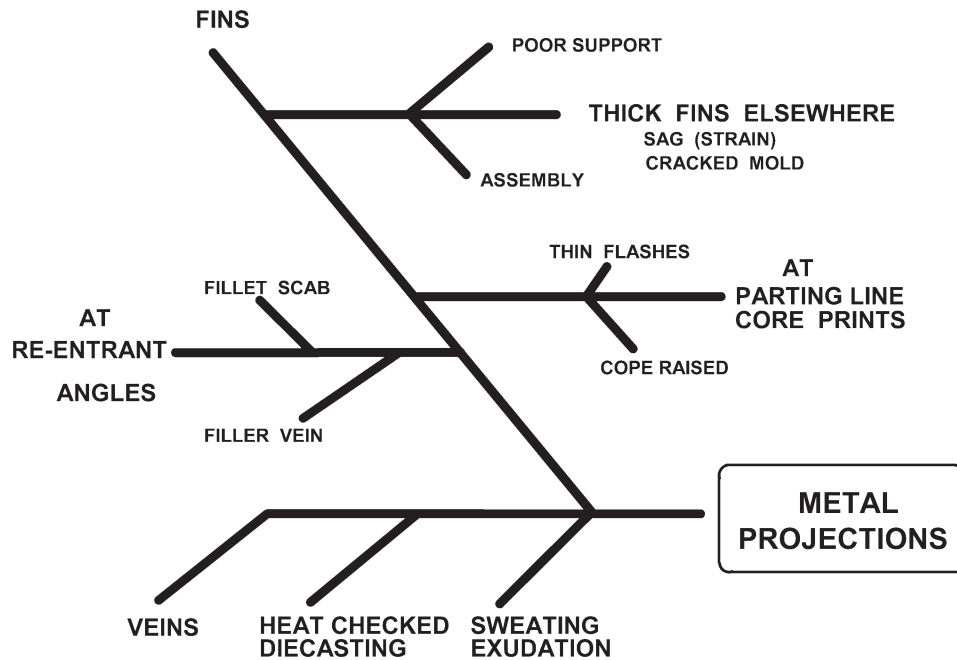


Fig. 15A-2. Defect classification chart for castings with fins, etc.

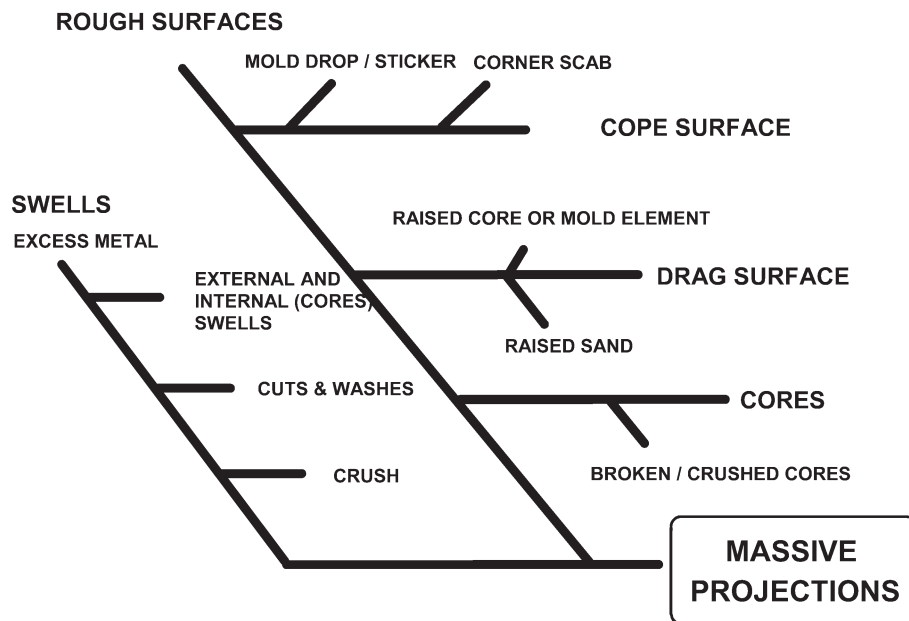


Fig. 15A-3. Defect Classification chart for castings with massive projections.

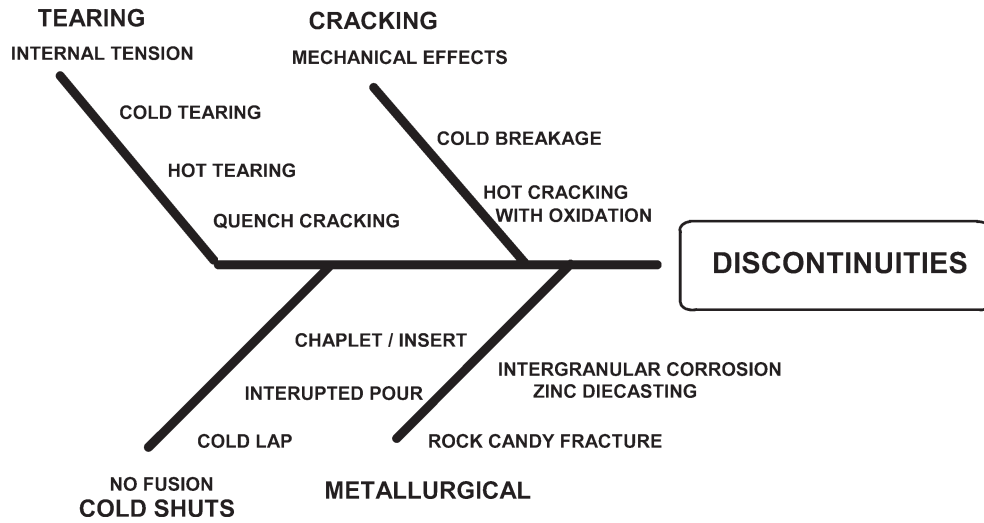


Fig. 15A-4. Defect classification chart for castings with discontinuities.

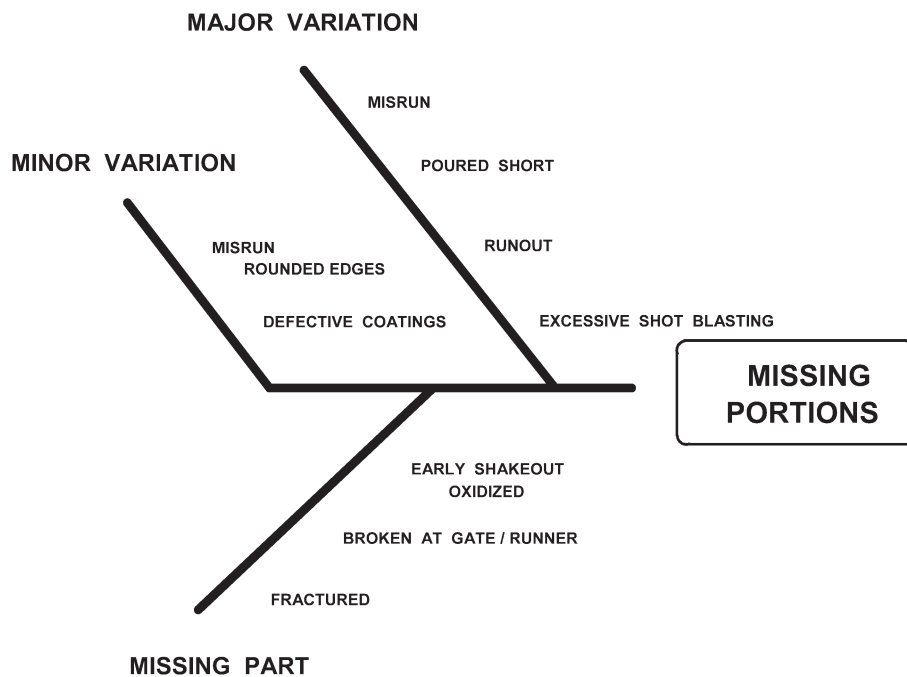


Fig. 15A-5. Defect classification chart for castings with parts missing.

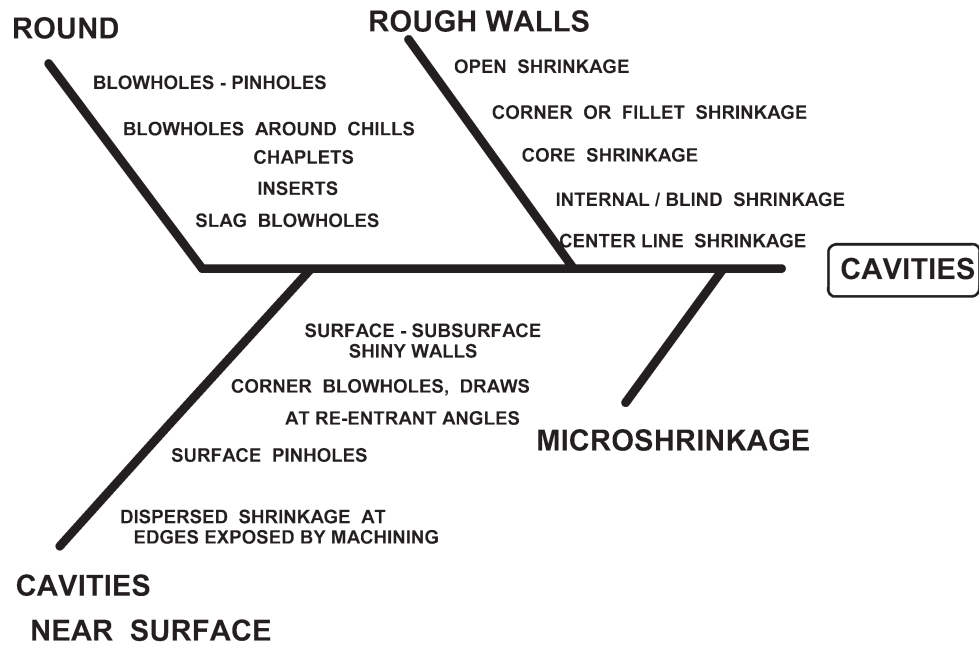


Fig. 15A-6. Defect classification chart for castings with cavities.

FISHBONE DIAGRAMS FOR
SAND RELATED DEFECTS

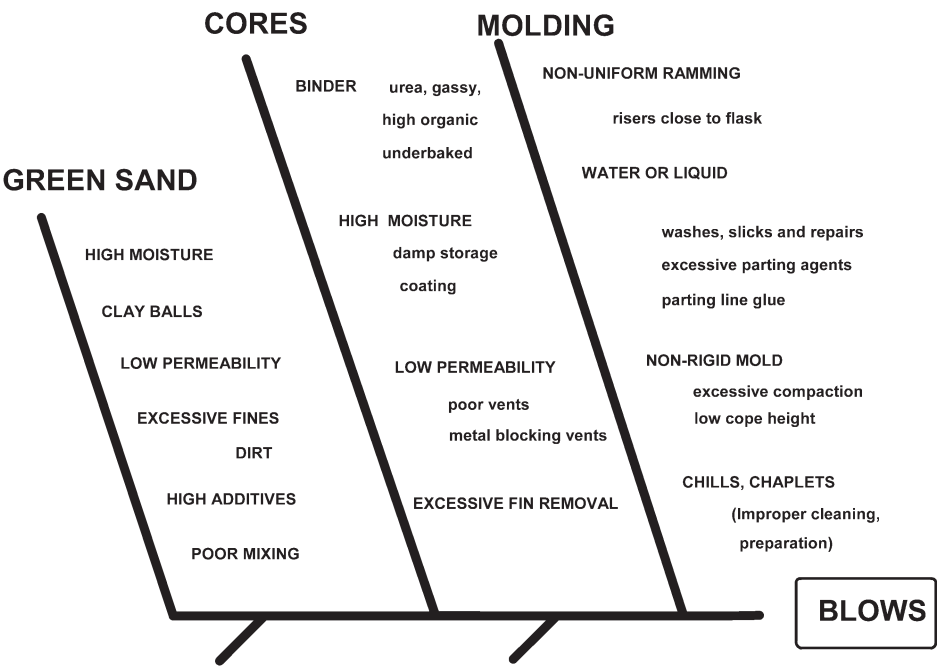


Fig. 15B-1a. Fish-bone diagram for castings with gas blows.

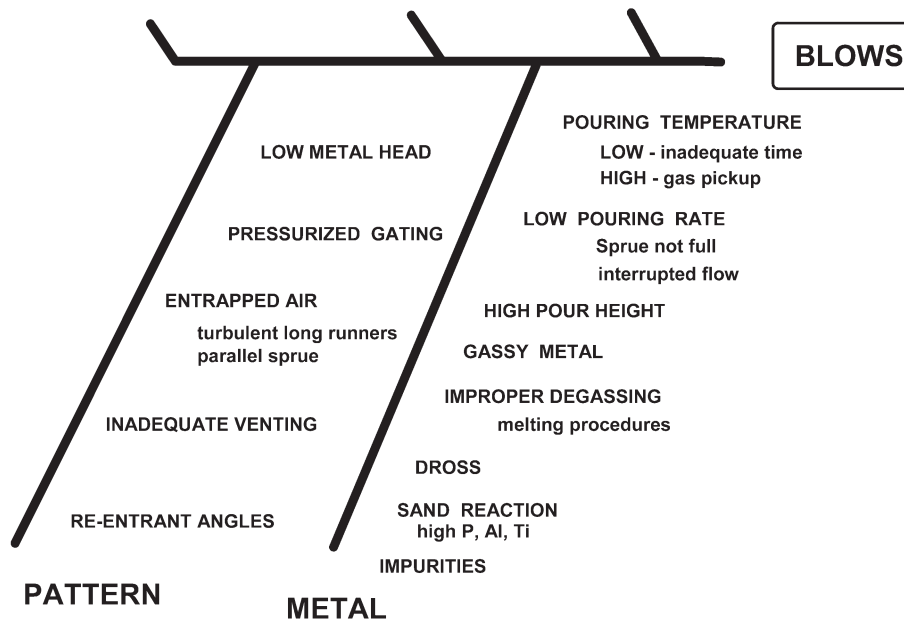


Fig. 15B-1b. Fish-bone diagram for castings with gas blows.

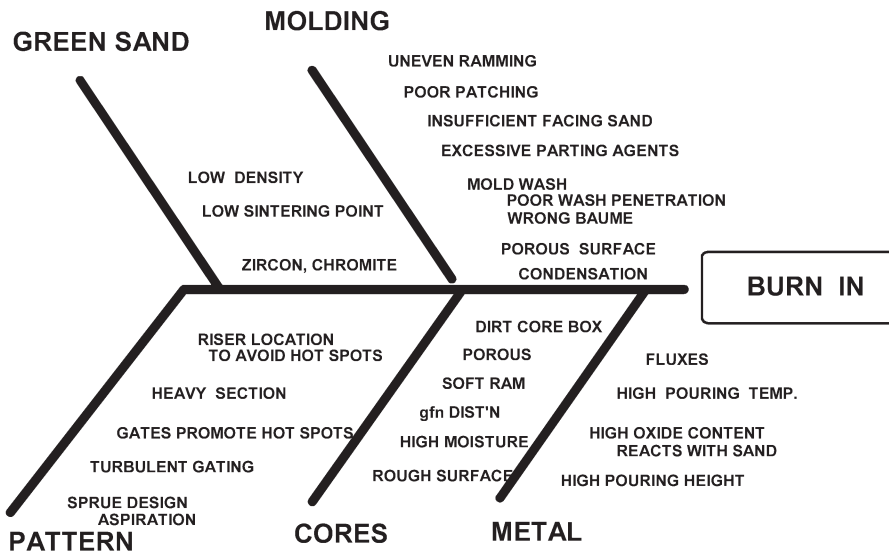


Fig. 15B-2. Fish-bone diagram for castings with sand burn in.

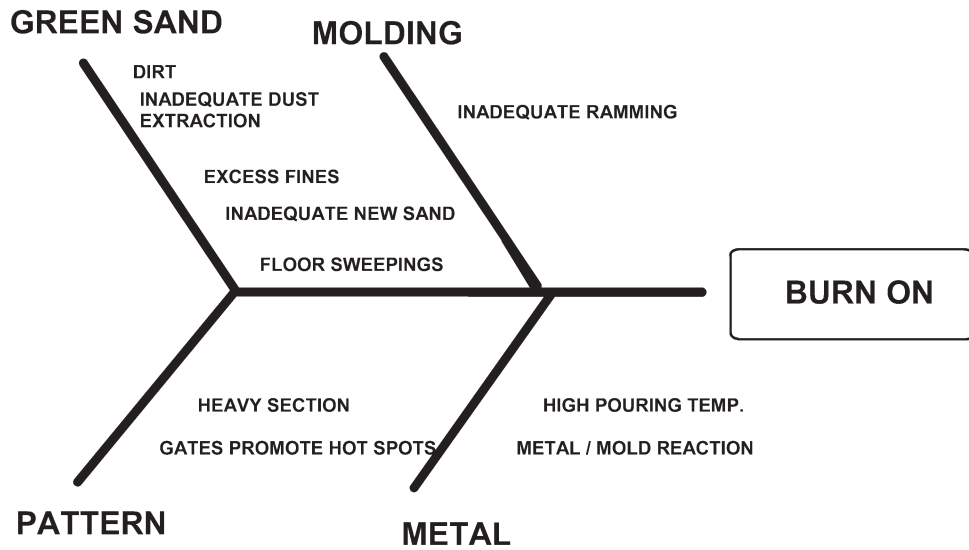


Fig. 15B-3. Fish-bone diagram for castings with sand burn on.

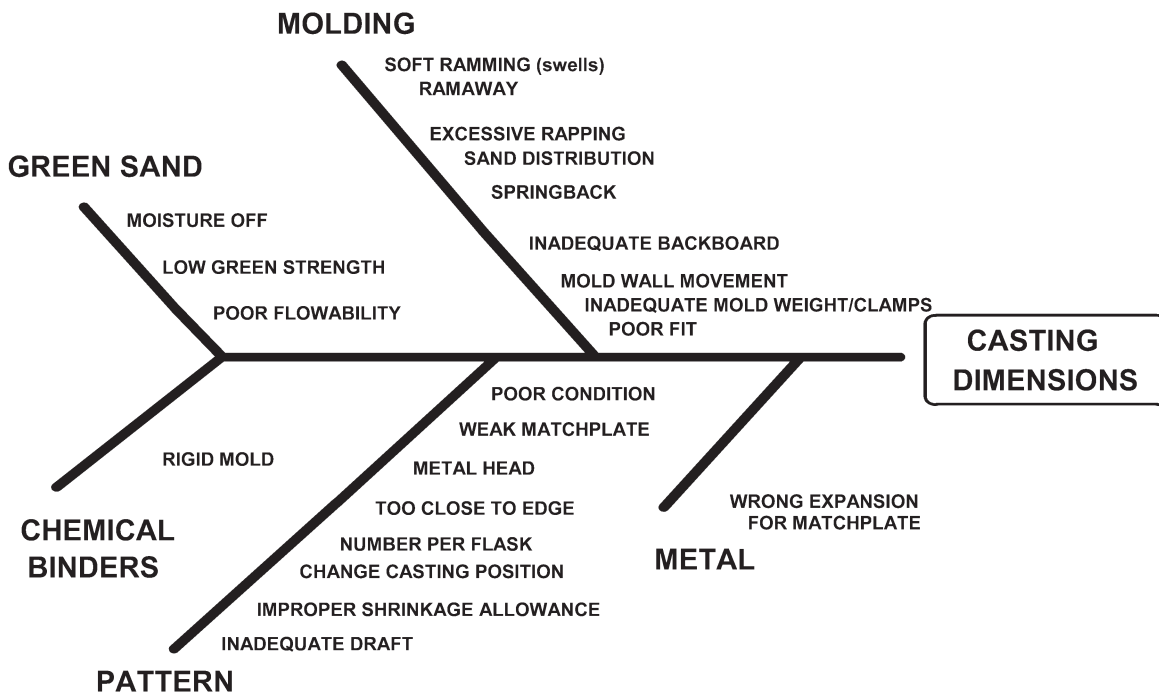


Fig. 15B-4. Fish-bone diagram for castings with wrong dimensions.

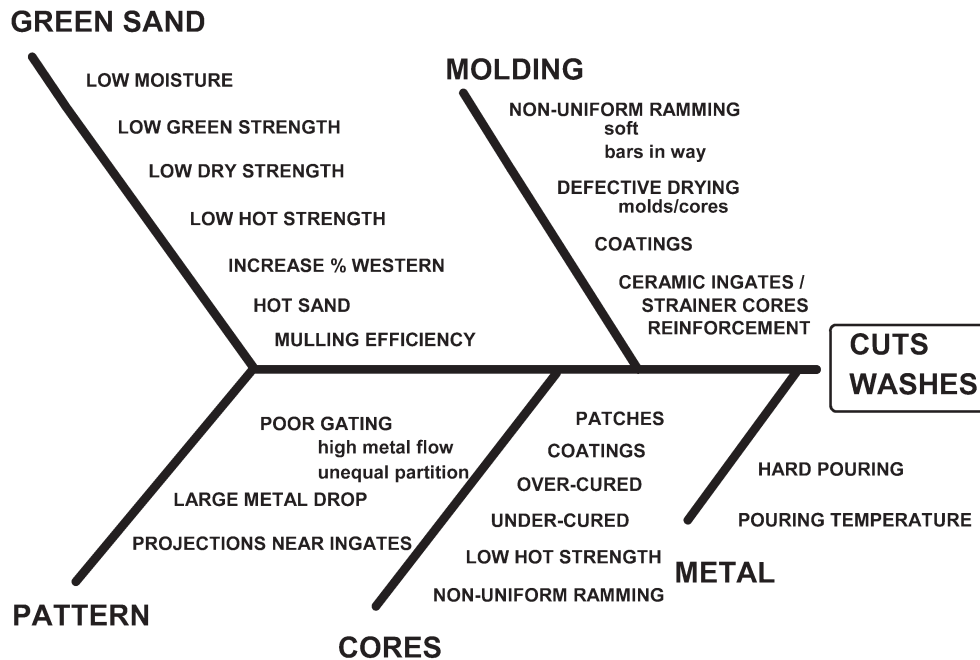


Fig. 15B-5. Fish-bone diagram for castings showing mold erosion.

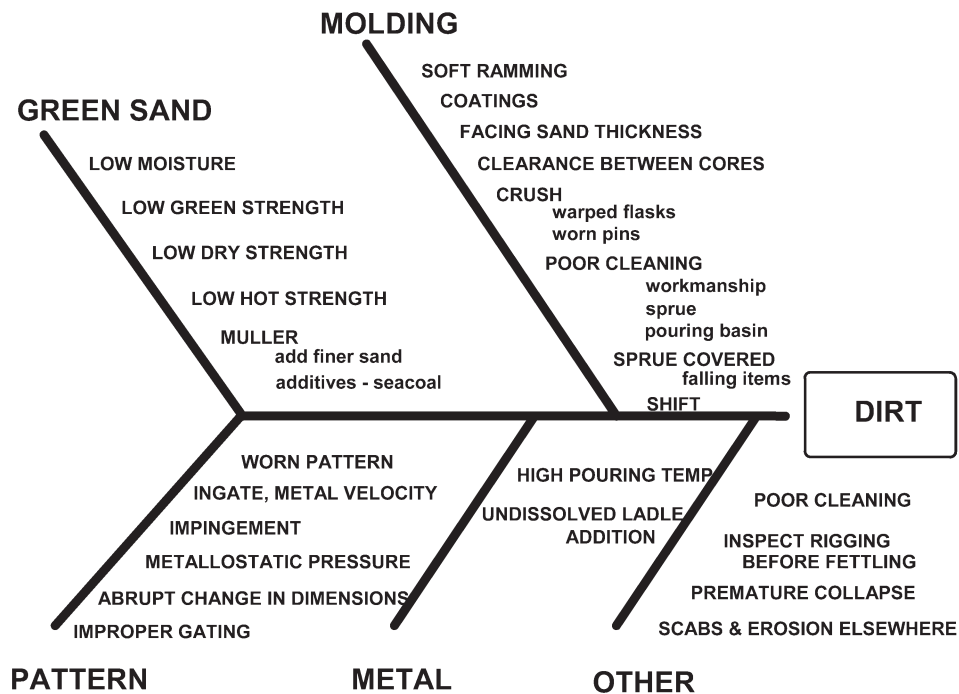


Fig. 15B-6. Fish-bone diagram for castings with dirt on surface.

