

Murat LUŞ

# Casting Copper-Base Alloys

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*Cover design by Margaret Nickele*

# PREFACE

In keeping with the objectives of earlier editions dealing with the casting of copper-base alloys, an attempt has been made here by the AFS Brass and Bronze Division to summarize and present current knowledge in a manner which will be beneficial to both technical and operating personnel.

The first AFS book containing information on copper-base alloys, *Recommended Practices for the Sand Casting of Non-Ferrous Alloys*, was published in 1944. It covered copper-base, aluminum and magnesium alloys. In 1952 a second edition appeared, *Copper-Base Alloy Foundry Practices*, which dealt only with alloys of copper. Rapidly changing foundry technology necessitated the publication of a second edition of the same title in 1965.

During the past two decades, even greater changes have taken place within the industry, not only in the

technology of foundry operations but also in the environmental sciences. This book extensively revises the earlier edition, providing up-to-date information required for the application of modern foundry principles and practices to the casting of copper-base alloys.

While not intended to be all-encompassing, this edition attempts to cover in a factual way the most important basic principles and techniques of copper-base alloy casting. Extensive references are cited throughout the book for further reading.

More than twenty years of research on alloy solidification behavior and melt quality control is contained in the new material presented here, in addition to data on sand control and chemical binder systems.

*Casting Copper-Base Alloys* provides information vital to experienced brass and bronze foundrymen as well as to newcomers in the industry.

Mervin T. Rowley  
*Coordinating Editor*

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Standard Designations for Copper and Copper Alloys  
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Conforming Specifications for Copper-Base Alloys  
*Arthur Cohen, Copper Development Association*

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# Chapter 1

## STANDARD DESIGNATIONS FOR COPPER AND COPPER ALLOYS

### INTRODUCTION

In the past, cast copper alloys were classified by a variety of systems including by 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. A new system was developed 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 now been expanded to five digits that follow a prefix letter "C," and have been made part of the Unified Numbering System for Metals and Alloys. The Unified Numbering System is managed jointly by the American Society for Testing and Materials, and the Society of Automotive Engineers. The UNS designations are expanded versions of the former designations. For example, copper alloy no. 836 in the original three-digit system became C83600 in the UNS system. The previous designations will continue to be used over a transition period of several years. Because the old numbers are incorporated in the new UNS numbers, there is little chance for confusion. This system is also being used in Australia and Brazil.

The designation system is administered by the Copper Development Association, Inc. 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:

- 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 which 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 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.

Table 1-1

| Alloy No.:             | C83600                                 |                         | C92200                                 |                         | C93700                                 |                         |
|------------------------|----------------------------------------|-------------------------|----------------------------------------|-------------------------|----------------------------------------|-------------------------|
| Casting Method:        | Sand<br>or<br>Centrifugal <sup>1</sup> | Continuous <sup>2</sup> | Sand <sup>1</sup><br>or<br>Centrifugal | Continuous <sup>2</sup> | Sand<br>or<br>Centrifugal <sup>1</sup> | Continuous <sup>2</sup> |
| Tensile Strength:      | 30                                     | 36                      | 34                                     | 38                      | 30                                     | 35                      |
| 0.5 Yield Strength:    | 14                                     | 19                      | 16                                     | 19                      | 12                                     | 20                      |
| Elongation % in 2 in.: | 20                                     | 15                      | 24                                     | 18                      | 15                                     | 6                       |

<sup>1</sup>ASTM B584-79, ASTM B271-73<sup>2</sup>ASTM B505-81

They do not preclude the manufacture or supply of products which 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 Table 1-2. 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 starts, 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 Chapter 17, and to *Standards Handbook, Cast Copper and Copper Alloy Products, Part 7—Alloy Data*, from Copper Development Assoc. Inc., 405 Lexington Avenue, New York, NY 10017.

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

#### COPPERS

COMPOSITION, PERCENT MAXIMUM  
(UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>NO. | Cu<br>(incl. Ag)<br>(% min.) | Ag       |                | B   |
|---------------|------------------------------|----------|----------------|-----|
|               |                              | %<br>min | Troy Oz<br>min |     |
| C80100        | 99.95                        | —        | —              | —   |
| C80300        | 99.95                        | .034     | 10             | —   |
| C80500        | 99.75                        | .034     | 10             | .02 |
| C80700        | 99.75                        | —        | —              | .02 |
| C80900        | 99.70                        | .034     | 10             | —   |
| C81100        | 99.70                        | —        | —              | —   |

Table 1-2, continued

## HIGH-COPPER ALLOYS

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu                    | Ag     | Be        | Co                   | Si      | Ni                   | Fe  | Al  | Sn  | Pb  | Zn  | Cr      |
|------------------------|-----------------------|--------|-----------|----------------------|---------|----------------------|-----|-----|-----|-----|-----|---------|
| C81300                 | 98.5min.              | —      | .02–.10   | .6–1.0               | —       | —                    | —   | —   | —   | —   | —   | —       |
| C81400                 | 98.5min.              | —      | .02–.10   | —                    | —       | —                    | —   | —   | —   | —   | —   | .6–1.0  |
| C81500                 | 98.0min.              | —      | —         | —                    | .15     | —                    | .10 | .10 | .10 | .02 | .10 | .40–1.5 |
| C81540                 | 95.1min. <sup>1</sup> | —      | —         | —                    | .40–.8  | 2.0–3.0 <sup>2</sup> | .15 | .10 | .10 | .02 | .10 | .10–.6  |
| C81700                 | 94.2min.              | .8–1.2 | .30–.55   | .25–1.5              | —       | .25–1.5              | —   | —   | —   | —   | —   | —       |
| C81800                 | 95.6min.              | .8–1.2 | .30–.55   | 1.4–1.7              | —       | —                    | —   | —   | —   | —   | —   | —       |
| C82000                 | 95.0min.              | —      | .45–.8    | 2.4–2.7 <sup>2</sup> | .15     | .20                  | .10 | .10 | .10 | .02 | .10 | .10     |
| C82100                 | 95.5min.              | —      | .35–.8    | .25–1.5              | —       | .25–1.5              | —   | —   | —   | —   | —   | —       |
| C82200                 | 96.5min.              | —      | .35–.8    | —                    | —       | 1.0–2.0              | —   | —   | —   | —   | —   | —       |
| C82400                 | 96.4min.              | —      | 1.65–1.75 | .20–.40              | —       | .10                  | .20 | .15 | .10 | .02 | .10 | .10     |
| C82500                 | 95.5min.              | —      | 1.90–2.15 | .35–.7 <sup>2</sup>  | .20–.35 | .20                  | .25 | .15 | .10 | .02 | .10 | .10     |
| C82510                 | 95.5min.              | —      | 1.90–2.15 | 1.0–1.2              | .20–.35 | .20                  | .25 | .15 | .10 | .02 | .10 | .10     |
| C82600                 | 95.2min.              | —      | 2.25–2.45 | .35–.7               | .20–.35 | .20                  | .25 | .15 | .10 | .02 | .10 | .10     |
| C82700                 | 94.6min.              | —      | 2.35–2.55 | —                    | .15     | 1.0–1.5              | .25 | .15 | .10 | .02 | .10 | .10     |
| C82800                 | 94.8min.              | —      | 2.50–2.75 | .35–.7 <sup>2</sup>  | .20–.35 | .20                  | .25 | .15 | .10 | .02 | .10 | .10     |

COPPER-TIN-ZINC AND COPPER-TIN-ZINC-LEAD ALLOYS  
(RED BRASSES AND LEADED RED BRASSES)

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu                     | Sn      | Pb      | Zn       | Fe               | Sb               | As               | Ni<br>(incl. Co) | S   | P <sup>3</sup> | Al   | Si   | Bi  |
|------------------------|------------------------|---------|---------|----------|------------------|------------------|------------------|------------------|-----|----------------|------|------|-----|
| C83300                 | 92.0–94.0              | 1.0–2.0 | 1.0–2.0 | 2.0–6.0  | —                | —                | —                | —                | —   | —              | —    | —    | —   |
| C83400                 | 88.0–92.00             | .20     | .50     | 8.0–12.0 | —                | —                | —                | —                | —   | —              | —    | —    | —   |
| C83410                 | 88.0–91.0 <sup>4</sup> | 1.0–2.0 | .10     | Rem.     | .05              | —                | —                | .05              | —   | —              | .005 | .005 | —   |
| C83450                 | 87.0–89.0              | 2.0–3.5 | 1.5–3.0 | 5.5–7.5  | .30              | .25              | —                | .8–2.0           | .08 | .03            | .005 | .005 | —   |
| C83500                 | 86.0–88.0 <sup>4</sup> | 5.5–6.5 | 3.5–5.5 | 1.0–2.5  | .25              | .25              | —                | .50–1.0          | .08 | .03            | .005 | .005 | —   |
| C83600                 | 84.0–86.0 <sup>4</sup> | 4.0–6.0 | 4.0–6.0 | 4.0–6.0  | .30              | .25              | —                | 1.0 <sup>4</sup> | .08 | .05            | .005 | .005 | —   |
| C83700                 | 83.0–88.0 <sup>4</sup> | —       | .50     | Rem.     | .30              | —                | .05–.20          | .30              | —   | —              | .005 | .005 | —   |
| C83800                 | 82.0–83.8 <sup>4</sup> | 3.3–4.2 | 5.0–7.0 | 5.0–8.0  | .30              | .25              | —                | 1.0 <sup>4</sup> | .08 | .03            | .005 | .005 | —   |
| C83810                 | Rem.                   | 2.0–3.5 | 4.0–6.0 | 7.5–9.5  | ( <sup>5</sup> ) | ( <sup>5</sup> ) | ( <sup>5</sup> ) | 2.0              | —   | —              | .01  | .02  | .10 |

## SEMI-RED BRASSES AND LEADED SEMI-RED BRASSES

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu <sup>4</sup> | Sn      | Pb      | Zn        | Fe  | Sb  | Ni <sup>4</sup><br>(incl. Co) | S   | P <sup>3</sup> | Al   | Si   |
|------------------------|-----------------|---------|---------|-----------|-----|-----|-------------------------------|-----|----------------|------|------|
| C84200                 | 78.0–82.0       | 4.0–6.0 | 2.0–3.0 | 10.0–16.0 | .40 | .25 | .8                            | .08 | .05            | .005 | .005 |
| C84400                 | 78.0–82.0       | 2.3–3.5 | 6.0–8.0 | 7.0–10.0  | .40 | .25 | 1.0                           | .08 | .02            | .005 | .005 |
| C84500                 | 77.0–79.0       | 2.0–4.0 | 6.0–7.5 | 10.0–14.0 | .40 | .25 | 1.0                           | .08 | .02            | .005 | .005 |
| C84800                 | 75.0–77.0       | 2.0–3.0 | 5.5–7.0 | 13.0–17.0 | .40 | .25 | 1.0                           | .08 | .02            | .005 | .005 |

## YELLOW BRASSES AND LEADED YELLOW BRASSES

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Sn      | Pb      | Zn        | Fe  | Sb  | Ni<br>(incl. Co) | Mn  | As                   | S   | P   | Al     | Si   |
|------------------------|-----------|---------|---------|-----------|-----|-----|------------------|-----|----------------------|-----|-----|--------|------|
| C85200                 | 70.0–74.0 | .7–2.0  | 1.5–3.8 | 20.0–27.0 | .6  | .20 | 1.0              | —   | —                    | .05 | .02 | .005   | .05  |
| C85210                 | 70.0–75.0 | 1.0–3.0 | 2.0–5.0 | Rem.      | .8  | —   | 1.0              | —   | .02–.06              | —   | —   | .005   | .005 |
| C85310                 | 68.0–73.0 | 1.5     | 2.0–5.0 | Rem.      | .8  | —   | 1.0              | —   | .02–.06 <sup>6</sup> | —   | —   | .01    | —    |
| C85400                 | 65.0–70.0 | .50–1.5 | 1.5–3.8 | 24.0–32.0 | .7  | —   | 1.0              | —   | —                    | —   | —   | .35    | .05  |
| C85500                 | 59.0–63.0 | .20     | .20     | Rem.      | .20 | —   | .20              | .20 | Rem.                 | —   | —   | —      | —    |
| C85700                 | 58.0–64.0 | .50–1.5 | .8–1.5  | 32.0–40.0 | .7  | —   | 1.0              | —   | —                    | —   | —   | .8     | .05  |
| C85710                 | 58.0–63.0 | 1.0     | 1.0–2.5 | Rem.      | .8  | —   | .10              | .50 | —                    | —   | —   | .20–.8 | .05  |
| C85800                 | 57.0min.  | 1.5     | 1.5     | 31.0–41.0 | .50 | .05 | .50              | .25 | .05                  | .05 | .01 | .55    | .25  |

Table 1-2, continued

## MANGANESE AND LEADED MANGANESE BRONZE ALLOYS

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Sn      | Pb      | Zn        | Fe      | Ni<br>(incl. Co) | Al      | Mn      |
|------------------------|-----------|---------|---------|-----------|---------|------------------|---------|---------|
| C86100                 | 66.0-68.0 | .20     | .20     | Rem.      | 2.0-4.0 | -                | 4.5-5.5 | 2.5-5.0 |
| C86200                 | 60.0-66.0 | .20     | .20     | 22.0-28.0 | 2.0-4.0 | 1.0              | 3.0-4.9 | 2.5-5.0 |
| C86300                 | 60.0-66.0 | .20     | .20     | 22.0-28.0 | 2.0-4.0 | 1.0              | 5.0-7.5 | 2.5-5.0 |
| C86400                 | 56.0-62.0 | .50-1.5 | .50-1.5 | 34.0-42.0 | .40-2.0 | 1.0              | .50-1.5 | .10-1.0 |
| C86500                 | 55.0-60.0 | 1.0     | .40     | 36.0-42.0 | .40-2.0 | 1.0              | .50-1.5 | .10-1.5 |
| C86700                 | 55.0-60.0 | 1.5     | .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     | .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 MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu       | Sn  | Pb  | Zn        | Fe  | Al  | Si      | Mn     | Mg  | Ni<br>(incl. Co) | S   | OTHER<br>NAMED<br>ELEMENTS                       |
|------------------------|----------|-----|-----|-----------|-----|-----|---------|--------|-----|------------------|-----|--------------------------------------------------|
| C87300                 | 94.0min. | -   | .20 | .25       | .20 | -   | 3.5-4.5 | .8-1.5 | -   | -                | -   | -                                                |
| C87400                 | 79.0min. | -   | 1.0 | 12.0-16.0 | -   | .8  | 2.5-4.0 | -      | -   | -                | -   | -                                                |
| C87410                 | 79.0min. | -   | 1.0 | 12.0-16.0 | -   | .8  | 2.5-4.0 | -      | -   | -                | -   | .03-.06As                                        |
| C87420                 | 79.0min. | -   | 1.0 | 12.0-16.0 | -   | .8  | 2.5-4.0 | -      | -   | -                | -   | .03-.06Sb                                        |
| C87430                 | 79.0min. | -   | 1.0 | 12.0-16.0 | -   | .8  | 2.5-4.0 | -      | -   | -                | -   | .03-.06P                                         |
| C87500                 | 79.0min. | -   | .50 | 12.0-16.0 | -   | .50 | 3.0-5.0 | -      | -   | -                | -   | -                                                |
| C87510                 | 79.0min. | -   | .50 | 12.0-16.0 | -   | .50 | 3.0-5.0 | -      | -   | -                | -   | .03-.06As                                        |
| C87520                 | 79.0min. | -   | .50 | 12.0-16.0 | -   | .50 | 3.0-5.0 | -      | -   | -                | -   | .03-.06Sb                                        |
| C87530                 | 79.0min. | -   | .50 | 12.0-16.0 | -   | .50 | 3.0-5.0 | -      | -   | -                | -   | .03-.06P                                         |
| C87600                 | 88.0min. | -   | .50 | 4.0-7.0   | .20 | -   | 3.5-5.5 | .25    | -   | -                | -   | -                                                |
| C87800                 | 80.0min. | .25 | .15 | 12.0-16.0 | .15 | .15 | 3.8-4.2 | .15    | .01 | .20              | .05 | .01P<br>.05As<br>.05Sb<br>.01P<br>.05As<br>.05Sb |
| C87900                 | 63.0min. | .25 | .25 | 30.0-36.0 | .40 | .15 | .8-1.2  | .15    | -   | .50              | .05 |                                                  |

## COPPER-TIN ALLOYS (TIN BRONZES)

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu                     | Sn        | Pb  | Zn      | Fe  | Sb  | Ni<br>(incl. Co) | S   | P <sup>3</sup> | Al   | Si   | Mn  |
|------------------------|------------------------|-----------|-----|---------|-----|-----|------------------|-----|----------------|------|------|-----|
| C90200                 | 91.0-94.0              | 6.0-8.0   | .30 | .50     | .20 | .20 | .50              | .05 | .05            | .005 | .005 | -   |
| C90250                 | 89.0-91.0              | 9.0-11.0  | .30 | .50     | .25 | .20 | .8 <sup>5</sup>  | .05 | .05            | .005 | .005 | .10 |
| C90300                 | 86.0-89.0 <sup>4</sup> | 7.5-9.0   | .30 | 3.0-5.0 | .20 | .20 | 1.0 <sup>5</sup> | .05 | .05            | .005 | .005 | -   |
| C90500                 | 86.0-89.0 <sup>4</sup> | 9.0-11.0  | .30 | 1.0-3.0 | .20 | .20 | 1.0 <sup>5</sup> | .05 | .05            | .005 | .005 | -   |
| C90700                 | 88.0-90.0              | 10.0-12.0 | .50 | .50     | .15 | .20 | .50              | .05 | .30            | .005 | .005 | -   |
| C90710                 | Rem.                   | 10.0-12.0 | .25 | .05     | .10 | -   | .10              | -   | .50-1.2        | .005 | .005 | -   |
| C90800                 | 85.0-89.0              | 11.0-13.0 | .25 | .25     | .15 | .20 | .50              | .05 | .30            | .005 | .005 | -   |
| C90810                 | 85.0-89.0              | 11.0-13.0 | .25 | .25     | .15 | .20 | .50              | .05 | .15-.8         | .005 | .005 | -   |
| C90900                 | 86.0-89.0              | 12.0-14.0 | .25 | .25     | .15 | .20 | .50              | .05 | .05            | .005 | .005 | -   |
| C91000                 | 84.0-86.0              | 14.0-16.0 | .20 | 1.5     | .10 | .20 | .8               | .05 | .05            | .005 | .005 | -   |
| C91100                 | 82.0-85.0              | 15.0-17.0 | .25 | .25     | .25 | .20 | .50              | .05 | 1.0            | .005 | .005 | -   |
| C91300                 | 79.0-82.0              | 18.0-20.0 | .25 | .25     | .25 | .20 | .50              | .05 | 1.0            | .005 | .005 | -   |
| C91600                 | 86.0-89.0              | 9.7-10.8  | .25 | .25     | .20 | .20 | 1.2-2.0          | .05 | .30            | .005 | .005 | -   |
| C91700                 | 84.0-87.0              | 11.3-12.5 | .25 | .25     | .20 | .20 | 1.2-2.0          | .05 | .30            | .005 | .005 | -   |

Table 1-2, continued

**COPPER-TIN-LEAD ALLOYS (LEADED TIN BRONZES)**

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu                     | Sn        | Pb      | Zn      | Fe  | Sb  | Ni<br>(incl. Co) | S   | P <sup>3</sup> | Al   | Si   | Bi  |
|------------------------|------------------------|-----------|---------|---------|-----|-----|------------------|-----|----------------|------|------|-----|
| C92200                 | 86.0-90.0 <sup>4</sup> | 5.5-6.5   | 1.0-2.0 | 3.0-5.0 | .25 | .25 | 1.0 <sup>4</sup> | .05 | .05            | .005 | .005 | -   |
| C92300                 | 85.0-89.0 <sup>4</sup> | 7.5-9.0   | .30-1.0 | 2.5-5.0 | .25 | .25 | 1.0 <sup>4</sup> | .05 | .05            | .005 | .005 | -   |
| C92310                 | 86.0-89.0              | 7.5-8.5   | .30-1.5 | 3.5-4.5 | -   | -   | 1.0              | -   | -              | .005 | .005 | .03 |
| C92400                 | 86.0-89.0 <sup>4</sup> | 9.0-11.0  | 1.0-2.5 | 1.0-3.0 | .25 | .25 | 1.0 <sup>4</sup> | .05 | .05            | .005 | .005 | -   |
| C92410                 | Rem.                   | 6.0-8.0   | 2.5-3.5 | 1.5-3.0 | .20 | .25 | 2.0              | -   | -              | .01  | .01  | .05 |
| C92500                 | 85.0-88.0              | 10.0-12.0 | 1.0-1.5 | .50     | .30 | .25 | .8-1.5           | .05 | .30            | .005 | .005 | -   |
| C92600                 | 86.0-88.5              | 9.3-10.5  | .8-1.5  | 1.3-2.5 | .20 | .25 | .7               | .05 | .03            | .005 | .005 | -   |
| C92610                 | Rem.                   | 9.5-10.5  | .30-1.5 | 1.7-2.8 | .15 | -   | 1.0              | -   | -              | .005 | .005 | .03 |
| C92700                 | 86.0-89.0              | 9.0-11.0  | 1.0-2.5 | .7      | .20 | .25 | 1.0              | .05 | .25            | .005 | .005 | -   |
| C92710                 | Rem.                   | 9.0-11.0  | 4.0-6.0 | 1.0     | .20 | .25 | 2.0              | .05 | .10            | .005 | .005 | -   |
| C92800                 | 78.0-82.0              | 15.0-17.0 | 4.0-6.0 | .8      | .20 | .25 | .8               | .05 | .05            | .005 | .005 | -   |
| C92900                 | 82.0-86.0              | 9.0-11.0  | 2.0-3.2 | .25     | .20 | .25 | 2.8-4.0          | .05 | .50            | .005 | .005 | -   |