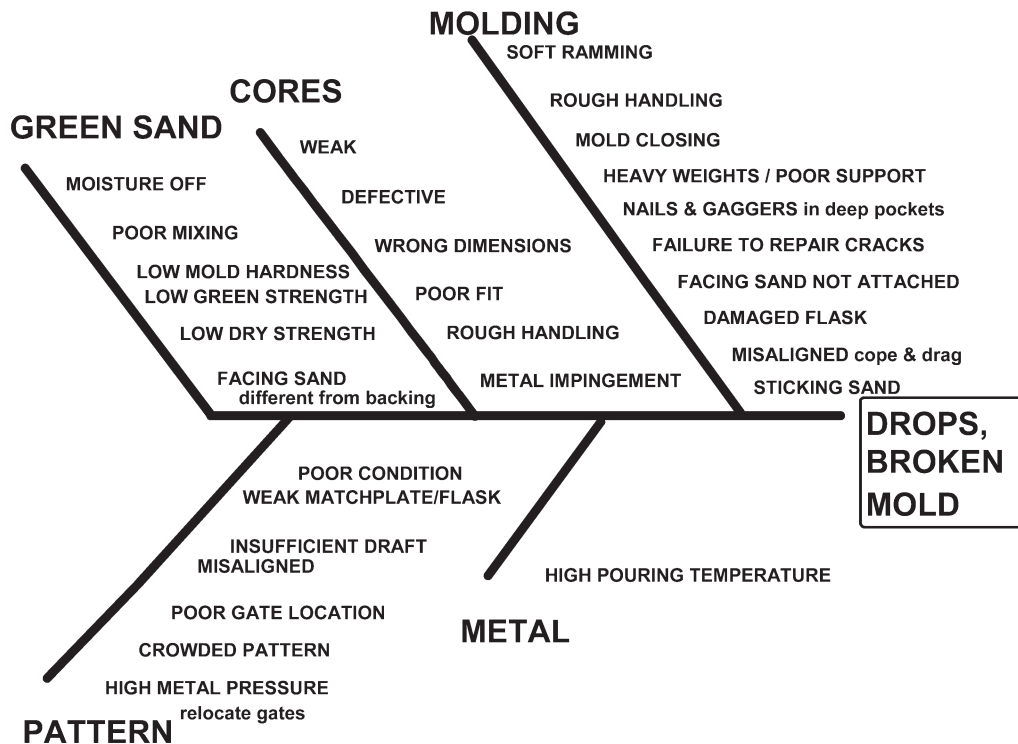


Fig. 15B-7. Fish-bone diagram for castings showing drops & broken molds.

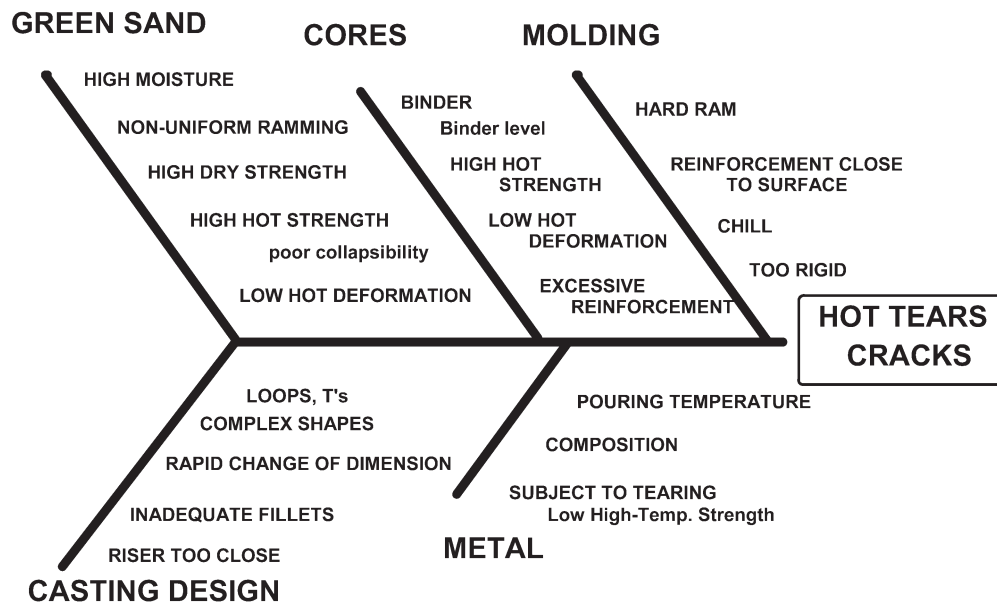


Fig. 15B-8. Fish-bone diagram for castings with hot tears and cracks.

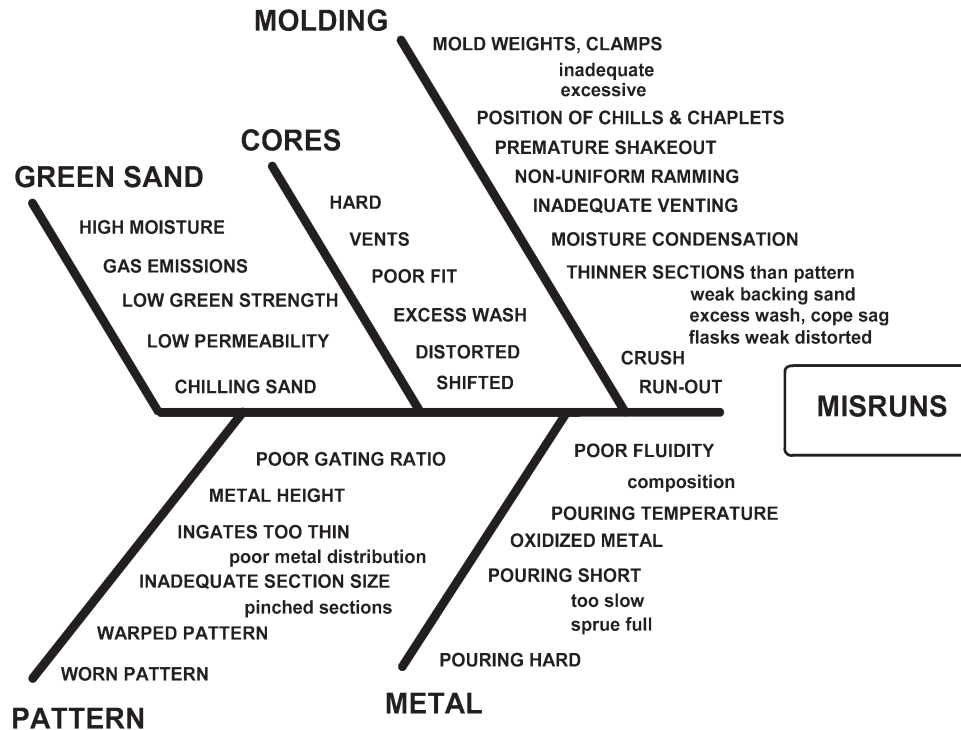


Fig. 15B-9. Fish-bone diagram for castings showing evidence of a misrun.

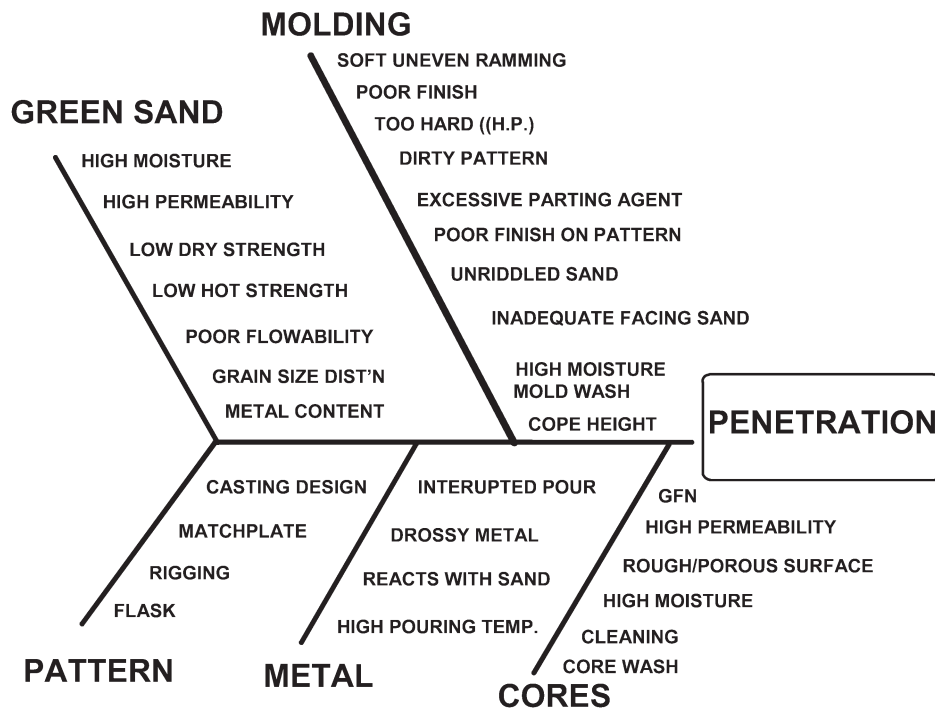


Fig. 15B-10. Fish-bone diagram for castings with rough surfaces.

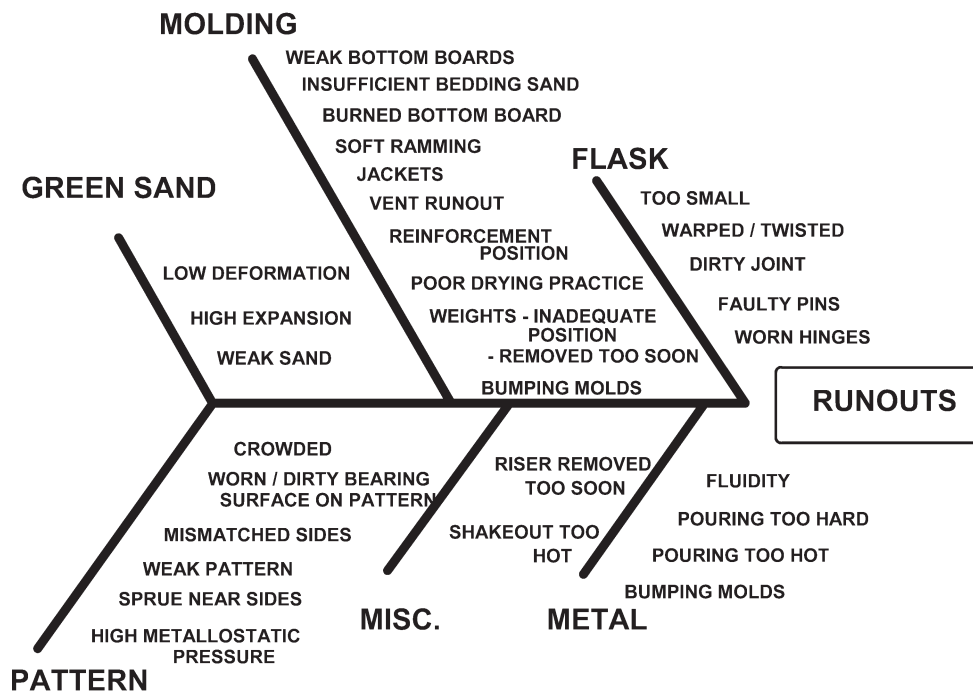


Fig. 15B-13. Fish-bone diagram for castings with runouts.

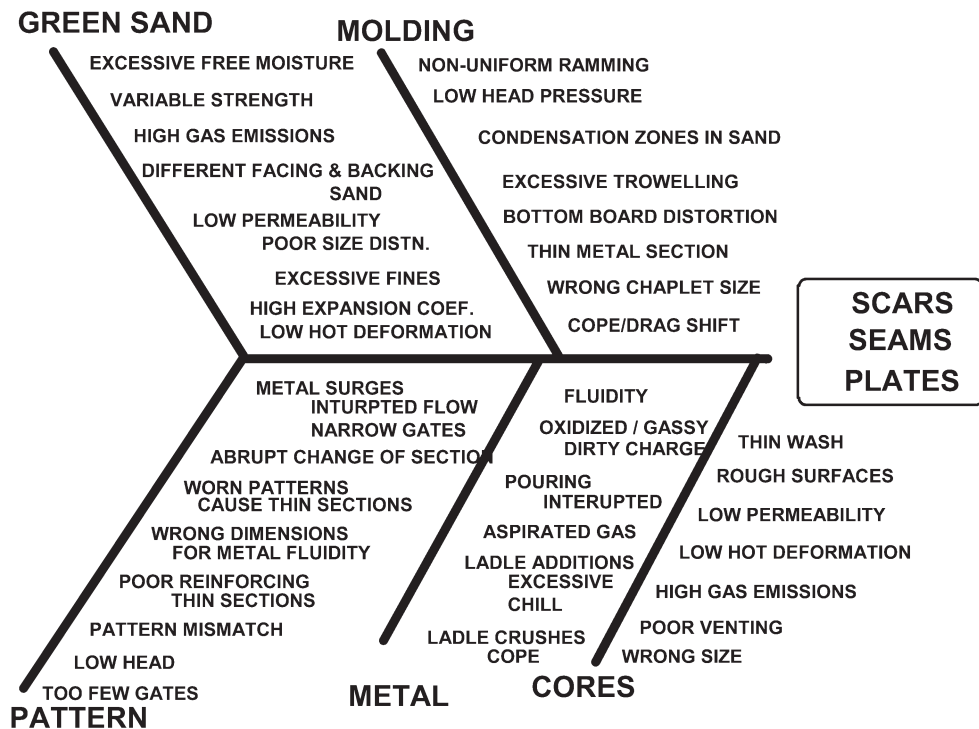


Fig. 15B-14. Fish-bone diagram for castings showing scars & seams.

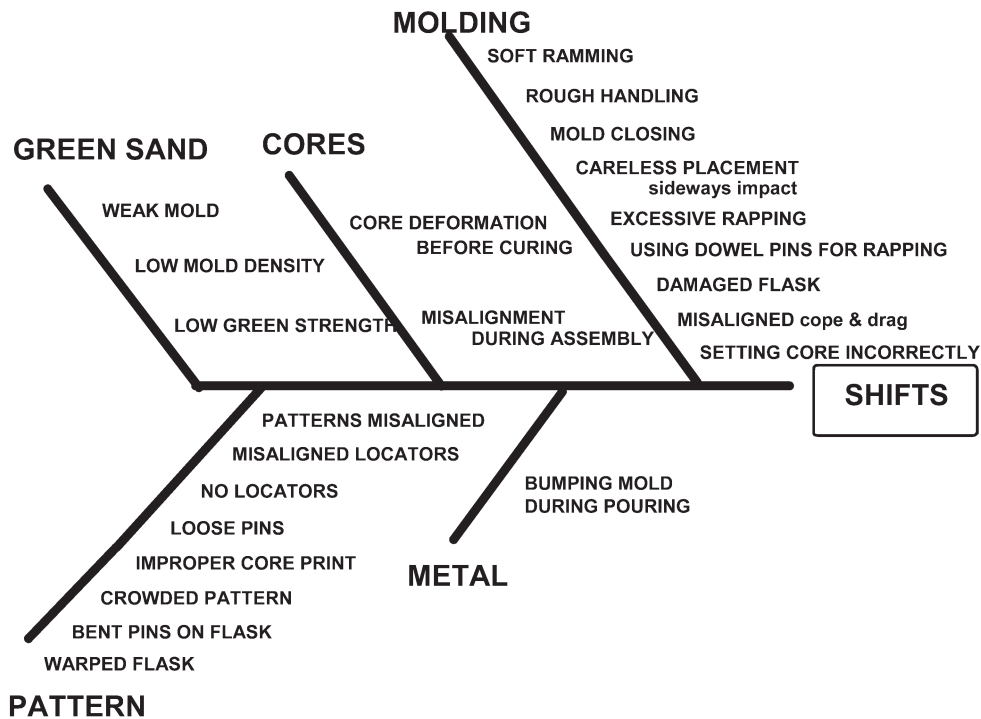


Fig. 15B-15. Fish-bone diagram for castings with parting line shifts.

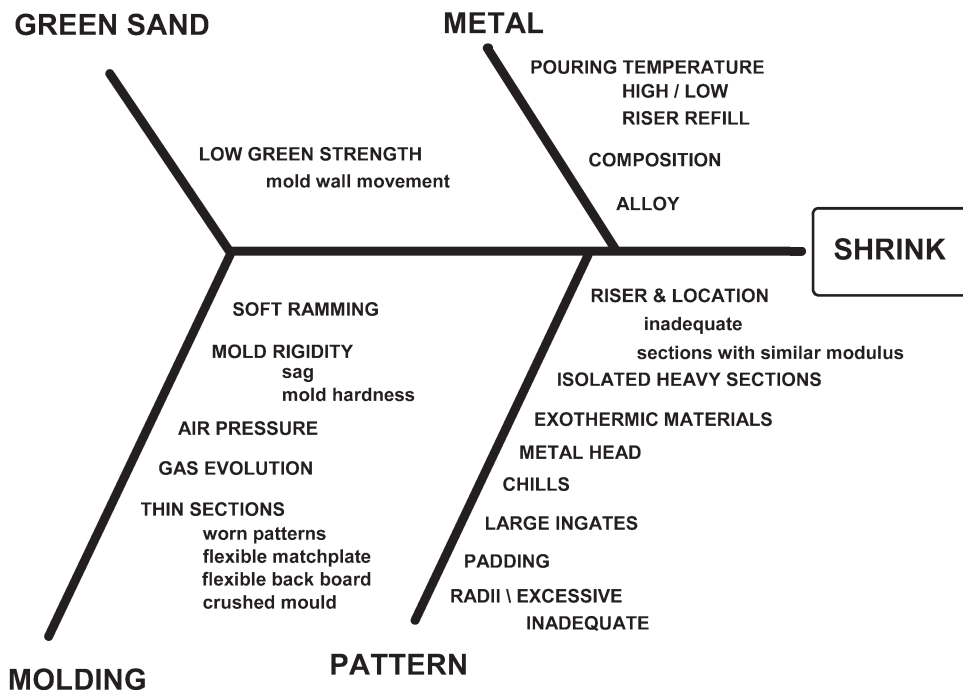


Fig. 15B-16. Fish-bone diagram for castings showing shrinkage.

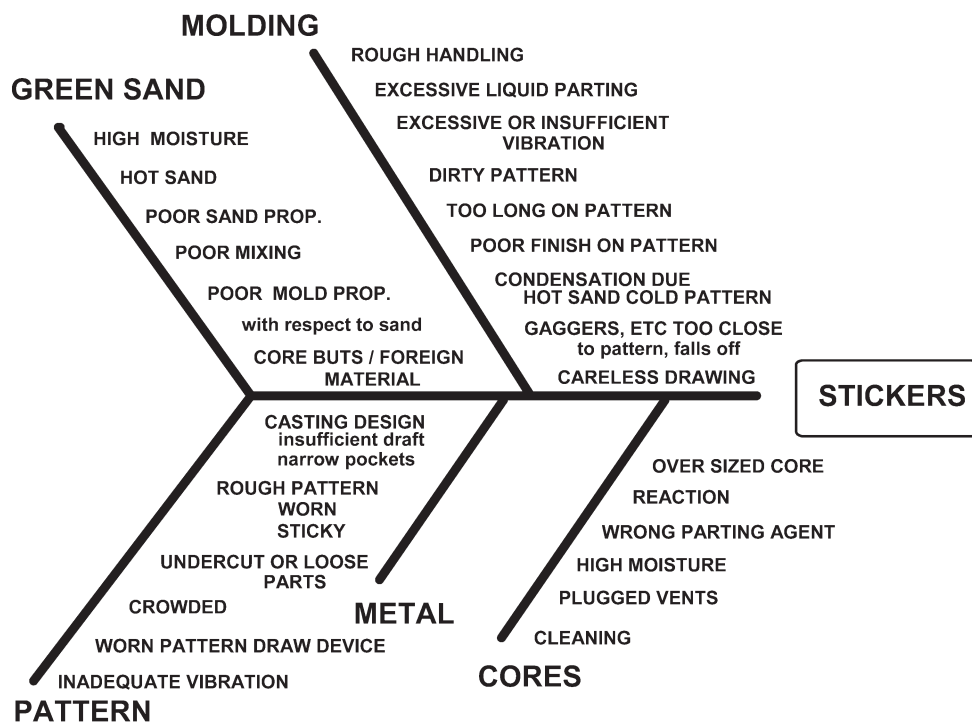


Fig. 15B-17. Fish-bone diagram for castings with stickers.

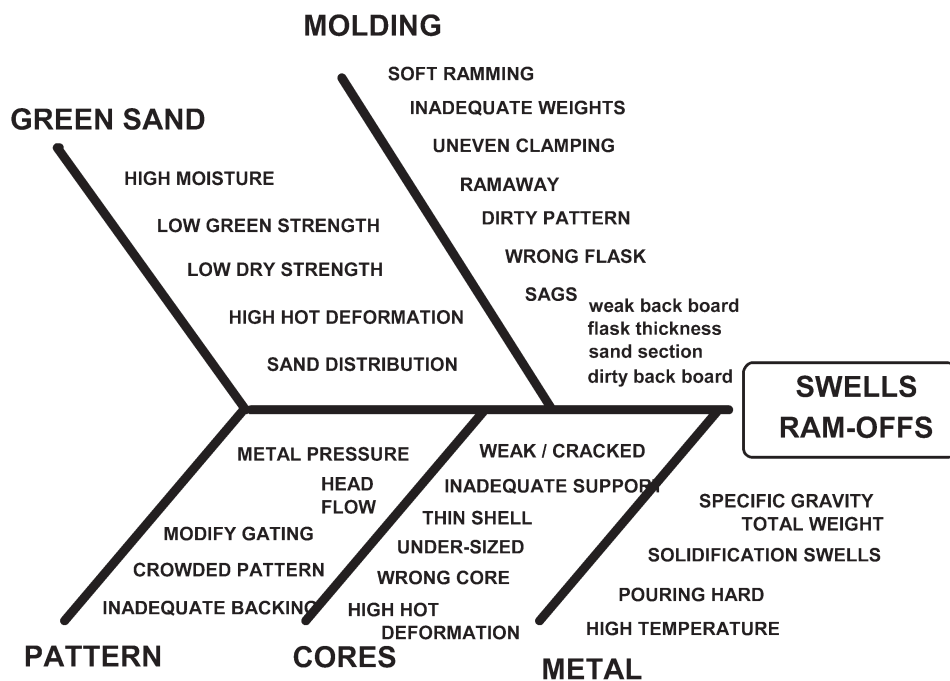


Fig. 15B-18. Fish-bone diagram for castings with swells.

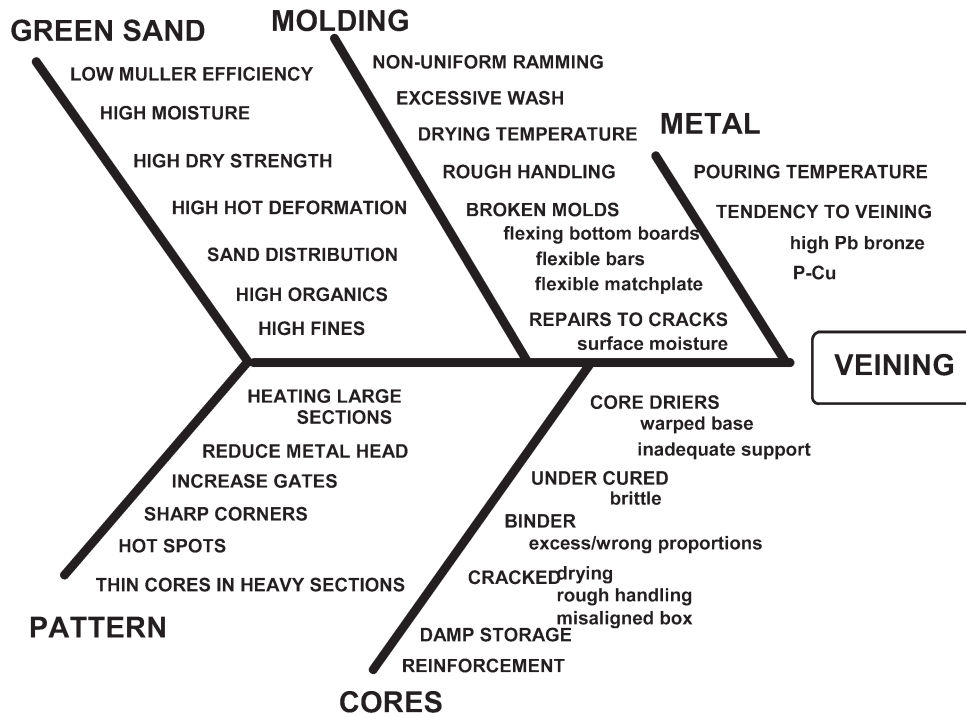


Fig. 15B-19. Fish-bone diagram for castings showing veining.

QUALITY CONTROL OF COPPER-BASE ALLOYS

INTRODUCTION

The term *quality control* signifies the entire process undertaken by both the foundry and its customer to ensure that the production of castings meets the mutually agreed requirements. Economics is an important factor in determining the degree and sophistication of a quality control program, and should be measured in terms of the stringency of the application of the product. For military use or critical engineering applications there are invariably specifications to be met, from which there can be little or no deviation. However, many commercial products involve less severe service, and somewhat less stringent requirements. Before a foundry can establish a quality control program that is both effective and economical, it is essential that the standards of casting quality be carefully defined and agreed upon in advance by both the producer and the user. The pricing structure for the parts being produced should be included in the agreement, which should also include the expense of quality control evaluations.

In the final analysis, the goal of a quality control program is to ensure the integrity and utility of the castings being produced. Emphasis is placed on the soundness and appearance of the castings. Non-conforming castings shall be rejected immediately, tagged and held in a designated area for evaluation. The evaluation must result in a root cause for the defect in order to develop the proper corrective action. The risks involved with defective castings reaching the consumer are even more severe when considered in light of product liability.

While the integrity of the finished castings must be monitored closely as part of the quality control program, it is also important that the processes and materials used in producing the castings be monitored and controlled so as to minimize the chances of producing defective castings. This involves control of the manufacturing operations themselves.

Many foundries are being required to develop an ISO 9000 Quality Program by their customers. A well-designed program should involve all personnel in the continuous effort to improve quality. Continuous improvement in both process and product will be essential requirements for progressive metalcasting operations.

In addition to controlled production processes, providing design assistance has become a competitive necessity. Before beginning the pattern construction process the use of the latest computer applications can improve the early success of new casting designs. Depending on the complexity of the casting the use of finite element analysis and solidification modeling should be considered. Working together with design engineers can help to avoid possible castability problems while improving the cost effectiveness of the design.

Many test procedures, both destructive and nondestructive, have been developed for evaluating the integrity of castings and the quality of the materials from which they are made. This chapter discusses various test methods. Since the complexity of some tests and their interpretations prevents adequate coverage in this book, such tests will be described in a general manner only and references will be cited for further information. Also included in this chapter are discussions of techniques and practical considerations for the control of various foundry processes.

CHARGE MATERIAL QUALITY

Ingots

By far, the largest proportions of castings made in this country utilize charges containing composition, or prealloyed, ingot. Whereas the use of this material minimizes the problems associated with alloying of the furnace charge by the foundry itself, it does not eliminate the need to confirm that the ingot supplied by the smelter is of suitable quality. There is no economic benefit in attempting to produce high quality castings from ingot that does not meet all of the required specifications.

The quality test most directly applicable to ingot is that of chemical analysis, from drillings or other forms of sampling, to determine that alloying elements and impurities are within specified limits. (The methods of chemical analysis will be discussed in a later section.)

One method for obtaining drillings from selected sample ingots (per ASTM E255—Practice for Sampling Copper and Copper Alloys for Determination of Chemical Composition) is to drill five holes approximately $\frac{1}{2}$ inch in diameter at points

equally spaced along a diagonal line between the ends of the ingot. Drilling is done through the total thickness of the ingot from top to bottom. Such sampling is intended to “average-out” any variations of composition within the ingot which might result from localized segregation during solidification.

The ASTM E255 specification also permits sampling by sawing or milling cuts made at the designated locations, from side to center, or through the entire ingot cross-section.

Two general types of ingots are available, the “smooth-top” and the “rough-top,” whose surface condition and appearance depend on the manner in which the metal is skimmed and treated during pouring into the ingot molds. The differences between these two types of ingot have never been proven to be highly significant and their choice is largely a matter of personal preference.

Regardless of ingot type, the top surface should not exhibit a gray, greasy appearance caused by excessive amounts of aluminum and/or silicon (in alloys for which these elements are impurities). It is also important to note whether the ingot surface has a proper “set,” or if it appears puffed. The latter condition is a strong indication that the ingot is highly gassed due to improper refining, and is apt to cause trouble upon remelting. Puffed ingots may also result, even with good-quality metal, from pouring into overheated iron molds. However, this condition is rarely encountered in ingots from reputable suppliers. For quality assurance, it is best to reject shipments of ingot whose top surfaces do not exhibit a level to slightly concave appearance.

The fracture of an ingot, while not too indicative of quality, should be uniform in color and free from slag as well as oxide inclusions and occluded gases.

The general requirements and tests for copper-base alloy ingots are given in ASTM Specification B30—Standard Specifications for Copper Alloys in Ingot Form. This includes chemical composition specifications as well as mechanical property requirements, and refers to other relevant standards on how these tests are to be conducted. Similar information is available in the specifications promulgated by other sources.

Foundries are often reluctant to incur the additional expense involved in including routine or periodic chemical analysis of incoming ingot in their quality control programs, whether by installation of in-house facilities or by use of commercial laboratories. As a cost-saving measure, ingot deliveries are usually accepted based on chemical analyses provided by the smelter. Compositional changes resulting from remelting are often overlooked. This invariably leads to problems, including:

- Errors in vendor analysis may go undetected, and incorrect alloys may be received.
- The vendor analysis may not include all the potentially harmful impurities present in any given lot of ingot.
- Remelting and recirculation of foundry scrap may cause losses of some elements and accumulation

of undesirable impurities, leading to defective heats of castings.

The minimum mechanical property requirements for materials in ingot form are based upon values obtained from separately cast test bars. The types of bars used, as described in ASTM B208 (Standard Practice for Preparing Tension Test Specimens for Copper Alloy Sand, Permanent Mold, Centrifugal, and Continuous Castings), may vary with the shrinkage characteristics of the alloy involved. This subject will be discussed more fully later in this chapter. It is improper and misleading to prepare test bars from sections cut from ingot since the properties of such samples show little correlation with those of separately cast bars.

As a part of a metalcaster’s overall quality control procedures a method to evaluate ingot acceptance criteria should be developed. The incoming ingot would be tagged or segregated until released for production. The standards required for acceptance should be established by mutual agreement between the ingot supplier and the foundry.

Remelt

Virtually all foundries remelt the gates, sprues, risers and rejected castings generated during production. Such material, generally termed internal scrap, should be properly segregated during handling and storage within the foundry to avoid mixing with, or possible contamination by, other alloys or materials. With successive remelting there will be a decided trend for the gradual loss of volatile elements such as zinc, as well as an accumulation of contaminants such as iron. Depending upon melting and subsequent deoxidation practices, the level of residual phosphorus in the melted returns may drift to dangerous levels. This necessitates the periodic monitoring of the composition of the internal scrap being reused. It is a common error to ignore the variations in the analysis of the circulating internal scrap until it is too late and an epidemic of defective castings occurs.

In order to control the composition of returns being charged for remelting, storage and handling procedures should be considered. Avoid the use of large scrap bins placed next to a wall or partition in such a manner that the last material dumped into the bin will be the first material remelted. If such storage facilities are necessary, one solution is to provide two bins for each alloy, side by side. As one bin is being filled with material from cleaning and finishing operations, the other is being emptied during charging operations. In this way, the internal scrap is circulated for remelting in the approximate sequence it is being generated, thus avoiding any abrupt composition changes in the charge.

A particularly serious contaminant in the case of the copper-tin-lead-zinc alloys is aluminum. Unfortunately, aluminum beverage cans and aluminum foil wrappers from foodstuffs or smoking materials are often allowed to be discarded indiscriminately. When these contaminants enter the melting furnace, even in small amounts, they may cause serious problems resulting in the rejection of all castings in the heat.

Furthermore, the metal from such heats must be discarded and resold to the smelter since its reuse could cause the same problem in successive remelting. The best solution to such contamination is to prohibit the presence of aluminum cans and foil wrappers within the foundry, or to restrict their use to cafeterias or rest areas.

In some instances, foundries are faced with remelting of borings and turnings generated from machining the castings they have produced. The condition of such material should be closely monitored as it is returned to the melting department to assure that it is not contaminated by moisture, oil, tramp iron, or other alloys.

It is very important to note that the melting of borings is only effective when using coreless or channel type induction furnaces. Very high melt losses are incurred when attempting to employ fuel-fired furnaces. This process is conducive to high volume foundries where only a very limited number of alloys are being cast. Due to the increased possibility for cross alloy contamination to occur, the melting of borings is not recommended for jobbing foundries or where machining is out-sourced and the foundry has little or no input at the machine shop.

When purchased scrap is used, nothing short of complete analysis of each melt will assure freedom from contamination. Some forms of purchased scrap are relatively reliable, such as heavy copper wire or bus bar and automotive radiators. Obsolete scrap from certain sources and applications may be reasonably reliable, however in most cases it will not have been properly sorted and therefore, can almost be guaranteed to result in contaminated heats. The principal purchasers of obsolete scrap are the smelters, who are adept at sorting and identification of mixed scrap and can remove reasonable levels of contaminant elements by refining techniques. Most foundries do not have established sources of consistent, reliable scrap nor do they have facilities for large-scale refining and analytical control. This explains the preference shown by most foundries for use of composition ingot, particularly when producing engineering castings with rigid quality standards.

CONTROL OF MELT QUALITY

The following section is intended to supplement the information given in the chapter on *Metal Quality* and to provide a number of practical guidelines relating to melting department operations.

Furnace Atmosphere Control

As discussed in earlier chapters, hydrogen absorption by molten copper-base alloys is a serious problem since it is a common cause of porosity and weakness in finished castings. To minimize the absorption of hydrogen during melting, the most effective measure is to minimize the amount of hydrogen in contact with the molten metal. In the case of electric induction and arc furnaces, the principal source of

hydrogen is the moisture in the air. For fuel-fired furnaces, the danger of hydrogen absorption is much greater because large volumes of water vapor are generated by the burning of the fuel, and this moisture is present in the products of combustion coming into contact with the molten metal in the furnace.

Regardless of the type of furnace used, a technique for minimizing hydrogen absorption is to melt under a slightly oxidizing atmosphere. When properly controlled, an oxidizing atmosphere over the melt will result in sufficient absorption of oxygen to suppress the hydrogen level to a low value. This technique is particularly effective with the copper-tin-lead-zinc alloys. The method for establishing and evaluating a sufficiently (but not overly) oxidizing atmosphere has traditionally been based more on experience than on scientific techniques. This method varies with the type of furnace being used, as will be explained.

Induction Furnaces

Maintaining an oxidizing atmosphere with induction furnaces is not a problem since the atmosphere in contact with the molten metal is the ambient air, containing 21% oxygen. Indeed, the problem of an atmosphere that is too oxidizing may occur, and may result in excessive drossing or melting losses. However, if melting is done rapidly, and the metal is poured as soon as the melt comes to temperature, few problems will be encountered with hydrogen or drossing. In cases of prolonged exposure of the melt, it is often advantageous to provide a cover of some inert or slightly reducing material.

Fluxes which produce a glassy, slag-like cover are sometimes advocated. However, these materials should be used only with discretion since they may have a tendency to pick up moisture during storage, thereby adding to the hydrogen problem. These fluxes also have the disadvantages of eroding or building up on the walls of the crucible or being entrained in the metal as it is poured. Often, a cover of graphite lumps or dry wood charcoal, free from pitch or other binders containing hydrocarbons, is preferable.

Fuel-Fired Furnaces

For purposes of discussion here, fuel-fired furnaces will be considered as either crucible- or hearth-type furnaces fired with natural gas, fuel oil, propane, or combinations thereof. As stated above, since these fuels are all hydrocarbons (compounds of carbon and hydrogen) their combustion results in the formation of large quantities of water vapor. The water vapor forms part of the visible flame which comes into contact with the molten metal before it is exhausted from the furnace. With the absence of any free oxygen in the furnace atmosphere, the moisture in the flame, by its reaction with the molten metal, will allow dangerously high amounts of hydrogen to be formed and dissolved by the melt. This is the most common cause for the occurrence of porous copper-alloy castings and emphasizes the importance of close control of the furnace atmosphere in fuel-fired furnaces.

Over the years many attempts have been made by brass metalcasters to avoid or prevent hydrogen contamination in fuel-fired furnaces by the use of a cover material on the surface of the molten bath. In general, this approach has been found to be ineffective, unreliable, or highly impractical. Porous cover materials such as charcoal do not prevent the moisture in the flame from reaching the melt surface, and serve only to react with any free oxygen present, thus adding to the problem of hydrogen contamination. The use of glassy, slag-like covers can be relatively effective in protecting the melt but there are many disadvantages. Most importantly, such covers prevent any oxygen in the furnace atmosphere from reacting with the bath. To overcome this problem the British practice has been to add oxidizing materials, such as cuprous oxide, to the slag cover. At best, however, the use of slag covers is a nuisance and a potential source of inclusions in the castings. From a practical standpoint, their use shortens the life of crucibles and furnace refractories and reduces the thermal efficiency during melting by shielding the melt surface from radiant heat. In hearth-type furnaces the use of a slag cover makes it virtually impossible for the furnace operator to judge metal temperature by observation of the degree of flaring of zinc.

The most commonly accepted practice for atmosphere control in fuel-fired furnaces, although imprecise and dependent on operator experience, is to melt under slightly oxidizing conditions. This means adjusting the fuel-to-air ratio of the burners so that slightly more air is used than that required for complete combustion, with the result that a small amount of free oxygen will be present in the flame. The precise amount of free oxygen desired has never been scientifically determined but authorities generally agree that the percentage should be around $\frac{1}{2}$ % of the volume of the gases in the products of combustion. This excess of oxygen, under normal circumstances, tends to saturate the melt with oxygen and thereby restrict the solubility of hydrogen to acceptably low levels. Subsequent deoxidation to remove the dissolved oxygen will thus permit the metal to solidify without formation of visible porosity from either hydrogen alone or hydrogen/oxygen reaction.

The most reliable method for assuring the presence of a slight excess of oxygen in the burner flame is to utilize a proportioning burner or other automatic control device which will constantly maintain the proper fuel to-air ratio. Such controls are readily available today and are strongly recommended as the most practical solution to atmosphere control.

On furnaces lacking automatic burner control, adjustment of the fuel-to-air ratio has depended upon operator skill and experience. It has been observed, particularly for crucible furnaces, that the existence of a short, sharp exhaust flame having a slightly green tinge around the outer edge indicates a properly oxidizing atmosphere. It is a mistaken idea that a green flame is always oxidizing. A long, lazy green flame has been observed on numerous occasions where reducing conditions actually exist. For this reason visual determination, unless made by a highly skilled operator, is often inaccurate. To be avoided at all costs is a yellow, yellowish-red

or smoky flame. These are strong indications of a reducing atmosphere.

Another control technique, likewise imprecise although helpful, is the zinc test. With this technique, a small piece of clean slab zinc is held in the open exhaust flame from the furnace for about 5 seconds, and is then observed for surface appearance. If the surface has become blackened, the atmosphere is highly reducing; if it has changed to a color ranging from straw-yellow to light gray, the atmosphere is slightly reducing; if the color remains unchanged, the atmosphere is oxidizing to some degree. This test procedure also depends upon the experience of the operator and provides only limited control.

Combustion analysis equipment has been available for many years and is undoubtedly the most reliable means for obtaining an accurate, quantitative measurement of the composition of flue gases emerging from the furnace. Although care is required in gas sampling, rapid determination of the levels of carbon dioxide, carbon monoxide, and free oxygen can be made. This is the recommended technique for monitoring of furnace atmospheres, regardless of whether or not the furnaces are provided with automatic burners.

METAL TEMPERATURE CONTROL

Every foundry, large or small, should have some type of reliable equipment for measuring molten metal temperature. Probably as many defective castings can be traced, directly or indirectly, to improper pouring temperature as to any other condition in the foundry. Every casting has an optimum pouring temperature, or temperature range, dependent upon such factors as casting size and shape, gating, number of pieces per mold, and so forth. It is fundamentally sound practice to pour any casting at the lowest temperature which is practical in order to avoid misruns, cold shuts, and shrinkage. For large production foundries with continuous molding lines, automatic pouring is the best means for control of pouring temperature, mold to mold. In most cases, such consistency in pouring temperature control is not possible. This is due to temperature losses which occur during transfer of the metal from the furnace to the pouring station, as well as to the continuous temperature drop between the pouring of the first and last mold from a given ladle or crucible.

If the average amount of metal to be poured from a ladle was 200 lbs, the temperature drop during the pouring of 10 to 15 molds could be expected to be at least 100°F (55°C) and might be as much as 150 to 200°F (83 to 111°C). This temperature loss can be minimized by insulating and covering pouring ladles; however, such procedures are impractical in cases where melting and pouring are done using the same crucible.

In practice, it becomes necessary to establish the best method possible, starting with an initial pouring temperature which may be higher than desired, that will yield acceptable castings and at the same time allow the last mold to be

poured without misruns or other defects attributable to low temperature. This judgment is not always easy to make since the defects associated with low pouring temperature are usually more immediately apparent than those resulting from pouring too hot. Thus, there is a tendency to raise the initial pouring temperature (in order to allow a full ladle of metal to be poured without misruns) without carefully evaluating the soundness of the castings from the first few molds. Re-examination may show that the castings poured at the higher temperatures are consistently defective internally. In such cases, the initial pouring temperature must be lowered. Unless misruns can be avoided in the last molds poured (by re-gating or some other technique), the best solution is to pour fewer molds per ladle. In any case, good temperature control involves accurate temperature measurement immediately before pouring begins; this may necessitate two readings (one at the furnace and one at the pouring station) if the time lag between tapping and pouring is too great or variable.

There are many good pyrometers on the market today for measurement of molten metal temperature, virtually all of them being of the immersion type. The most reliable and maintenance-free pyrometers utilize thermocouples enclosed in stainless steel protection tubes in which the hot junction of the couple is welded internally to the tip of the tube. This allows for good heat transfer and rapid response, while permitting numerous immersions before replacement is required. Modern pyrometers utilize solid-state circuitry and are available either with dial-type scales or with digital readout. The latter are usually simpler for shop personnel to read and have better visibility from a distance. Personnel responsible for temperature readings should be trained in the techniques for using immersion thermocouples. Also, equipment should be checked at frequent intervals to ensure proper calibration.

Optical pyrometers are practically never used in brass foundries because of wide variations in the emissivity of the molten metal surface due to oxide and dross formation.

The control of metal temperatures within the furnace requires operator skill and experience since the use of pyrometers is rather impractical. With electric melting, recording power meters are a reliable means of predicting the temperature of superheated metal in the furnace since the energy required to melt and superheat a given weight of metal tends to be rather constant for a given alloy, unless there are significant differences in melting and pouring cycles. With fuel-fired furnaces metal temperatures can be estimated on the basis of elapsed time after the burner is ignited, given constant alloy, charge weight, and furnace lining temperature. An experienced operator, particularly with hearth-type furnaces, becomes surprisingly adept at judging metal temperature by the degree of flaring of zinc when working constantly with a given red brass alloy. Even here, however, many factors such as small variations in barometric pressure and humidity can lead to errors in judgment.

TESTS FOR MELT QUALITY

Any test for evaluating melt quality must not only be sensitive and reproducible but must also be relatively quick and simple so that a decision can be made while the metal is still waiting to be cast. It obviously serves little purpose to learn that a heat of metal is defective by finding that the castings are useless after the molds have been cast.

Traditionally, metalcasters have been required to make use of tests which involve visual, qualitative judgments of melt quality, based upon observations of the behavior of small samples allowed to solidify in test molds. One such test has been used to evaluate the solidification shrinkage behavior of the metal, as an indicator of the level of dissolved gases. The other test has been based upon the appearance of a fractured surface of sample castings, a characteristic which is related in a complex way to an interaction between alloy shrinkage and the release of dissolved gases during solidification.

Shrinkage Test

A relatively simple test is to cast a tapered cylinder of the alloy, approximately 2 in. dia x 4 in. long, into a dry sand mold and to allow the sample to solidify slowly. An insulated riser sleeve, backed with system sand, is an excellent source of blind sprue mold material. The surface of the sample is preferably covered with a layer of insulating material such as vermiculite, immediately after pouring, to prevent its freezing over prematurely. For narrow-freezing-range alloys such as aluminum bronze or pure copper (for which this test is particularly sensitive), gas-free heats will exhibit deep, localized piping from the surface downward. Heats containing dissolved gases will exhibit a variety of characteristics, ranging from reducing piping to internal blowholes. In extreme cases, the released gas may even cause exudation of molten metal from the surface of the casting.

The test is less sensitive for alloys having wide freezing ranges, since these materials, even when gas-free, exhibit only moderate surface depressions as a result of solidification shrinkage. Badly gassed heats, however, will show a “puffing” of the surface of the sample and may show evidence of bubbling or “spitting” as gas is released during freezing. High-leaded bronzes may exhibit “lead sweat” when severely gassed.

Fracture Test

The fracture test involves the examination of a freshly broken cross-section of a casting or cast specimen, noting any abnormalities in either the color or texture, or the presence of voids or inclusions. Valuable information can be derived from such a test once personnel have learned to distinguish between normal and abnormal fracture appearance for the alloy in question. Unfortunately, it is difficult to define specifically what is to be expected as normal or abnormal.

In order to learn how to correlate fracture appearance with metal quality it is necessary to prepare a series of fracture specimens for each alloy from heats melted and poured over a wide range of conditions. For example, a heat melted under oxidizing conditions and severely overheated might then be used to cast a series of fracture bars at 100F increments in pouring temperature (duplicate series could be cast, with and without deoxidation). Similar series should be cast from heats melted under reducing atmospheres and from charges containing extreme levels of residual phosphorus. The effects of deliberate contamination with aluminum and silicon might also be noted. It should be emphasized that fractured surfaces should be examined immediately, as they have a tendency to tarnish unless stored in a dry, inert atmosphere.

Those experienced in evaluating fracture appearance can distinguish, at least qualitatively, between hydrogen porosity, hydrogen/oxygen (steam reaction) porosity and shrinkage in the wide-freezing copper-tin-lead-zinc alloys. The test is most frequently applied for this family of alloys.

Many foundries use fracture testing to determine melt quality of tin bronzes, red and semi-red brasses and high strength yellow brasses with respect to pouring temperature and gas content. Test methods involve casting in sand molds (a) a flat plate with a notch or groove or (b) a step block plate with three section thicknesses. These two types of plates can be cast at a very high temperature and then gradually decreasing the pouring temperature by 50–100F (10–38C) to evaluate the effect of pouring temperature on melt quality. Similarly, they can be cast in the as-melted condition (before degassing or deoxidation) followed by casting after degassing or deoxidation to know effect of gas on melting. The plates can be mounted on a vice and fractured using a heavy hammer. The fracture surface can be examined visually, or using a magnifying glass or better by using an optical microscope to know the color and texture of the fracture face. This examination should be done immediately after fracture to avoid surface contamination or tarnishing. The design of the fracture plate (step block) is such that fracture can occur at the junctions of any two section thicknesses.

DEOXIDATION PRACTICE FOR RED BRASSES AND TIN BRONZES

Comments were made in a previous section of this chapter regarding the importance of monitoring the level of residual phosphorus in foundry returns being remelted. It has been pointed out that the phosphorus content of molten copper-tin-lead-zinc alloys, after deoxidation with phosphor-copper, should preferably be in the range of 0.010% to 0.030%. High lead tin bronzes and no lead red brass w/Bi alloys would require a residual P of 0.025 to 0.035%. Below this range, the alloy may be gassed by moisture from the mold during pouring, above this range the metal is not only prone to penetrate and react with sand molds to produce defective surface conditions but also, and more importantly, high residual phosphorus levels in the charge material prevent the melt from absorbing oxygen even though the furnace

atmosphere is adjusted to be slightly oxidizing as has been recommended.