**COPPER-TIN-LEAD (HIGH-LEADED TIN BRONZES)**

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu <sup>4</sup> | Sn        | Pb        | Zn      | Fe               | Sb  | Ni<br>(incl. Co.)    | S                | P <sup>3</sup> | Al   | Si   |
|------------------------|-----------------|-----------|-----------|---------|------------------|-----|----------------------|------------------|----------------|------|------|
| C93100                 | Rem.            | 6.5-8.5   | 2.0-5.0   | 2.0     | .20              | .25 | 1.0                  | .05              | .30            | .005 | .005 |
| C93200                 | 81.0-85.0       | 6.3-7.5   | 6.0-8.0   | 2.0-4.0 | .20              | .35 | 1.0 <sup>4</sup>     | .08              | .15            | .005 | .005 |
| C93400                 | 82.0-85.0       | 7.0-9.0   | 7.0-9.0   | .8      | .20              | .50 | 1.0                  | .08              | .50            | .005 | .005 |
| C93500                 | 83.0-86.0       | 4.30-6.0  | 8.0-10.0  | 2.0     | .20              | .30 | 1.0 <sup>4</sup>     | .08              | .05            | .005 | .005 |
| C93600                 | 79.0-83.0       | 6.0-8.0   | 11.0-13.0 | 1.0     | .20              | .35 | 1.0                  | .08              | .15            | .005 | .005 |
| C93700                 | 78.0-82.0       | 9.0-11.0  | 8.0-11.0  | .8      | .15 <sup>7</sup> | .55 | 1.0 <sup>4</sup>     | .08              | .15            | .005 | .005 |
| C93800                 | 75.0-79.0       | 6.3-7.5   | 13.0-16.0 | .8      | .15              | .8  | 1.0 <sup>4</sup>     | .08              | .05            | .005 | .005 |
| C93900                 | 76.5-79.5       | 5.0-7.0   | 14.0-18.0 | 1.5     | .40              | .50 | .8 <sup>4</sup>      | .08              | 1.5            | .005 | .005 |
| C94000                 | 69.0-72.0       | 12.0-14.0 | 14.0-16.0 | .50     | .25              | .50 | .50-1.0 <sup>4</sup> | .08 <sup>8</sup> | .05            | .005 | .005 |
| C94100                 | 65.0-75.0       | 4.5-6.5   | 15.0-22.0 | 3.0     | .25              | .8  | .8                   | .08              | .05            | .005 | .005 |
| C94300                 | 68.5-73.5       | 4.5-6.0   | 22.0-25.0 | .8      | .15              | .8  | 1.0 <sup>4</sup>     | .08              | .05            | .005 | .005 |
| C94400                 | Rem.            | 7.0-9.0   | 9.0-12.0  | .8      | .15              | .8  | 1.0                  | .08              | .50            | .005 | .005 |
| C94500                 | Rem.            | 6.0-8.0   | 16.0-22.0 | 1.2     | .15              | .8  | 1.0                  | .08              | .05            | .005 | .005 |

**COPPER-TIN-NICKEL ALLOYS (NICKEL-TIN BRONZES)**

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Sn      | Pb               | Zn      | Fe  | Sb  | Ni<br>(incl. Co) | Mn  | S   | P   | Al   | Si   |
|------------------------|-----------|---------|------------------|---------|-----|-----|------------------|-----|-----|-----|------|------|
| C94700                 | 85.0-90.0 | 4.5-6.0 | .10 <sup>9</sup> | 1.0-2.5 | .25 | .15 | 4.5-6.0          | .20 | .05 | .05 | .005 | .005 |
| C94800                 | 84.0-89.0 | 4.5-6.0 | .30-1.0          | 1.0-2.5 | .25 | .15 | 4.5-6.0          | .20 | .05 | .05 | .005 | .005 |
| C94900                 | 79.0-81.0 | 4.0-6.0 | 4.0-6.0          | 4.0-6.0 | .30 | .25 | 4.0-6.0          | .10 | .08 | .05 | .005 | .005 |

Table 1-2, continued

## COPPER-ALUMINUM-IRON AND COPPER-ALUMINUM-IRON-NICKEL ALLOYS (ALUMINUM BRONZES)

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Pb  | Fe      | Ni<br>(incl. Co) | Al        | Mn        | Mg  | Si      | Zn  | P   |
|------------------------|-----------|-----|---------|------------------|-----------|-----------|-----|---------|-----|-----|
| C95200                 | 86.0 min. | —   | 2.5-4.0 | —                | 8.5-9.5   | —         | —   | —       | —   | —   |
| C95210                 | 86.0 min. | —   | 2.5-4.0 | —                | 8.5-9.5   | —         | —   | —       | —   | —   |
| C95300                 | 86.0 min. | —   | .8-1.5  | —                | 9.0-11.0  | —         | —   | —       | —   | —   |
| C95400                 | 83.0 min. | —   | 3.0-5.0 | 1.5              | 10.0-11.5 | .50       | —   | —       | —   | —   |
| C95410                 | 83.0 min. | —   | 3.0-5.0 | 1.5-2.5          | 10.0-11.5 | .50       | —   | —       | —   | —   |
| C95500                 | 78.0 min. | —   | 3.0-5.0 | 3.0-5.5          | 10.0-11.5 | 3.5       | —   | —       | —   | —   |
| C95600                 | 88.0 min. | —   | —       | .25              | 6.0-8.0   | —         | —   | 1.8-3.3 | —   | —   |
| C95700                 | 71.0 min. | .03 | 2.0-4.0 | 1.5-3.0          | 7.0-8.5   | 11.0-14.0 | —   | .10     | —   | —   |
| C95710                 | 71.0 min. | 1.0 | 2.0-4.0 | 1.5-3.0          | 7.0-8.5   | 11.0-14.0 | —   | .15     | .50 | .05 |
| C95800                 | 79.0 min. | .03 | 3.5-4.5 | 4.0-5.0          | 8.5-9.5   | .8-1.5    | —   | .10     | —   | —   |
| C95810                 | 79.0 min. | .10 | 3.5-4.5 | 4.0-5.0          | 8.5-9.5   | 1.5       | .05 | .10     | .50 | —   |

## COPPER-NICKEL-IRON ALLOYS (COPPER-NICKELS)

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Pb                | Fe      | Ni<br>(incl. Co) | Mn      | Si  | Nb      | C   | Be      | OTHER<br>NAMED<br>ELEMENTS                  |
|------------------------|-----------|-------------------|---------|------------------|---------|-----|---------|-----|---------|---------------------------------------------|
| C96200                 | 84.5-87.0 | .03 <sup>10</sup> | 1.0-1.8 | 9.0-11.0         | 1.5     | .30 | 1.0     | .10 | —       | —                                           |
| C96300                 | Rem.      | .03 <sup>10</sup> | .40-1.0 | 18.0-22.0        | 1.0     | .7  | 1.0     | —   | —       | —                                           |
| C96400                 | 65.0-69.0 | .03 <sup>10</sup> | .25-1.5 | 28.0-32.0        | 1.5     | .50 | .50-1.5 | .15 | —       | —                                           |
| C96600                 | Rem.      | .01               | .8-1.1  | 29.0-33.0        | 1.0     | 1.5 | —       | —   | .40-.7  | —                                           |
| C96700                 | Rem.      | .01               | .7-1.0  | 29.0-33.0        | .7      | .15 | —       | —   | 1.1-1.2 | .10-.20Zr<br>.10-.20Ti<br>( <sup>11</sup> ) |
| C96800                 | Rem.      | .005              | .50     | 9.5-10.5         | .05-.30 | .05 | .10-.30 | —   | —       | —                                           |

## COPPER-NICKEL-ZINC ALLOYS (NICKEL SILVERS)

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Sn      | Pb       | Zn        | Fe  | Sb  | Ni<br>(incl. Co) | S   | P   | Al   | Mn  | Si  |
|------------------------|-----------|---------|----------|-----------|-----|-----|------------------|-----|-----|------|-----|-----|
| C97300                 | 53.0-58.0 | 1.5-3.0 | 8.0-11.0 | 17.0-25.0 | 1.5 | .35 | 11.0-14.0        | .08 | .05 | .005 | .50 | .15 |
| C97400                 | 58.0-61.0 | 2.5-3.5 | 4.5-5.5  | Rem.      | 1.5 | —   | 15.5-17.0        | —   | —   | —    | .50 | —   |
| C97600                 | 63.0-67.0 | 3.5-4.5 | 3.0-5.0  | 3.0-9.0   | 1.5 | .25 | 19.0-21.5        | .08 | .05 | .005 | 1.0 | .15 |
| C97800                 | 64.0-67.0 | 4.0-5.5 | 1.0-2.5  | 1.0-4.0   | 1.5 | .20 | 24.0-27.0        | .08 | .05 | .005 | 1.0 | .15 |

Table 1-2, continued

## COPPER-LEAD ALLOYS (LEADED COPPERS)

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | Cu        | Sn  | Pb        | Ag  | Zn  | P   | Fe  | TOTAL<br>OTHER<br>ELEMENTS |
|------------------------|-----------|-----|-----------|-----|-----|-----|-----|----------------------------|
| C98200                 | 73.0-79.0 | .50 | 21.0-27.0 | —   | —   | —   | .35 | .45                        |
| C98400                 | 67.0-74.0 | .25 | 25.0-32.0 | 1.5 | .10 | .02 | .35 | .15                        |
| C98600                 | 60.0-70.0 | .50 | 30.0-40.0 | 1.5 | —   | —   | .35 | .30                        |
| C98800                 | 56.5-62.5 | .25 | 37.5-42.5 | 5.5 | .10 | .02 | .35 | .30                        |

## SPECIAL ALLOYS

COMPOSITION, PERCENT MAXIMUM (UNLESS SHOWN AS A RANGE OR MINIMUM)

| COPPER<br>ALLOY<br>NO. | OTHER<br>DESIG-<br>NATIONS | Cu        | Sn      | Pb  | Ni        | Fe      | Al        | Co      | Si      | Mn        | OTHER<br>NAMED<br>ELEMENTS |
|------------------------|----------------------------|-----------|---------|-----|-----------|---------|-----------|---------|---------|-----------|----------------------------|
| C99300                 | Incramet<br>800            | Rem.      | .05     | .02 | 13.5-16.5 | .40-1.0 | 10.7-11.5 | 1.0-2.0 | .02     | —         | —                          |
| C99400                 | .....                      | Rem.      | —       | .25 | 1.0-3.5   | 1.0-3.0 | .50-2.0   | —       | .50-2.0 | .50       | .50-5.0Zn                  |
| C99500                 | .....                      | Rem.      | —       | .25 | 3.5-5.5   | 3.0-5.0 | .50-2.0   | —       | .50-2.0 | .50       | .50-2.0Zn                  |
| C99600                 | Incramute 1                | Rem.      | .10     | .02 | .20       | .20     | 1.0-2.8   | .20     | .10     | 39.0-45.0 | .20Zn<br>.05C              |
| C99700                 | .....                      | 54.0 min. | 1.0     | 2.0 | 4.0-6.0   | 1.0     | .50-3.0   | —       | —       | 11.0-15.0 | 19.0-25.0Zn                |
| C99750                 | .....                      | 55.0-61.0 | .50-2.5 | —   | 5.0       | 1.0     | .25-3.0   | —       | —       | 17.0-23.0 | 17.0-23.0Zn                |

## NOTES

<sup>1</sup>Includes Ag.<sup>2</sup>Ni + Co.<sup>3</sup>For continuous castings, phosphorus shall be 1.5% maximum.<sup>4</sup>In determining copper minimum, copper may be calculated as Cu + Ni.<sup>5</sup>Fe + Sb + As shall be .8 max.<sup>6</sup>By agreement between supplier and consumer.<sup>7</sup>The iron shall be .35% max. when used for steel-backed bearings.<sup>8</sup>For continuous castings, sulfur shall be .25% max.<sup>9</sup>The mechanical properties of Copper Alloy No. C94700 (heat treated) may not be attained if the lead content exceeds .01%.<sup>10</sup>For welding grades, Pb may not exceed .01%.<sup>11</sup>The following additional impurity limits shall apply: Al, .10 max; B, .001 max; Bi, .001max; Mg, .005-.15; P, .005 max; S, .0025 max; Sb, .02 max; Sn, 7.5-8.5; Ti, .01 max; Zn, 1.0 max.



## Chapter 2

# CONFORMING SPECIFICATIONS FOR COPPER-BASE ALLOYS

The foundryman is often confronted with a confusing array of specification requirements. The objective of this chapter is to provide guidance as to where definitions of such specifications can be found, and to explain the relationships between various sets of specifications. These relationships are based on the alloy numbers, which are listed in Table 2-1 in numerical order, together with the relevant specification numbers for different products. This list covers only data from the major national standards-writing bodies (including the Brass and Bronze Ingot Institute) 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 *Standards Handbook—Cast Copper and Copper Alloy Foundry Products*, Part 6—"Specifications Index" of the Copper Development Association, Inc.

Copies of specifications may be obtained from the

sources listed in Table 2-2. 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 SB 584.

It is a consolation to know that there has recently been a marked trend towards unification and uniformity in copper standards, and agreement on compositions as defined by the alloy numbers, under the leadership of CDA and ASTM. This trend is continuing and the federal administration has adopted a policy to abandon its own standards wherever commercial standards can be accepted or modified to meet its requirements.

Table 2-1. Relationship Between the CDA/UNS Copper Alloy Number and Other Specification Systems

|                                  |                                            |                                                          |
|----------------------------------|--------------------------------------------|----------------------------------------------------------|
| <b>COPPER NO. C80100</b>         | <b>COPPER ALLOY NO. C81500</b>             | <b>SAND</b><br>FEDERAL QQ-C-390                          |
| <b>INGOT</b><br>FEDERAL QQ-C-521 | <b>CENTRIFUGAL</b><br>MILITARY MIL-C-19310 | <b>VALVES</b><br>FEDERAL WW-V-1967                       |
| <b>COPPER NO. C80300</b>         | <b>SAND</b><br>MILITARY MIL-C-19310        | <b>COPPER ALLOY NO. C82500</b>                           |
| — NONE —                         |                                            | <b>CENTRIFUGAL</b><br>FEDERAL QQ-C-390                   |
| <b>COPPER NO. C80500</b>         | <b>COPPER ALLOY NO. C81700</b>             | <b>INVESTMENT</b><br>AMS 4890<br>MILITARY MIL-C-22087    |
| — NONE —                         | — NONE —                                   | <b>PRECISION</b><br>MILITARY MIL-C-11866, COMPOSITION 17 |
| <b>COPPER NO. C80700</b>         | <b>COPPER ALLOY NO. C81800</b>             | <b>SAND</b><br>FEDERAL QQ-C-390                          |
| — NONE —                         | — NONE —                                   | <b>COPPER ALLOY NO. C82600</b>                           |
| <b>COPPER NO. C80900</b>         | <b>COPPER ALLOY NO. C82000</b>             | <b>SAND</b><br>FEDERAL QQ-C-390                          |
| — NONE —                         | <b>SAND</b><br>FEDERAL QQ-C-390            | <b>VALVES</b><br>FEDERAL WW-V-1967                       |
| <b>COPPER NO. C81100</b>         | <b>COPPER ALLOY NO. C82100</b>             | <b>COPPER ALLOY NO. C82700</b>                           |
| — NONE —                         | — NONE —                                   | <b>SAND</b><br>FEDERAL QQ-C-390                          |
| <b>COPPER ALLOY NO. C81300</b>   | <b>COPPER ALLOY NO. C82200</b>             | <b>VALVES</b><br>FEDERAL WW-V-1967                       |
| — NONE —                         | — NONE —                                   | <b>COPPER ALLOY NO. C82800</b>                           |
| <b>COPPER ALLOY NO. C81400</b>   | <b>COPPER ALLOY NO. C82400</b>             | <b>SAND</b><br>FEDERAL QQ-C-390                          |
| — NONE —                         | <b>CENTRIFUGAL</b><br>FEDERAL QQ-C-390     |                                                          |

Table 2-1, continued

**VALVES**  
FEDERAL WW-V-1967

### COPPER ALLOY NO. C83300

**INGOT**  
INGOT NO. 131

### COPPER ALLOY NO. C83400

**BANDS, PROJECTILE ROTATING**  
MILITARY MIL-B-46066

### COPPER ALLOY NO. C83500

**INGOT**  
INGOT NO. 251

### COPPER ALLOY NO. C83600

**CENTRIFUGAL**  
AMS 4855  
ASME SB271  
ASTM B271  
FEDERAL QQ-C-390  
MILITARY MIL-C-15345, ALLOY 1  
SAE J461  
J462

**CONTINUOUS**  
AMS 4855  
ASTM B505  
FEDERAL QQ-C-390  
SAE J461  
J462

**FITTINGS**  
ANSI B16.15  
B16.18  
B16.23  
B16.26  
B16.32  
ASME SB62  
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

### COPPER ALLOY NO. C83800

**CENTRIFUGAL**  
ASTM B271  
FEDERAL QQ-C-390

SAE J461  
J462

**CONTINUOUS**  
ASTM B505  
FEDERAL QQ-C-390  
SAE J461  
J462

**FITTINGS**  
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  
FEDERAL QQ-C-390  
SAE J461  
J462

**UNIONS**  
FEDERAL WW-U-516

**VALVES**  
FEDERAL WW-V-1967

### COPPER 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

### COPPER ALLOY NO. C84400

**CENTRIFUGAL**  
ASTM B271  
FEDERAL QQ-C-390

**CONTINUOUS**  
ASTM B505  
FEDERAL QQ-C-390

**FITTINGS**  
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

### COPPER ALLOY NO. C84500

**INGOT**  
INGOT NO. 125

### COPPER 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  
FEDERAL QQ-C-390

### COPPER ALLOY NO. C85200

**CENTRIFUGAL**  
ASTM B271  
SAE J461  
J462

**CONTINUOUS**  
SAE J461  
J462

**INGOT**  
ASTM B30  
INGOT NO. 400

**SAND**  
ASTM B584  
FEDERAL QQ-C-390

**VALVES**  
FEDERAL WW-V-1967

### COPPER ALLOY NO. C85400

**CENTRIFUGAL**  
ASTM B271  
SAE J461  
J462

**CONTINUOUS**  
SAE J461  
J462

**INGOT**  
ASTM B30  
INGOT NO. 403

**PERMANENT MOLD**  
SAE J461  
J462

**SAND**  
FEDERAL QQ-C-390  
SAE J461  
J462

**VALVES**  
FEDERAL WW-V-1967

### COPPER ALLOY NO. C85500

**CENTRIFUGAL**  
FEDERAL QQ-C-390  
MILITARY MIL-C-15345, ALLOY 2

**SAND**  
FEDERAL QQ-C-390

**VALVES**  
FEDERAL WW-V-1967

### COPPER ALLOY NO. C85700

**CENTRIFUGAL**  
ASTM B271  
FEDERAL QQ-C-390  
MILITARY MIL-C-15345, ALLOY 3

**INGOT**  
ASTM B30  
INGOT NO. 406

Table 2-1, continued

**SAND**  
ASTM B584  
FEDERAL QQ-C-390

**COPPER ALLOY NO. C85800**

**DIE**  
ASTM B176  
MILITARY MIL-B-15894  
SAE J461  
J462

**INGOT**  
ASTM B30  
INGOT NO. 405.1

**COPPER 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

**COPPER 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  
FEDERAL QQ-C-390  
MILITARY MIL-C-22229  
SAE J461  
J462

**VALVES**  
FEDERAL WW-V-1967

**COPPER 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**  
FEDERAL WW-V-1967

**COPPER 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  
FEDERAL QQ-C-390

**VALVES**  
FEDERAL WW-V-1967

**COPPER 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  
FEDERAL QQ-C-390  
MILITARY MIL-C-22229  
SAE J461  
J462