The principal cause of high residual phosphorus is, of course, over-deoxidation. This usually occurs for one of two reasons: 1) porosity problems are erroneously thought to be the result of insufficient deoxidation, hence extra phosphorus is routinely added as “insurance,” and 2) extra phosphorus is known to impart greater fluidity to the metal and, hence, is added to avoid misruns in thin castings, or when pouring cold metal. The deliberate practice of over-deoxidation is guaranteed to result in epidemics of gassy castings for copper-tin-lead-zinc alloys and will negate efforts to maintain low hydrogen levels during melting.

It is misleading to recommend, recipe-fashion, a specific phosphorus addition as standard procedure for deoxidation. This is because the proper addition actually depends on the oxygen content of the melt, and this will vary from one foundry to another according to charging and melting practice.

Experience has shown that, in general, satisfactory results can be expected by deoxidizing with about 1 to 3 oz of 15% phosphorus copper per 100 lb of melt. This indicates that about one-half of the phosphorus added is expended in deoxidizing, leaving a residual level in the 0.010% to 0.030% range. The importance of controlling melting and deoxidation practices so as to keep the residual phosphorus level within the proper range cannot be overemphasized. Should this level start drifting up or down, the charge make-up (ingot/remelt ratio) or deoxidation level should be adjusted so as to reverse the trend as necessary.

Deoxidation should be assigned to responsible personnel and the practice followed should be designed to give consistent results. When separate pouring ladles are used, the deoxidizer may be added when the ladle is 1/3 full. The turbulence of the metal entering the ladle is sufficient to cause thorough, rapid mixing. Where the melting crucible is used for pouring, it is preferable to first skim off any surface dross or slag and then add the deoxidizer by plunging it beneath the surface and stirring gently with a top to bottom motion so that it melts before it can rise to the surface and be partially lost by oxidation in the air. If iron tools are used for this purpose they should be coated with a dried refractory wash to prevent iron pickup by the melt.

The deoxidizer, if added in shot form, can be measured volumetrically by use of a properly sized cup. If in the form of lumps, the deoxidizer must be carefully preweighed and placed in containers suitable for handling.

CASTING QUALITY CONTROL TESTS

Purchasing Standards

In general, castings are purchased to meet the particular requirements of their end use, and casting-quality tests should therefore be specified to assure that the parts do in-

deed conform to such requirements. As an example, we may consider the requirements listed in ASTM B584—Standard Specifications for Copper-Alloy Sand Castings for General Applications:

- A. Materials and Manufacture—states the limitations on raw materials and manufacturing methods to be used;
- B. Chemical Requirements—lists the specified range and limits of elements comprising the alloy;
- C. Mechanical Requirements—lists the minimum mechanical property requirements as determined from separately cast test-bars and requirements for test-bar design;
- D. Other Requirements—comments on various special tests which may be specified, such as pressure-tightness, fracture testing, casting soundness compared to radiographic standards, etc.;
- E. Workmanship and Finish—describes general requirements regarding appearance, dimensions, and visible defects;
- F. Casting Repair—where permissible, describes size limitations of repairable defects and methods and conditions of repair.

All these factors, which are of importance to both purchaser and producer alike, should comprise part of the purchase agreement and should be included in the foundry's checklist for quality control.

The requirements for materials and manufacturing, included in point "A" above, have already been covered in this book. Earlier sections of this chapter have dealt with control of raw material quality and melting operations; the chapter on *Processes and Materials* covered process control points involved in molding and coremaking.

Chemical Requirements

Specifications for the chemical composition of purchased castings include not only the acceptable range for each element desired in the alloy, but also the limits for the content of various metallic impurities. Conformance to chemical composition specifications is an indication that the material will exhibit satisfactory chemical and physical properties. It also implies that the castings, if otherwise sound, are likely to have adequate mechanical properties.

The customer's purchase agreement should specify the frequency of the testing and reporting of chemical composition. This may vary considerably, depending upon customer requirements and the severity of the application. For ordinary commercial castings, one analysis per order may suffice (or possibly one per day, in the case of long runs). Some customers, having first made a "quality audit" to satisfy themselves with the supplier's quality control program and capability, may actually waive a report on chemical analysis while reserving the right to make random examinations of the customer's laboratory records. For critical applications,

it is not uncommon for the customer to require a certified chemical analysis for each heat of metal cast, with the castings themselves identified accordingly.

Procedures for chemical analysis will be discussed in a later section.

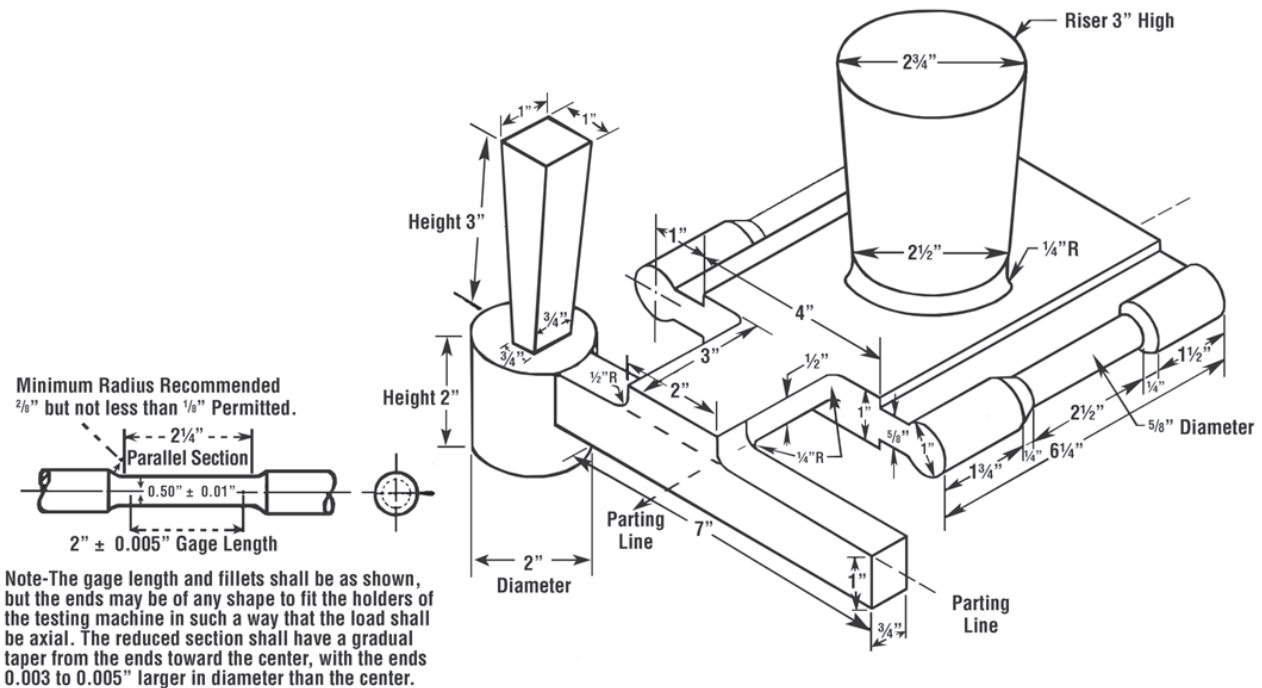
Mechanical Requirements

The most commonly specified mechanical properties are the static tensile properties (ultimate tensile strength, yield strength, elongation). In general, these properties are measured by testing separately cast tensile bars. The choice of test-bar mold geometry for copper-base alloys, so far as gating and risering are concerned, depends somewhat on the solidification characteristics of the individual alloy. The specification most commonly used in the United States is ASTM B208—Standard Practice for Preparing Tension Test Specimens for Copper Alloy Sand, Permanent Mold, Centrifugal and Continuous Casting. Included in this specification are three test-bar mold designs for sand castings. The first (double keel block test-bar) is intended for narrow-freezing-range alloys such as aluminum bronzes, which are sensitive to turbulence and oxidation during pouring. A second (double, vertical web-type) bar is recommended specifically for wide-freezing-range alloys, while a third (double, horizontal full-web type) design is recommended for both classes of alloy. The latter bar design is shown in Fig. 16-1. It should be noted that the test bar should be considered a heavy casting and poured as cold as is possible. It should also be noted that aluminum bronze test bars should be shaken out no later than 15 minutes after pouring.

It is important for customers and producers alike to carefully consider the significance of separately cast test-bar properties. The casting designers would like to believe (and often do) that test-bar properties reflect those found in the castings themselves. Unfortunately, this is not necessarily the case. Casting properties may actually be higher than those indicated by the test bar because of faster cooling rates in the mold. On the other hand, the casting is prone to many defects related to pouring, gating and risering, and molding which the test bar is not, and may therefore contain defects of structure not indicated by a test bar. These potential defects of casting structure, visible or not, necessitate other methods of quality assurance testing. With these ideas in mind, it will be appreciated that the properties of separately cast test bars indicate only the quality of the metal as it is poured into molds. In a sense, the mechanical properties of separately cast test bars reinforce the results of chemical analysis, while providing added information as to whether the metal has been damaged by dissolved gases, foreign materials, or impurities not detected by chemical tests.

The foregoing idea is expressed in ASTM B208 as follows:

"3.1 The mechanical properties determined from test bars for sand, permanent mold, and centrifugal castings poured in accordance with this practice represent the properties of the metal going into castings poured from



This is because the relatively dense, sound surface layers of the casting wall have been machined away, leaving a rather porous internal section which leaks under pressure.

If examination of fractured areas adjacent to the point of leakage likewise shows discoloration and evidence of porosity, then there is reason to suspect damaged metal conditions. This might mean that pouring temperature was excessive or that severe metal/mold reactions occurred. Gas porosity, in itself, does not usually cause leakage during pressure testing unless it is extremely severe. This is because gas voids tend to occur as small, isolated bubbles which do not interconnect with each other. The surface of gas bubbles, when observed by fracture testing, appears relatively smooth and somewhat brassy in color. Shrinkage porosity, on the other hand, shows voids which are rough (dendritic). They may or may not be discolored. A further complication in viewing porous areas is the fact that both solidification and gas porosity may be present simultaneously. Thus, it takes experience and a practiced eye to interpret fracture surfaces when diagnosing the causes of leakers.

Often times, while reviewing the fractures of rejected castings, sub-surface defects may become exposed. These new found problems may have nothing to do with the rejection and may even distract the determination of the deleterious defects. For this reason it is also recommended that you fracture castings, which have passed, all test parameters or, better yet, castings, which have successfully completed their life cycle. Evaluating these castings will help prevent wasting time on insignificant casting discontinuity.

Another important use of the fracture test is with polished ware such as that used for plumbing fixtures. It is not uncommon, after a polished casting has been chromium-plated, to find indications of surface porosity. Fracturing of parts will usually reveal whether the condition is restricted to the surface (and can probably be eliminated by a little extra polishing), or whether the porosity is widespread.

In the examination of fracture surfaces the foundry will benefit by investing in a good quality binocular microscope, capable of magnifications from about 5x to 15x and providing high-intensity cross-lighting. Microscopic examination at low power of nearly any foundry material or product will usually disclose conditions invisible to the naked eye. Such a microscope is one of the single most important pieces of equipment in any foundry quality control department.

Purchasers of castings for use as pressure vessels (valves, fittings, etc.) almost invariably insist upon pressure-tightness as a casting requirement, reserving the right to subject the castings to tests for leakage, usually after machining, and returning all leakers for replacement. Foundries that produce such castings are faced with the problem of making sound parts without a reliable, economic method for testing them before shipment. In some cases, jobbing foundries have equipped themselves with apparatus for pressure testing on a sample basis, however this is often neither effective nor practical. The most effective means of avoiding excessive

customer returns due to leakage is to isolate the most common causes, based on past experience and trouble-shooting, and then establish reliable process control methods to avoid such defects.

Except for relatively critical applications and for certain alloys, tests of soundness by radiography are seldom required for copper-base alloys as a part of a purchase specification. Such testing may be used, however, not only to verify the internal soundness of finished castings but as a means of evaluating gating and risering systems for new and experimental castings. (Additional comments on radiographic examination will be made in a later section.)

Workmanship and Finish

For purchase specifications related to workmanship and finish, refer to visual quality standards. Generally stated, the requirements may indicate only that parts be of "good" workmanship and "free from injurious defects." Such general terms are obviously unsatisfactory to either producer or user, since they are subject to individual interpretation. The subjects of surface cleanliness and finish, presence of any or all kinds of visible defects, and dimensional tolerances of the parts should be dealt with explicitly in the purchase agreement and clearly understood by both buyer and seller. Quality can never be absolute since it depends on a variety of design, material, and process factors. The minimum standards of quality should reflect those required for the application and should be rigorously enforced. The costs of maintaining such quality should reflect the number and kind of tests required and the process parameters involved.

Foundries and casting users, in striving for quality and reliability, should consider supplementing or replacing the time-honored concept of 100% inspection with modern statistical quality control and acceptance sampling techniques.

Casting Repair

Defect repair by such techniques as welding, plugging, impregnation or peening, although frequently effective and practical, should never be done without the full knowledge and consent of the purchaser. Although salvage by these techniques is permissible, the conditions and limitations must be defined and understood by both supplier and purchaser. Cosmetic repair should not be considered in the same way as structural unsoundness repair. Weld repair is applicable to only a relatively few families of copper-base alloys, and purchase agreements should stipulate in such cases that acceptable techniques are used, possibly including a weldability test (see ASTM B369—Standard Specification for Copper Nickel Alloy Castings).

LABORATORY TESTS

Whereas a number of the tests previously discussed can or must be made on the foundry floor, there are others that must be conducted in a laboratory, often with sophisticated

equipment operated by trained personnel. In a book of this scope, such tests can be considered only briefly and in general terms.

CHEMICAL ANALYSIS

In the past, practically all chemical analyses were done by the gravimetric and volumetric methods of “wet” chemistry. These techniques are accurate and reliable when properly conducted, and continue to be employed today for the important purposes of “referee analysis,” calibration of analytical standards, and the quantification of unusual or non-standard elements in samples. Details for conducting wet chemical analysis for most of the elements commonly found in copper-base alloys are given in the following *ASTM Standards*:

E478—Standard Test Methods for Chemical Analysis of Copper Alloys

E255—Standard Practice for Sampling Copper and Copper Alloys for Determination of Chemical Composition

Such analytical methods have the disadvantage of being quite slow, in most cases, making it virtually impossible to obtain results for production heats until well after the metal has been cast. This limits their value as a tool for process control. These methods also require a significant investment in laboratory facilities and the employment of trained analytical chemists. With today’s availability of equipment for rapid, accurate chemical analysis at moderate cost, foundries tend to rely on commercial laboratories for the special non-routine analyses requiring wet chemical methods.

A number of different types of sophisticated equipment are now available, making it possible to obtain an analysis of a dozen or more elements in a sample, if necessary, within five minutes of its receipt. Where economically justified, as for large heats of metal or those intended for production of critical castings, these analytical methods can be used for monitoring the composition of the metal before it is cast. More commonly, the analyses are used to verify the composition of raw materials (ingot and scrap) being melted and to monitor trends in alloy composition, based on periodic sampling of production materials. The most common methods used today for rapid chemical analysis are optical emission spectroscopy and x-ray fluorescence. All are based on the measurement of some form of radiant energy in the electromagnetic spectrum.

Optical Emission Spectroscopy

In the process of optical emission spectroscopy, the sample material is exposed to the intense heat of an electric arc. The radiant-energy given off by the vaporized metal atoms is focused by a collimator lens onto a prism, or diffraction grating, which disperses the visible and ultraviolet radiation into a spectrum, or rainbow-like band of radiant energy. Since each element emits characteristic wavelengths of energy, detectors can be placed at various locations along the band in such a way as to measure the energy emitted

by each element present in the arc. Previously, the measurement of energy intensity was commonly done by use of photographic film; the intensity of particular spectral lines was read in comparison with known standards, calibrated in terms of the concentration of the metals present. Today’s spectrographs make use of photoelectric sensors which can amplify and cumulatively measure the amount of radiant energy emitted for any desired wavelength. The energy stored by these sensors can then be displayed directly, either on a strip chart, print-out sheet, or digital display screen in units of percentage. A trained technician is required to operate such equipment. The equipment must be operated in a controlled environment and periodically checked for calibration by use of spectrographic standards for each element.

X-Ray Fluorescence

Whereas the optical emission spectrum of electromagnetic radiation contains hundreds of characteristic energy bands, or wavelengths, for the various elements, the x-ray spectrum produced by fluorescence contains relatively few. This spectrographic technique involves the irradiation of a metallic sample with an x-ray beam of fixed wavelength. This causes the elements in the surface of the sample to be energized, and to emit secondary, fluorescent x-rays. The wavelengths of the secondary x-rays are characteristic of the element producing them. The fluorescent x-rays from the sample are first caused to pass through a crystal, which serves to diffract the beam into a spectrum of x-rays of discrete wavelengths. The intensity of any given wavelength (selected to represent the element of interest) is then measured by highly sensitive detectors such as scintillation counters. Cumulative emission energy values for the selected wavelength are automatically recorded and displayed in percentage units.

Atomic Absorption Analysis

With atomic absorption analysis, metallic samples are first dissolved, usually in acids, to form solutions of metallic salts. The solution to be tested is introduced slowly, as a fine mist, into the combustion chamber of the apparatus where it is exposed to the intense heat of an acetylene flame. The heat of the flame destroys the molecular bonds of the chemical compounds in the solution and releases free metal atoms into the flame.

Light of a selected wavelength, characteristic of the metal being analyzed, is then passed through the flame and caused to fall on a photoelectric device. This light is produced by a hollow cathode lamp, a different lamp being required for each metal. For comparison purposes, a separate beam of light from the lamp falls directly on the sensor, without passing through the flame.

Because of the metal atoms in the flame, a greater or lesser amount of the light from the lamp will be absorbed as it passes through, depending upon the concentration of the metal present. The degree of absorption can be measured and recorded as a percentage value.

Since only one element at a time can be analyzed, this method is more time-consuming than is spectroscopy, although it is somewhat more sensitive and can be applied to wider ranges of analysis without problems of recalibration. Greater automation can be achieved by use of systems incorporating microprocessors, at somewhat greater initial cost.

Inductive Couple Plasma Analysis

Very recently the foundry industry has seen the use of the inductive couple plasma (ICP) system of analysis. Sample preparation is similar to that for atomic absorption analysis; however, excitation of the sample is accomplished using a plasma-arc discharge in an inert gas such as argon. Analysis of the energized sample resembles that of mass spectroscopy. In spite of its versatility, the system is relatively expensive and sophisticated and may find greater initial use in commercial laboratories or research centers.

For more detailed discussion of these and other methods of chemical analysis the reader is referred to the *Annual Book of ASTM Standards: Copper and Copper Alloys*.

MECHANICAL TESTING

The mechanical tests usually associated with copper base foundry alloys are those for tensile properties, hardness and, much less frequently, impact strength.

Tensile Properties

The factors governing choice of design for separately cast test-bars, as related to the different families of alloys, were discussed in earlier sections of this chapter. The significance of test-bar properties and the limited value of their interpretation compared with actual castings were also emphasized.

In nearly all cases, copper alloy test-bars require machining before testing. (Machining dimensions are given in *ASTM B208 Standard Practice for Preparing Tension Test Specimens for Copper Alloy Sand, Permanent Mold, Centrifugal, and Continuous Castings*.)

A wide variety of tensile testing machines of varying load capacity are available on today's market, many featuring microprocessors and automatic digital readout. These will not be discussed in detail here. Consideration should be given, however, to the recommended procedures for conducting the tensile test for copper-base alloys, as detailed in *ASTM Standard E8—Standard Test Methods for Tension Testing of Metallic Materials*. Many copper-base alloys are sensitive to strain rate (the rate of load application) so far as load-elongation behavior is concerned. This means that measurement of yield-strength by the offset method can be influenced by loading rate. Some copper-base alloys are notch sensitive and will have premature failure if not properly machined.

Hardness

In general, the hardness of an alloy is measured in terms of its resistance to penetration, or indentation under some specified indenter load. The Brinell test consists of forcing a hardened steel, or carbide ball of fixed diameter and under specified load, into the surface of a specimen. The diameter of the impression is a measure of the volume of metal displaced. This information, together with the load applied, is used to calculate a hardness number. In practice, the hardness number can be read directly from a tabular chart as a function of the average diameter of the hardness indentation.

The Rockwell hardness test likewise employs an indenter and a system for applying a selected load. Indenter size and material, as well as the size of the applied load, can be varied in accordance with the hardness range of the material being tested. The Rockwell test involves the application of an initial, minor load after which the scale of the instrument is set to zero. A major load is then applied, causing the scale reading to measure the distance of added indentation caused by application of the major load.

Although both tests find some application in the testing of copper-alloy castings, the Brinell test is generally found to be more reproducible and consistent since it employs a larger indenter that tends to "average out" variations in the cast structure such as grain size.

Hardness is related in a general way to strength, and therefore to chemical composition. This relationship is not precise enough to enable a prediction of ultimate strength or yield-strength from a hardness test alone. In some instances, however, the hardness value can be used with sufficient accuracy as the basis for sorting mixed batches of materials of different chemical composition or treatment.

For the large family of copper-tin-lead-zinc alloys, the utility of the hardness test is questionable. This is because the indentation resistance of these alloys is strongly affected by the presence of free lead in their microstructures, making it difficult to evaluate the true hardness of the matrix structure. For this reason a 500 Kg load is used on all wide-freezing range alloys.

On the other hand, hardness testing is particularly applicable to the high-strength manganese bronzes, aluminum bronzes and other copper alloys hardenable by heat treatment, such as the beryllium coppers and chromium coppers. Such tests are used regularly in control work, both as an indicator of proper chemical analysis and to check response to heat treatment.

It is imperative to understand that hardness numbers are for information only and should not be used to address acceptance criteria for castings. Hardness values obtained from castings are very unreliable. The main reason for this is that hardness values are dependent on many variables. Surface conditions, section thickness and solidification parameters

will have an effect on the hardness. ASTM B148 (Standard Specification for Aluminum-Bronze Sand Castings) dictates that hardness values are for information only and are to be obtained from the grip end of a separately cast test bar. The hardness values, published in this specification, are typical values and should not be mistaken for minimum requirements. If necessary, hardness values and test location of actual castings should be agreed upon prior to the issuance of a purchase order.

Impact Strength

Most copper-base alloys are inherently notch-tough and not subject to embrittlement at low temperatures. For this reason, measurement of impact strength is not a common requirement. The impact strength test involves measurement of the energy absorbed in the bending and/or breaking of a specimen by the blow of a swinging pendulum. The most common specimen design is the Charpy bar, having a 10 mm x 10 mm square cross section and provided with a notch at mid-length (the point of impact during testing). The notch may be in the form of a "V," as is the usual case for ductile materials, or may be keyhole-shaped. During testing, the specimen is held securely in an anvil which is designed to position the point of impact against the un-notched face in precise alignment with the centerline of the notch. The test is intended to give an indication of the resistance of the material to cracking and brittle failure under dynamic shock loading. For further details of specimen design and test procedure the reader is referred to the appropriate general ASTM standard covering the impact testing of metallic materials.

RADIOGRAPHIC INSPECTION

Radiographic examination of metallic objects is a means of observing internal defects non-destructively by using either x-rays or gamma-rays. The source of radiation may be an x-ray tube, designed to produce radiation of the desired wavelength and intensity, or may consist of a radioactive isotope that emits gamma rays. The density and thickness of the material to be examined as well as the relative severity of the defect to be detected will determine the type of radiation used.

Both x-ray and gamma-ray radiation have extremely short wavelengths, which are of the same order of magnitude as the spacing between the atoms comprising the crystalline structure of the metal casting. This permits the radiation to pass slowly through solid objects, at a rate which is proportional to the density of the material. In areas where the radiation encounters less dense structures such as voids or non-metallic inclusions, it passes through at a greater rate than elsewhere. Therefore, if a photosensitive material such as a fluorescent screen or photographic film is placed beneath the test piece, the location and shape of internal defects can be observed from the images formed by the variations in the degree of radiation which has passed through the test piece.

Effective use of radiography depends upon skillful application of test procedures and experience in the interpretation of radiographic images. As with any test, there are distinct limits to its sensitivity. This makes it most difficult, for example, to detect narrow cracks or seams in the test piece, however serious such defects may be.

Radiographic inspection tends to be slow and costly. These factors must be considered by both user and producer in terms of casting cost, and weighed against the value of the test in assessing the internal soundness of the parts. A foundry not experienced in making castings to radiographic standards of soundness should not assume that the only increment in cost will be that of the additional testing required. Production costs will also, as a minimum, include the replacement or salvage (if possible and permissible) of defective castings. It may be found, in fact, that the attainment of adequate internal soundness can be accomplished only by a significant change in foundry processes. In other words, some jobs may be found to exceed the process capability of the contracting foundry. Any foundry planning to produce high-integrity castings should first evaluate its ability to do so.

In the gating and risering of new castings which are unusually large, or which must be of high integrity, it is often economical and desirable to evaluate the soundness of pilot runs by means of radiographic examination. This can be cheaper in the long run than trial-and error changes made during production runs. Most commonly, of course, radiography is used as a verification procedure for final casting inspection, as part of the customer's purchase specification.

As is true for external defects, the internal soundness of a casting is never an absolute condition. Unsoundness is a matter of degree, and the perfect casting has yet to be made. It thus becomes the responsibility of the casting designer to decide, for each class of internal defect, what limits must be set on defect size and location to avoid undue risks of service failure. In some cases this can be considered by the designer as an awesome responsibility. Designers may tend to specify internal soundness standards so that no defect may be present beyond a level barely detectable by radiography. This provides the ultimate confidence possible, assuming that such conditions can be attained at all, regardless of cost and delivery requirements. More realistically, experienced designers recognize that some types of defects pose lesser hazards than do others and many can be innocuous when restricted to low-stress areas. On this basis, the American Society for Testing and Materials (ASTM) has developed and promulgated a series of visual radiographic standards, representing varying severity levels for each of several different classes of defects. Such standards can be used by the purchaser of castings to define specific levels of soundness required, as part of the purchase agreement. Figures 16-2 through 16-5 are included to illustrate radiographs showing internal unsoundness in different classes of copper alloys.

Foundries involved with radiographic inspection of castings, even those which do not have in-house equipment, should

familiarize themselves at least generally with techniques and interpretation. Recommended reading includes the following sections from the ASTM Standards:

E94 Standard Guide for Radiographic Examination

E272 Standard Reference Radiographs for High-Strength Copper-Base and Nickel-Copper Alloy Castings

E310 Standard Reference Radiographs for Tin Bronze Castings

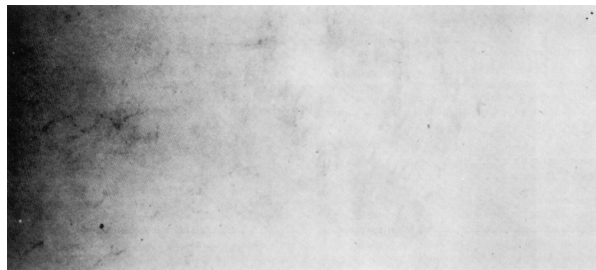


Fig. 16-2. A radiograph of manganese-aluminum-bronze showing feathery shrinkage is shown.

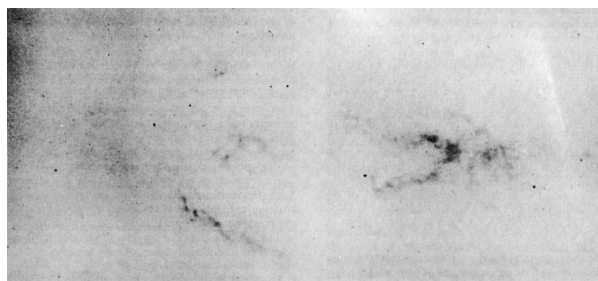


Fig. 16-3. A radiograph of manganese-aluminum-bronze showing spongy shrinkage

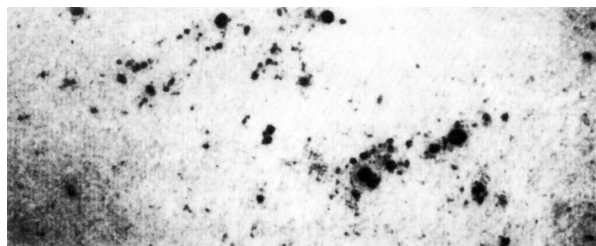


Fig. 16-4 This radiograph of tin bronze shows porosity.

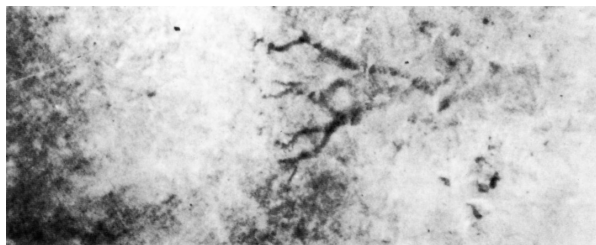


Fig. 16-5. This radiograph of tin bronze shows linear shrinkage.

METALLOGRAPHY

Metallography involves sectioning and polishing a metal sample, etching its surface to reveal its crystalline structure, and then analyzing the nature of this structure by observation under a microscope. Whereas sample preparation and photographing of microstructures can be accomplished by trained technicians, it usually requires a trained metallurgical engineer to interpret structural features which relate to quality standards as affected by process parameters. The reader is referred to E883—Standard Guide for Reflected-Light Photomicrography and ASTM E3-11 Standard Guide for Preparation of Metallographic Specimens both of which are contained in Part 11 of the *ASTM Annual Book of Standards*.

The importance of microscopic examination (most commonly at magnifications from 50x to 150x) lies in the fact that casting properties are strongly influenced by structural features such as grain size and shape, location and distribution of non-metallic inclusions, segregation, lead particle distribution, unwanted metallic compounds, and heterogeneous distribution of alloy phases. With copper-base alloys, some of the most common uses of microscopic examination are for monitoring the effects of heat treatment of aluminum bronzes, and verifying proper lead particle shape and distribution in the leaded bronzes.

Porosity, whether caused by shrinkage or gas, tends to be rather coarse in appearance and can best be evaluated at low magnifications of 5x to 15x. This is referred to as macroscopic examination. The same technique can be applied to polished surfaces or to deeply etched samples where the evaluation of dendritic freezing behavior is desired (or other large-scale features of the sample).

DYE PENETRANT INSPECTION

The dye penetrant procedure is designed to detect flaws which extend to the surface of the casting, but which may be difficult or impossible to see with the unaided eye. Cracks (hot tears) and seams (cold shuts, oxide film inclusions) are the principal kinds of defects which can be found by such inspection. Defects of this type are often critical under service stresses, where they may cause failure of the casting.

Castings to be inspected are first cleaned and dried to remove any interfering films of oil or other foreign material. The castings are then either sprayed with, or immersed in a tank of penetrant fluid—a material of low surface tension and containing either a brightly colored dye or a fluorescent material. The penetrant fluid is allowed to seep into exposed cracks and seams by capillary action. Parts are then cleaned thoroughly of excess penetrant, again dried, and then coated with a thin layer of developer—a quick-drying fluid containing a fine suspension of chalk-like material. The thin, porous coating formed when the developer dries acts as an ink blotter, causing any dye retained in cracks in the casting surface to seep out where it can be seen. Where fluorescent materials

are used in the penetrant (common in the mass inspection of small parts), inspection is done in a darkened area under an ultraviolet (black) light.

This inspection method is relatively inexpensive, can be mechanized to save time, and will reveal defects normally missed by both visual and radiographic inspection.

MISCELLANEOUS

Other special quality tests may sometimes be required. These may include the measurement of physical properties such as electrical conductivity (or resistivity), magnetic behavior, damping characteristics and thermal conductivity. Parts for corrosive applications may require tests to demonstrate their resistance to stress corrosion, dezincification or resistance to salt-spray or other environments designed to simulate accelerated service conditions.

No discussion of the control of quality of copper-base alloy castings would be complete without consideration of molding and coremaking materials and processes, which can be referred to in-depth in the chapter on *Casting Processes and Materials*.

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PROPERTIES OF CAST COPPER-BASE ALLOYS

This chapter covers, in tabular form, the various properties of commonly used cast copper-base alloys. Typical properties, as opposed to the minimum values mentioned in the various specifications in the chapter on *Standard Designations* and the chapter on *Conforming Specifications*, are dealt with herein.

Covered in this chapter are such mechanical and physical properties as tensile and yield strengths, modulus of elasticity, Brinell hardness, compression strength, impact strength, fatigue strength, electrical and thermal conductivity and specific gravity. These properties are shown in Table 17-1.

Tensile properties at elevated temperatures and cryogenic temperatures are listed in Tables 17-2 and 17-3, respectively.

Closely allied with these values are those for limiting creep-strength at elevated temperatures, as listed in Table 17-4. Although somewhat limited in scope, these data represent the major part of that which is available for cast copper-base alloys.

Other important properties compared for the most common alloys are machinability (Table 17-5), bearing and bushing characteristics (Table 17-6), and joining (welding, brazing, soldering) characteristics (Table 17-7).

Useful data on the corrosion resistance of copper base alloys in various chemical environments is shown in Table 17-8.

Table 17.1. Typical Properties of Copper-Base Alloys

UNS Number	Alloy Name	NOMINAL CHEMICAL ANALYSIS							TENSILE PROPERTIES			
		Cu	Sn	Pb	Zn	Fe	Al	Others	UTS, ksi	YS, ksi	Elong.	E, psi x 10 ⁶
C81100	Copper	100							28	4	45	17
C82500	Beryllium copper	97						2Be, .5Co	80	40	20	18
C83450	Leaded red brass	88	2.5	2	6.5			1 Ni	37	15	34	
C83600		85	5	5	5				38	16.5	34	12
C83800		83	4	5	7				36	16	30	
C84400	Leaded semi-red Brass	81	3	7	9				34	14	27	10
C84800		76	2.5	6.5	15				38	14.9	37	15
C85200	Leaded yellow Brass	72	1	3	24				38	13	40	13
C85400		67	1	3	29				34	12	35	13
C85700		61	1	1	37		.3		52	18	50	
C86200	Manganese bronze	64			26	3	4	3 Mn	94	48	22	15
C86300		61			23	3	6	3 Mn	120	69	16	14
C86400		58		1	38	1	.5	.5 Mn	69	26	23	13
C86500		58			39	1	1	1 Mn	72	30	37	15
C87500	Silicon brass	82			14			4 Si	67	32	20	15
C90300	Tin bronze	88	10		2				48	21	36	15
C90500		88	8		4				47	20	38	15
C92200	Leaded tin bronze	88	6	1.5	4.5				42	18	43	13
C92300		87	8	1	4				44	18	35	14
C92600		87	10	1	2				44	20	32	14
C93200	High-leaded tin Bronze	83	7	7	3				40	18	35	15
C93500		85	5	9	1				35	17	30	12
C93700		80	10	10					39	18	30	12
C93800		78	7	15					34	17	30	10
C94300		71	5	25					27	14	20	11
C95200	Aluminum bronze	88				3	9		82	27	40	17
C95300		89				1	10		77	28	21	16
C95400		85				4	11		90	35	15	18
C95500		81				4	11	4 Ni	102	43	11	19
C95800		81.3				4	9	4.5Ni, 1.2 Mn	96	38	25	19
C96400	Cupronickel 30%	67				1		30Ni	70	40	25	21
C96800	Spinodal Cu-Ni-Sn	Re.	8	0.005	1	0.50		10Ni, 0.2Nb	125	100	3	
C97300	Leaded nickel Silver	57	2	9	20			12 Ni	39	17	35	16
C97400		60	3	5	16			16 Ni	40	17	30	16
C97600		64	4	4	8			20 Ni	48	26	22	19
C97800		66	5	2	2			25 Ni	58	33	15	19

E=modulus of elasticity

Table 17.1. Typical Properties of Copper-Base Alloys (cont'd)

UNS Number	Alloy Name	COMPRESSION		Bhn	Impact* ft. lbs.	Fatigue str.** , ksi.	Spec. gravity	Thermal cond. % of copper	Electrical cond. % IACS
		.001 in. set	.010 in. set						
C81100	Copper			40	C-45		8.9	100	100
C82500	Beryllium copper			150			8.3	30	20
C83450	Leaded red brass	10	14	55		13	8.8		20
C83600		14	18	65	C - 11	11	8.8	18	15
C83800		12		63	I - 8		8.7	18	15.2
C84400	Leaded semi-red brass			55			8.7	18	16.6
C84800		13	16	58	C - 12	11	8.8	18	16.5
C85200	Leaded yellow brass	9		46			8.5	21	18.6
C85400		9		55			8.5	23	19.6
C85700				77			8.4	22	21.8
C86200	Manganese bronze	50		180	I-12		7.9	9	7.4
C86300		71	97	235	C - 14	25	7.7	9	7.7
C86400		23		88	I-30		8.2	22	19.3
C86500		24	35	130	C - 30	21	8.3	22	21.5
C87500	Silicon brass	27	43	120	C - 32	22	8.3	7	6.5
C90300	Tin bronze			80	I-10	13	8.7	19	10.9
C90500		13		70	C - 14		8.7	19	12.4
C92200	Leaded tin bronze	15	18	64	C - 19	11	8.7	18	13.8
C92300		10		70	I-14		8.8	18	12.3
C92600		13		70	I - 9		8.8	13	10.8
C93200	High-leaded tin bronze			67		16	8.9	15	12.4
C93500		13		60	I - 8		8.9	17	14.9
C93700		18	22	65	C -11	13	9.0	12	10.0
C93800		15		61	I - 5	10	9.2	13	11.6
C94300		13		55	I - 5		9.4	16	9.0
C95200	Aluminum bronze	28		125	I-40	23	7.5	13	12.2
C95300		20		140	I-30	22	7.5	16	15.1
C95400				160	I-15	30	7.5	15	13.0
C95500				195	C-9	32	7.5	11	8.9
C95800		35	48	160	C-15	31	7.5	11	8.9
C96400	Cupronickel 30%		140	C-78	I - 8	8.9	8	8.9	
C97300	Leaded nickel silver			60			8.9	7	6.5
C97400				65			8.9	7	5.4
C97600		24	31	80	C-11	15	8.9	6	5.0
C97800				130			8.9	6	4.6

* I = Izod; C = Charpy ; ** = Endurance limit-100 million cycles

Table 17-2. Elevated Temperature Properties of Cast Copper Base-Alloys

		Temperature							
		80F (27C)			250F (121C)	300F (149C)	350F (177C)	400F (204C)	450F (232C)
UNS. No.	Alloy Name	TS	YS	%E	TS YS %E	TS YS %E	TS YS %E	TS YS %E	TS YS %E
C92200	Navy M	40	16	46	39.5 13 45				
C93700	80-10-10	39.5	17	30	33 15 21				30 15 18
C83600	85-5-5-5	35	15	31	32 14 27				30 12 26
C84400	81-3-7-9	30	12	25		25.5 10.2 18.5		24 9.8 16.8	
C84800	76-2½-6½-15	38	16	35				33 12 28	
C86500	Manganese bronze	71	30	40			54 30 60		44 30 53
C86300	Manganese bronze	118	68	19			105 67 22		91 63 29
C95400	Aluminum bronze	95	36	18				90 32.5 16	
C97600	20% Nickel silver	48	26	20				35 20 16	
C87500	Silicon brass	68	30	19					68 30 22
C95700	Mn-Al bronze	105	46	25		102 49 25			97 47 22
		Temperature							
		500F (260C)			550F (288C)	600F (316C)			
		TS YS %E			TS YS %E	TS YS %E			
C92200	Navy M				28 13 20				
C84400	81-3-7-9	22	9.5	16					
C84800	76-2½-6½-15				28 12 22				
C95400	Aluminum bronze					80 35 15			
C97600	Silicon bronze	34.5	12	21		29 12 15			
C87500	Silicon brass				56 30 12				
C95700	Mn-Al bronze	92	42	18					
TS – Tensile Strength ; YS – Yield Strength ; % E – Elongation, percent									

Table 17-3. Low Temperature Properties of Cast Copper-Base Alloys

		Temperature											
		80F (27C)			-40F (-40C)		-107F (177C)			-310F (190C)		-424F (-253C)	
UNS No.	Alloy Name	TS	YS	%E	TS YS %E		TS	YS	%E	TS YS %E		TS YS	%E
C90500	Navy G	40.2	18.6	31.3									
C92200	Navy M	40	16	46	42	20 45				45.3 30.5 15.3			
C92700	88-10-2-0	44		30						54 -- 12	60 –	9	
C93700	80-10-10	39.5	17	30	42	20 28							
C83600	85-5-5-5	35	15	31	39	18 39							
C84800	76-2 ½ -6½-15	38	16	35	40	18 35							
C86500	Manganese bronze	71	30	40	73	31 31							
C86300	Manganese bronze	118	68	19	120	70 15							
C95300	Aluminum bronze	70.3	29	33			85.9	42.6	25				
C97600	20% Nickel silver	48	26	20	51	30 22							
C87500	Silicon brass	68	30	19	69	32 19							
C95700	Mn-Al bronze	105	46	25			116	55	28	129 62 15			
TS – Tensile Strength ; YS – Yield Strength ; % E – Elongation, percent													

Table 17-4. Limiting Creep Strength of Cast Copper-Base Alloys

UNS No. Alloy Name	Creep Strength, ksi								
	250F	350F	450F	500F	550F	600F	700F	800F	900F
	(121C)	(177C)	(232C)	(260C)	(288C)	(316C)	(371C)	(427C)	(482C)
C92200 Navy M		16.0	11.2		6.2				
C93700 80-10-10		10.4	7.4		1.8				
C836QO 85-5-5-5		12.5	11.1		7.0				
C84800 76-2½-6½-15		11.9	8.0		3.0				
C86500 Manganese bronze	28.0	6.2	1.7						
C86300 Manganese bronze	56.5	19.0	0.5						
C97600 20% Nickel silver			32.5		22.2				
C87500 Silicon brass		28.0	11.0		1.4				
C95700 Mn-Al bronze				20.4		4.2	2.3		
C95200 Aluminum bronze (88-3-9)				7.2			4.6	1.6	1.4
C95400 Aluminum bronze (86-4-10)						7.4	4.0	2.3	1.2
C95500 Aluminum bronze (81-4-11-4)						10.5	5.5	2.4	

UNS No. Alloy Name	Creep Strength, ksi (for creep rate of 1.0% per 10,000 hr)			
	250F	350F	450F	550F
	(121C)	(177C)	(232C)	(288C)
C92200 Navy M		25.6	14.1	10.2
C93700 80-10-10		15.9	11.0	4.2
C83600 85-5-5-5		22.3	13.5	9.9
C84800 76-2½-6½-15		16.4	13.0	8.0
C86500 Manganese bronze	35.2	9.6	4.2	
C86300 Manganese bronze		29.0	4.4	
C87500 Silicon brass		38.0	19.3	6.8

Table 17-5. Machinability Ratings of Several Copper Casting Alloys

UNS number	Common name	Machinability
Group 1-Free-cutting Alloys	Leaded red brass	90
C83800	Leaded red brass	90
C84400	Leaded semi-red brass	90
C84800	Leaded semi-red brass	90
C94300	High-leaded tin bronze	90
C85200	Leaded yellow brass	80
C85400	Leaded yellow brass	80
C93700	High-leaded tin bronze	80
C93800	High-leaded tin bronze	80
C93200	High-leaded tin bronze	70
C93500	High-leaded tin bronze	70
C97300	Leaded nickel brass	70
Group 2-Moderately Machinable Alloys	Leaded high-strength manganese bronze	60
C92200	Leaded tin bronze	60
C92300	Leaded tin bronze	60
C90300	Tin bronze	50
C90500	Tin bronze	50
C95600	Silicon-aluminum bronze	50
C95300	Aluminum bronze	35
C86500	High-strength manganese bronze	30
Group 3-Hard-to-Machine Alloys	High-strength manganese bronze	20
C95200	9% aluminum bronze	20
C95400	11 % aluminum bronze	20
C95500	Nickel-aluminum bronze	20

Table 17-6. Bearing and Bushing Properties of Copper-Base Casting Alloys

Leaded materials in order of decreasing lead	UNS Number	Chemical composition				Brinell Hardness	Compressive Yield Strength					
		Cu	Sn	Pb	Zn			Higher Speeds to Lower Speeds	Lower Loads to Higher Loads	Lower Operating Temperatures to Higher Operating Temperatures	More Abrasive Conditions to Less Abrasive Conditions	Lower Shaft Hardness to Higher Shaft Hardness
Leaded Tin Bronzes	C94300	70	5	25		48	14,000					
	C93800	78	7	15		55	16,000					
	C93700	80	10	10	63		20,000					
	C93200	83	7	7	3	60	21,000					
	C83600	85	5	5	5	60	16,000					
	C92700	88	10	2		70	32,000					
Non-Leaded Tin Bronzes	C90500	88	10	0	2	65	26,000					
	C90300	88	8	0	4	68	25,000					
Aluminum Bronze	C95400	88	(Fe) 4	(Al) 11		195	31,000					

Table 17-7. Joining Characteristics of Copper-Base Casting Alloys

UNS No.	Alloy Name	Inert Gas Tungsten Arc Weldability	Inert Gas Consumable Arc Weldability	Oxy- Acetylene Weldability	Carbon Arc Weldability	Metal Arc Weldability	Brazeability	Solderability
C90300	Tin bronze	B	B	B	B	B	A	A
C90500								
C92200	Leaded tin bronze	B	B	B	B	B	A	A
C92300								
C93200	High-leaded tin bronze	C	C	C	C	C	A	A
C93500								
C93700								
C93800								
C94300								
C83600	Leaded red brass	C	C	C	C	B	A	A
C83800								
C84400	Leaded semi-red brass	C	C	C	C	B	A	A
C84800								
C85200	Leaded yellow brass	C	C	C	C	C	B	A
C85400								
C86400	Leaded Mn bronze	C	C	C	C	C	B	A
C86200	Manganese bronze	A	A	A	A	A	A	A
C86300								
C86500								
C95200	Aluminum bronze	A	A	B	B	A	C*	C*
C95300	Aluminum bronze (as cast)	A	A	A	A	A	C*	C*
C95400								
C95500								
C97300	Leaded Ni silver	C	C	C	C	C	B	A
C97400								
C97600								
C97800								
C87500	Silicon brass	B	B	B	-	-	B	C
C96400	Cupronickel (70-30)	A	A	A	-	A	A	A
C81100	Copper (deoxidized)	A	A	A	B	-	A	A
A = Good; B = Fair; C = Poor; * = with special flux								

Table 17-8. Corrosion Ratings of Cast Copper Metals in Various Media

Corrosive medium	Copper	Tin bronze	Leaded tin bronze	High-leaded tin bronze	Leaded red brass	Leaded semi-red brass	Leaded yellow brass	Leaded high strength yellow brass	High strength yellow brass	Aluminum bronze	Leaded nickel brass	Leaded nickel bronze	Silicon bronze	Silicon brass
Acetate solvents	B	A	A	A	A	A	B	A	A	A	A	A	A	B
<u>Acetic acid</u>														
20%	A	C	B	C	B	C	C	C	C	A	C	A	A	B
50%	A	C	B	C	B	C	C	C	C	A	C	B	A	B
Glacial	A	A	A	C	A	C	C	C	C	A	B	B	A	A
Acetone	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Acetylene (a)	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Alcohols (b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Aluminum chloride	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Aluminum sulfate	B	B	B	B	B	C	C	C	C	A	C	C	A	A
Ammonia, moist gas	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonia, moisture-free	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ammonium chloride	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonium hydroxide	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonium nitrate	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ammonium sulfate	B	B	B	B	B	C	C	C	C	A	C	C	A	A
Aniline and aniline dyes	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Asphalt	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Barium chloride	A	A	A	A	A	C	C	C	C	A	A	A	A	C
Barium sulfide	C	C	C	C	C	C	C	C	B	C	C	C	C	C
Beer (b)	A	A	B	B	B	C	C	C	A	A	C	A	A	B
Beet sugar syrup	A	A	B	B	B	A	A	A	B	A	A	A	B	8

Table 17-8. Corrosion Ratings of Cast Copper Metals in Various Media (cont'd)