**VALVES**  
FEDERAL WW-V-54  
WW-V-1967

**COPPER ALLOY NO. C86700**

**CENTRIFUGAL**  
ASTM B271

**INGOT**  
ASTM B30  
INGOT NO. 422

**SAND**  
ASTM B584

**COPPER ALLOY NO. C86800**

**DIE**  
ASTM B176

**SAND**  
FEDERAL QQ-C-390

**VALVES**  
FEDERAL WW-V-1967

**COPPER ALLOY NO. C87200**

**CENTRIFUGAL**  
ASTM B271  
SAE J461  
J462

**INGOT**  
ASTM B30  
INGOT NO. 500

**INVESTMENT**  
SAE J461  
J462

**PERMANENT MOLD**  
SAE J461  
J462

**PRECISION**  
MILITARY MIL-C-11866, COMPOSITION 19

**SAND**  
ASTM B584  
FEDERAL QQ-C-390  
MILITARY MIL-C-22229  
SAE J461  
J462

**VALVES**  
FEDERAL WW-V-1967

**COPPER ALLOY NO. C87400**

**CENTRIFUGAL**  
ASTM B271  
SAE J461  
J462

**DIE**  
SAE J461  
J462

**INGOT**  
ASTM B30

**INVESTMENT**  
MILITARY MIL-C-22087  
SAE J461  
J462

**PERMANENT MOLD**  
SAE J461  
J462

**SAND**  
ASTM B584  
FEDERAL QQ-C-390  
SAE J461  
J462

**VALVES**  
FEDERAL WW-V-51  
WW-V-1967

Table 2-1, continued

**COPPER ALLOY NO. C87410**

— NONE —

**COPPER ALLOY NO. C87420**

— NONE —

**COPPER ALLOY NO. C87430**

— NONE —

**COPPER ALLOY NO. C87500****CENTRIFUGAL**

|      |      |
|------|------|
| ASTM | B271 |
| SAE  | J461 |
|      | J462 |

**DIE**

|     |      |
|-----|------|
| SAE | J461 |
|     | J462 |

**INGOT**

|           |      |
|-----------|------|
| ASTM      | B30  |
| INGOT NO. | 500T |

**INVESTMENT**

|          |             |
|----------|-------------|
| MILITARY | MIL-C-22087 |
| SAE      | J461        |
|          | J462        |

**PERMANENT MOLD**

|     |      |
|-----|------|
| SAE | J461 |
|     | J462 |

**SAND**

|         |          |
|---------|----------|
| ASTM    | B584     |
| FEDERAL | QQ-C-390 |

**VALVES**

|          |            |
|----------|------------|
| FEDERAL  | WW-V-51    |
|          | WW-V-54    |
| MILITARY | MIL-V-1187 |
|          | MIL-V-1202 |

**COPPER ALLOY NO. C87510**

— NONE —

**COPPER ALLOY NO. C87520**

— NONE —

**COPPER ALLOY NO. C87530**

— NONE —

**COPPER ALLOY NO. C87600****INGOT**

|           |     |
|-----------|-----|
| ASTM      | B30 |
| INGOT NO. | 500 |

**SAND**

|      |      |
|------|------|
| ASTM | B584 |
|------|------|

**VALVES**

|          |            |
|----------|------------|
| FEDERAL  | WW-V-51    |
|          | WW-V-54    |
| MILITARY | MIL-V-1202 |

**COPPER ALLOY NO. C87800****DIE**

|          |             |
|----------|-------------|
| ASTM     | B176        |
| MILITARY | MIL-B-15894 |
| SAE      | J461        |
|          | J462        |

**INGOT**

|           |     |
|-----------|-----|
| ASTM      | B30 |
| INGOT NO. | 500 |

**COPPER ALLOY NO. C87900****DIE**

|          |             |
|----------|-------------|
| ASTM     | B176        |
| MILITARY | MIL-B-15894 |
| SAE      | J461        |
|          | J462        |

**INGOT**

|      |     |
|------|-----|
| ASTM | B30 |
|------|-----|

**COPPER ALLOY NO. C90200****INGOT**

|           |     |
|-----------|-----|
| INGOT NO. | 242 |
|-----------|-----|

**COPPER 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**

|           |          |
|-----------|----------|
| ASTM      | B30      |
| 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        |
| FEDERAL  | QQ-C-390    |
| MILITARY | MIL-C-22229 |
| SAE      | J461        |
|          | J462        |

**VALVES**

|         |           |
|---------|-----------|
| FEDERAL | WW-V-1967 |
|---------|-----------|

**COPPER ALLOY NO. C90500****CENTRIFUGAL**

|         |          |
|---------|----------|
| AMS     | 4845     |
| 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      |
|         | B584     |
| FEDERAL | QQ-C-390 |
| SAE     | J461     |
|         | J462     |

**COPPER 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 |

**COPPER ALLOY NO. C90800****CENTRIFUGAL**

|      |      |
|------|------|
| ASTM | B427 |
|------|------|

**INGOT**

|      |     |
|------|-----|
| ASTM | B30 |
|------|-----|

**SAND**

|      |      |
|------|------|
| ASTM | B427 |
|------|------|

**COPPER ALLOY NO. C90900****INGOT**

|           |     |
|-----------|-----|
| INGOT NO. | 199 |
|-----------|-----|

**COPPER 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 |
|---------|----------|

**COPPER ALLOY NO. C91100****SAND**

|      |     |
|------|-----|
| ASTM | B22 |
|------|-----|

**COPPER 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 |

Table 2-1, continued

**COPPER 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 |
|------|------|

**COPPER ALLOY NO. C91700****CENTRIFUGAL**

|      |      |
|------|------|
| ASTM | B427 |
|------|------|

**INGOT**

|      |     |
|------|-----|
| ASTM | B30 |
|------|-----|

**SAND**

|      |      |
|------|------|
| ASTM | B427 |
|------|------|

**COPPER 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         |
|          | B584        |
| FEDERAL  | QQ-C-390    |
| MILITARY | MIL-B-16541 |
| SAE      | J461        |
|          | J462        |

**VALVES**

|          |             |
|----------|-------------|
| FEDERAL  | WW-V-51     |
|          | WW-V-54     |
|          | WW-V-1967   |
| MILITARY | MIL-V-1187  |
|          | MIL-V-17547 |

**COPPER 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        |
| FEDERAL  | QQ-C-390    |
| MILITARY | MIL-C-16540 |
| SAE      | J461        |
|          | J462        |

**COPPER ALLOY NO. C92400****INGOT**

|           |     |
|-----------|-----|
| INGOT NO. | 220 |
|-----------|-----|

**COPPER 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 |
|---------|-----------|

**COPPER ALLOY NO. C92600****INGOT**

|           |     |
|-----------|-----|
| INGOT NO. | 215 |
|-----------|-----|

**COPPER 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 |

**COPPER ALLOY NO. C92800****CONTINUOUS**

|      |      |
|------|------|
| ASTM | B505 |
|------|------|

**INGOT**

|           |     |
|-----------|-----|
| ASTM      | B30 |
| INGOT NO. | 295 |

**COPPER ALLOY NO. C92900****CENTRIFUGAL****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 |

**COPPER 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     |
| FEDERAL | QQ-C-390 |
| SAE     | J461     |
|         | J462     |

**COPPER 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 |

**COPPER 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**

Table 2-1, continued

ASTM B584  
FEDERAL QQ-C-390  
SAE J461  
J462

**COPPER 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  
J462

**INGOT**

ASTM B30  
INGOT NO. 305

**PERMANENT MOLD**

SAE J461  
J462

**SAND**

AMS 4842  
ASME SB584  
ASTM B22  
B584  
FEDERAL QQ-C-390  
SAE J461  
J462

**COPPER 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  
FEDERAL QQ-C-390

**COPPER ALLOY NO. C93900****CONTINUOUS**

ASTM B505  
FEDERAL QQ-C-390

**INGOT**

ASTM B30  
FEDERAL QQ-C-525

**COPPER 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

**COPPER 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

**COPPER ALLOY NO. C94300****CENTRIFUGAL**

AMS 4840  
ASTM B271  
FEDERAL QQ-C-390  
SAE J461  
J462

**CONTINUOUS**

ASTM B505  
FEDERAL QQ-C-390

**INGOT**

ASTM B30  
INGOT NO. 322

**SAND**

AMS 4840  
ASTM B66  
B584  
FEDERAL QQ-C-390

**COPPER ALLOY NO. C94400****INGOT**

ASTM B30  
INGOT NO. 312

**SAND**

ASTM B66

**COPPER ALLOY NO. C94500****INGOT**

ASTM B30  
INGOT NO. 321

**SAND**

ASTM B66

**COPPER 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  
FEDERAL QQ-C-390  
SAE J461  
J462

**VALVES**

FEDERAL WW-V-1967

**COPPER ALLOY NO. C94800****CONTINUOUS**

ASTM B505  
FEDERAL QQ-C-390

**INGOT**

ASTM B30

**PERMANENT MOLD**

SAE J461  
J462

**SAND**

ASTM B584  
FEDERAL QQ-C-390  
SAE J461  
J462

**VALVES**

FEDERAL WW-V-1967

**COPPER ALLOY NO. C94900****INGOT**

ASTM B30

**SAND**

ASTM B584

**COPPER ALLOY NO. C95200****CENTRIFUGAL**

ASME SB271  
ASTM B271  
FEDERAL QQ-C-390  
SAE J461  
J462

**CONTINUOUS**

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  
FEDERAL QQ-C-390  
MILITARY MIL-C-22229  
SAE J461  
J462

**VALVES**

FEDERAL WW-V-1967

**COPPER ALLOY NO. C95300****CENTRIFUGAL**

ASTM B271  
FEDERAL QQ-C-390  
SAE J461  
J462

**CONTINUOUS**

ASTM B505  
FEDERAL QQ-C-390  
SAE J461  
J462

Table 2-1, continued

|                                |                             |  |  |
|--------------------------------|-----------------------------|--|--|
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| FEDERAL                        | QQ-B-675                    |  |  |
| INGOT NO.                      | 415                         |  |  |
| <b>PERMANENT MOLD</b>          |                             |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>PRECISION</b>               |                             |  |  |
| MILITARY                       | MIL-C-11866, COMPOSITION 22 |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASME                           | SB148                       |  |  |
| ASTM                           | B148                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>VALVES</b>                  |                             |  |  |
| FEDERAL                        | WW-V-1967                   |  |  |
| <b>COPPER ALLOY NO. C95400</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| AMS                            | 4870                        |  |  |
|                                | 4871                        |  |  |
| ASTM                           | B271                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-C-15345, ALLOY 13       |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>CONTINUOUS</b>              |                             |  |  |
| ASTM                           | B505                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| FEDERAL                        | QQ-B-675                    |  |  |
| INGOT NO.                      | 415                         |  |  |
| <b>PERMANENT MOLD</b>          |                             |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>PRECISION</b>               |                             |  |  |
| MILITARY                       | MIL-C-11866, COMPOSITION 23 |  |  |
| <b>SAND</b>                    |                             |  |  |
| AMS                            | 4872                        |  |  |
|                                | 4873                        |  |  |
| ASME                           | SB148                       |  |  |
| ASTM                           | B148                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>VALVES</b>                  |                             |  |  |
| FEDERAL                        | WW-V-1967                   |  |  |
| <b>COPPER ALLOY NO. C95410</b> |                             |  |  |
| — NONE —                       |                             |  |  |
| <b>COPPER ALLOY NO. C95500</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| ASTM                           | B271                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-C-15345, ALLOY 14       |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>CONTINUOUS</b>              |                             |  |  |
| ASTM                           | B505                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| FEDERAL                        | QQ-B-675                    |  |  |
| INGOT NO.                      | 415                         |  |  |
| <b>INVESTMENT</b>              |                             |  |  |
| MILITARY                       | MIL-C-22087                 |  |  |
| <b>PERMANENT MOLD</b>          |                             |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASTM                           | B148                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-B-24480                 |  |  |
|                                | MIL-C-22229                 |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>VALVES</b>                  |                             |  |  |
| FEDERAL                        | WW-V-1967                   |  |  |
| <b>COPPER ALLOY NO. C96200</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| ASTM                           | B369                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-C-15345, ALLOY 25       |  |  |
|                                | MIL-C-20159, TYPE II        |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASTM                           | B369                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-C-20159, TYPE II        |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>VALVES</b>                  |                             |  |  |
| FEDERAL                        | WW-V-1967                   |  |  |
| <b>COPPER ALLOY NO. C96300</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| ASTM                           | B492                        |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASTM                           | B492                        |  |  |
| <b>COPPER ALLOY NO. C96400</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| ASTM                           | B369                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-C-15345, ALLOY 24       |  |  |
|                                | MIL-C-20159, TYPE I         |  |  |
| <b>CONTINUOUS</b>              |                             |  |  |
| ASTM                           | B505                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASTM                           | B369                        |  |  |
| FEDERAL                        | QQ-C-390                    |  |  |
| MILITARY                       | MIL-C-20159, TYPE I         |  |  |
| <b>VALVES</b>                  |                             |  |  |
| FEDERAL                        | WW-V-51                     |  |  |
|                                | WW-V-1967                   |  |  |
| MILITARY                       | MIL-V-1202                  |  |  |
| <b>COPPER ALLOY NO. C96600</b> |                             |  |  |
| <b>SAND</b>                    |                             |  |  |
| MILITARY                       | MIL-C-81519 (AS)            |  |  |
| <b>COPPER ALLOY NO. C97300</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| ASTM                           | B271                        |  |  |
| <b>CONTINUOUS</b>              |                             |  |  |
| ASTM                           | B505                        |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| INGOT NO.                      | 410                         |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASTM                           | B584                        |  |  |
| <b>VALVES</b>                  |                             |  |  |
| FEDERAL                        | WW-V-51                     |  |  |
| <b>COPPER ALLOY NO. C97400</b> |                             |  |  |
| <b>INGOT</b>                   |                             |  |  |
| INGOT NO.                      | 411                         |  |  |
| <b>COPPER ALLOY NO. C97600</b> |                             |  |  |
| <b>CENTRIFUGAL</b>             |                             |  |  |
| ASTM                           | B271                        |  |  |
| <b>CONTINUOUS</b>              |                             |  |  |
| ASTM                           | B505                        |  |  |
| SAE                            | J461                        |  |  |
|                                | J462                        |  |  |
| <b>INGOT</b>                   |                             |  |  |
| ASTM                           | B30                         |  |  |
| INGOT NO.                      | 412                         |  |  |
| <b>SAND</b>                    |                             |  |  |
| ASME                           | SB584                       |  |  |

Table 2-1, continued

|                                |                        |                         |                         |
|--------------------------------|------------------------|-------------------------|-------------------------|
| ASTM<br>MILITARY               | B584<br>MIL-C-17112    | NONE —                  | COPPER ALLOY NO. C99500 |
| <b>VALVES</b>                  |                        |                         | NONE —                  |
| FEDERAL                        | WW-V-51                | COPPER ALLOY NO. C98400 |                         |
| MILITARY                       | WW-V-54<br>MIL-V-18436 | <b>BEARINGS</b>         | COPPER ALLOY NO. C99600 |
|                                |                        | AMS 4820                | NONE —                  |
| <b>COPPER ALLOY NO. C97800</b> |                        | COPPER ALLOY NO. C98600 |                         |
| <b>CENTRIFUGAL</b>             |                        | NONE —                  | COPPER ALLOY NO. C99700 |
| ASTM                           | B271                   |                         | NONE —                  |
| <b>CONTINUOUS</b>              |                        | COPPER ALLOY NO. C98800 |                         |
| ASTM                           | B505                   | NONE —                  | COPPER ALLOY NO. C99750 |
| <b>INGOT</b>                   |                        |                         |                         |
| ASTM                           | B30                    | COPPER ALLOY NO. C99300 | DIE                     |
| INGOT NO.                      | 413B                   |                         | ASTM B176               |
| <b>SAND</b>                    |                        | NONE —                  |                         |
| ASTM                           | B584                   | COPPER ALLOY NO. C99400 |                         |
| <b>VALVES</b>                  |                        | NONE —                  |                         |
| FEDERAL                        | WW-V-51                |                         |                         |
| MILITARY                       | WW-V-54<br>MIL-V-18436 |                         |                         |
| <b>COPPER ALLOY NO. C98200</b> |                        | NONE —                  |                         |

Table 2-2. Directory of Specification Sources

**CDA**  
Copper Development Association, Inc.  
405 Lexington Avenue New York,  
New York, New York 10017  
(212) 953-7300

**ANST**  
American National Standards Institute, Inc.  
1430 Broadway  
New York, N.Y. 10018  
(212) 868-1220

**ASTM**  
American Society for Testing and Materials  
1916 Race Street  
Philadelphia, Pennsylvania 19103  
(215) 299-5400

**ASME**  
American Society of Mechanical Engineers  
United Engineering Center  
345 East 47th Street  
New York, N.Y. 10017  
(212) 644-7820

**SAE**  
Society of Automotive Engineers, Inc.  
400 Commonwealth Drive  
Warrendale, Pennsylvania 15096  
(412) 776-4841

**AMS**  
Aerospace Materials Specifications  
Society of Automotive Engineers, Inc.  
400 Commonwealth Drive  
Warrendale, Pennsylvania 15096  
(412) 776-4841

**Federal & Military**  
U.S. Naval Supply Depot  
5801 Tabor Avenue  
Philadelphia, Pennsylvania 19120  
(215) 697-3321

**Ingot No.**  
Brass and Bronze Ingot Institute  
33 N. LaSalle Street, Room 3500  
Chicago, Illinois 60602  
(312) 236-2715

# Chapter 3

## CASTING PROCESSES AND MATERIALS

### INTRODUCTION

Foundrymen have at their disposal many different methods for the casting of metal shapes, and certain of these methods are uniquely suited for the production of specific kinds of castings. Although a foundry may utilize more than one casting process, this 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. The higher operating costs for certain processes may, in some cases, be outweighed by their greater precision. With greater precision, certain finishing or machining operations may possibly be eliminated, thus actually reducing the net cost of the casting.

Parts produced in expendable sand molds comprise more than 85% of the annual tonnage of copper-base alloy castings. A major portion of this chapter will be devoted to this subject. Vast amounts of information have been published on foundry sands, binders, additives, and related molding and coremaking processes. The material which follows on these subjects 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 re-usable metal molds or dies, utilizing either gravity or mechanical forces for introducing the molten metal into the mold cavity. Such processes include pressure die casting, permanent mold casting, centrifugal casting, and continuous casting. Relatively little has been published in the foundry literature regarding the application of these processes to the production of copper-base alloy 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 limited portion of the industry is involved in producing precision castings made using expendable molds of plaster (gypsum) or ceramic material. 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
- Skin-dried 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

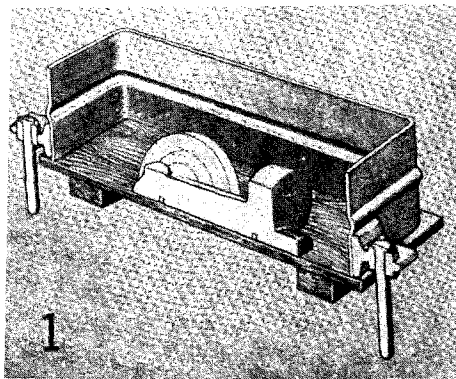
#### Green Sand Molding

The green sand process utilizes a molding aggregate whose 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).

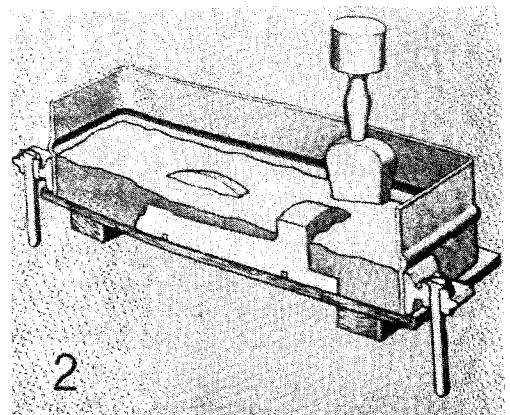
Green sand molding is the most diversified and widespread process used for casting production today, particularly for small- to medium-size castings. Molding consists of compacting the tempered sand about the pattern (usually inside a flask of some type) by one or more mechanical means such as jolting, 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.

Contributing to the economy and versatility of the process is the relative ease with which the molding aggregate can be prepared for use (by mulling or mixing), transported, and stored. Additionally, the sand mixture can be re-used 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 matter.

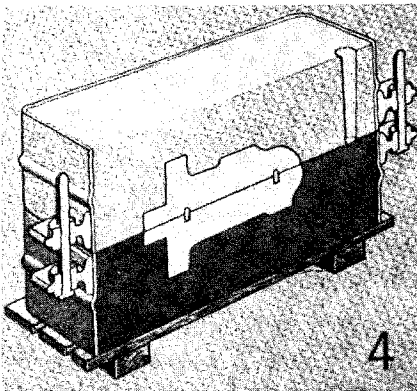
The quality of castings made in green sand molds is highly dependent on the properties of the molding aggregate as well as those of the mold. These are para-



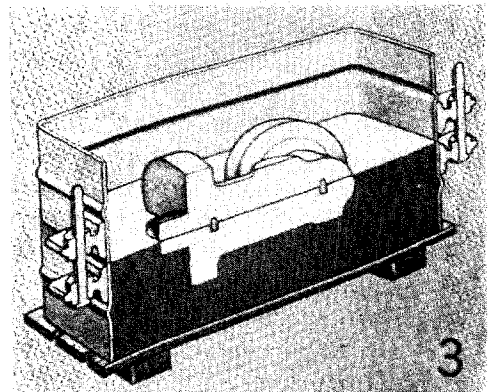
Cross section of the first step in making a green sand mold. Bottom half of the pattern is on the mold board and surrounded by the bottom or drag half of the flask.