Benzene	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Benzoyl	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Boric acid	A	A	A	A	A	A	A	B	A	A	A	A	A	A
Butane	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Calcium bisulfite	A	A	B	B	B	C	C	C	C	A	B	A	A	B
Calcium chloride (acid)	B	B	B	B	B	B	C	C	C	A	C	C	A	C
Calcium chloride (alkaline)	C	C	C	C	C	C	C	C	C	A	C	A	C	B
Calcium hydroxide	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Calcium hypochlorite	C	C	B	B	B	C	C	C	C	B	C	C	C	C
Cane sugar syrups	A	A	B	A	B	A	A	A	A	A	A	A	A	B
Carbonated beverages (b)	A	C	C	C	C	C	C	C	C	A	C	C	A	C
Carbon dioxide, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Carbon dioxide, moist (b)	B	B	B	C	B	C	C	C	C	A	C	A	A	B
Carbon tetrachloride, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Carbon tetrachloride, Moist	B	B	B	B	B	B	B	B	B	B	B	A	A	A
Chlorine, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Chlorine, moist	C	C	B	B	B	C	C	C	C	C	C	C	C	C
Chromic acid	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Citric acid	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Copper sulfate	B	A	A	A	A	C	C	C	C	B	B	B	A	A
Cottonseed oil (b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Creosote	B	B	B	B	B	C	C	C	C	A	B	B	B	B
Ethers	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ethylene glycol	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Ferric chloride, sulfate	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Ferrous chloride, sulfate	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Formaldehyde	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Formic acid	A	A	A	A	A	B	B	B	B	A	B	B	B	C

Table 17-8. Corrosion Ratings of Cast Copper Metals in Various Media (cont'd)

Freon	A	A	A	A	A	A	A	A	A	A	A	A	A	B
Fuel oil	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Furfural	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Gasoline	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Gelatin	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glucose	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glue	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Glycerin	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydrochloric or muriatic acid	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Hydrofluoric acid	8	B	B	B	B	B	B	B	B	A	B	B	8	B
Hydrofluosilicic acid	B	B	B	B	B	C	C	C	C	B	C	C	B	C
Hydrogen	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydrogen peroxide	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Hydrogen sulfide, dry	C	C	C	C	C	C	C	C	C	B	C	C	B	C
Hydrogen sulfide, moist	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Lacquers	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Lacquer thinners	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Lactic acid	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Linseed oil	A	A	A	A	A	A	A	A	A	A	A	A	A	A
<u>Liquors</u>														
Black liquor	B	B	B	B	B	C	C	C	C	B	C	C	B	B
Green liquor	C	C	C	C	C	C	C	C	C	B	C	C	C	B
White liquor	C	C	C	C	C	C	C	C	C	A	C	C	C	B
Magnesium chloride	A	A	A	A	A	C	C	C	C	A	C	C	A	B
Magnesium hydroxide	B	B	B	B	B	B	B	B	B	A	B	B	B	B
Magnesium sulfate	A	A	A	A	B	C	C	C	C	A	C	B	A	B
Mercury, mercury salts	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Milk (b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Molasses (b)	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Natural gas	A	A	A	A	A	A	A	A	A	A	A	A	A	A

Table 17-8. Corrosion Ratings of Cast Copper Metals in Various Media (cont'd)

Nickel chloride	A	A	A	A	A	C	C	C	C	B	C	C	A	C
Nickel sulfate	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Nitric acid	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Oleic acid	A	A	B	B	B	C	C	C	C	A	C	A	A	B
Oxalic acid	A	A	B	B	B	C	C	C	C	A	C	A	A	B
Phosphoric acid	A	A	A	A	A	C	C	C	C	A	C	A	A	A
Picric acid	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Potassium chloride	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Potassium cyanide	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Potassium hydroxide	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Potassium sulfate	A	A	A	A	A	C	C	C	C	A	C	C	A	C
Propane gas	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Seawater	A	A	A	A	A	C	C	C	C	A	C	C	B	B
Soap solutions	A	A	A	A	B	C	C	C	C	A	C	C	A	C
Sodium bicarbonate	A	A	A	A	A	A	A	A	A	A	A	A	A	B
Sodium bisulfate	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Sodium carbonate	C	A	A	A	A	C	C	C	C	A	C	C	C	A
Sodium chloride	A	A	A	A	A	B	C	C	C	A	C	C	A	C
Sodium cyanide	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Sodium hydroxide	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Sodium hypochloride	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Sodium nitrate	B	B	B	B	B	B	B	B	B	A	B	B	A	A
Sodium peroxide	B	B	B	B	B	B	B	B	B	B	B	B	B	B
Sodium phosphate	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sodium sulfate, silicate	A	A	B	B	B	B	C	C	C	A	C	C	A	B
Sodium sulfide, thiosulfate	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Stearic acid	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sulfur, solid	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Sulfur chloride	C	C	C	C	C	C	C	C	C	C	C	C	C	C

Table 17-8. Corrosion Ratings of Cast Copper Metals in Various Media (cont'd)

Sulfur dioxide, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Sulfur dioxide, moist	A	A	A	B	B	C	C	C	C	A	C	C	A	B
Sulfur trioxide, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
<u>Sulfuric Acid</u>														
78% or less	B	B	B	B	B	C	C	C	C	A	C	C	B	B
78% to 90%	C	C	C	C	C	C	C	C	C	B	C	C	C	C
90% to 95%	C	C	C	C	C	C	C	C	C	B	C	C	C	C
Fuming	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Tannic acid	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Tartaric acid	B	A	A	A	A	A	A	A	A	A	A	A	A	A
Toluene	B	B	A	A	A	B	B	B	B	B	B	B	B	A
Trichloroethylene, dry	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Trichloroethylene, moist	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Turpentine	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Varnish	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Vinegar	A	A	B	B	B	C	C	C	C	B	C	C	A	B
Water, acid mine	c	C	C	C	C	C	C	C	C	C	C	C	C	C
Water, condensate	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Water, potable	A	A	A	A	A	A	B	B	B	A	A	A	A	A
Whiskey (b)	A	A	C	C	C	C	C	C	C	A	C	C	A	C
Zinc chloride	C	C	C	C	C	C	C	C	C	B	C	C	B	C
Zinc sulfate	A	A	A	A	A	C	C	C	C	B	C	A	A	C

Note:

Ratings: A = recommended; B = acceptable; C = not recommended.

(a) Acetylene forms an explosive compound with copper when moist or when certain impurities are present and the gas is under pressure. Alloys containing less than 65% Cu are satisfactory under this use. When gas is not under pressure other copper alloys are satisfactory.

(b) Copper and copper alloys resist corrosions by most food products. Traces of copper may be dissolved and affect taste or color. In such cases, copper metals are often tin coated.

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HEALTH AND SAFETY ASPECTS OF COPPER-BASE ALLOY FOUNDRY PRACTICE

ATMOSPHERIC CONTAMINANTS

Metals

Many metals are used in the manufacture of copper base alloys. Exposures above federal or state occupational limits for these metals can present a health hazard. The effects of these different metals are considered individually in this chapter.

Beryllium

Beryllium (Be) is a gray-white, brittle, extremely toxic metallic element similar in appearance to magnesium and is usually encountered in foundry copper alloys. It has a melting point of 2343F (1284C) and a boiling point of 5036F (2780C). Beryllium can be generated as an air contaminant in melting, pouring, cleaning and machining operations. Processing of alloys containing only 2% beryllium can result in excessive exposures if proper engineering controls are not provided. Improper cleaning techniques of exhaust systems or air-cleaning apparatus can result in high exposures to beryllium and/or its oxides.

Because of the extreme toxicity of beryllium, copper beryllium alloys must be produced only under stringent environmental control in all stages of manufacturing (see Table 18-1 for Occupational Health & Safety Administration (OSHA), Permissible Exposure Limits (PELs). Exposure to airborne beryllium or a beryllium compound can cause berylliosis, a disease that is characterized by a serious (immediate or delayed) reaction in the lungs and, in some cases, by death. Chills, fever, painful cough and accumulation of fluid in the lungs are common symptoms related to this reaction. Long-term effects can be progressive in severity and can persist for years after cessation of exposure. In other cases, symptoms may not appear for long periods following exposure.

Copper

Copper (Cu) is a reddish-brown, ductile, malleable metal that occurs in nature as free copper or as a sulfide ore. It has a melting point of 1981F (1083C) and a boiling point of 4703F (2595C). Because of its very high electrical and thermal conductivity, it is a principal constituent in a wide

range of alloys used in the manufacture of cooking utensils, pipe, electrical wires, tubing and bars.

In the foundry, copper metal is found in ingot form, as scrap in the melt room, as a fume during melting and pouring and as a dust during cutting and grinding operations. Because of copper's high boiling point, the concentration of copper fume generated during foundry melting and pouring operations does not usually exceed the exposure limit. Excessive fume exposure, which can cause upper respiratory tract irritation and "metal fume fever," is more commonly encountered in welding copper alloys.

Inhalation of copper dust can also cause upper respiratory tract irritation, but this is a nonspecific reaction to the inhaled dust as a foreign substance in the respiratory system. Skin contact with the dust, especially in the presence of perspiration, can cause skin discoloration but it does not usually cause irritation. Excessive airborne concentrations of copper dust can cause nose bleeds. There is no evidence that exposure above federal or state limits for copper fume or dust causes chronic poisoning. If exposure to copper salts is heavy or prolonged, it can cause severe local irritation to the skin or eyes upon direct contact, to the nasal septum if inhaled, or to the stomach lining if swallowed.

Lead

Lead (Pb) is a bluish-gray, heavy metal with a relatively high density (11.29). It has a melting point of 621F (327C) and a boiling point of 3137F (1725C). It is added to copper-base alloys to improve free machining qualities and to reduce porosity. Exposures to lead fume during melting and pouring and to lead dust during cleaning operations may be excessive, even though the percentage of lead in the alloy may be relatively small (e.g., less than 5%).

Lead is readily absorbed into the blood, primarily by inhalation of the fume or dust and, to a lesser degree, by ingestion. Symptoms of lead intoxication, such as colic and constipation, usually involve the gastrointestinal tract. Other symptoms, such as loss of appetite, metallic taste in the mouth, anemia, pallor, weakness, insomnia, headache, nervous irritability, muscle and joint pains and fine tremors may also be present. Lead has a specific OSHA Health Standard; see 29CFR 1910.1025 for complete conformance requirements.

Table 18-1. OSHA Permissible Exposure Limits (PELs)

Substance	CAS No.	PEL (TWA)
Acrolein	107-02-8	0.1 ppm
Ammonia	7664-41-7	50 ppm
Beryllium	7440-41-7	2 µg/m ³
Cadmium	7440-43-9	2.5 µg/m ³ (AL)
(See 29 CFR 1910.1027)		5.0 µg/m ³ (PEL)
Carbon Dioxide	124-38-9	5000 ppm
Carbon Monoxide	630-08-0	50 ppm
Copper (Fume)	7440-50-8	0.1 mg/m ³
(Dusts & Mists)	" "	1.0 mg/m ³
Dimethylamine (DEMA)	124-40-3	10.0 ppm
Ethyl Alcohol (Ethanol)	64-17-5	1000 ppm
Formaldehyde	50-00-0	0.10 ppm (Training level)
(See 29 CFR 1910.1048)		0.50 ppm (AL)
		0.75 ppm (PEL)
Furfuryl Alcohol	98-00-0	50 ppm
Hexamethylenetetramine-formaldehyde	—	(No established limit) liberates ammonia on decomposition
Isopropyl Alcohol (2-Propanol)	67-63-0	400 ppm
Lead (See 29 CFR 1910.1025)	7439-92-1	30.0 µg/m ³ (AL)
		50.0 µg/m ³ (PEL)
Manganese	7439-96-3	5.0 mg/m ³ (C)
Methyl Alcohol (Methanol)	67-56-1	200 ppm
Methylene Bisphenyl Isocyanate (MDI)	101-68-8	0.02 ppm (C)
Nuisance Dust		
Respirable Fraction	—	5 mg/m ³
Total Dust	—	15 mg/m ³
Phenol	108-95-2	5 ppm
Phosphoric Acid	7664-38-2	1.0 mg/m ³
Silica Crystalline		
Quartz (Respirable)	14808-60-7	$\frac{10 \text{ mg/m}^3}{\% \text{ SiO}_2 + 2}$
Cristobalite (Respirable)	14464-46-1	$\frac{10 \text{ mg/m}^3}{\% \text{ Quartz} + 2(\% \text{ Cristobalite}) + 2}$
Silicones	—	15mg/m ³ (Total Dust)
		5 mg/m ³ (Resp. Dust)
Sodium Silicate	—	(No established limit)
Sulfuric Acid	7664-93-9	1 mg/m ³
Tin (Inorganic compound)	7440-31-5	2.0 mg/m ³
Tin (Organic compounds as Sn)	7440-31-5	0.1 mg/m ³
Toluene-2,4 diisocyanate (TDI)	584-84-9	0.02 ppm (C)
Toluene	108-88-3	200 ppm
Triethylamine (TEA)	121-44-8	25 ppm
Urea	—	(No established limit) liberates ammonia on decomposition.
Zinc Oxide Fume	1314-13-2	5 mg/m ³

Legend

TWA	8-hour time-weighted average
CAS No.	Chemical Abstract Service Number
(C)	Ceiling value should not be exceeded in any part of the working day
ppm	Parts per million
mg/m ³	Milligrams per cubic meter
µg/m ³	Micrograms per cubic meter
AL	Action Level
PEL	Permissible Exposure Limit
ACGIH	American Council of Governmental Industrial
TLV	Threshold Limit Value
OSHA	Occupational Safety & Health Administration

Manganese

Manganese (Mn) is a silvery-gray, hard and brittle metal mined as a manganese oxide, carbonate, sulfide, or silicate ore. It is usually reduced to the oxide and purified by electrolysis. It has a melting point of 2275F (1246C) and a boiling point of 3563F (1962C). Manganese is used as a constituent in copper alloys, such as manganese bronze and high-manganese aluminum bronzes that may contain up to 14% manganese, special alloys may contain more.

Inhalation of the dust in plants processing manganese ore or producing ferromanganese alloys, offers the highest potential for overexposure. In the foundry, the potential for excessive exposure is related to the manganese content of the alloy. Exposure can be greatest at welding and cutting operations; to a lesser extent, excessive exposures are possible at melting and pouring operations.

Manganism (manganese poisoning) is predominantly a chronic disease occurring after repeated heavy exposure to dust or fumes. The chief symptoms are related to central nervous system damage—headache, apathy, muscle weakness or rigidity, mental confusion, hallucinations— and may be irreversible in advanced cases. Pneumonitis (lung inflammation) has also been observed in persons heavily exposed to fine dusts or fumes.

Tin

Tin is a soft, pliable, silvery-white metal found in many copper-based alloys. It has a melting point of 450F (232C) and a high boiling point of 4118F (2270C). Inhalation of tin fume leads to a benign pneumoconiosis (stannosis) and cases have been known to occur among foundry workers. Tin fume deposits in the lung can be detected as opaque shadows upon x-ray examination. The deposits are non-disfiguring and non-disabling and do not interfere with lung function.

Because of the high boiling point, tin usually does not present a problem in the bronze foundry. The nodular-like shadows seen on x-ray in cases of stannosis may be confused with the fibrotic nodules caused by overexposure to other dusts, such as silica.

Zinc

Zinc is a silvery metal of low to intermediate hardness. It has a melting point of 787F (419C) and a boiling point of 1665F (907C). Zinc oxide (ZnO) is a powdery, white fume generated at melting, pouring, welding, burning and cutting of zinc, zinc alloys, brasses and nickel silver (particularly yellow and high tensile).

Excessive exposure to freshly-formed zinc oxide fume can cause metal fume fever. This is often called by other names such as “brass chills,” “foundry shakes,” and “Monday morning fever.” The symptoms of chills and fever usually occur a

few hours after exposure and are of short duration, usually lasting less than 24 hours. A temporary period of immunity follows; however, this is ordinarily lost after a few days without exposure. Although no known permanent effects are suffered as a result of exposure, it is important that a proper diagnosis be made, since more serious types of metal poisoning often display the same or similar symptoms.

The occurrence of “brass chills” indicates the potential overexposure to other elements carried over with the zinc fume and the need for more effective fume control and employee training.

CHEMICAL VAPORS AND GASES FROM RESINOUS BINDERS

Many different resinous binder systems are used in the manufacture of copper-base alloy castings. Each binder system is unique and consists of various chemical components. During mixing, molding and coremaking, liberation of the chemical components can occur if the sand temperature is too high and airborne concentrations of these materials will increase with increased sand temperature. Exposures to some of these chemicals, as well as their thermal decomposition products, can present a health hazard.

Carbon monoxide is the principal hazard of these thermal decomposition products, although some of the other decomposition products may present a health hazard if excessive exposures occur. The specific decomposition products will be a function of the binder system used. The effects of the different resinous binder systems and their chemical components are considered individually in the following paragraphs.

Acrolein

Acrolein (C₃H₄O) is a colorless to yellowish liquid with a pungent, disagreeable odor. It is an ingredient in one variety of tear gas. In foundries, acrolein vapor may be formed by the thermal decomposition of the vegetable oils that are present in many core oils. Employees can be exposed to acrolein while unloading core ovens or at pouring and/or shakeout operations where oil sand cores are at the concentrations normally encountered in foundries, acrolein can cause irritation of the eyes and nose. Serious cases of overexposure are rare, because intense irritation at higher levels causes the employee to avoid exposure. The odor threshold of acrolein is slightly higher than the exposure limit.

Amines

I. Description and Use

Amines are organic nitrogen compounds related to ammonia which are used as catalysts for organic binder systems. The amines most often used are triethylamine (TEA), dimethylethylamine (DMEA) and hexamethylenetetramine (HEXA).

Amine	Binder System
Triethylamine (TEA)	Phenolic Urethane (coldbox) Alkyd oil-Urethane (nobake)
Dimethylethylamine (DMEA)	Phenolic Urethane (coldbox)
N,N-Dimethylisopropylamine (DMIPA)	Phenolic Urethane (coldbox)
Hexamethylenetetramine (HEXA)	Shell Process
Triethylene diamine	Alkyd oil-Urethane (nobake)
Aryl-substituted pyridine	Phenolic-Urethane (nobake)

Ammonia is derived from HEXA as a by-product of the curing reaction in the shell sand process.

II. Exposure Limits

Material	CAS No.	OSHA-PEL	ACGIH-TLV
TEA	121-44-8	25 ppm	1 ppm (Triethylamine TEA)
Ammonia	7664-41-7	50 ppm	25 ppm
DMEA	124-40-3	10 ppm	5 ppm (Dimethylamine (DMEA))
DMIPA	996-35-0	None	None (N,N-Dimethylisopropylamine)
HEXA	100-97-0	None	None (Hexamethylenetetramine [HEXA])
Aryl-substituted Pyridine	None	None	None

See legend, p. 304

III. Physical and Health Hazards

TEA, DMEA and DMIPA are liquids at 68F (20C) and are highly flammable. All of these amines are irritating to the eyes and the upper respiratory tract. Contact with the eyes can cause severe chemical burns. TEA, DMEA and DMIPA can be absorbed through the skin and skin contact can cause chemical burns.

TEA, DMEA and DMIPA vapors are known to cause corneal edema, which causes foggy vision and the appearance of a halo when looking at lights. All of these amines have a strong odor, detectable at concentrations well below the OSHA and ACGIH exposure limits, which clearly indicates their presence.

HEXA is a powdery crystalline solid at 68F (20C). Prolonged skin contact with HEXA can cause skin irritation. Continued exposure may lead to sensitization in some individuals. Fine HEXA powder can present a dust explosion hazard.

In the presence of water, HEXA can decompose to formaldehyde and ammonia, especially when acids or heat are also

present. Ammonia is a gas that acts as an irritant to the eyes, skin and mucous membranes. At high concentrations, it can cause severe chemical burns, irritation of the respiratory tract and congestion. Formaldehyde is an eye and mucous membrane irritant and is a suspect carcinogen.

Aryl-substituted pyridines are usually liquids at 68F (20C). They are irritating to the eyes and the skin and emit a strong odor. Triethylenediamine is a solid crystal at 68F (20C). It has a strong odor and is irritating to the eyes, the upper respiratory tract and the skin. It may also sensitize the skin.

Triethylenediamine is a solid crystal at 68F (20C). It has a strong odor and is irritating to the eyes, the upper respiratory tract, and the skin. It may also sensitize the skin.

IV. Safe Use Procedures

Engineering Controls—local exhaust ventilation should be used to control vapors or airborne dust at the point of generation. For TEA and DMEA, a low-volume exhaust system with sealed core boxes is the best method of control. When

HEXA is used, local exhaust ventilation may be needed at the pouring, cooling and shakeout areas to control formaldehyde and ammonia, generated by the thermal decomposition when molten metal contacts HEXA.

Personal Protection Equipment—personal respiratory protective devices should be used when employee exposure cannot be adequately controlled by ventilation or in the interim period during which these controls are being installed. Since

virtually all amines are irritating to the eyes, a full-face piece respirator approved by National Institute for Occupational Safety and Health (NIOSH) should be used for protection against the amines in question. The respirator should be used in accordance with the Occupational Safety & Health Administration (OSHA) standard on respiratory protection (29 CFR 1910.134). Adequate protective clothing for an appropriate type, including gloves, should be used to prevent skin irritation and burns.

Epoxy Resins

I. Description and Use

Epoxy resins generally consist of a resin, a hardening or curing agent and catalyst. The two liquid components are mixed together shortly before use and cure by chemical polymerization. Sulfur dioxide gas is used as a catalyst for epoxy coldbox binder systems. Epoxy materials are usually found in the pattern shop, maintenance areas and core rooms.

II. Exposure Limits

None established for epoxy resins as a group. Exposure limits have been adopted for some of the components.

Material	CAS No.	OSHA-PEL	ACGIH-TLV
n-Butyl glycidyl ether (BGE)	2426-08-6	50 ppm	3 ppm
Ethylene glycol	107-21-1	None	100 mg/m ³ (C)
Epichlorohydrin	106-89-8	5 ppm	0.5 ppm
Diethylene triamine (Hardener)	111-40-0	None	1 ppm
Sulfur dioxide	7446-09-5	5 ppm	0.25 ppm
Triethylene tetramine (Hardener)	112-24-3	None	None

See legend, p. 304

III. Physical and Health Hazards

Epoxy resins in the completely cured state usually do not present a skin hazard. The principal hazard in epoxy resin systems is skin irritation as a result of skin contact with the curing agents, hardeners, catalysts and solvents used in these systems. Exposure to those agents in the uncured or partially cured resins can sensitize the individual, causing serious skin or asthmatic-like reactions. There can also be asthmatic-like reactions to some types of amine hardeners or catalysts, or to airborne contaminants generated by the cutting or grinding of cured resins.

IV. Safe Use Procedures

Engineering Controls—personal and workbench cleanliness are essential to prevent or minimize skin contact. Exhaust ventilation may be required in areas where resin and curing agents are mixed and in coremaking areas where sulfur dioxide is used.

Personal Protective Equipment—gloves and other protective clothing may be necessary to prevent skin contact.

Furan Binders

I. Description and Use

Furan binders are synthetic, thermosetting resins used to bond all types of sand for the production of cores and molds. They are used in the nobake, hotbox, warm box and coldbox processes. While they are marketed under a variety of proprietary names, furan binders are based on furfuryl alcohol. They may also include urea, formaldehyde, water, phenol or phenolic derivatives and many other chemicals, depending on the specific proprietary formula chosen.

Most furan binders are yellowish- to dark-colored liquids of moderate viscosity, with a mild sweet odor which can be

mildly irritating depending on the level of free formaldehyde in the resin. Nobake furans cure at room temperature with active catalysts; the catalyst may be aqueous and/or alcohol solutions of sulfonic acids (toluenesulfonic, TSA; benzene-sulfonic, BSA; etc.), or phosphoric acid (70 to 85% solution). Low percentages of sulfuric acid may also be present in the above catalysts. Heat and latent catalysts are used to cure furan hotbox and furan warm box binders. Furan coldbox binders are cured at room temperature with sulfur dioxide gas in the presence of an oxidizing agent.