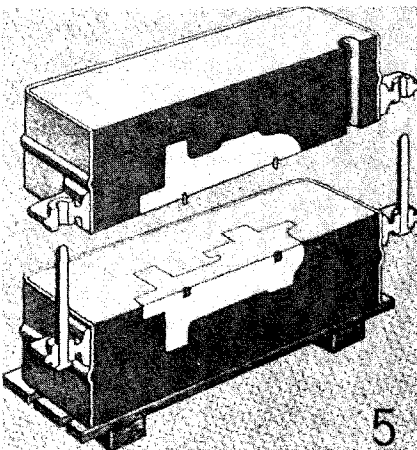
Molding sand is rammed around the pattern in multiple steps to provide uniform density.



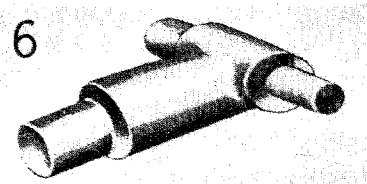
Section through the completed mold with pattern still in place and the sprue hole formed for entrance of molten metal.



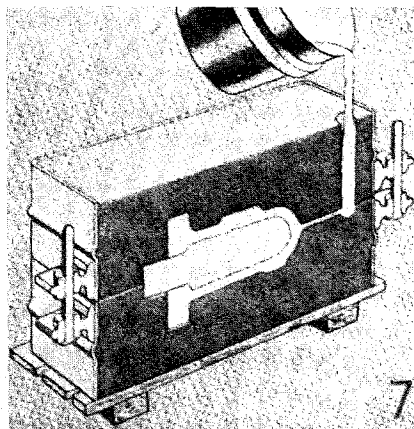
After the bottom half of the mold is filled, it is rolled upright and the top half of the pattern and flask are put in place to complete the mold.



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. Making a green sand mold. 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.

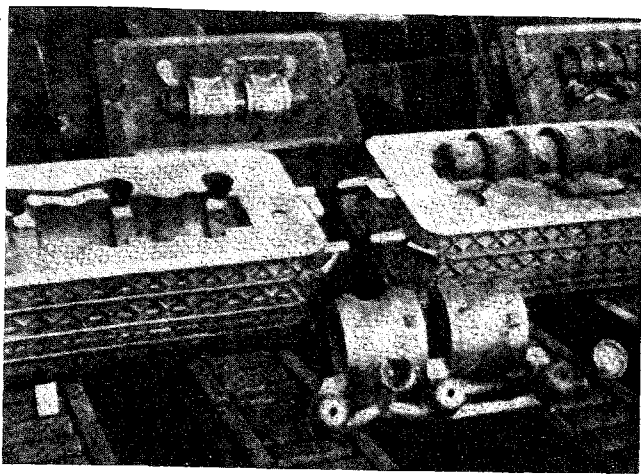


Fig. 3-2. A typical green-sand molded cope and drag showing the castings produced from this mold.

meters which can easily change from hour to hour or from day to day unless close control is 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 comprised largely of silicon dioxide ( $\text{SiO}_2$ ). Natural contaminants such as particles of feldspar, mica or metal oxides may also be present.

The term *sand* may also denote a class of material which includes several other minerals. Thus, zircon, chromite, olivine, and other refractory materials may be regarded as sands if their grain size falls within the range described above.

In regular foundry production, silica sand is the most widely used base material for both molding and core-making 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*.

#### Naturally-Bonded Sands

Naturally-bonded sands are water-deposited sands found in nature, combined with various clay minerals. They may exhibit a wide range of grain sizes or clay contents, depending upon their origin and location. 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 dry the sand partially (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.

Naturally-bonded sand is as old as the foundry industry, and its use dates back to prehistory. Early foundry development in North America progressed more rapidly in certain geographical locations than in others, depending in large measure upon the local availability of good molding sands. The naturally-bonded sands, being a product of nature, were found to vary greatly in their characteristics; those from certain locations were found to have superior properties. Until a few decades ago, depletion of local sand supplies meant the shut-down or relocation of the foundry since long-distance shipment of sand was either impossible or expensive. With the development of improved and expanded railway and motor freight transportation, and with foundries concentrated in heavily industrialized areas in a number of eastern and midwestern states, it became both practical and necessary to purchase sand from commercial sources often located many miles away. During the past sixty years or so, a number of areas having extensive deposits of superior, naturally-bonded sands have become well-known to both ferrous and nonferrous foundrymen. These sands carry such designations as Albany, New Jersey, McConnellsville, Windsor Lock, Provincetown, Mississippi, Tennessee, and so on. Brass and bronze foundries in North America have traditionally used naturally-bonded sands, especially those of finer grain size, for green sand molding. Although many still follow this practice, the use of naturally-bonded sand is decreasing due to the depletion of deposits and changes and inconsistencies in sand characteristics.

One important problem for users of naturally-bonded sands is 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. The cost of removal of the clay balls by riddling is excessive, in addition to the cost of replenishment by new bonding clay. To avoid this problem, the following measures should be observed:

- Check incoming sand to see that clay balls are absent.
- Purchase sand having a water content below 8%.
- Specify a sand having a grain fineness no higher than necessary.
- Specify a clay content which is no higher than required.
- Minimize handling, shoveling, mulling and riddling of the sand.
- Prevent excessive accumulation of fines in the system sand.
- Reduce the ash content in the system sand, formed by combustion of organic additives.

- Avoid making sudden large additions of new sand to the sand system.
- In critical circumstances, use a riddled facing sand (free of clay balls) against the pattern.

In summary, 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.

Another serious problem with naturally-bonded sands is their susceptibility to the formation of expansion-type defects such as buckles, scabs, and rat tails. 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 occurrence 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 by a suitable exhaust 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.

In addition to the trend toward depletion of satisfactory deposits of naturally-bonded molding sands, recent years have seen 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 have emphasized the need for more uniform, high-quality sands having properties consistent with the requirements of modern 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 added to produce a 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*

Unbonded sands used in foundries are predominately silica sands. 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, and so on—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 invariably screened, washed, de-slimed and dried for purposes of removing clay and other contaminants. Frequently the screening process may include classifying the sand to control grain size distribution.

In respect to grain shape, base sands are frequently designated as being angular, sub-angular, or rounded. A fourth type, *compound-grain* sand also exists; however, this form has low thermal shock resistance and 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 foundrymen because of their better flowability and lower binder requirement. The angular sands are not from natural deposits 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. In addition, 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), resulting in additional expansion. This behavior may be seen from the appropriate curve in Fig. 3-3, which illustrates a total thermal expansion of quartz of some 1.3% within the range of normal casting temperatures. This characteristic of quartz causes expansion of mold surfaces when exposed to thermal shock and, unless

### THERMAL EXPANSION OF SILICA MATERIALS

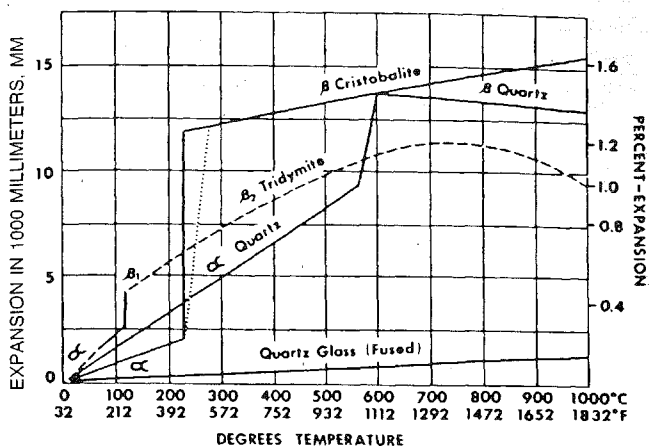


Fig. 3-3. Thermal expansion of silica materials.

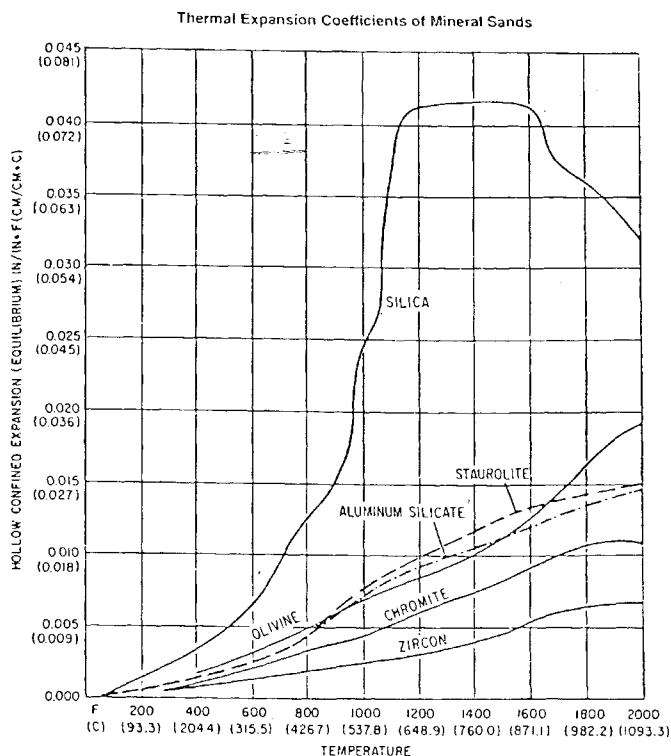


Fig. 3-4. Thermal expansion of non-silica aggregates as compared with silica sand.

precautionary measures are taken, can result in casting surface defects such as rat tails, buckles, and scabs. Other disadvantages of silica sands are their relatively low chilling power and their toxicity, as airborne dusts, in causing respiratory problems.

In recent years, foundrymen have increasingly made use of various specialty sands composed of minerals other than silica. These are limited in supply and are much more expensive than is silica. 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 non-ferrous foundries are olivine and zircon sand.

### Olivine

Olivine is a non-siliceous (contains no free silica) mineral which 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 also exhibits somewhat higher thermal conductivity than does silica.

Olivine is a magnesium-iron orthosilicate,  $(\text{Mg}, \text{Fe})_2\text{SiO}_4$ , consisting of a solution of the two minerals forsterite  $(\text{Mg}_2\text{SiO}_4)$  and fayalite  $(\text{Fe}_2\text{SiO}_4)$  in approximately equal proportions. It is the primary constituent 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. At such point, the rate of breakdown becomes stabilized. This characteristic must be taken into account when selecting the fineness grade of purchased sand.

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 (as 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 are largely restricted to Australia and northern Florida. The concentration of zircon in Australian deposits is about 15%, whereas in Florida it is only about 1.5%. The zircon produced from these deposits is actually a by-product of separation procedures intended to extract 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 it difficult to coat with binders.

With a thermal expansion coefficient less than one-eighth that of silica (Fig. 3-4), zircon is the most heat-

Table 3-1. 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 in                                     | Wyoming and South Dakota   | Mississippi-Alabama        | Ohio-Pennsylvania<br>Illinois-Alabama |
| Method of mining                             | 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             |
| NOTE: A micron is about 1/25,000 of an inch. |                            |                            |                                       |

| RELATIVE VALUE OF VARIOUS TYPE OF CLAYS    |           |                 |        |
|--------------------------------------------|-----------|-----------------|--------|
|                                            | Kaolinite | MONTMORILLONITE |        |
|                                            |           | Calcium         | Sodium |
| Green compression strength                 | 3         | 1               | 2      |
| Dry compression strength                   | 2         | 3               | 1      |
| Permeability                               | 3         | 2               | 1      |
| Least tempering water required             | 3         | 1               | 2      |
| Greatest durability                        | 2         | 3               | 1      |
| Highest flowability                        | 2         | 1               | 3      |
| Best collapsibility                        | 2         | 1               | 3      |
| Sand toughness                             | 2         | 3               | 1      |
| Highest hot compression strength at 1650°F | 2         | 3               | 1      |
| Highest hot compression strength at 1850°F | 2         | 3               | 1      |
| Highest hot compression strength at 2000°F | 2         | 3               | 1      |
| Least contraction at 2500°F                | 1         | 2               | 3      |
| Fewest lumps in shakeout sand              | 2         | 1               | 3      |
| Least intensive mixing effort required     | 3         | 1               | 2      |

stable of all available foundry sands. 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 of 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—thus resulting 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.

### Clays

Clays are mineral substances having extremely fine grain sizes, on the order of a few microns or less. They are composed chiefly of oxides of aluminum and silicon in various ratios, in the form of platelets of aluminum silicates. Other elements 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 which can be used to bond sand grains together. There are numerous types of clay found in nature and these vary significantly in properties, composition, and structure. From a foundry standpoint, only two groups of clays are of interest: kaolinites and montmorillonites.

### Kaolinite Clays

As a mineral group, kaolinite clays, when uncontaminated, are characterized by being highly refractory. These clays exhibit lower green bonding strengths, in general, than do the montmorillonite clays. The most important member of the kaolinite group, for foundry purposes, is *fireclay*.

Fireclays, the common bonding material found in naturally-bonded sands, also occur as free deposits. In a sand/clay mixture brought to proper temper by water addition and thorough mulling, approximately 12% by weight of fireclay is required to attain the same green compression strength as would occur if 4.5% of a montmorillonite clay were used. Likewise, sands bonded with fireclay require higher levels of temper water for proper molding (that is, approximately 5% by weight as compared with 3% for sands with a montmorillonite clay). In many other respects, however, fireclay properties compare favorably with the montmorillonites (Table 3-1).

### Montmorillonite Clays

Montmorillonite is the primary mineral occurring in bentonite clays, constituting 80% or more of the better commercial grades. The two important members of this group, both of which are used extensively for bonding of sands used for green sand molding are *Southern bentonite* and *Western bentonite*. These bentonites have significantly different properties, which should be understood when selecting them for use.

Southern bentonite contains calcium in its crystalline structure, in the form of bivalent ions ( $\text{Ca}^{++}$ ). For this reason, Southern bentonite is commonly called *calcium bentonite*. 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 ( $\text{Na}^+$ ) and is thus commonly referred to as *sodium bentonite*. Western bentonite absorbs water slowly, but does so with a high degree of volumetric expansion (swelling) accompanied by the formation of a thixotropic gel.

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 3-1, however, other characteristics of the two bentonites are significantly different.

Sands bonded with Southern bentonite require less energy to mull, since this clay absorbs water more readily. Such sands are also more flowable (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 a lesser tendency toward formation of 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—the results of which are usually 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 the formation of sand expansion defects. Many authorities ascribe this behavior to the poor wet-tensile strength.

By contrast, Western bentonite has excellent dry and hot strength. As a green-sand bonding clay, it offers the maximum resistance to the formation of sand expansion defects. We may cite as disadvantages all those factors listed above in favor of Southern bentonite.

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 foundries. 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, and so on, 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 the use of simple blade-type or paddle mixers quickly disperses the moisture throughout a naturally-bonded sand. By contrast, much more mechanical energy and time are necessary in order to plasticize the bentonite clays and to distribute them uniformly around the sand grains. This has led to the development and use of mullers utilizing high wheel-pressures to accelerate the process. Recently, blade-type, high-intensity mixers have been developed for the same purpose.

The mulling of green sand mixtures first serves to mix and blend the various ingredients together until they are dispersed homogeneously. Further mulling is required so that continued absorption and equalization of the water in the clay will occur, thereby developing 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 a system sand is no simple matter, since sand property requirements will vary from one foundry to another. The problem is further complicated by the fact that the sand mixture in use partially deteriorates with each cycle, both chemically and physically, from exposure to the molten metal. Additionally, various kinds of debris and contaminants enter the sand, and sufficient heat can build up so as to cause serious changes in properties. The recycling process can be thought of as the establishment of "steady-state" conditions, whereby the sand is cleansed each cycle and suitable additions of new material are made in order to either dilute or replenish materials formed or lost during the casting process. The net objective of recycling, simply stated, is to maintain the characteristics and properties of the system sand within acceptable working limits.

### Designing a System Sand

Whether choosing a naturally-bonded sand or a washed-and-dried sand to be blended with clay bond, it is good practice to select a material having a grain fineness number no greater than absolutely necessary. Fines tend

to form and accumulate in system sands during their recycling because of thermal and mechanical forces. Modern molding machines, and especially the high-density, high-pressure type, 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 five-screen grain distribution. Such sands require the least amounts of clay bond and temper water to develop optimum properties.

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 shakeout
- 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 utilizing fireclay or Southern bentonite as the predominant bonding material can be improved in their resistance to sand expansion defects by the use of small, controlled amounts of organic additives—usually as some form of cellulose (wood flour, cob flour, rice hulls, and so on). 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 rat tails, buckles and scabs. *The limit of effectiveness for such*

*cellulose additives is reached at addition levels of approximately 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. With excessive cellulose additions, additional temper water is necessary in order to develop proper green compression strength. This factor, plus the gas-forming tendency of the additive, combine to aggravate the sand expansion problems (by the formation of wet-condensation layers) causing 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 a 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 core binders.

#### *Recycling System Sands*

The recycling of a system sand begins after mold shakeout and removal of the casting, 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 counterflow for partial cooling and fines removal)
- Batch re-mulling takes place, with appropriate additions of new clay, new sand, temper water and other additives
- Sand is discharged from muller (possibly with aeration to remove lumps of caked sand and additional metallics)
- Sand is transferred to storage at molding stations
- Sand is re-used in molding (with or without riddling to remove fine sand lumps and metallics)

The effectiveness of some of the foregoing operations can be assessed by visual examination of the sand, either before or after screening. This is particularly the case for evaluating the removal of metallics, lumps of sand, 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 first important 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

# EFFECT OF HOT SANDS

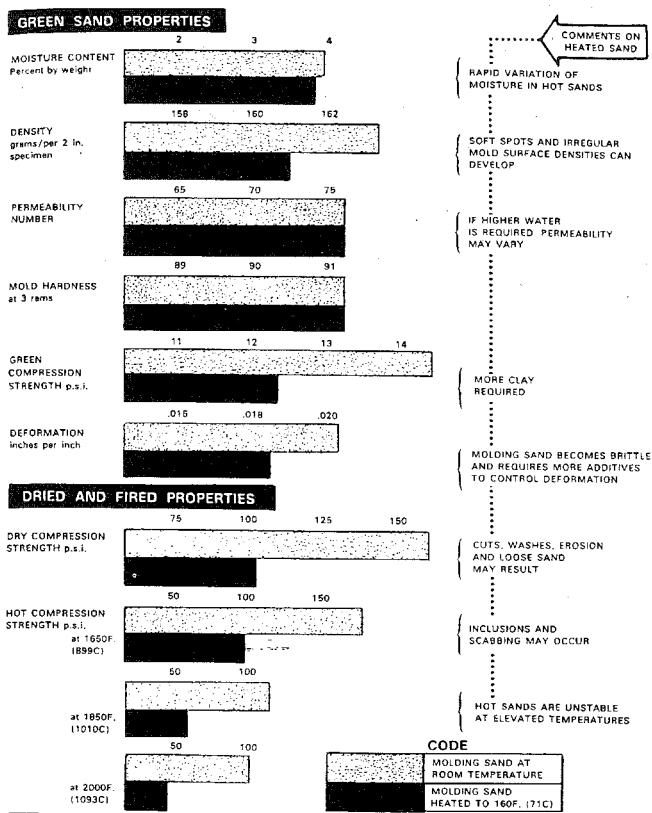


Fig. 3-5. Effect of hot sands

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, acting merely as so much silt. During each casting cycle, therefore, some portion of the clay present in the sand is rendered useless—the amount depending upon the depth of the sand layer in contact with the casting, which reaches the limiting temperature. This is related to 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 designed to measure active clay levels in the sand.

**Generation of fines.** The grains of base sand are constantly being worn away by mechanical forces as they are recycled. They likewise crack and fragment 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 to note trends. Unless a balance can be effected between sand carry-out rate and new sand input by cores and muller additions so as to stabilize the level of fines, 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 to the system in order to avoid abrupt swings in sand properties.

**Overheated system sand.** A basic error made by many foundries is the underdesign, or over-utilization of their sand system, 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, often inexact amounts, to allow for increased evaporation losses between the muller and the molding station. Hot sand against the 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.

## Green Sand Testing

As stated earlier, the net objective in the control of a recycled system sand is to maintain sand characteristics and properties within acceptable working limits. Many foundries 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. It is also true that no one property can be optimized without compromising other properties.

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 a group of seven tests, considered to be the most important tools for system sand control. These tests involve:

- Compactibility
- Moisture content
- Specimen weight
- Permeability
- Green compression strength
- Methylene blue (M.B.) clay content
- Sand temperature

**Compactibility.** Compactibility of a 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 molder's "feel test," which relates to compactibility, indicates the degree of sand temper (clay/water ratio). 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 a 0.10% variation in sand moisture level).

In the last decade, the development of the compactibility test has enabled closer control of sand properties and has made quicker and more accurate testing possible on the production floor. Many foundries have installed 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, an automatic unit is also available which is designed to 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. This system works 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 made 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, permeability, and loss-on-ignition) in order to evaluate the cause.

**Specimen weight.** A simple and convenient test for evaluating changes in a system sand involves the measurement of the weight of sand required to form a standard 2 in. by 2 in. AFS rammed specimen. The accumulation of dead clay, fines, and ash (materials on USA 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 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, and so on). 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.

**Green compression strength.** The test for green compression strength has been used to determine the effects of the clay bond in a 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 should be used in conjunction with the compactibility and methylene blue tests in order to evaluate the active clay level and muller efficiency.

**Methylene blue clay.** The methylene blue clay test provides a quick and accurate method for determining the level of active clay in a 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.

### **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

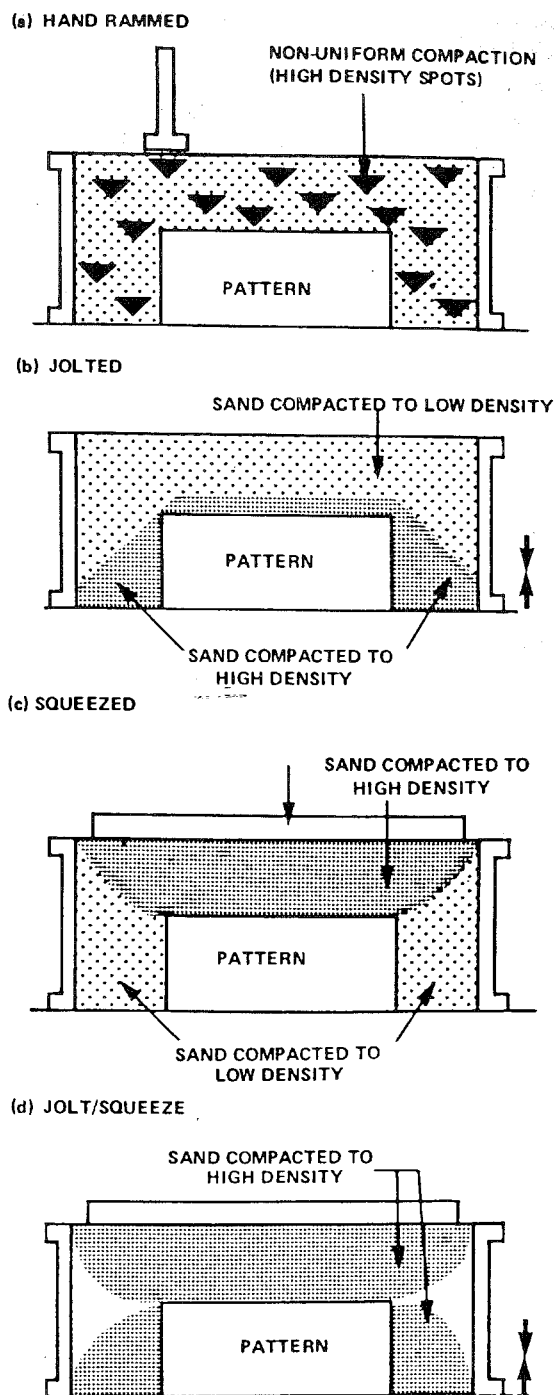


Fig. 3-6. Compaction of molding sands using various molding methods.

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. Two things are necessary when forming a mold of 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 flatback 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).

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.

Sandslinging, 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, it should be pointed out that the true economy of a green sand molding system depends upon the effectiveness of: 1) a well-formulated system sand, 2) a well-designed and operated sand recycling system, 3) a systematic testing program for monitoring the properties of the system sand and those of its ingredients, and 4) 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 a 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 *bentonites*, 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.

A 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 (SAE 40) is generally a good for-

mulation. Most foundries using such sands work at green compression strengths of 8-12 psi. Dry compression strengths are usually over 50 psi, with 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 more 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, ra-

diant heaters or infra-red 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 and 600F (204 and 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 chemically-setting (no-bake) resins.



Fig. 3-7. Bronze propeller at shakeout, cast in a cement-bonded mold. (Courtesy Columbian Bronze Corp., Freeport, NY)

### 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). 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 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, however, require higher temperatures drying by the 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.

### CHEMICALLY-BONDED SAND MOLDING & COREMAKING SYSTEMS

Prior to the late 1940's, 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 began to occur, first with the introduction of heat-cured resin binders and gas-hardened silicate systems. These were followed later by a flood of chemically-cured and gas-hardened resin systems.

Introduction of many of these new binder systems necessitated the design and development of new hardware—including patterns, coreboxes and machines—for their use. In some instances existing hardware could be converted for use. Within the last 30 years, numerous types of binder systems have found acceptance both for molding and coremaking. The rates of their increased use are 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.

The array of binder materials available today to the foundry industry presents a complex combination of chemistries, properties, advantages, limitations, and relative costs. The multitude of chemical binders available have been conveniently classified by committees of the AFS Molding Methods & Materials Division 4, as presented in Fig. 3-9.

The various binder systems are classified into two major groups: organic and inorganic. Each group, in turn,

is comprised of three families characterized by their hardening, or curing mechanism—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 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. 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 (hot-box 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. Washed-and-dried silica sand of appropriate grain fineness is first coated with approximately 2% to 4% of a novolak resin, using one of three different mixing techniques—cold, warm, or hot coating. A novolak 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 hexamethylenetetramine (hexa). The latter is a product of a reaction between ammonia and formaldehyde, and serves to supply the missing formaldehyde for the curing reaction when heat is applied to the coated sand. Temperatures from about 350 to 500F (176 to 260C) are normally required for the sand mix to cure.

In practice, 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 dumped back into the storage hopper and the cured shell mold or core is

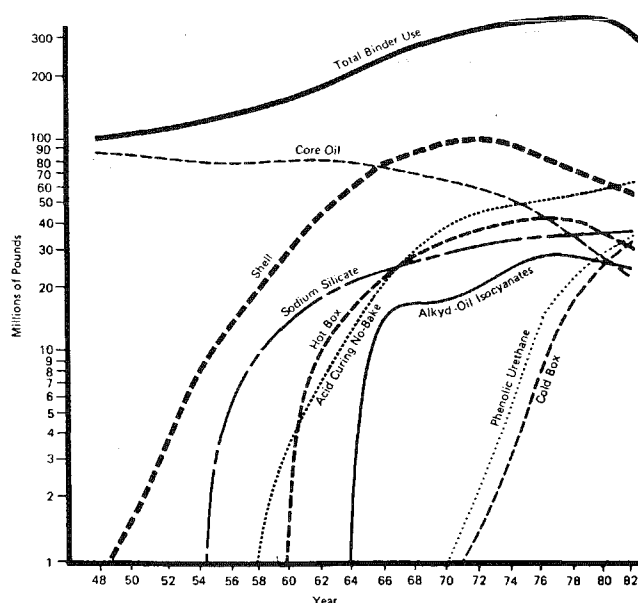


Fig. 3-8. Introduction and growth of chemically bonded sand systems in the United States market.

separated or extracted. 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*, 2nd edition (1973).

During some 35 years of industrial usage, 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 have been lower productivity rates, expensive pattern equipment required, 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 1950's was due to the fact that it offered a means of eliminating the traditional coreblowers, 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. Its use is now slowly declining, although it still remains as one of the most popular foundry processes. This decline has resulted from at least three factors: 1) the rapid escalation of energy costs beginning in the 1970's, together with threatened curtailment of natural gas for industrial use; 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.

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

|           | Relative Tensile Strength (1)                  | Rate of Gas Evolution (1) | Degree of Thermal Plasticity (1) | Collapsibility Speed (1) | Ease of Shake-out (2) | Moisture Resistance (2) | Curing Speed (1) | Strip Time (Min) (5) | Resistance to Overcure (2) | Optimum Temperature °C (°F) | Clay & Fines Resistance (2) | Flowability (2) | Air Drying Rate (1) | Pouring Smoke (1) | Metals Not Recommended |
|-----------|------------------------------------------------|---------------------------|----------------------------------|--------------------------|-----------------------|-------------------------|------------------|----------------------|----------------------------|-----------------------------|-----------------------------|-----------------|---------------------|-------------------|------------------------|
| ORGANIC   | <b>THERMOSETTING SHELL PROCESSES:</b>          |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | 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                 |                        |
|           | <b>HOT BOX PROCESSES:</b>                      |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | FURAN                                          | H                         | H                                | L                        | H                     | G                       | F                | H                    | F                          | 230 (450)                   | P                           | G               | M                   | M                 | (3)                    |
|           | PHENOLIC                                       | H                         | H                                | L                        | M                     | G                       | G                | H                    | F                          | 230 (450)                   | P                           | G               | M                   | M                 | STEEL                  |
|           | <b>OILS:</b>                                   |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | CORE OIL                                       | M                         | M                                | M                        | H                     | G                       | G                | L                    | P                          | 205 (400)                   | F                           | F               | H                   | M                 |                        |
|           | <b>SELF SETTING</b>                            |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | <b>FURAN NO-BAKES:</b>                         |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | 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                 |                        |
|           | <b>PHENOLIC NO-BAKES:</b>                      |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | PHENOLICS - ACID                               | M                         | M                                | L                        | M                     | G                       | G                | 2-45                 |                            | 27 (80)                     | P                           | G               | H                   | M                 |                        |
|           | <b>URETHANES:</b>                              |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | 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                 | (4)                    |
| INORGANIC | <b>VAPOR-CURED (COLD BOX)</b>                  |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | PHENOLIC URETHANE - AMINE                      | M                         | H                                | L                        | H                     | G                       | F                | H                    | G                          | 24 (75)                     | P                           | G               | H                   | M                 | (4)                    |
|           | PHENOLIC/PEROXIDES - SO <sub>2</sub>           | M                         | H                                | L                        | M                     | G                       | G                | H                    | G                          | 24 (75)                     | P                           | G               | M                   | M                 |                        |
|           | SOLVENT EVAPORATION - AIR                      | M                         | H                                | -                        | -                     | -                       | G                | H                    | G                          | -                           | -                           | G               | H                   | -                 | -                      |
|           | <b>THERMOSETTING SILICATE (WARM BOX)</b>       |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | SILICATE (WARM BOX)                            | H                         | L                                | L                        | M                     | P                       | F                | H                    | F                          | 120 (250)                   | P                           | G               | M                   | M                 | (3)                    |
|           | <b>SELF SETTING SILICATES:</b>                 |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | 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 - 2 CaO SiO <sub>2</sub> CURED | L                         | L                                | L                        | L                     | P                       | P                | 30                   |                            | 24 (75)                     | F                           | G               | H                   | N                 |                        |
|           | <b>CEMENTS:</b>                                |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | CEMENT - HYDRAULIC CURED                       | M                         | L                                | L                        | L                     | P                       | F                | 45                   |                            | 24 (75)                     | F                           | F               | L                   | N                 |                        |
|           | CEMENT (FLUID SAND) - HYDRAULIC CURED          | L                         | L                                | L                        | L                     | P                       | F                | 30-60                |                            | 24 (75)                     | P                           | G               | L                   | L                 |                        |
|           | <b>PHOSPHATES:</b>                             |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | PHOSPHATE - OXIDE CURED                        | M                         | L                                | L                        | M                     | G                       | P                | 30-60                |                            | 32 (90)                     | F                           | F               | H                   | N                 |                        |
|           | <b>VAPOR CURED</b>                             |                           |                                  |                          |                       |                         |                  |                      |                            |                             |                             |                 |                     |                   |                        |
|           | SODIUM SILICATE - CO <sub>2</sub>              | 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) Use minimum N<sub>2</sub> levels for Steel  
 (4) Iron oxide required for Steel  
 (5) Rapid strip times required special mixing equipment

Prepared By  
 AFS Molding Methods and Materials, Division 4  
 Cured Sand Committees 80 - 1 - 1 and 80 - 1 - 2

Fig. 3-9. A comparison of the properties of various mold and core binder systems.

are two basic hot box binder systems: the *urea-furan* and the *phenolic 1-step* resins. In the majority of 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—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). The mixing cycle for a conventional, vertical-wheel muller is typically a total of 5 minutes—2 minutes after adding the catalyst and 3 minutes after adding the resin. The amount of catalyst and resin will naturally vary, depending upon foundry needs.

The tensile strength of a hot-box 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.

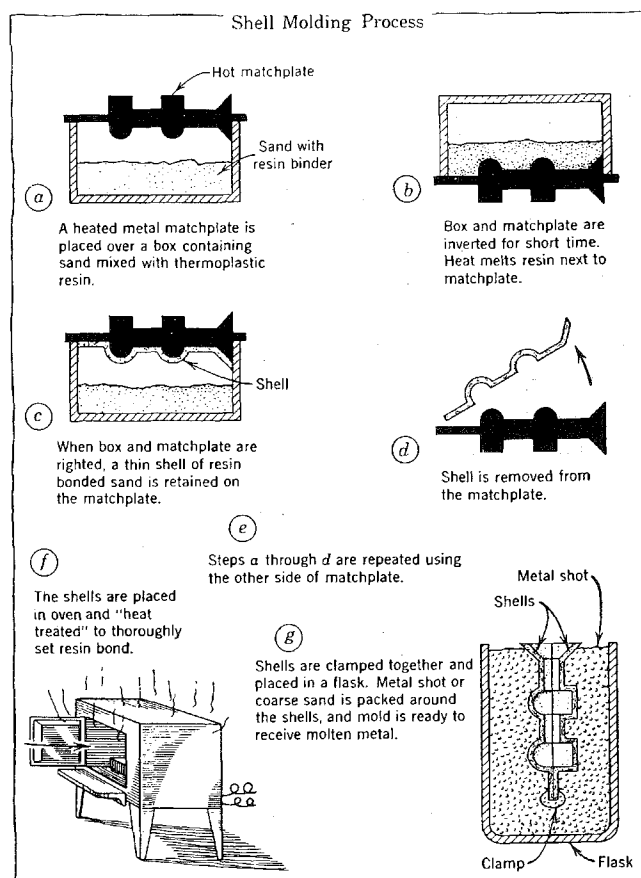


Fig. 3-10. Shell molding process

The hot-box process requires the use of cast-iron core boxes provided with means for 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 core driers. In such cases, the savings in core driers will usually offset the cost of the more expensive core box required for hot-box production.

Post-curing of hot-box 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 hot-box coremaking facilities include a means for post-curing as the need arises.

**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, oil, and cereal. Other additives 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 has an effect on the four principal core properties:

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

Commercial core oils are usually formulated with three basic ingredients: a drying (or oxidizing) oil or resin, a petroleum resin which is at least 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.

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 driers 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 addition the slower the speed of baking. 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 no-bake resins, b) phenolic no-bake resins, and c) urethanes.

**Furan no-bake** is the generic name for a family of foundry binder systems based on furfuryl alcohol which cure at room temperature. The system is composed of a liquid binder (or resin) and a liquid catalyst. Although consisting principally of furfuryl alcohol, the resins may be modified with urea, formaldehyde, or additives such as phenolic resins. 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 with the copper-base alloys.

The catalyst component of furan no-bake systems is an acid mixture. Furan no-bake resins are usually proprietary mixtures of acids and solvents, sometimes containing color-code dyes. The two main classes of catalysts are: phosphoric-acid-based (a 75–85% concentration of phosphoric and sulfuric acids in water), and sulfonic-acid-based (a solution of benzenesulfonic acid BSA; toluenesulfonic acid, TSA; or other sulfonic acids, usually in combination). Solvents for these acids are water and methanol.

Washed-and-dried silica sands (and zircon) are readily used with furan no-bake 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 and 80F (21 and 27C). Where sand temperature control is a problem the binder supplier should be consulted.

In using self-hardening sand mixtures, *working time* and *strip time* are both a measure of the cure rate. 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. The working time for furan no-bakes is usually about 50% 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 no-bake* (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 no-bake 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 no-bakes, phenolic no-bakes should not be catalyzed with phosphoric acid since this results in slow curing and low properties.

Typical mixtures with phenolic no-bakes consist of about 1.5% resin ( $\pm 0.5\%$ ) and catalyst levels ranging from 20 to 45% of the weight of resin added. Recommended procedures for mixing and use, as well as control of cure rates and properties are essentially the same as discussed for furan no-bakes. In general, the strength of sands bonded with phenolic no-bakes is somewhat lower than for the furan no-bakes.

*Urethane no-bake* systems are of two different types: alkyd oil urethanes and phenolic urethanes.

Alkyd oil urethane binders are available precatalyzed 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/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 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 1% 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. Because this stage is oxygen-dependent, section size and foundry conditions can affect the curing time. 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. 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 metallic driers which determine the speed of the reaction as well as the overall curing characteristics of the 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 control in varying the catalyst (Part B) when small flows are required (under 0.5% 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 will allow the catalyst to become dispersed in the alkyd (oil) resin and thus will 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 with the small amounts of Part B required. This premix particularly can be used when sand temperatures can be maintained at a constant temperature. The percentage of Part B in the premix may be often adjusted to compensate for varying in-plant temperatures.

Part C is the polyisocyanate component which 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 deficiency, moisture in the sand and typical foundry variables. Part C, par-

ticularly 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 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 negatively affecting this 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 flowability of the mixture)
- High acid-demand value (ADV) of the base sand (alkaline impurities speed up the reaction)
- Aeration of the sand mixture (solvents evaporate, thus decreasing the flowability of the mixture)

Alkyd-oil urethane systems are generally less sensitive to sand types than are other no-bake 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 which will significantly affect the properties and productivity of the alkyd (oil) urethane systems are:

- Combustibles—The loss-on-ignition (LOI) should be maintained below 2% maximum. 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 80–90F (27–32C) and maintain this temperature within  $\pm 5F$  (3C) for reproducible cure rates. Approximately a 1°F (0.5°C) change in temperature increases or decreases the strip time by 1 minute.
- Segregation—Segregation of the grain sizes of 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%–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 (149–204C) 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 (204C) is detrimental and should be avoided.

*Phenolic urethane no-bake (PUNB) binders* are systems capable of producing strippable cores or molds within 1 to 15 minutes of pattern or corebox filling. Phenolic urethane no-bakes are three-part binder systems. Part I is a phenolic resin blended with solvents. Part II is a blend of polymeric methylene diisocyanate and solvents. The catalysts are various blends of pyridine derivatives and solvents. 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 per-

cent 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 0.7–2.0%. 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 60/40. This should be discussed with the binder supplier. 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 0.5–10.0% 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. 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 PUNB's, 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**—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 and lower strengths.
- **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  $\pm 5F$  ( $\pm 3C$ ). 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 1.5–2% foundry-grade red or black iron oxide may be required for optimum casting finish resulting 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 time 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  $\pm 2\%$  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 no-bake 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 (cold box) systems are hybrids since the process is based on chemistry which is 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-SO<sub>2</sub> system.

*The phenolic urethane-amine system* has experienced phenomenal growth. Similar to the phenolic urethane no-bake process, the cold-box version consists of a three-part resin system: phenolic resin, isocyanate, and amine catalyst. This resin components are typically used in proportions varying from 1% to 2%. The most common catalysts currently in use are triethylamine (TEA) and diethylamine (DMEA). These low-boiling-point amines are vaporized in a 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 and bank sand, contain alkaline impurities which decrease the bench life of the system. On the other hand, neutral sands normally have a bench life in excess of three hours. High temperatures result in solvent evaporation, which lowers bench life and may result in friable core surfaces. A usable sand-temperature working range is 50 to 100F (10 to 37.8C). 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.

*The furan-SO<sub>2</sub> system* is basically a gas-curing furan system which, instead of using a liquid catalyst, relies on the passage of SO<sub>2</sub> gas through the uncured sand mix in the presence of an oxidizing agent (in this case organic peroxide) to create the acid. This produces an instantly-cured core or mold exhibiting all the characteristics of a conventional furan no-bake system.

The SO<sub>2</sub> process is comprised of five components: sand, resin, adhesion promoter, organic peroxide, and the SO<sub>2</sub> gas. Any high-purity silica sand with a moisture content below 0.3%, a low acid demand value (ADV), and suitable grain size and distribution (the same as used with conventional furan no-bakes) is suitable. Chromite sand and zircon sand can also be used. Resins currently used are nitrogen-free furan polymer types with a low monomeric furfuryl alcohol content. These resins have been specifically formulated for use with the SO<sub>2</sub> process and addition rates vary from 0.7% to 1.5% depending on application and quality of the sand. Although furan or phenolic resin binders have been used with the SO<sub>2</sub> system, the greatest use has been with the furan resin binders.

The adhesion promoter (silane) is used to improve the bonding of the resin to the sand grains, and can be added directly to the resin during manufacture or as a separate additive at the mixer. When added at the mixer, an extender is used to aid the pump metering. The solution is usually 90 parts solvent to 10 parts adhesion promoter. Addition rates vary between 3% to 10% of the binder weight, again dependent upon the application and sand quality.

The organic peroxide is usually methyl-ethyl-ketone peroxide, referred to as MEKP. This is a 50% solution phlegmatised with dimethyl phthalate. Addition rates vary normally between 25% to 50% of the binder weight.

Sulfur dioxide (SO<sub>2</sub>) is supplied in cylinders as a liquified gas when at a pressure of 35 lbs per square inch

at 77F (25C). Gas displacement from the cylinder is by either nitrogen or dry air. Once heated, the liquid sulfur dioxide takes the form of a gas. Consumption will normally be under 4 kg per ton of cured sand. The blown and purged 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.