II. Exposure Limits

	CAS No.	OSHA-PEL	ACGIH-TLV
Benzene*	71-43-2	1 ppm	0.5 ppm
Carbon Monoxide	630-08-0	50 ppm	25 ppm
Formaldehyde**	50-00-0	0.75 ppm 0.50 ppm (Action Level) 0.10 ppm (Training Level)	0.3 ppm(C)
Furfuryl Alcohol	98-00-0	50 ppm	10 ppm
Phenol	108-95-2	5 ppm	5 ppm
Phosphoric Acid	7664-38-2	1 mg/m ³	1 mg/m ³
Sulfur Dioxide	7446-09-5	5 ppm	0.25 ppm
Sulfuric Acid	7664-93-9	1 mg/m ³	0.2 mg/m ³
Toluene	108-88-3	200 ppm	20 ppm

* Benzene is regulated by OSHA Standard 29CFR1910.1028

** Formaldehyde is regulated by the OSHA Standard 29CFR1910.1048

See legend, p. 304

III. Physical and Health Hazards

Resins, and especially nobake catalysts, are potential eye and skin irritants. Exposures to furfuryl alcohol vapor and formaldehyde gas can occur during sand mixing and core-making. Vapors, especially formaldehyde and phenol, are eye and respiratory system irritants. The degree of exposure to vapors increases as the temperature of the sand exceeds 76F (24C). If the vapors from furan binders are breathed in excessive concentrations, narcosis can result with the person affected feeling inebriated and developing dizziness and headache. Prolonged or repeated contact with the skin can produce dermatitis and cause defatting which can leave the skin prone to other infection. The presence of residual amounts of free formaldehyde also could pose a potential sensitization problem for some individuals. High vapor concentrations also are irritating to the eyes and respiratory tract. Exposure to thermal decomposition products such as carbon monoxide can occur during pouring and shakeout.

IV. Safe Use Procedures

Engineering Controls—do not directly mix resin and catalyst. Without sand present, the reaction is rapid and hazardous due to expansion and heat release. All system components should be used in strict accordance with technical instructions.

Personal Protection—physical contact with resins and catalysts should be controlled by the use of protective equipment, such as gloves, aprons and goggles. In case of spills, label instructions should be followed carefully. When respiratory protection is indicated or required, respirators should be selected from those approved by the National Institute for Occupational Safety and Health (NIOSH). For further information, consult the Guide, "Respiratory Protection."

Hotbox Resins

I. Description and Use

Hot resins are liquid, synthetic, thermosetting resins used in combination with liquid or dry catalysts to produce hot-box cores. They may be characterized by strong phenol or formaldehyde odors and furfuryl alcohol odor. The resins can be phenol formaldehyde, urea-formaldehyde, furfuryl alcohol-formaldehyde, or combinations of these. The catalysts are usually combinations of salts, such as ammonium chloride or ammonium nitrate, with urea and water.

II. Exposure Limits

	Phenol	Formaldehyde*	Carbon Monoxide	Furfuryl Alcohol	Ammonia
CAS No.	108-95-2	50-00-0	630-08-0	98-00-0	7664-41-7
ACGIH-TLV	5 ppm	0.3 ppm (C)	25 ppm	10 ppm	25 ppm
OSHA-PEL	5 ppm	0.75 ppm 0.50 ppm Action Level 0.10 ppm Training Level	50 ppm	50 ppm	50 ppm

* Formaldehyde is regulated by OSHA Standard 29CFR1910.1048
See legend, p. 304

III. Physical and Health Hazards

Liquids—resins and catalysts in the uncured form can cause skin and eye irritation. Those containing phenol are noteworthy because phenol can be absorbed through the skin.

Mixing—excessive exposures to formaldehyde, phenol, furfuryl alcohol and ammonia may occur during mixing heat curing of hotbox resins.

Curing—during pouring, casting cooling and shakeout, excessive amounts of carbon monoxide, phenol and other gases and vapors may be generated.

IV. Safe Use Procedures

Engineering Controls—ventilation should be provided at mixers, core blowers, core cooling, pouring, casting cooling and shakeout areas as required to control exposures.

Personal Protection—wear appropriate protective clothing and gloves to avoid skin contact with resins and catalysts. If skin contact should result from an accident, the affected areas should be washed thoroughly with soap and water. Clothing wet with resins or catalysts should be immediately removed. When respiratory protection is indicated or required, respirators should be selected from those approved by NIOSH. For further information consult the “Guide to Industrial Respiratory Protection,” NIOSH 87-116.

Nobake Resins

I. Description and Use

Nobake resins or binders are used to bond sand for the production of cores and molds for the casting of all types of metals. Each of these resins is used in combination with a catalyst, which causes the resin to cure at room temperature. Some of the resins that are used as nobake binders are furans, phenolics, alkyds and urethanes (isocyanate-based), sodium silicates and aluminum phosphates.

II. Exposure Limits

For recommended exposure limits for the particular binder system or material being used, please see the specific Safety Data Sheet (SDS) for that binder or material.

III. Physical and Health Hazards

Physical contact with or exposure to gases or vapors from any of these binders may constitute a hazard. These binders can cause irritation of the eyes and skin, respiratory irritation, sensitization of the skin and respiratory tract and depression of the central nervous system including headache, dizziness, nausea, drowsiness, etc. Gases or vapors can be a hazard at sand mixing, coremaking, core baking or torching, metal pouring and shakeout stations.

For more specific information, see the Safety Data Sheet (SDS) for the particular binder system or material being used.

IV. Safe Use Procedures

Engineering Controls—exposures to gases or vapors should be controlled by engineering methods. Some nobake resin systems contain flammable components. Information concerning flammability and toxicity can be obtained from the SDS for the particular binder.

Personal Protection—gloves, aprons and goggles should be used as required to prevent contact with various resins and catalysts. When respiratory protection is indicated or required, respirators should be selected from those approved by NIOSH.

Phenolic Resins

I. Description and Use

Phenolic resins are synthetic, thermosetting resins used to bond sand for the production of cores and molds. They are used in baking applications, in the hotbox process, as nobake binders, in the shell sand process and in the coldbox process. Phenolic resins are made from phenol and formaldehyde

and are sometimes modified with urea, furfuryl alcohol or other substances. Solvents may also be present. A variety of catalysts are used with phenolic resins depending upon the application.

II. Exposure Limits

Material	CAS No.	OSHA-PEL	ACGIH-TLV
Phenol	108-95-2	5 ppm	5 ppm
Formaldehyde*	50-00-0	0.75 ppm* 0.50 ppm* (Action Level) 0.10 ppm* (Training Level)	0.3 ppm(C)
Ethyl alcohol (Ethanol)	64-17-5	1000 ppm	1000 ppm
Furfuryl alcohol	98-00-0	50 ppm	10 ppm

* Formaldehyde is regulated by OSHA Standard 29CFR1910.1048.
See legend, p. 304

III. Physical and Health Hazards

Baking Applications—phenol and formaldehyde can cause irritation of the eyes and respiratory tract. Direct contact with the resin may irritate the skin.

Hotbox Process—in the hotbox process, liquid or powdered acid catalysts are used. These catalysts are skin irritants. When used in the dry powdered form, they may constitute a dust hazard. Excessive exposure to phenol and formaldehyde from the resin may cause irritation of the eyes and respiratory tract. Contact with the resin can cause skin irritation

Nobake Process—phenolic resins are used either alone or in combination with furan resins or isocyanate. When used alone or in combination with furan resins, acid catalysts are required. Serious skin irritation can result from contact with acids. Exposure to phenol and formaldehyde can cause eye and respiratory irritation and contact with resin can cause serious skin irritation. In combination with isocyanates, phenolic resins produce so-called “urethane nobake binders.” The pyridine-like catalysts used with these binders are alkaline and skin contact can cause irritation. Excessive exposure to phenol, formaldehyde, isocyanate and solvent vapors from the resins can cause eye and respiratory irritation. Exposure to isocyanate vapors can also cause the asthma-like attacks associated with isocyanates.

Shell Process—in the shell process, hexamethylenetetramine (HEXA) is used as a catalyst; waxes and calcium stearate are used as lubricants. HEXA is a skin sensitizer; physical contact can cause severe irritation. Liquid shell resins contain solvents that evaporate during sand coating. These solvents are often flammable and potentially explosive. The solvents can cause eye and respiratory tract irritation and dizziness. Exposure to phenol and formaldehyde from the resin and to

formaldehyde and ammonia from the HEXA can cause eye and respiratory tract irritation. On heating, HEXA liberates formaldehyde and ammonia. Physical contact with liquid phenolic resins can cause skin irritation.

Coldbox Process—in the coldbox process, phenolic resins are used in combination with isocyanates to produce urethane resins. Amines carried in air, carbon dioxide, or nitrogen are used as catalysts. The amines are highly flammable. Excessive exposure to amines can cause eye and respiratory tract irritation. Exposure to isocyanate vapors can also cause the asthma-like attacks typically associated with isocyanates.

Since solvent components of phenolic resin systems vary widely the specific MSDS should be reviewed.

IV. Safe Use Procedures

Engineering Controls—exposure to air contaminants should be controlled with local exhaust ventilation or other engineering methods.

Personal Protection—physical contact with resins and catalysts should be controlled by the use of protective equipment such as gloves, aprons and goggles. Clothing contaminated with resin or catalyst should be removed and laundered before reuse. Phenolic resin on the skin should be removed promptly with soap and water. In case of irritation or rash, consult a physician.

Respiratory protection should be used as supplemental protection when exposure may be high. Respirators approved by NIOSH and Mine Safety & Health Administration (MSHA) should be used in a manner consistent with OSHA regulation 29CFR1910.34.

Shell Resin Sands

I. Description and Use

Shell resin sands can be prepared on-site or purchased for use in molds and cores. On-site coating of sands with liquid or solid resins is generally performed in a mechanical mixer of the pug-mill or muller type. Three accepted coating procedures are described below:

Cold Coating—phenol-formaldehyde Novolac shell resin (either powdered resin followed by a suitable volatile solvent such as alcohol, or predissolved resin) is blended with room-temperature sand and mixed until dry and free-flowing. A powdered hexamethylenetetramine (HEXA)/calcium stearate mixture is added with the resin or prior to addition of the resin.

Warm Coating—resin and room temperature sand are blended and then dried using heated air.

Hot Coating—granular, flaked or water-borne Novolac resin is blended with preheated sand, which melts the resin and allows coating of the sand grains. A dry, free-flowing state is attained by quenching the blend with a slurry of HEXA and stearate in water followed by drying with room temperature air.

The application of external heat from the pattern in the shell-molding process causes the resin to melt and polymerize with the HEXA, thus bonding the sand grains. The molding process may release both phenol and formaldehyde that can be detected by odor. Phenol has a characteristic sweet, tarry odor detectable below 5 ppm. Formaldehyde has an irritating pungent odor, best described as suffocating that is easily detectable at 1 ppm. Eye irritation also occurs at 1 ppm, but experienced workers may not experience eye irritation below 3 ppm.

II. Exposure Limits

Exposure limits for other materials may be found in Tables Z1-Z3 in the OSHA Standards. Material Safety Data Sheets for process materials may indicate which chemicals could be present.

	Phenol	Formaldehyde*
CAS No.	108-95-2	50-00-0
OSHA-PEL	5 ppm	0.75 ppm 0.50 ppm (Action Level) 0.10 ppm (Training Level)
ACGIH-TLV	5 ppm	0.3 ppm (C)

* Formaldehyde is regulated by OSHA Standard 29CFR1910.1048.
See legend, p. 304

III. Physical and Health Hazards

A major hazard in shell sand coating is the danger of fire or explosion that may be caused by the solvents used to dissolve the resins, particularly when heated air is used in the process. The use of granular or flaked resins in the hot coating procedure eliminates this hazard; the use of water-borne resins in hot coating reduces it, but all of these resins contain at least small amounts of solvent.

Exposure of these liquid or solid resins/or additives may cause dermatitis; in addition, vapors can cause respiratory and eye irritation. Uncontrolled mixing or mulling of dry sand with the resins can release a high concentration of airborne silica dust.

IV. Safe Use Procedures

Engineering Controls—to prevent fire and explosion in the mixer, electrical grounding and bonding and explosion-proof

gears, motors and blades must be used. Resin binders should be stored in covered containers under a roof; they should not be exposed to direct sunlight.

Local exhaust ventilation should be used as required to control dust and vapors at their point of generation. It should be noted that standard mixer or muller exhaust ventilation rates do not apply to mixers utilizing solvents. When flammable solvents are used, the minimum exhaust volume should be calculated to control the solvent vapors to 25 percent of the lower explosive limit (LEL). For more complete details, see the American Conference of Governmental Industrial Hygienists manual, "Industrial Ventilation, a Manual of Recommended Practice."

Personal Protection—skin contact should be avoided; protective gloves face shields, or chemical goggles should be required when handling resins and/or additives.

Sodium Silicate Binder Systems

I. Description and Use

Sodium silicate is an inorganic alkaline liquid which, when used as a binder, may often contain other ingredients such as sugar. Three to six percent sodium silicate binder is mixed with sand along with a number of organic and inorganic additives to produce a variety of bonding characteristics.

II. Exposure Limits:

No exposure limits for sodium silicate have been established. The MSDS should be reviewed to determine the hazards of the additives and activators used.

III. Physical and Health Hazards

The sodium silicate solutions encountered in foundry practices are strongly alkaline. They are irritating to the skin and highly irritating to the eyes. Carbon dioxide as employed in the system is normally not a hazard. The major thermal decomposition product of the organic additives and organic chemical activators during pouring is carbon monoxide. Generally, very little information is available concerning the extent or consequences of exposure to the other decomposition products. Should the hose separate from the CO₂ hand applicator, the operator's hand may freeze to the applicator.

The molds or cores are usually cured by passing carbon dioxide (CO₂) gas through the sand (commonly known as the CO₂ process). They also can be cured by heat and by chemical activators such as ferrosilicon, sodium silicofluoride, dicalcium silicate, Portland cement and organic esters such as glycerol triacetate, glycol diacetate and diacetin.

IV. Safe-Use Procedures

Engineering Controls—exposure to carbon monoxide and other thermal decomposition products during pouring and shakeout should be controlled by engineering methods, preferably local exhaust ventilation at the source.

Personal Protection—physical contact with sodium silicate solution should be controlled by the use of protective equipment such as gloves, aprons and goggles.

Urea-Formaldehyde Resins

I. Description and Use

Urea-formaldehyde resins are liquid, synthetic, thermosetting resins used in combination with cereal, water, kerosene and fatty acid release agents to bond sand. Urea-formaldehyde resins are usually characterized by a moderately strong irritating odor from the vapors of formaldehyde. They normally appear as a yellowish liquid of moderate viscosity. Cores are cured by baking in conventional or dielectrically heated ovens. For dielectric curing, boric acid is sometimes used in the mix. Dry sand molds can also be made from these resins in a similar manner. Ammonia and formaldehyde gases are liberated at coremaking or pouring operations.

II. Exposure Limits for By-Products

	Formaldehyde*	Ammonia
CAS No.	50-00-1	7664-41-7
OSHA-PEL	0.75 ppm 0.50 ppm (Action Level) 0.10 ppm (Training Level)	50 ppm
ACGIH-TLV	0.3 ppm (C)	25 ppm

STEL = Short term exposure limit

TLV = Threshold limit values

PEL = Permissible exposure limit

* Urea formaldehyde resins, as such, have not been assigned a TLV or PEL. Formaldehyde is regulated by OSHA Standard 29CFR1910.1048.

See legend, p. 304

III. Physical and Health Hazards

Exposure to ammonia and formaldehyde gases will irritate the eyes and respiratory tract. Exposed workers may develop some tolerance to these irritant effects. Contact with these resins can cause skin or eye irritation. Repeated or prolonged contact with the liquid resins on the skin can cause dermatitis and possibly lead to sensitization.

IV. Safe Use Procedures

Engineering Controls—excessive exposure to ammonia and formaldehyde should be controlled by engineering methods. Local exhaust ventilation control at the source is preferable in most cases to general dilution ventilation.

Personal Protection—gloves, aprons and goggles should be used as required to prevent contact with the resin. When respiratory protection is indicated or required, respirators should be selected from those approved by NIOSH.

Urethane Resins

I. Description and Use

Urethane binders are known in the foundry industry as alkyd-isocyanates or oil-isocyanates, oil urethanes, phenolic-isocyanates, phenolic urethanes, or just as isocyanates or urethanes. They are supplied as liquid two- or three-component systems consisting of polyol, isocyanate and catalyst. When mixed, the components form tough, solid plastics. Urethane binders are used in making both cores and molds. Other urethane resins may be used for pattern coatings, corebox liners and as pattern wear pads.

Polyols in particular, phenolic polyether polyols, and isocyanates are usually dissolved in solvents such as kerosene, mineral spirits, aromatic petroleum solvents, ketones and esters. Isocyanates used as components of core binders are

always of the polymeric MDI (methylene bisphenylisocyanate) type. TDI is not used in the alkyd oil-isocyanate nobake or phenolic urethane nobake and coldbox binders. Other isocyanates, e.g., TDI (toluene diisocyanate), are used to make corebox liners and pattern wear plates. Catalysts can be amines such as triethylamine (TEA), dimethylamine (DMEA) and dimethylisopropylamine (DMIPA) for urethane coldbox binders. Triethylenediamine, as well as metal salts such as cobalt naphthenate, lead phthalate and dibutyl tin dilaurate are used as catalysts for alkyd oil urethane nobake binders and for certain nonferrous polyol urethane nobake binders. Aryl-substituted pyridine compounds, such as 4-phenylpropylpyridine and methylimidazole, are used as catalysts for phenolic urethane nobake binders.

II. Exposure Limits

Material	CAS No.	OSHA PEL	ACGIH TLV
Methylene bisphenyl isocyanate (MDI)	101-68-8	0.02 ppm(C)	0.005 ppm
Toluene-2,4-diisocyanate (TDI)	584-84-9	0.02 ppm(C)	0.02 ppm(C) 0.005 ppm
Triethylamine (TEA)	121-44-8	25 ppm	1 ppm
Phenol	108-95-2	5 ppm	5 ppm

III. Physical and Health Hazards

The polyols can cause skin irritation from contact and respiratory irritation from vapor inhalation. Catalysts and isocyanates also are potential skin, eye and respiratory irritants. Skin contact and vapor inhalation are potential hazards wherever liquid components are handled in the open, for example, at sand mixing stations. TDI and MDI are known respiratory sensitizers.

Vapors generated at baking ovens, metal pouring operations and shakeout are potential respiratory irritation hazards. Amines used with the coldbox process are highly flammable. Isocyanates react with water, alcohols and other active hydrogen compounds, such as ammonia. Do not mix these with isocyanates in bulk containers or in closed systems, as pressure can develop due to heat or the evolution of gases.

IV. Safe Use Procedures

Engineering Controls—ventilation will normally be required to control vapors of MDI from urethane binders during sand mixing and after pour off. The most effective method of controlling vapors is local ventilation at the source.

Personal Protection Equipment—avoid contact with materials that are potentially irritating to the skin. Physical contact should be controlled by the use of protective equipment such as gloves, aprons and goggles. Some urethane binder or resin systems contain flammable components. For more information concerning specific urethane resin systems, the SDS should be obtained.

Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, tasteless gas. It is a product of incomplete combustion and can be generated in the foundry by internal combustion engines, melting processes based on combustion, or during pouring and cooling operations. CO will go into solution in a wet scrubber used to clean air. Processing of the water from such a scrubber can cause the gas to come out of solution; therefore, open tanks should be considered a potential source of exposure. Negative pressure conditions within a plant which cause back drafting of products of incomplete combustion through thermal flues can create other sources of exposure.

Excessive exposure can cause headache, throbbing in the temples, weariness, weakness, dizziness, nausea, vomiting, loss of strength and muscular control, increased breathing rate, slowing of pulse and death.

Inert Nuisance Particulates

Non-silica molding aggregates generally have been classified as nuisance dusts. These dusts have little adverse effect on the lungs and do not produce significant organic disease or toxic effect when exposures are kept under reasonable control. The nuisance dusts have also been called (biologically) inert dusts, but the latter term is inappropriate because all dusts evoke some response in the lung when inhaled in sufficient amount. However, the lung-tissue reaction caused by inhalation of nuisance dusts is characterized by the fact that the architecture of the air spaces remains intact, that scar tissue is not formed to a significant extent and that the tissue reaction is potentially reversible. This is in contrast to silica dust, which causes scar tissue to be formed in the lung when inhaled in excessive amounts.

Excessive concentrations of nuisance dusts in the workroom air can seriously reduce visibility; cause irritation in the eyes, ears and nasal passages; or cause injury to the skin or mucous membranes by chemical or mechanical action per se or by the rigorous skin cleansing procedures necessary to remove the dusts.

Examples of inert or nuisance particulates are:

- Alundum [aluminum oxide, corundum, alumina, emery (Al_2O_3)]
- Calcium carbonate [albacar, aeromatt, limestone, precipitate chalk (CaCO_3)]
- Cellulose (paper fiber)
- Portland Cement
- Carborundum (silicon carbide)
- Glass, fibrous or dust
- Graphite (synthetic)
- Gypsum [calcium sulfate, plaster of paris, alabaster, selenite ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)]
- Iron oxide dust (rust- Fe_2O_3)
- Kaolin
- Magnesite (MgCO_3)
- Rouge [pink talc, mineral graphite, $\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$]
- Sucrose (sugar)
- Tin oxide
- Titanium dioxide [titanic acid (TiO_2)]

Free Silica—(Silicon Dioxide, Quartz)

I. Description and Use

Free silica is a major constituent of foundry sand and can be present in high concentrations in silica flour and in some silica mold or core washes. Tridymite and cristobalite are other crystalline forms of silica that can be generated at the mold-metal interface as a result of the high-temperature transformation of quartz.

In many foundry operations, employees are exposed to fine dust generated from the mechanical or thermal fracture of

sand particles. The main sources of exposure in foundries are 1) the handling, mixing, or mulling of new sand or dry sand from shakeout; 2) use of silica-containing parting compounds or mold washes; 3) shakeout and 4) casting cleaning. Other sources of silica dust exposure include general maintenance and cleaning and furnace and ladle repair operations.

II. Exposure Limits

Exposure limits vary with the crystalline structure of the silica particle.

	CAS No.	OSHA-PEL	ACGIH-TLV
<i>Crystalline forms</i>			
Quartz	14808-60-7	$\frac{10 \text{ mg/m}^3}{\% \text{ SiO}_2 + 2}$ *	0.025mg/m ³ *
Cristobalite	14464-46-1	**	0.025mg/m ³ *

* = respirable dust

** = $\frac{1}{2}$ the value calculated from the respirable dust formula for quartz

III. Physical and Health Hazards

Very small quartz particles (less than 10 microns in diameter) in the lung cause fibrosis or scarring. The degree of hazard depends on the free silica content, concentration, and size of airborne dust particles and the length of exposure. Silicosis (occasionally complicated by tuberculosis) is the occupational disease associated with excessive exposures. High exposures have produced symptoms less than one year after initial exposure; less heavy exposures, however, normally do not produce symptoms for many years, if ever. High temperatures may change crystalline structure to form tridymite or cristobalite that are greater health hazards than quartz.

IV. Safe Use Procedures

Engineering Controls—inhalation of dust is the major hazard associated with silica. Consequently, handling and use should be directed toward keeping airborne dust concentrations at a minimum. Working with moist products will help keep the silica dust levels down to a minimum. For example, in foundries the green sand can usually be handled on belt conveyors without causing too much dust. However, dry return sand and new sand can easily create too much dust. Substitution of other materials, such as nonsilica mold-parting compounds, molding aggregates and abrasive grits, should be considered first. Practice good housekeeping. Keep dust from collecting on overhead surfaces. Do not use compressed air to clean floors, walls and ledges. All sources of dust exposure should be enclosed to the greatest extent possible and exhaust ventilated to a suitable collector. Some dust sources, such as abrasive blasting operations, mullers, screens and some shakeouts can be completely enclosed. Other operations, however, such as chipping and grinding operations and most shakeouts can only be partially enclosed. The poorer the enclosure, the greater the exhaust capacity required to provide positive control.

Personal Protection—if dust control ventilation is not able to keep exposures below the Permissible Exposure Limit (PEL), the use of respiratory protection is required. Respirators approved by NIOSH and MSHA for protection against dust containing quartz should be used.