Sand mixing can be accomplished either in the batch mullers or continuous mixers. The resin, adhesion promoter, and peroxide 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 SO<sub>2</sub> gas is introduced. Curing is then instantaneous with very high tensile strengths being obtained.

Sand chemistry has a significant effect on the curing rate and quality of SO<sub>2</sub> process cores. Sands which are basic in nature, such as lake sands, inhibit the acid reaction of the process. Use of these sands generally results in longer cure times and extremely low tensile strengths. High-purity silica sands are generally recommended for this process. Sand temperature is a critical aspect for producing high-quality cores. Temperatures of 86-95F (30-35C) are recommended since they promote rapid water evaporation (to assure fast cure rates) and improve resin reactivity. It is very common to use heated purge air to aid in core curing. Similar to furan no-bakes, the resin is slightly tolerant of low sand-moisture levels. These levels should be maintained at a minimum to promote good core curing and tensile strengths.

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 cold-box 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. Where jolt/squeeze, hand-ramming, or mechanical vibration methods are employed, 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 SO<sub>2</sub> gas, thus extending the life of the solution within the scrubbing unit. As with any gas-cured cold-box system, the SO<sub>2</sub> 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 venting area must be sufficiently 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. Excess SO<sub>2</sub> is disposed of by using an air purge and discharging it into a chemical scrubbing unit. Due to the toxic nature of this gas, the system must be closed to prevent leakage into the working environment.

### Mixing and Foundry Use of No-Bake Sands

There are several types of mixers used with no-bake binder systems. The best mixer to use for a particular operation depends on the binder used 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 no-bake systems since 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 size of the pattern or core box to be filled and the amount of time available for filling.

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 no-bake system. Gear pumps with an 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 the 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 no-bake 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:

- No-bake 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 which 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.
- Vibration compaction is a good method of consolidating no-bake 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 no-bake 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.

### Foundry Control Tests of No-Bake Sands

The various tests used for chemically-bonded sands are primarily for evaluating and monitoring process para-

meters. 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 percentages of sand and binder 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 correlation between tensile strength and core quality.

**Work-time/Strip-time.** The test for work-time and strip-time can be very useful in a no-bake 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, thereby increasing productivity and avoiding the use of sand which has surpassed its work-time. Similar tests can be used with vapor-cured (cold box) 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 general rule-of-thumb is that for every 15°F (9.4°C) decrease in sand temperature, the reaction time of the binder is doubled. Thus, if a consistent operation is desired, sand temperatures must be consistent. 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.

**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.

**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.

**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**

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 aluminophosphate and phosphoric acids which are hardened by reacting with an addition of magnesium oxide. This inorganic no-bake system has found relatively little use in copper-base alloy foundries.

Silicates have been used as mold and core binder materials since the early 1950's, principally in the form of the well-known CO<sub>2</sub>-silicate (vapor-cure) system. No-bake 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 following deals only with the CO<sub>2</sub>-silicate system as a coremaking application which finds use in copper-base alloy foundries.

The CO<sub>2</sub>-silicate system consists of liquid sodium silicate and CO<sub>2</sub> gas. Typical silicate binders are odorless, non-flammable, and 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.

Properties of the silicates vary according to the silica (SiO<sub>2</sub>)-soda(NaO) ratio of the sodium silicate base that is used to formulate the binder. Considerable care must be used when gassing with CO<sub>2</sub> since overgassing and undergassing adversely affect the properties of the cured binder system. 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 Baume (Be.) and a silica-to-soda ratio (SiO<sub>2</sub>:Na<sub>2</sub>O) between 2.0 and 2.6. 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. 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 overgassed, resulting in molds and cores with a shortened shelf life.

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).

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. A 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 CO<sub>2</sub> 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/CO<sub>2</sub>-hardened cores, to date the cores so that the oldest cores are used first.

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
- polymers

Approximately 1 to 2 lbs of CO<sub>2</sub> (8.5 to 17 ft<sup>3</sup> gas) are required for 100 lbs of silicate-coated sand. This figure can be used to estimate CO<sub>2</sub> consumption in order to determine the capacity of the CO<sub>2</sub> supply to be installed. A sufficient supply of CO<sub>2</sub> gas, plus a CO<sub>2</sub> 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 CO<sub>2</sub> is required for gassing and the poorer the collapsibility
- The recommended CO<sub>2</sub> gas pressure range is 20 to 60 psi gauge pressure; for most applications, a pressure between 30 to 40 psig works the 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. CO<sub>2</sub> 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 into 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 gasketed covers or hoods which 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 by brushing or 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 AFS' *Mold and Core Coatings Manual*. A few of the more popular chemically-bonded sand systems are described below.

- 1) *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.
- 2) *Furan Binders*. Most commercial core washes, regardless of suspension agent, are compatible with furan no-bake 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. If coatings are applied too soon after stripping, a friable surface results. Regardless of the coating suspension agent, the wash should be thoroughly dried by ignition, evaporation, or heating before the mold is closed and poured.

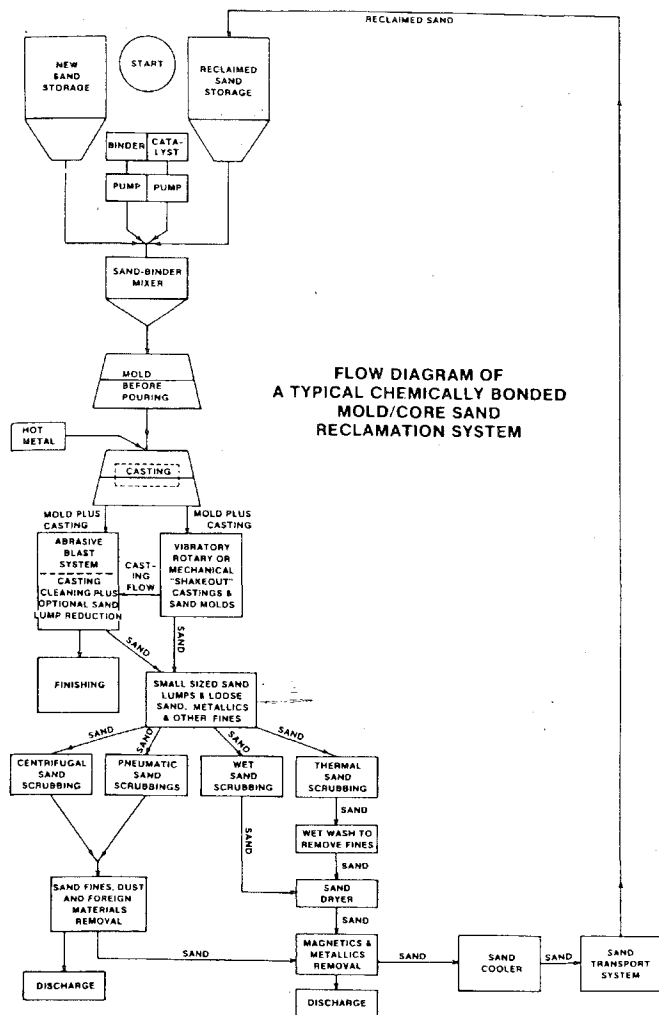


Fig. 3-11. Flow diagram of a typical chemically-bonded mold/core sand reclamation system.

- The high disposal costs posed by the growing use of chemically-bonded sands for molds and cores.
- Rising costs of new sand and higher freight rates for delivery
- Increasing environmental restrictions on the mining of new sands
- Increasing environmental restrictions on the permissibility of solid waste disposal and its effects on the availability and cost of using approved landfill sites.

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.

Although the molding aggregate is indeed rejuvenated and restored to proper working condition, the recycling of green molding sand, as described previously, does not fall within the usual concept of reclamation. Reclamation is normally applied to sand systems in which most, if not substantially all, of the sand binder material is removed from the grains. Although this does not preclude use with clay-bonded sand systems, reclamation is more frequently used with chemically-bonded sands.

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 Reclamation

After cores and molds are mechanically reduced to small lumps (by crushing, grinding, abrasive blasting, and so on), the sand is next subjected to a scrubbing operation which is designed to abrade away the adherent layers of binder on the sand grains. Scrubbing is accomplished by either mechanical or pneumatic forces which 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 somewhat more effective for clay removal.

For best efficiency, both scrubbing techniques require that the sand first be reduced to near-grain size and that metallics be removed to reduce wear. The scrubbing systems must be provided with dust collection equipment for fines removal, particularly since the fines contain a high proportion of the removed binder.

## SAND RECLAMATION

The increasing importance of sand reclamation is due to several factors:

During wet reclamation, the thoroughly crushed shake-out 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, since 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  $\text{Na}_2\text{O}$  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.

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

## PRESSURE DIE CASTING

### Introduction

The pressure die casting process utilizes high-pressure injection of molten metal into steel dies to form the cast shape, which is then 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 die trimming to remove gates and flash.

The pressure die-casting 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

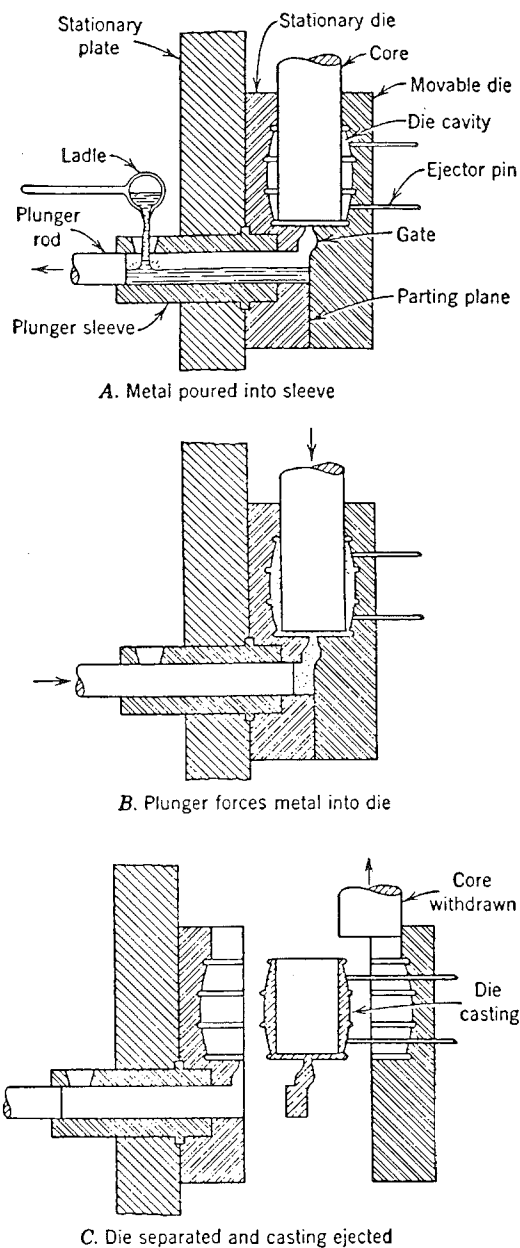
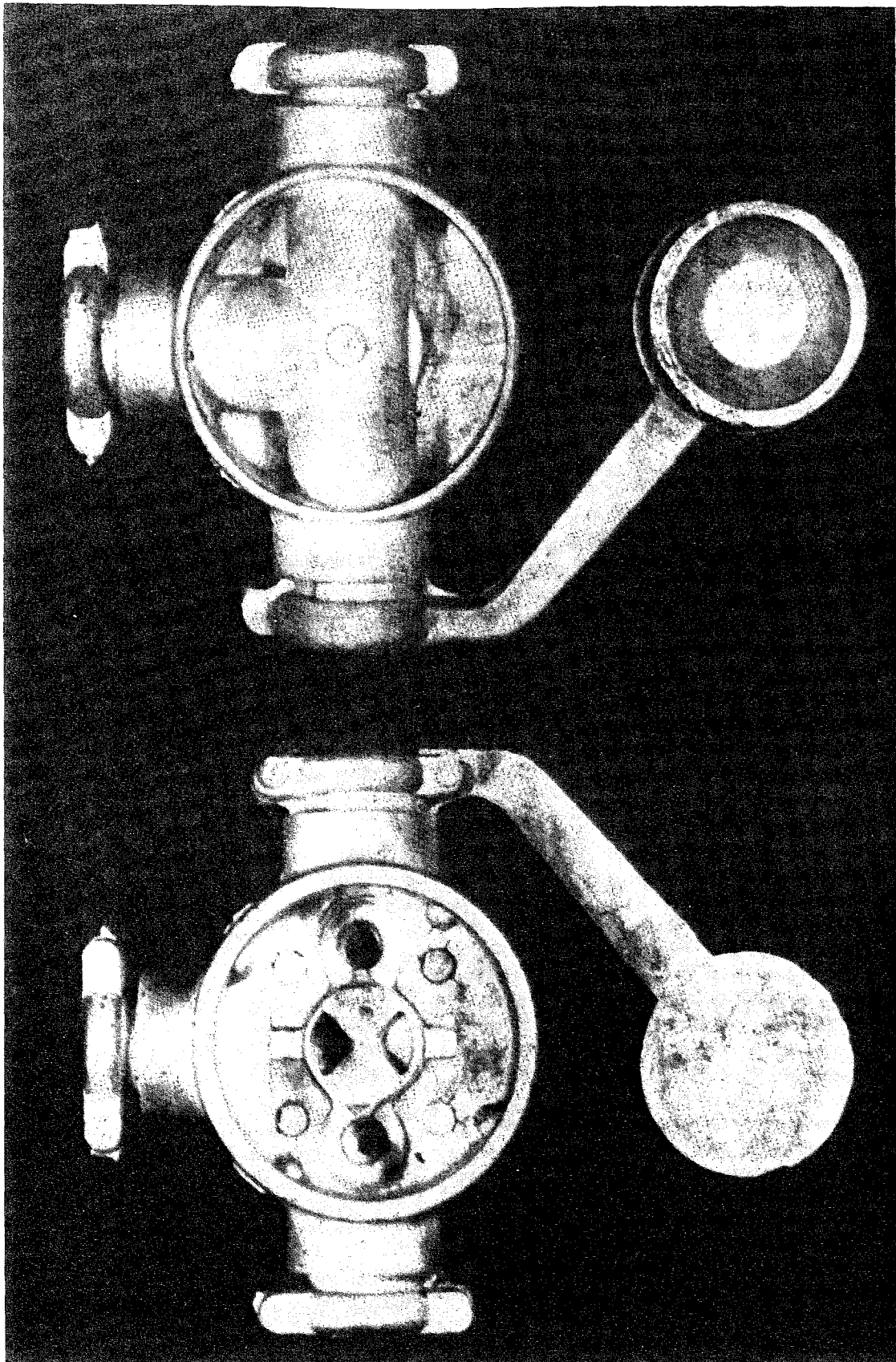


Fig. 3-12. Cold chamber die casting

bath, as there was relatively little attack of the steel components by the 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, 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. A typical, multi-cavity die half, and the gate of castings produced from it, are shown in Fig. 3-14.



*Fig. 3-13. A die-cast shower control valve showing the fixed and moveable die sides of the casting.*

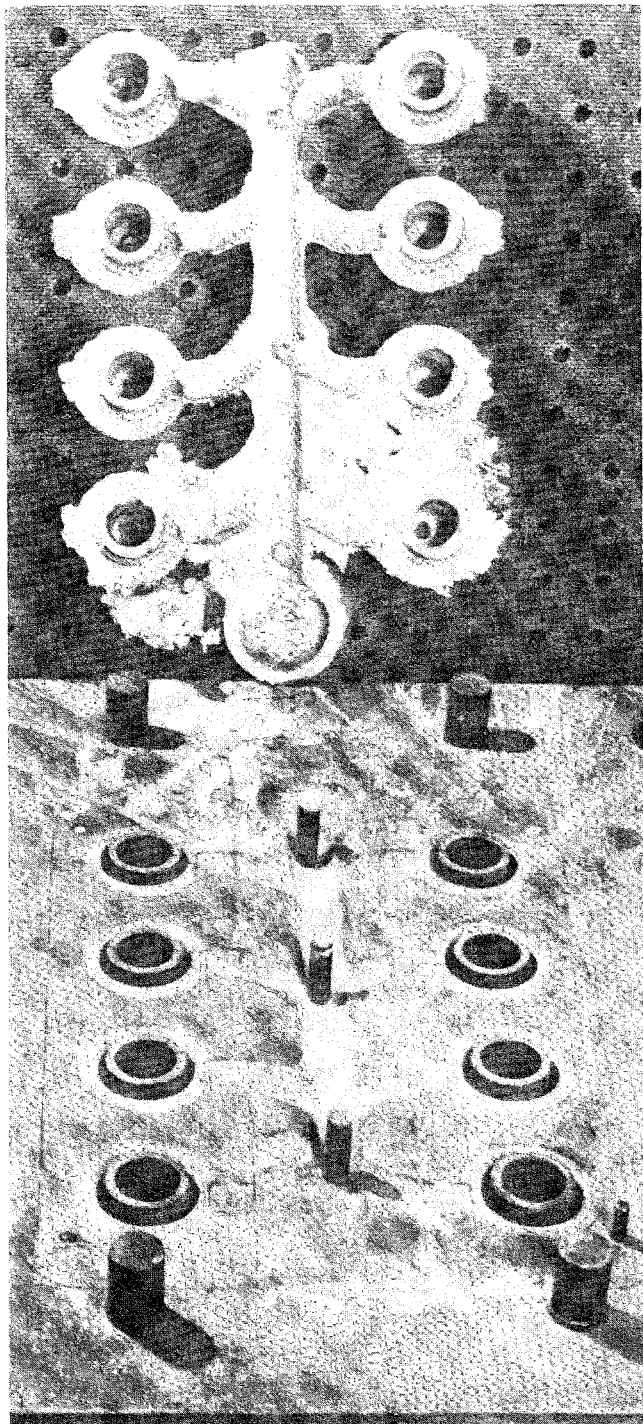


Fig. 3-14. Ejector die half and the corresponding face of the brass die casting. (Note inserts in main die block to form runner and cavities and ejector plate and pins raised.)

### Die Casting Machines

Die casting 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 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

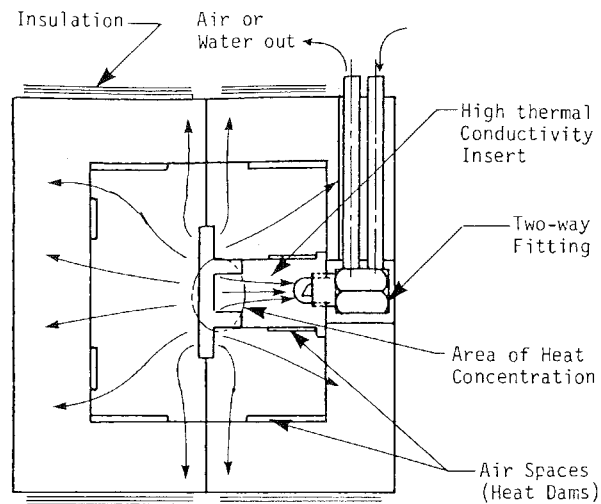


Fig. 3-15. Carefully placed air spaces in the seams between the various die components, plus external insulation, can be used to restrict and direct heat flow paths through the die. Areas of heat concentration can be isolated by using inserts and cooling by a forced cooling medium such as water or air.

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 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 die heating system) and that lost by radiation and the water-cooling of the die or mounting platens. Otherwise, the relatively narrow temperature range over which the die will produce satisfactory castings cannot be maintained, and scrap losses will occur. 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. For copper-base alloys, however, the dies must operate at higher temperatures—typically about 500C (932F), and heat losses are correspondingly greater at these higher temperatures. In practice, therefore, less cooling is actually required when casting copper-base alloys. Indeed,

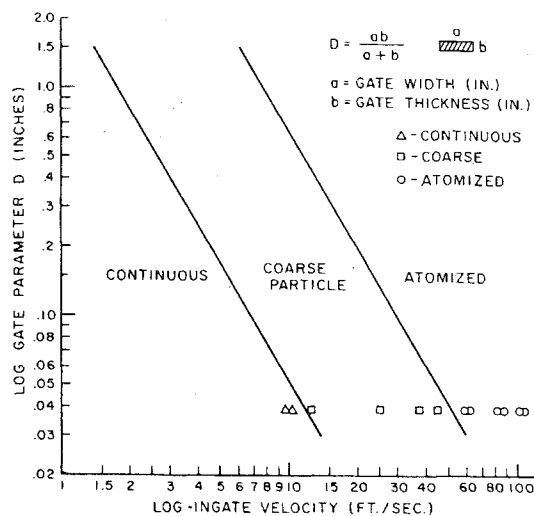


Fig. 3-16. Jet flow character of molten brass die-casting alloy as a function of flow velocity and gate parameter  $D$ , and data obtained by high-speed filming of the molten metal stream.

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. 3-15.

#### Metal Flow and Gating

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

Die castings 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 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

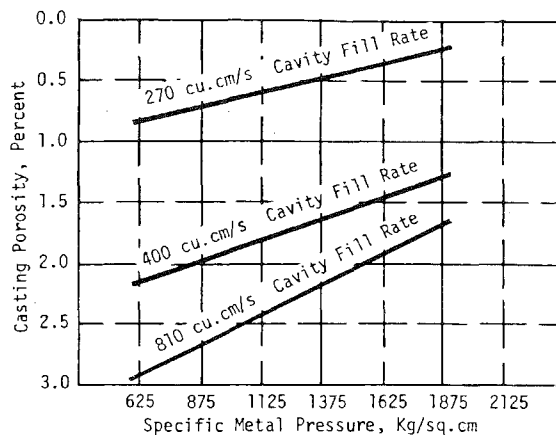


Fig. 3-17. These test results show that increased static metal pressure results in increased density. Even with a slow fill rate of 270 cc/sec, the metal pressure had a significant effect.