PERSONAL PROTECTIVE EQUIPMENT

The wearing of eye protection with side shields should be a mandatory requirement in all foundry areas, including those where mold washes and binders are mixed or handled. Protective eye wear that meets the ANSI (Z87.1) Standard Practice for Occupational and Educational Foundry Personal Eye and Face Protection devices should be worn by all foundry employees. Additional protection, such as goggles, should be worn by people working on chipping and grinding lines.

Leggings that protect the lower leg and instep must be worn by all persons who handle molten metal. They also should be worn by employees having a potential exposure to hot sand. The pants should be worn over the leggings to prevent spilled metal or hot sand from getting between the protective equipment and the pants or from running down into a shoe. As much of the body as possible should be covered by normal clothing (no polyester). Clothing that is resistant to burning is desirable. Such clothing should fit closely at the neck and wrists and sleeves should not be rolled up. Wearing of torn, ragged and oil/grease-soaked clothing is a hazard and should not be permitted.

The use of metatarsal guards on shoes should be mandatory in such areas as mill rooms, where there is a possibility that heavy castings may fall on feet. The wearing of steel-toed shoes throughout the foundry is good practice and should be encouraged.

Gauntlet-type gloves should never be worn because the gauntlet cuff acts as a funnel for hot metal or sand. Shirt sleeves should be worn over the snug-fitting gloves to protect the hands and prevent the entrapment of hot metal in the gloves.

When concentrations of airborne toxic materials are not reduced by engineering or administrative controls to levels below applicable permissible exposure limits, respirators should be worn. Only respirators approved by the National Institute for Occupational Safety and Health for the specific contaminants involved should be used. Respirators should be fitted and worn properly and they must be kept clean and in good repair. Self-contained respiratory protection is required when working in oxygen-deficient atmospheres. Respiratory protection may also be required for certain sporadic operations or for emergency conditions involving exposure to air contaminants (Reference OSHA Standard 29 CFR 1910.134). Hard hats must be worn if there is a potential for head injuries from falling or flying objects. If only certain areas in the foundry have such hazards, the wearing of hard hats must be enforced in these areas.

If noise exposure exceeds established limits in certain foundry areas because of the nature of the work being done, hearing protection may be necessary. Reducing these noise levels below the established limits by use of engineering and/or administrative controls may not always be possible. Consequently, ear muffs or ear plugs must be worn by employees

working in these areas. Ear protection devices are effective if fitted properly, worn properly and accompanied by a good educational program explaining why they are needed and how to use them. Appropriate medical surveillance, including audiometric examinations, is required for an effective hearing conservation program.

For additional personal protective equipment (PPE) recommendations see the American Foundry Society publication, "Guide for the Selection & Use of Personal Protective Equipment & Special Clothing for Foundry Operations".

Ventilation and Makeup Air

Local exhaust ventilation systems with close-capture hoods are preferred over general dilution ventilation (e.g., roof ventilators) for control of exposures to toxic air contaminants. The use of local exhaust systems has the following advantages:

The contaminant is removed before it can reach the employees' breathing zone.

Makeup air requirement is much lower, with a subsequent reduction in cost when compared to general dilution ventilation, especially when enclosing or closely coupled hoods are used to provide control at a minimum exhaust rate.

Makeup air should be supplied to the foundry at a rate at least equal to the total exhaust rate. Lack of makeup air will decrease the efficiency of exhaust systems, cause unwanted drafts and cause differential pressure on doors. High-velocity cross-drafts (e.g., from air-cooling fans or air diffusers) may disrupt exhaust hood airflow patterns, with a subsequent reduction in overall effectiveness.

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COPPER ALLOYS FOR SPECIAL APPLICATIONS

This chapter is a compilation of issues that the AFS Technical Committee, Copper Alloy Division considers will affect the copper and brass foundry industry in the near future.

COPPER AVAILABILITY

The U.S. Geological Survey (USGS) has followed the U.S. and world demand for copper and other minerals and metals for over 100 years. In 2013, the USGS completed a geology-based cooperative international assessment of world-wide copper resources. The collaborators included mineral resource experts from many national geological surveys as well as industrial and academic experts from around the world.¹⁻³

The planning and decisions for mining mineral deposits, sustainability, and resource development used a long-term global perspective and integrated approach to land use and to resource and environmental management. This integrated approach also required unbiased information on the global distribution of identified and undiscovered mineral deposits, the economic factors influencing their development, and the environmental consequences of exploiting the various deposits.

The methodology used for the assessment employed included: (a) a literature survey of geological data and characterization of identified deposits for each location, (b) delineation of geographic areas for geology suitable for copper deposits defined in the mineral deposit models, (c) evaluation of the amounts of copper in typical deposits using grade-tonnage models, and (d) probabilistic estimation of numbers of undiscovered deposits. Probable amounts of undiscovered resources were calculated by combining estimates of numbers of undiscovered deposits with grade and tonnage models using Monte Carlo simulation. Then, the results for individual areas were summed for each region, assuming the areas were independent.

The USGS assessed discovered porphyry copper deposits distributed throughout igneous intrusions (60% of world's copper) and discovered sediment-hosted stratabound copper deposits (~20% of world's copper). This ignores the vast amounts of copper in deep sea nodules or land-based and submarine massive sulphide deposits which have less predictable origins.

The assessment indicated that there are 690 million metric tons (Mt) of delineated reserves, and a total of 2,100 Mt of copper in identified resources. As US annual copper consumption was 2 Mt and global consumption was 20 Mt, there is at least a 40 year supply. This level for the life expectancy of mapped economic copper deposits has been maintained for decades. The study also indicated that there should be 3,500 Mt of undiscovered copper in 225 tracts in 11 regions spanning six continents (Table 19.1).

Chinese demand has influenced the world price and production levels of copper in recent years. Recent price declines are the result of decreased Chinese imports, stockpiling, and surplus production. However, while imports have declined rapidly in the last couple of years (17% decline year after year), China continues to use more copper (expected to increase 7.7% in 2015). Although demand should increase steadily from developing economies, reserves are adequate for the next 50–70 years, and new discoveries should create sufficient supply sources more than 100 years beyond that. Deep sea mining of nodules and sulphide deposits will require new technologies. Most uses of copper are not dissipative and can last decades, so recycling will be a steady source for foundry alloys.⁴

The demand for copper may surpass \$260 billion by 2019. Besides China, demand in North America, especially the U.S., will increase significantly due to their anticipated rise in the construction industry.⁵

ANTIMICROBIAL PROPERTIES OF COPPER

Copper is essential to all living organisms as a trace dietary mineral. Copper is a constituent of the blood pigment hemocyanin in mollusks and crustaceans, but is replaced by the iron-complexed hemoglobin in fish and other vertebrates. Humans obtain copper by digesting plants, where it is used in the liver, muscle and bone.

Copper was used for its antimicrobial properties, long before Louis Pasteur developed the germ theory of disease in the nineteenth century. The “Hippocratic Collection” (460 to 380 B.C.), recommended the use of copper for leg ulcers associated with varicose veins. Pliny the Elder, (A.D. 23 to 79), used copper oxide with honey to treat intestinal worms. The Aztecs gargled with a mixture containing copper to treat

Table 19-1. Assessment results for identified and undiscovered copper deposits by region.

Region		Tract extent (km ²)	Undiscovered resources (Mt)				Identified resources (Mt)
			90	50	10	Mean	
South America	Porphyry Sediment-hosted	1,200,000 99,000	500	730	1,000	750	810 0.51
Central America and the Caribbean	Porphyry	540,000	78	150	280	170	42
North America	Porphyry Sediment-hosted	3,200,000 450,000	250 15	370 48	540 110	400 57	470 18
Northeast Asia	Porphyry	2,300,000	76	220	500	260	8.8
North Central Asia	Porphyry Sediment-hosted	3,200,000 180,000	210 22	360 49	590 90	440 53	130 48
South Central Asia and Indochina	Porphyry Sediment-hosted	3,800,000 29,000	280	490	770	510	63 4.5
Southeast Asia Archipelagos	Porphyry	850,000	180	290	430	300	130
Australia	Porphyry	580,000	1.9	14	54	21	15
Eastern Europe and Southwestern Asia	Porphyry Sediment-hosted	1,200,000 4,800	130 0.052	220 4.8	370 36	240 13	110 6.4
Western Europe	Porphyry Sediment-hosted	73,000 190,000	38	110	230	120	1.6 77
Africa and the Middle East	Sediment-hosted	200,000	81	150	260	160	160
Total copper			3,500				2,100

sore throats. It has been known for centuries that water stored in copper vessels or transported in copper plumbing systems was of better quality (i.e., no or little visible slime formation) than water contained or transported in other materials. Copper compounds are used to restrict bacteria, and in fungicides, and wood preservatives.

The wooden hulls of early sailing ships were attacked by shipworm and various marine weeds, which adversely affected the ships structurally, speed and handling. Although copper sheathing was suggested in 1708, it was not until the mid-1750s that the British Navy experimented with copper sheaths. Copper sheathing was the practice of protecting a ship's under-water hull from the corrosive effects of salt water by attaching copper plates to the outer hulls of ships.

Two ships were fully clad in 1761 and 1764, but after several years the iron bolts holding the copper cladding deteriorated. In 1769, a new ship that had been constructed using bolts made from a copper alloy proved more favorable. Although four naval wars (1776–1780) prevented the re-bolting, the Royal Navy set about coppering the bottoms of the entire fleet and by 1781, 393 ships had been coppered. Finally, a suitable alloy of copper and zinc was found for the hull bolts and in 1786, the Admiralty decided to re-bolt every ship in the navy, thus finally eliminating the bolt corrosion problem. The cladding of wooden ships continued unchanged, and was adapted by copper plating steel hulls, until the advent of modern anti-fouling paint. Pure copper was partially superseded in the 19th century by cheaper Muntz metal (60% Cu, 40% Zn, and a trace of iron).

The toxicity (oligodynamic effect) of certain metal ions on living cells, algae, molds, spores, fungi, viruses, prokaryotic and eukaryotic microorganisms, even in relatively low concentrations was discovered in 1893.⁶ This antimicrobial effect is shown by ions of copper as well as mercury, silver, iron, lead, zinc, bismuth, gold, and aluminium. When Dick, Wray, and Johnston at Battelle Columbus Laboratories⁷ conducted a comprehensive review in 1973, they found over 300 references including those on the “bacteriostatic and sanitizing properties of copper and copper alloy surfaces.” Copper, in very small quantities, is toxic to a wide range of molds, fungi, algae and harmful microbes; even the metal in air is toxic to microbes.

It was not until recent times that copper’s ability to destroy germs was rigorously analyzed for its potential for frequently touched surfaces. Copper-alloy surfaces have natural intrinsic properties to destroy a wide range of microorganisms (e.g., *E. coli* O157:H7, methicillin-resistant *Staphylococcus aureus* (MRSA), *Staphylococcus*, *Clostridium difficile*, influenza A virus, adenovirus, and fungi).⁷⁻⁹ Specifically, bacterial colonies placed on copper surfaces are reduced from over one hundred million to zero. Similar testing demonstrates that a range of copper alloys (brass, bronze, copper nickel), including cast alloys, exhibits the same effect (Figs. 19-1 and 19-2). Almost no reduction occurs on stainless steel or plastic surfaces after 6 hours at 68F (20C). Copper doorknobs

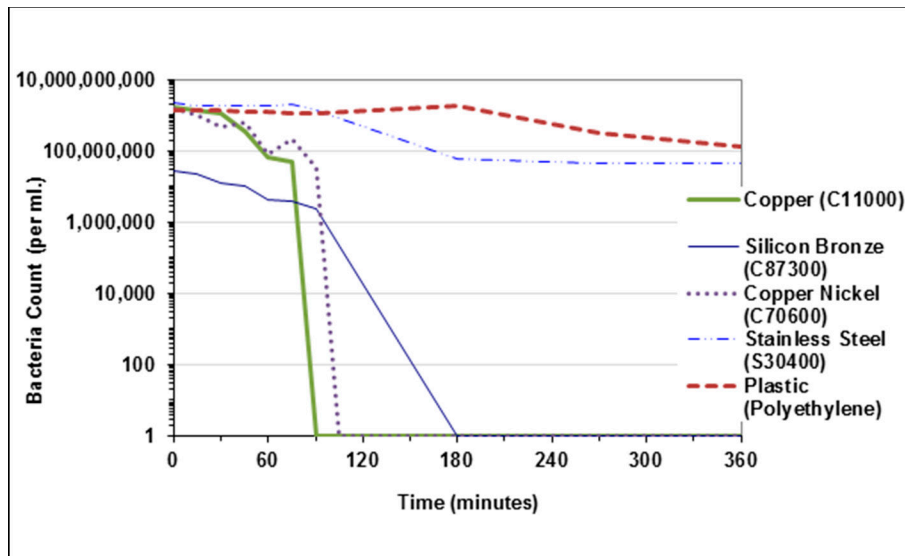


Fig. 19-1. Antimicrobial efficacy of various wrought and cast copper alloys, stainless steel, and plastic, against *E. coli* O157:H7.^{8,9}

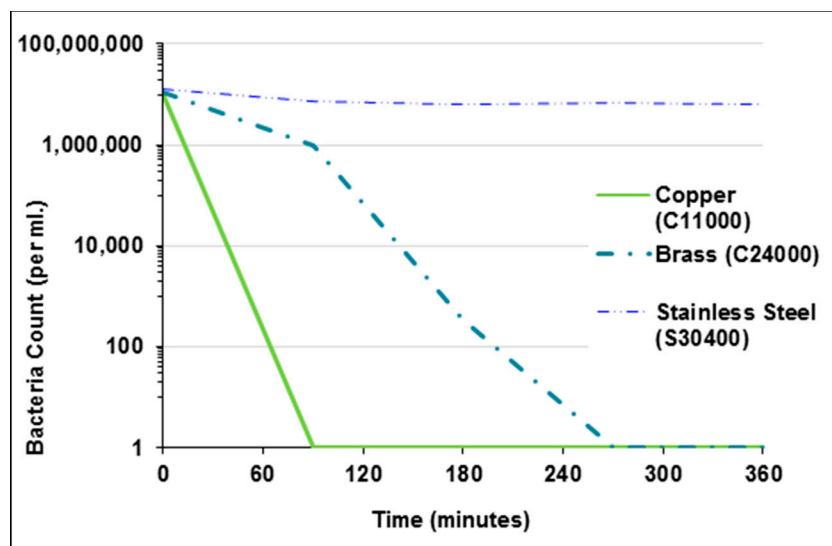


Fig. 19-2. Antimicrobial efficacy of wrought copper, brass, and stainless steel against the superbug MRSA.^{8,9}

are used by hospitals to reduce the transfer of disease and Legionnaires' disease is suppressed by copper tubing in plumbing systems. Antimicrobial copper alloy products are now being installed in healthcare facilities in the U.K., Ireland, Japan, Korea, France, Denmark, and Brazil, and in the subway transit system in Santiago, Chile, where copper-zinc alloy handrails were installed in some 30 stations.

Japanese investigators were among the earliest to patent antibacterial applications.¹⁰ The market for antibacterial products in Japan expanded from \$300 million (U.S.) in 2000 to \$8 billion by 2013, although growth was delayed when counterfeit goods were released to the market. The Japanese Patent office classifies six categories: photocatalyst, silver, heterocyclic compound, copper, vegetable matter, and amine or quaternary ammonium salts in the order of frequency. The market amounts to 2000 tons of material spread over seven applications: water treatment, domestic goods, fabrics, machinery & appliances, construction & paint, separation, and other. The approximately 360 Japanese patent applications relating to antibacterial applications of silver although spread over all seven applications, were concentrated in fabrics (~24%), construction & paints (~33%), and other (~24%), while the ~300 patents on copper antibacterial applications were concentrated in construction & paint (~30%). Since 1993, 12 patent applications a year were received by the Japanese Patent Office for silver antibacterial applications, previously all from Japan (up to 1999) but now 50% foreign. Copper antibacterial applications increased to 12 from Japan and one foreign a year in 1998 to 3 or 4 a year from Japanese sources and 10 foreign in 2007–2011.

In 2008, after a rigorous review of the scientific evidence supporting the antimicrobial efficacy of copper alloys, U.S. Environmental Protection Agency (EPA) granted antimicrobial public health registrations for copper alloys. These registrations allow EPA registered copper alloys to be marketed as materials that continuously kill more than 99.9% of six specific disease-causing bacteria within two hours. These bacteria are: Methicillin-resistant *Staphylococcus aureus* (MRSA), Vancomycin-resistant *Enterococci* (VRE), *E. coli* O157:H7, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Enterobacter aerogenes*. In total, 355 copper alloys with a minimum copper content of 60% are included in the registration. Of these, 62 are cast alloys. The United States Environmental Protection Agency (EPA) has approved the registrations of these copper alloys as "antimicrobial materials with public health benefits," which allows manufacturers to legally make claims as to the positive public health benefits of products made with registered antimicrobial copper alloys (>60% Cu). In addition, the EPA has approved a long list of antimicrobial copper products made from these alloys, such as bedrails, handrails, over-bed tables, sinks, faucets, door knobs, toilet hardware, computer keyboards, health club equipment, shopping cart handles, etc. The full EPA approved marketing claims are available on <http://www.antimicrobialcopper.org/>.*

U.S. DEPARTMENT OF DEFENSE STUDY

The U.S. Department of Defense (with input from the Copper Development Association) funded a study to assess the clinical performance of antimicrobial copper alloys in the intensive care units (ICUs) of three hospitals during a five-year period (2006 to 2011).¹¹ At that time, healthcare associated infections (HAIs) resulted in significant patient morbidity and mortality. Each year, 2 million U.S. citizens contract a hospital-acquired infection; of those, one out of twenty die, or approximately 100,000.¹² In an ICU, the number is one out of four. During the five-year period, HAIs were the fourth leading cause of deaths in the U.S. In 2009, U.S. Medicare Services stopped paying for the treatment of certain HAIs, and the costs to treat these infections would thereafter be borne by hospitals or insurers. The study provides the medical community the double-blind test that copper surfaces do reduce bacteria and will reduce costs and save lives.

Commonly touched items are known to harbor microorganisms, and although current cleaning methods can effectively remove pathogens from surfaces, studies show that more than half are not adequately cleaned, and may become re-contaminated within minutes. Microbial surface contamination can be readily transmitted to the hands of staff or visitors who subsequently have direct contact with patients. Hand washing reduces the transmission of pathogens, but frequently falls short. There is a need for a method to continuously reduce microbial contamination on surfaces.

The first phase of the study determined the number of bacteria on six frequently touched surfaces, (Fig. 19-3). These products were traditionally made of plastic, wood, composite materials, or painted steel. The number of bacteria on these six frequently touched, non-copper objects was 52 times greater than the level generally considered to represent a risk to the patient,¹³ 250 cfu/100cm². Objects closest to patients (plastic bed rails and nurse's call devices) had the highest bacterial burden. *Staphylococcus aureus* was the most common organism found.¹¹

For the second phase, prototype objects were manufactured solely for this study in copper alloys. The only casting (C87610 Cu-Si) was for the IV pole base. They replaced non-copper equivalents in eight randomly selected rooms within the ICUs from December 2007 to June 2011.¹¹ The bacterial burden on the six surfaces in these and another eight rooms with control products were then sampled weekly. During the study, all rooms were used, cleaned and operated in the usual manner.

Copper surfaces reduced the bacterial burden on common touch surfaces in the ICUs.¹¹ The reduction was significant and consistent. The median bacterial burden on copper objects was 98% lower than on the non-copper objects approaching those in controlled laboratory conditions. The result is consistent with those attained in clinical trials at other sites throughout the world.¹⁴⁻¹⁶

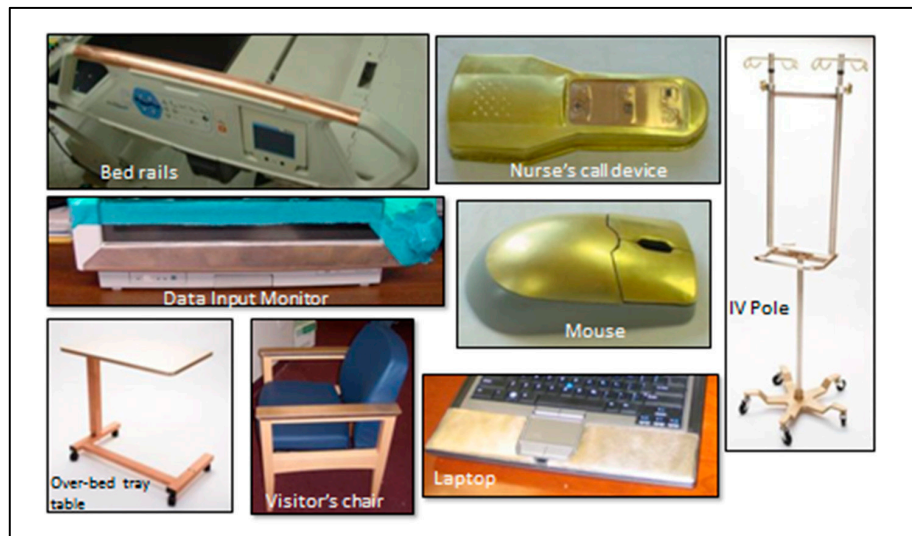


Fig. 19-3. Copper alloy objects installed in ICU rooms.¹¹

The bacterial populations on copper surfaces routinely approached the targeted terminal cleaning levels and were frequently below the 250 cfu/100cm² benchmark. Methicillin-resistant *Staphylococcus aureus* (MRSA) was found 0.14% of those copper objects sampled, whereas the incidence level was 15 times higher (2.1%) on non-copper objects.

The data revealed that 80% of the plastic bed rails sampled had bacterial concentrations *above* the risk threshold for transferring/transmitting infectious bacteria, whereas only 19% of the copper bed rails had levels above this risk threshold. Over the course of sampling, 45% of the copper bed rails assessed had no bacteria. In contrast, only 2% of the plastic bed rails sampled failed to yield viable bacteria. The majority of the copper objects samples had low burdens; 82% of nurse call buttons; 90% of the chair arms; 97% tray tables; 98% IV poles and 98% data input devices were below the standard.

The third phase examined the risks of healthcare associated infections (HAI) for patients that stayed in rooms with copper objects and compared it to the HAI rates of patients in rooms that did not contain copper objects. The second phase was concluded on June 14, 2011.¹¹ Preliminary findings indicated:

- **The risk of contracting an HAI for patients in rooms equipped with copper objects was 40% lower** than for patients in rooms without copper objects.
- During the study, some of the beds with copper-clad rails were displaced from their rooms. Phase one showed that the bedrails are the most contaminated objects within the rooms. It's believed that due to their proximity to patients, they have a very significant impact on patient outcomes. **Patients that stayed in rooms with copper objects and used beds with copper rails had a 61% lower risk of contracting an infection** than patients that stayed in rooms without copper objects.

- Throughout the study, several of the other mobile copper objects (IV poles and overbed tray tables) traveled into rooms with no copper objects. **Patients that stayed in rooms with copper objects and in which all six copper objects never left the room had a 69% lower risk of contracting an infection** than patients that stayed in rooms with no copper objects.

The initial results suggest that the materials in the ICUs play a substantial role in the contraction of HAI's. The environment likely caused at least 40% of the HAI's. Even a few continuously active antimicrobial copper surfaces substantially lowered the risk of contracting an HAI. Since the average HAI leads to an additional 19 days of hospitalization, and another \$43,000 (2011) in costs which may have to be absorbed by the hospital, while exposing an ICU patient to a 27% chance of death, the use of antimicrobial copper surfaces warrant consideration.

The use of copper and silver utensils over the last couple of millennia was beneficial, but their tendency to tarnish, and the need to reduce cleaning costs, led the use of stainless steels starting in the 1960s. In hospital environments the substitution by plastics, laminates and steels may not be cost effective. This presents a substantial opportunity for foundries and others to manufacture copper alloy touch surface products for healthcare facilities. Foundries have the ability to supply products with intricate shapes. It is up to the metalcasters to approach medical equipment suppliers to determine which components are best replaced by copper castings. Especially since a domestic and international supply chain of antimicrobial copper surfaces from wrought alloys is being developed. A portfolio of end-use products is currently available and many more are expected to reach the marketplace in the near future. Medical equipment already offers a market for castings, why not copper alloy castings?

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