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.

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. 3-16.

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. 3-17. For maximum soundness, casting pressures in excess of 26,000 psi (1800 kg/cm<sup>2</sup>) are recommended.

#### Process Control

In recent years great progress has been made in the control of the die casting process by the installation of thermocouples, pressure-transducers, and accelerometers on the machines. Likewise, refinements have been made in hydraulic systems to permit sequential control of shot

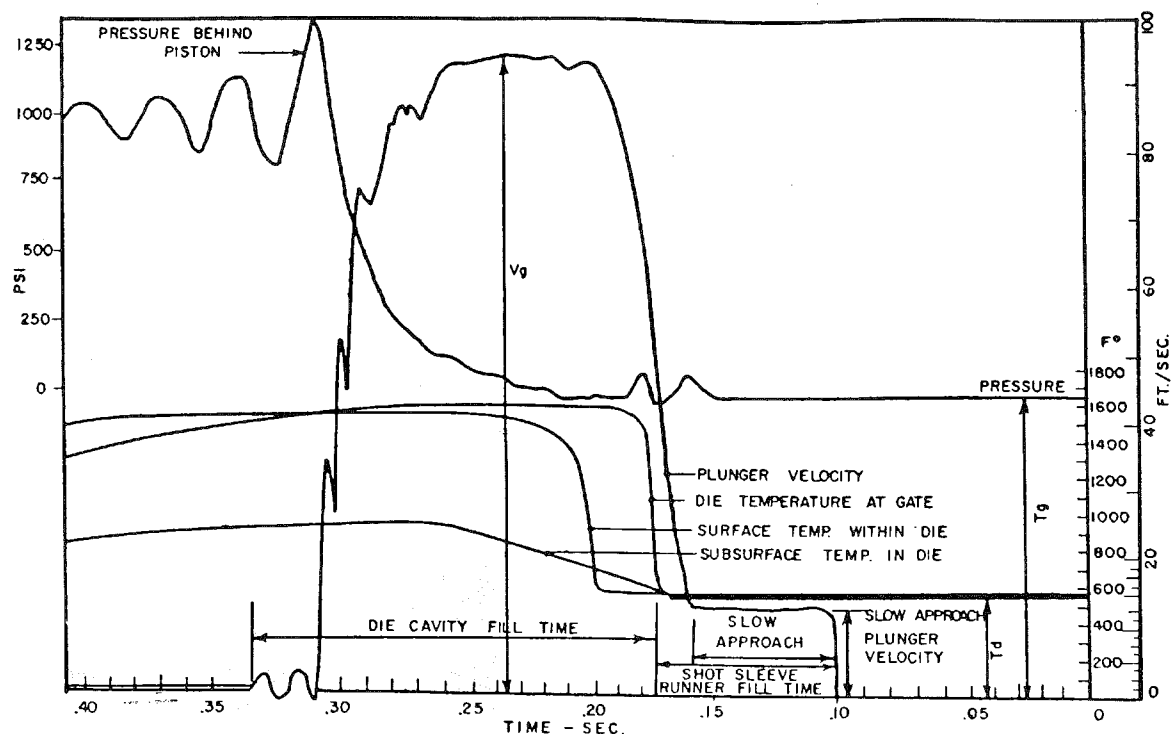


Fig. 3-18. Typical Visicorder trace of velocity, pressure, and temperature measurements during the die casting of a brass alloy.

speed, injection pressure, etc. 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 3-18 shows a typical Visicorder trace for a copper-base alloy casting made in a 400-ton cold chamber machine.

As with any casting process, die casting 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 section.

### 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 die casting 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 die casting as compared with 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.

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. In recent years considerable experience has been gained with the use of refractory alloys which are resistant both to soldering and heat-checking. Table 3-2 gives the nominal composition of typical die insert materials, and Table 3-3 lists recommended heat treatments. Different materials should be used for the various die components, as suggested in Table 3-4.

Table 3-2. Composition of Die Materials

| STEELS                          |      |         |      |      |      |      |      |      |     |
|---------------------------------|------|---------|------|------|------|------|------|------|-----|
|                                 | 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 | 0.30    | 0.30 | 3.33 | —    | 0.25 | 9.00 | —    | Rem |
| QRO45 <sub>1</sub> .....        | 0.30 | 0.30    | 0.30 | 2.80 | 2.80 | 0.50 | —    | 2.8  | Rem |
| TM— Special <sub>2</sub> .....  | 0.32 | 0.30    | 0.30 | 1.45 | 0.40 | —    | 4.00 | 5.   | Rem |
| REFRACTORY ALLOYS               |      |         |      |      |      |      |      |      |     |
|                                 | C    | Ni      | Al   | Cr   | Mo   | Ti   | W    | Co   | Fe  |
| Rene 41 <sub>3</sub> .....      | 0.1  | Rem     | 1.5  | 19.0 | 10.0 | 3.0  | —    | 11.0 | 3.0 |
| Anviloy 1150 <sub>4</sub> ..... | —    | 4.0     | —    | —    | 4.0  | —    | 90.0 | —    | 2.0 |
| Mo-TZM .....                    | —    | 0.12 Zr | —    | —    | Rem  | 0.5  | —    | —    | —   |

1 Proprietary name of Bofors Aktiebolaget, Sweden

2 Proprietary name of Teledyne Vasco, USA

3 Proprietary name of General Electric Co., USA

4 Proprietary name of P. R. Mallory Co., USA

Table 3-3. Heat Treatment

| Material           | Anneal Temp.<br>Anneal Time<br>Cooling                                                                                    | Stress Relief Temp<br>Stress Relief Time<br>Cooling | Hard. Temp<br>Hard. Time<br>Cooling   | Temper Temp<br>Temper Time*<br>Cooling |
|--------------------|---------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------|---------------------------------------|----------------------------------------|
| H-13 .....         | 1550-1625 °F<br>1/4hr/in. 50 F/hr.                                                                                        | 1200 °F<br>2 hrs. at temp. fur. cool                | 1795-1975 °F<br>45-15 min. air quench | 1000-1200 °F<br>1-2 hr.* air           |
| H-19 .....         | 1600-1650 °F<br>1/4hr/in. 50 F/hr.                                                                                        | 1200 °F<br>2 hrs. at temp. fur. cool                | 2100-2200 °F<br>15 min. air quench    | 1000-1300 °F<br>1-2 hr.* air           |
| H-21 .....         | 1600-1650 °F<br>2 hrs. at temp. 50 °F/hr.                                                                                 | 1200 °F<br>2 hrs. at temp. fur. cool                | 2150-2200 °F<br>15 min. air quench    | 800-1300 °F<br>1-2 hr.* air            |
| QRO 45 .....       | 1560 °F<br>2 hrs. at temp. 50 °F/hr.                                                                                      | 1200 °F<br>2 hrs. at temp. fur. cool                | 1830-1975 °F<br>15-45 min. air quench | 1000-1200 °F<br>1-2 hr.* air           |
| Rene 41 .....      | —                                                                                                                         | —                                                   | 1950-1975 °F<br>4 hrs. air            | 1400 °F<br>16 hrs air                  |
| Anviloy 1150 ..... | 1850 °F<br>1 hr/in. of thick (Vacuum or Dry Hydrogen Atmos.)                                                              | —                                                   | —                                     | —                                      |
| MoTZM .....        | 2000-2500 °F<br>Use manufacturer's recommendation as to temperature,<br>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.

### Copper-Base Die Casting Alloys

Although many copper-base alloys have been used in die casting with varying degrees of success, the choice is normally limited to those with low melting points. Such alloys minimize deterioration of die materials due to heat-checking and soldering. The nominal compositions of the most commonly used die casting alloys are listed in Table 3-5. 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. 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.

Table 3-4. 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 <sub>1</sub> , TM Special <sub>2</sub> , Anviloy 1150 <sub>3</sub> , MoTZM, Rene 41 <sub>4</sub> |
| Runner blocks and Risers . . . . . | H-13, H-21, H-19, QRO-45 <sub>1</sub> , TM Special <sub>2</sub>                                                           |

## (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

High-copper alloys generally have the greatest corrosion resistance. Their disadvantages are higher melting temperature; higher cost; 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 a series of alpha ( $\alpha$ ) solid solutions. Beyond 35% Zn, a second, beta ( $\beta$ ) phase appears, being a solid solution having a body-centered cubic structure. 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 die casting 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 of the alloys in Table 3-5, *OM-Metal* and *A-Metal*, are proprietary compositions which have been 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 die castings.

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

Tables 3-5 through 3-7 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-base die casting 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, these 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-

Table 3-5. Nominal Compositions of Copper-Base Die-Casting Alloys

| Alloy Number<br>or Name | C87900 | C87800 | C86500 | C86200 | C85800 | C99750 | OM<br>Metal <sup>a</sup> | A<br>Metal <sup>b</sup> | C99700 |
|-------------------------|--------|--------|--------|--------|--------|--------|--------------------------|-------------------------|--------|
| Cu.....                 | 65.00  | 82.00  | 58.00  | 64.00  | 58.00  | 59.50  | 63.5                     | 64.5                    | 58.00  |
| Sn.....                 | <.25   | <.25   | 0.50   | <.20   | 1.00   | <.50   | 0.50                     | 1.0                     |        |
| Pb.....                 | .25    | .15    | <.40   | <.20   | 1.00   | 1.50   | 2.00                     | 2.50                    | <1.00  |
| Zn.....                 | bal.   | bal.   | bal.   | bal.   | bal.   | bal.   | bal.                     | bal.                    | bal.   |
| Fe.....                 | <.15   | <.15   | 1.00   | 3.00   | <.50   | <.25   | <.50                     | <.15                    |        |
| Al.....                 | <.15   | <.15   | 1.00   | 4.00   | <.25   | 1.25   | 0.40                     | 0.30                    | <1.00  |
| Si.....                 | 1.00   | 4.00   |        |        | <.25   | <.50   | 0.70                     | 0.50                    |        |
| Mn.....                 | <.15   | <.15   | 1.00   | 3.00   |        | 19.50  | 0.50                     | 0.30                    | 13.00  |
| Ni.....                 |        |        | <.50   |        |        |        |                          |                         | 5.00   |
| Sb.....                 |        |        |        |        |        |        | .05                      |                         |        |
| All others.....         | <.50   | <.25   |        |        | <.50   | <.50   | <.50                     |                         |        |

<sup>a</sup> Proprietary name of Olof Manner AB, Sweden

<sup>b</sup> Proprietary name of Andersson & Co. AB, Sweden

Table 3-6. Mechanical Properties of Copper-Base Die-Casting Alloys

| Alloy Name<br>or number          | C87900 | C87800 | C86500 | C86200 | C85800 | C99750 | OM<br>Metal | A<br>Metal | C99700 |
|----------------------------------|--------|--------|--------|--------|--------|--------|-------------|------------|--------|
| Tensile Str., ksi.....           | 70     | 85     | 71     | 95     | 55     | 75     | 70          | 67         | 60     |
| Yield Str., ksi.....             |        |        |        |        |        |        |             |            |        |
| .5% Ext. Under.....              |        |        |        |        |        |        |             |            | 27     |
| .2% offset.....                  | 35     | 50     | 28     | 48     | 30     | 40     | 35          | 41         |        |
| Elong. in 2", %.....             | 25     | 25     | 30     | 20     | 15     | 20     | 25          | 10         |        |
| Hardness.....                    |        |        |        |        |        |        |             |            |        |
| Rockwell B.....                  | 70     | 85     |        |        | 55     | 82     | 70          |            | 70     |
| Brinell - 500 kg.....            |        |        | 100    |        |        | 119    | 80          |            |        |
| Brinell - 3000 kg.....           |        |        | 130    | 180    |        |        |             | 145        | 120    |
| Modulus of Elasticity, ksi... 15 | 15     | 20     | 15     | 15     | 15     | 18     | 15          | 15         | 16     |
| Impact Str., ft-lb.....          |        |        |        |        |        |        |             |            |        |
| Izod.....                        |        |        |        | 12     |        |        |             |            |        |
| Charpy Unnotched.....            | 50     | 70     |        |        | 40     | 75     | 50          |            |        |
| Charpy V-notch.....              |        |        | 32     |        |        |        |             |            |        |

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

| Alloy Name<br>or Number                                            | C87900 | C87800 | C86500 | C86200 | C85800 | C99750 | OM<br>Metal | A<br>Metal | C99700 |
|--------------------------------------------------------------------|--------|--------|--------|--------|--------|--------|-------------|------------|--------|
| Melting Pt. (Liq.) °F.....                                         | 1700   | 1680   | 1616   | 1725   | 1650   | 1550   | 1634        | 1660       | 1650   |
| Melting Pt. (Sol.) °F.....                                         | 1650   | 1510   | 1583   | 1650   | 1600   | 1505   | 1607        | 1570       | 1600   |
| Density @ 68F, lb/in <sup>3</sup> .....                            | .308   | .300   | .301   | .288   | .305   | .29    | .308        |            | .296   |
| Specific Gravity.....                                              | 8.5    | 8.3    | 8.3    | 7.85   | 8.4    | 7.8    | 8.5         |            | 7.9    |
| Coeff. Thermal Exp.<br>at 68F, in/in x 10 <sup>-6</sup> .....      |        | 10.9   | 11.3   | 12     |        |        |             |            |        |
| Thermal Conductivity<br>at 68F, Btu/ft <sup>2</sup> /ft/hr/°F..... |        | 16.0   | 50.0   | 20.5   |        |        |             |            |        |
| Electrical Conductivity<br>at 68F, % IACS.....                     | 15     | 6.7    | 22.0   | 7.5    | 20     | 2.0    |             |            | 3.0    |
| Specific Heat at 68F,<br>Btu/lb/°F.....                            | .09    | .09    |        | .09    | .09    |        |             | .09        |        |

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 brasses, 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 die cast. 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 die casting 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, die cast 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 & Mechanical Properties

The mechanical properties of the die-cast copper-base alloys are generally superior to those of the light metals (see Table 3-6). 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 3-7.

Copper-base alloy die castings should be considered for products requiring physical or mechanical properties approaching those shown in Tables 3-6 and 3-7. The die caster must be careful to melt and handle the metal properly and to control the die casting process to assure the maintenance of the required properties.

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 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 die casting. 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 die cast.

### 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 die casting 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 die casting, 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 die casting 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 die casting, 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 used too frequently, deposits tend to be cleaned away too thoroughly, cleaning out heat checks in a badly-worn die sufficiently to cause stickers to occur.

### PERMANENT MOLD CASTING

The term *permanent mold* is somewhat of a misnomer. It refers to the fact that the casting process employs a *reusable*, rather than an *expendable* mold (as for sand casting). Ordinarily, the process is carried out under normal atmospheric conditions, utilizing the force of gravity for pouring the mold. Outside the United States, the process is referred to as “gravity die casting,” “chill casting,” or simply “die casting” (as distinct from pres-

sure die casting). This should be noted when reading the literature from other countries.

The permanent mold casting process dates back 5,000 years to the time when stone molds were used to cast copper (and later, bronze) axe heads and arrowheads. In modern times, however, because of inherent difficulties and limitations the permanent mold casting of copper-base alloys has not been fully exploited. This is particularly true in North America, where the process accounts for only about 0.5% of copper-base casting production; in Europe the figure is closer to 5%. The reason for the rather large difference between North American and European production levels is not clear, but may be associated with differences in alloy acceptability, particularly for plumbing ware.

In terms of product characteristics and process parameters, permanent mold casting may be considered as being intermediate between sand casting and pressure die casting. The section in this chapter on pressure die casting should be referred to for information on process parameters and materials common to both permanent mold and die casting.

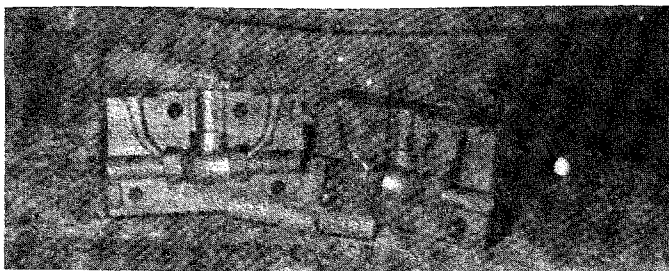
Parts produced by permanent mold casting usually range in size from 1/4 to 10 lb, but may be as small as one ounce or as large as 50 lb in weight. Molds are sized accordingly and, depending on complexity, those for producing smaller parts are often multi-cavity, both to conserve heat and reduce labor costs.

### Casting Characteristics

Permanent mold castings, in the as-cast condition, are considerably more expensive than are sand castings largely due to the cost of the mold itself—which must be amortized over its production life expectancy. Offsetting the cost of the mold are reductions in labor costs and the reduction or elimination of expensive finishing and machining operations. These savings make it possible to reduce the net cost of the part in the final product. Therefore, where production requirements warrant the investment in an expensive mold, permanent mold castings are found to be cost-effective. No hard and fast rules can be given for minimum production requirements. Although mold life expectancy can vary depending on part complexity, 5000 pours is not unreasonable and mold lives of 20,000 to 50,000 pieces have often been reported. If the mold is purchased outright by the customer, amortization of cost need not be a concern.

The following are the general characteristics of copper-base alloy permanent mold castings:

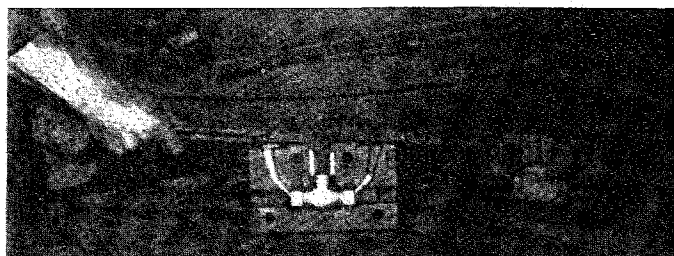
- 1) Dimensional tolerances are closer than those obtained for sand casting, plus uniformity is better between individual castings of the same or different production runs. Where only a graphite mold dressing is used, tolerances equal or exceed those of closed-die forgings and approach those attainable for investment castings or pressure die



*a. The mold is preheated and coated with a graphite wash, ready for use. Note sand core in foreground.*



*b. Pouring. Note the tilting of the mold at the beginning of the operation.*



*c. The mold is opened after the metal has solidified.*



*d. The casting and its core are removed. Notice here, and in view c, the zinc oxide deposit in the mold cavity.*



*e. Note here the release of steam.*

*Fig. 3-19. Permanent mold casting of a brass globe valve body. (Courtesy of Fonderie Sept. 1957).*

castings. Specifically, the following linear tolerances may be expected, depending on design complexity—

*Across parting lines*

Up to one inch =  $\pm 0.010$  in.

For each additional inch  $\pm 0.002$  in.

*Same mold half*

Up to one inch =  $\pm 0.008$  in.

For each additional inch =  $\pm 0.002$  in.

- 2) Provide excellent as-cast surface finish, especially with use of graphite mold dressing, exceeding that of sand castings and comparable to those of forgings, investment castings, and pressure die castings.
- 3) Possess higher mechanical properties than do sand castings because of fine grain size.
- 4) Possess better soundness than do sand castings or pressure die castings. The fast cooling rate and mold design of permanent mold castings are favorable for directional solidification and freedom from the gas and shrinkage porosity found in sand castings. Similarly, gravity pouring prevents the usual entrainment of air holes found in pressure die castings.
- 5) Capable of producing larger castings and heavier sections than are possible with pressure die casting (plus a wider range of alloys can be used).
- 6) Conventional sand cores can be incorporated to produce complex internal cavities. (The combination of reusable metal molds and expendable sand cores is referred to in North America as the “semi-permanent mold” casting process.)

### Permanent Mold Casting Equipment

Unlike the pressure die-casting process which utilizes rather large, often fully automatic machines, permanent mold casting is accomplished with a range of much less sophisticated equipment. The majority of parts, in fact, are manually poured in rather simple molds at operators' benches where metal is provided from adjacent bale-out furnaces. Here, the molds are dressed (coated with a wash), fitted with removable parts or cores, clamped, tilted, and poured. When the casting has solidified, the mold is disassembled, the casting removed, and the process repeated—all by hand. Figure 3-19(a) illustrates a typical globe valve body mold which is poured in this manner. An important feature of the manual-pouring technique is the initial, tilted mold position (Fig. 3-19, b) which is used to minimize turbulence. As the mold fills, the operator continuously rotates the mold to a horizontal position. This is best seen in the schematic views shown in Fig. 3-20. Another feature of the mold illustrated here is the ability to use a “flow-through” technique, whereby the first metal entering the mold flows on through the cavity and enters

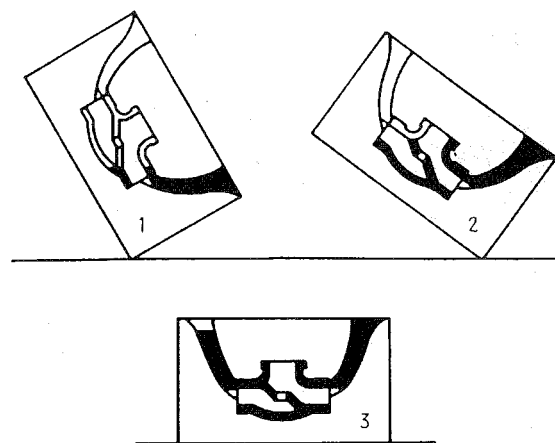


Fig. 3-20. Successive tilt positions of permanent mold during pouring. (Courtesy of Fonderie Sept. 1957)

an overflow well resembling a second sprue. This same principal is used in pressure die casting to avoid flow marks and entrapment of oxides.

Alternatively, and particularly for large castings, combinations of rack-and-pinion gearing, screw mechanisms, or hydraulic cylinders are used for opening and closing of the mold, tilting, and ejection of castings. A hydraulic version of such a machine is shown in Figure 3-21, together with a sectional view of a typical die which might be mounted on such a machine.

To achieve higher production rates, a number of relatively simple, mechanized molds may be mounted on a turntable, or carousel, so that the different operations of mold preparation, pouring, cooling and ejection take place at different stations. Maintenance of strict cycling frequency is particularly important in order to maintain the proper thermal balance of the molds.

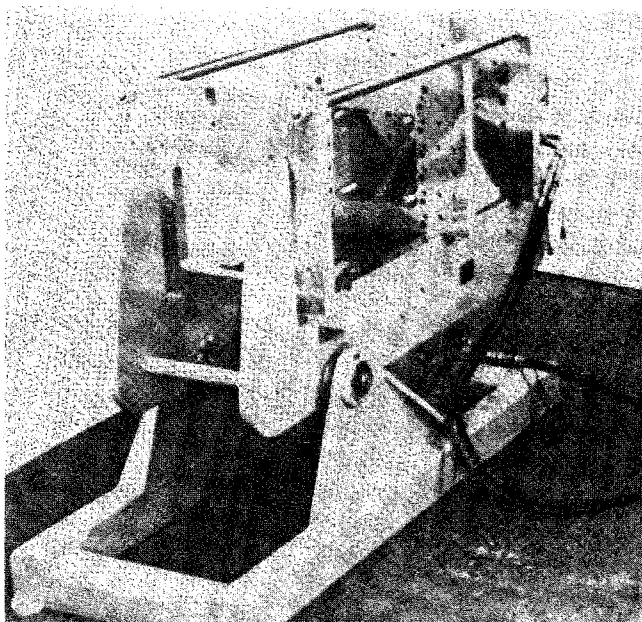
Where maximum production rates are required, as for hardware and plumbing goods, sophisticated machines are available (particularly in Europe) whose complexity rivals that of pressure die casting machines.

### Process Parameters and Casting Quality

Aside from the factors of mold design and melt quality, which will be discussed later, the following operational variables all can have a marked effect on casting quality:

- 1) Pouring temperature
- 2) Pouring rate
- 3) Mold temperature
- 4) Angle and tilt rate of mold
- 5) Dwell time between casting and ejection
- 6) Cycle time between successive pours
- 7) Mold dressing material and mode of application

For successful operation it is essential that balance be maintained between the heat input to the mold by the molten metal and that lost by conduction, radiation, forced-air cooling (where required) and the cooling caused by application of mold wash (especially by dip-



typical mold operating temperatures range from 400 to 800F (204 to 426C). In the case of aluminum bronzes, whose pouring temperatures are in excess of 1965F (1074C), it is common practice, particularly in Europe, to maintain mold operating temperatures at a dull-red heat—that is, 1200F (649C) or more.

In practice, establishment of optimum mold temperature is done empirically by noting the temperature range over which satisfactory castings are obtained. The cadence of operations is then adjusted to maintain the mold temperature within this range during production. Close control of pouring temperature is also necessary for this.

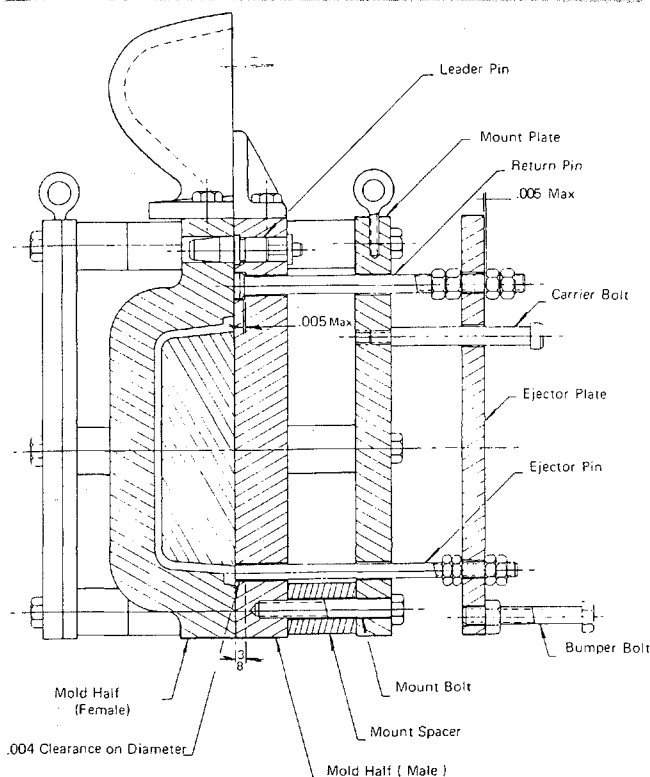
Undue disruption of the heat balance from one cycle to another can lead to scrap of various kinds. High pouring temperature or premature ejection of the casting from the mold can cause casting breakage, because of the fact that the part is insufficiently rigid to withstand the stresses of being ejected. In such cases, portions of the broken casting may lodge in the mold and must be pried loose. This causes delays in the production cycle, excessive loss of mold temperature, and possible damage to the mold dressing.

Delays in ejection can be equally serious, allowing the casting to contract too tightly against unyielding mold surfaces, thus causing sticking or hot-cracking of the casting at these locations. The problems of reduced pouring temperature or mold temperature are of another kind and include misruns, cold shuts, and gas entrapment.

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

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

Suspensions of colloidal graphite in mineral-free (preferably de-ionized) water are the most commonly used mold washes for the production of copper-base alloy castings. These washes may be sprayed, but are most often applied by dipping the hot mold halves into a tank of the constantly-stirred wash. The 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 mold surfaces tends to “explode” away the oxide deposits caused by the volatilization of the zinc from the casting alloy (see Fig. 3-19, view c, which shows these deposits). Secondly, the evaporation of the water (Fig. 3-19, view e) is effective in cooling the mold. (This evaporation action would leave behind mineral deposits unless the water were de-



*Fig. 3-21. Top: Hydraulic, tilting-type permanent mold casting machine with platens for mounting of mold halves. Bottom: Section view of typical permanent mold with mounting plates, ejector plate and pins, and pouring basin.*

ping). In manual operation, heat balance is effected by operator technique and the rhythm of operations maintained to produce acceptable castings. Quantitative control of heat balance can be accomplished by measuring mold temperature, and then programming operations (particularly pouring and casting ejection) accordingly. For most of the yellow brasses and Cu-Si-Zn alloys which are used for permanent mold casting (whose pouring temperatures are in the vicinity of 1700F),

Table 3-8. Typical Compositions of Non-Graphitic Coating for Permanent Molds

| Coating No. | Composition, % by weight (remainder, water) |         |           |             |                    |               |         |         |          |
|-------------|---------------------------------------------|---------|-----------|-------------|--------------------|---------------|---------|---------|----------|
|             | Insulators                                  |         |           |             |                    | Lubricants    |         |         |          |
|             | Sodium silicate                             | 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.

ionized.) The graphite in such washes serves both to prevent soldering and as a lubricant. By its constant replacement, cycle-to-cycle, together with oxide deposit removal as described, the graphite wash also is effective in maintaining a smooth surface finish. It should be noted that often small amounts of ammonium chloride are added to the wash tank in order to adjust the pH of the water, thereby aiding in keeping the colloidal graphite in suspension.

Insulating mold washes are usually applied by spraying or brushing, since they are used only at specific locations in the mold and are touched up as required. 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 common. Table 3-8 gives typical compositions of non-graphitic mold washes used in the production of both copper-base and aluminum alloy permanent mold castings. Many shops have their own private formulations while others purchase proprietary washes with instructions for use. One of the major disadvantages of these kinds of washes is the fact that their texture (and the resulting casting finish) changes with repeated use. Also, the thickness of the wash layer may 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.

### Mold Material & Design

Relatively little information has been published in North America on the subject of permanent molds for copper-base alloy castings. This undoubtedly reflects the limited number of commercial producers of such castings and their reluctance to publish data on shop practice. An excellent summary on design and construction principles, although somewhat brief, has appeared in French literature,<sup>3</sup> which reports that European prac-

tice is to use three general classes of materials for permanent molds for copper-base alloy castings:

- fine-grained, pearlitic gray cast iron
- special steels
- nonferrous alloys

For casting the lower-melting-point brasses and silicon bronzes, gray cast iron molds are most common, having the general composition range of 3.4% to 3.5% C, 1.50% to 1.80% Si (varies according to thickness), 0.90% Mn, less than 0.10% S, and less than 0.20% P.

To improve the thermal shock resistance of the iron a small addition of molybdenum (0.70% to 0.90%) may be used. Cast blocks to be used for molds must have flawless internal structures, since the least blowhole or spongy area at the surface of the final mold cavity will cause serious surface defects on the casting. These fine-grained, pearlitic cast irons, with or without the presence of molybdenum, are reported to provide mold lives of 15,000 to 20,000 castings.

Certain special low-alloy steels have also been found to provide good results (20,000 to 25,000 castings), although the steels are more prone to distortion. Steels for molds have the average composition 0.25% C, 0.70% Mn, less than 0.40% Si, 1.00% Cr, and 0.15 to 0.35% Mo.

For limited production requirements (4,000 to 5,000 castings), brass or bronze molds are used. Beryllium-copper molds have also given promising results. European practice is to use high-alloy steels for the casting of aluminum bronzes. These are assumed to be air-hardening die steel compositions, although this is not specified in the literature.

Molds can be manufactured either by machining directly from solid blocks of cast iron or forged steel or by use of cast-to-shape blanks of contoured thickness, which are cast from master patterns. The first method mentioned, generally speaking, is restricted to tooling for rather small parts. The second method is the most commonly used, since it provides a means for controlling mold wall thickness in order to assure proper

balance of heat flow which is necessary for good production and casting quality. Details regarding other features of mold design, with emphasis on venting, chills and draft angles for moving parts, can also be found in the French literature.<sup>3</sup>

## Gating

Generally speaking, gating systems for the production of copper-base permanent mold castings must follow certain rules. For proper filling of the mold cavity, filling must be continuous (not interrupted) and properly adapted to casting and alloy requirements. Air must be displaced from the mold cavity as it is filled. To assure casting soundness, there must be no turbulence in the runner system or in the mold cavity during pouring. The gating system also must permit complete filling of the cavity, and the direction of metal flow must be such that solidification defects do not occur.

Since the majority of the brasses and bronzes which are cast in permanent molds are sensitive to shrinkage, cracking, and oxidation, isolated massive sections should be avoided wherever possible. When they are present, gating should be directly into such sections. The casting must be positioned in the mold and poured in such a fashion that the cavity fills completely and continuously during pouring. As an additional means of avoiding oxidation, it is good practice to employ bottom-gating and, for this reason, it is often necessary to resort to the practice of tilt-pouring (Fig. 3-19, view b). Displacement of air from the mold must be accomplished by the use of ample vents or *relief risers*, and by the use of large overflow cavities. These cavities have the advantage of permitting a "washing" of the mold cavity, by flow-through of metal, which is necessary in order to obtain a good surface finish on the casting.

## Casting Alloy Characteristics

### Compositions

As is the case for pressure die casting, the most commonly used alloys for permanent mold casting are the yellow brasses (including silicon brass and manganese bronze). The metallurgical characteristics of these alloys are covered in the section on pressure die casting as well as in Chapters 10 and 12.

Another family of alloys widely used for permanent mold casting is the aluminum bronze group, and particularly alloys C95200 and C95300. These materials are not pressure die-cast because of their susceptibility to oxide film formation under conditions of turbulent flow.

In fact, by proper mold design and care in gating and pouring, a wide variety of copper-base alloys can be successfully cast in permanent molds. Such alloys include high-conductivity copper, chromium-copper, nickel silver, phosphor bronze, and even certain leaded tin bronzes. The higher melting points of these alloys have a marked effect on mold life, however. Also, casting dif-

ficulty increases as the alloy freezing range becomes wider, except for the simplest shapes. The much higher freezing rates of permanent mold castings, as compared with sand castings, cause modifications in alloy microstructure and properties; hence, for permanent molding the optimum composition may require some adjustment.

### Physical and Mechanical Properties

The physical properties of the various permanent-mold casting alloys can be found in CDA's *Standards Handbook*,<sup>4</sup> and are related to composition rather than to casting process.

Mechanical properties of permanent mold castings have not been well documented due to the lack of a standard test bar. This is a matter of concern to the industry because the generally superior properties of chill-cast alloys are thus hard to merchandize. Individual manufacturers can cite properties for various alloys based upon use of their own test bar, but no standard test bar exists in North America.

Some specifications quote properties in accordance with 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), cast from the mold shown in Fig. 3-22. The latter is intended to be tilt-poured, as shown in Fig. 3-23.

The mechanical 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. This is due to the fact that the rapid freezing rate causes the formation of a fine-grained, dense, solid skin on the casting, extending 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 & 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 normally carried out in the furnace room and the metal then transferred to holding furnaces in the pouring areas. The holding furnaces are normally designed to permit bale-out pouring, whether done manually or mechanically.

Gas control of the metal is more critical in permanent mold casting than it is 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 volu-

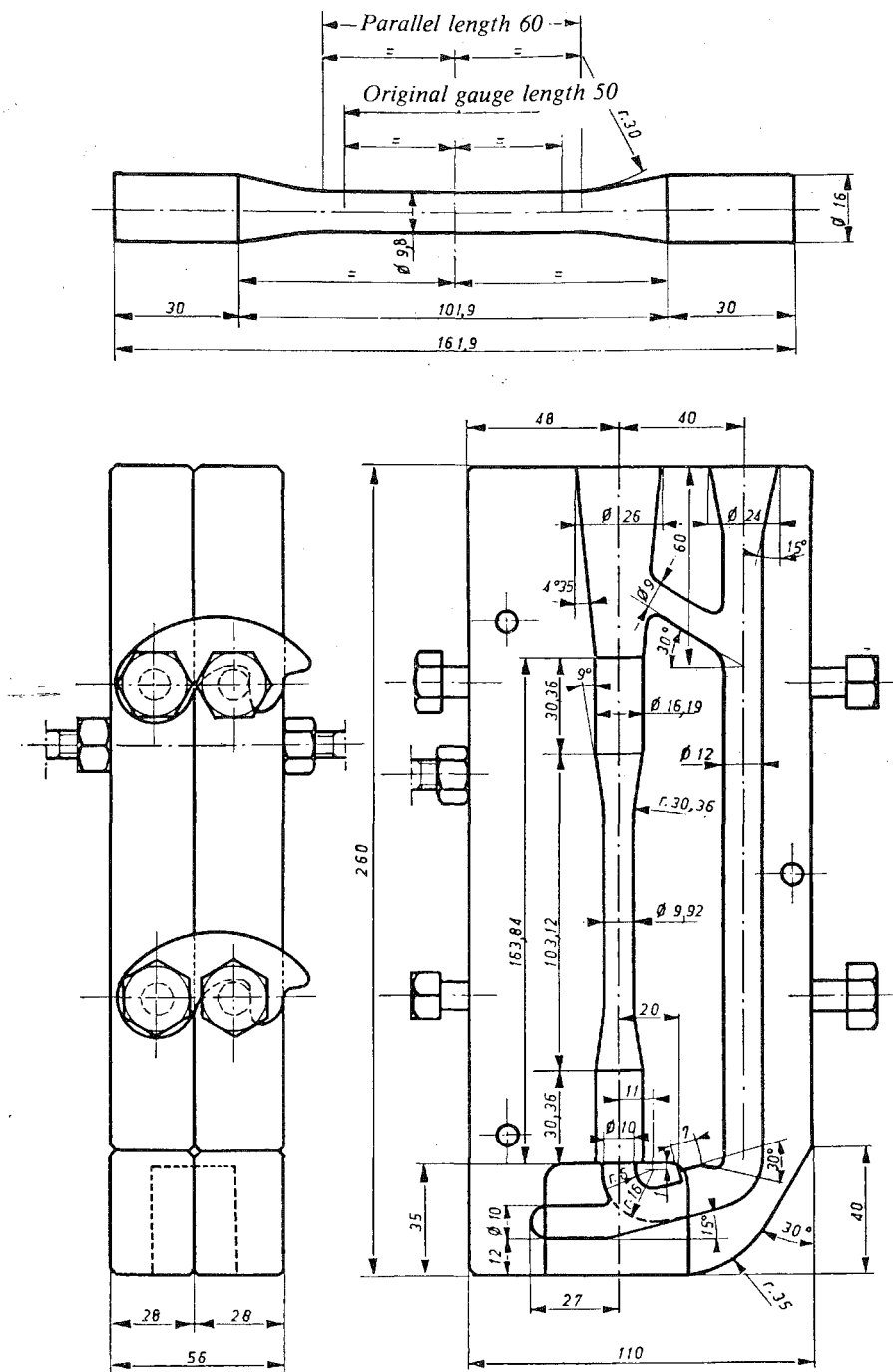


Fig. 3-22. ISO test bar and mold for copper-base alloys, per ISO 1338-1977(E).

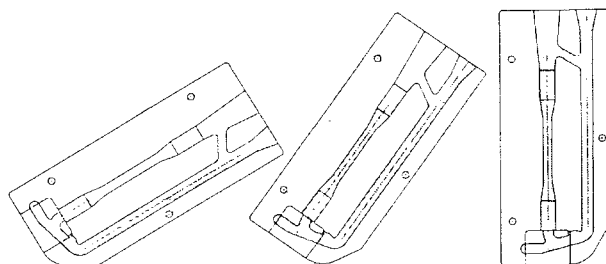


Fig. 3-23. Illustration of filling sequence of test bar mold, poured in tilted position and rotated to vertical position.

metric shrinkage and, in accordance with Pellini's strain theory of hot tearing, to assist in feeding hot spots—thus reducing 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 and design as well.

One complication of the permanent mold casting process, in terms of melt control, is the fact that relatively small amounts of metal are cast per unit time. This means prolonged holding times, with the likelihood that gas level, composition, and inclusion content will change considerably within the furnace. It is thus necessary to exercise careful control over the quality of the melt, with adequate monitoring and adjustments performed to assure readiness for pouring at all times. This should include evaluation of the need for readjustment of the gas level, skimming, or replacement of zinc loss.

### Conclusion

The permanent mold casting process for copper-base alloys appears to be under-utilized in comparison to its use with aluminum alloys, and also with the much wider application of the process in Europe. Expanded use of the process seems a distinct possibility for the future in North America, particularly if dezincification problems of the yellow brasses can be moderated to meet plumbing-ware specifications. Permanent mold casting can also be expected to gain impetus in view of the growing concern with the toxicity of foundry solid wastes, including 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.

The process has the following inherent advantages:

- 1) It lends itself readily to the utilization of progressive solidification.
- 2) Dross and nonmetallics of low density move toward the inside surface where they may be removed by machining.
- 3) It develops extremely high casting pressures, which promote soundness by providing effective feeding, increasing gas solubility, and keeping to a low volume any gas which may be trapped or liberated in freezing.
- 4) It is readily adaptable to the use of permanent chill molds, in which fine-grained castings of exceptional soundness and uniformity may be produced.

- 5) 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.

- 6) 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 (as shown in Fig. 3-24).

#### Centrifuging

Centrifuging is probably the least important of the three types of centrifugal casting, a typical example being the investment casting of "Christmas 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 10 G. (G = acceleration due to the force of gravity.) An alternate version of the centrifuging process utilizing more conventional sand molds is shown in Fig. 3-25; this can, of course, be applied to simple cope-and-drag molds as well as stacks. The 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. A typical example is shown in Fig. 3-26, and 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 "fixed" even before solidification starts and it is therefore necessary to make the riser considerably higher than would be the case with static casting.

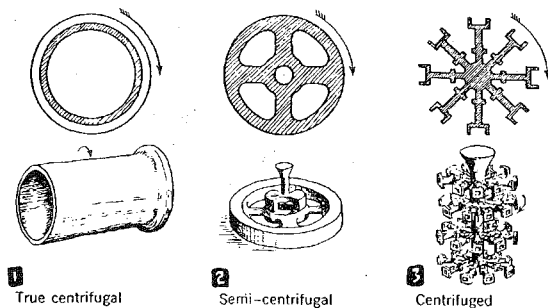


Fig. 3-24. Variations of the centrifugal casting process

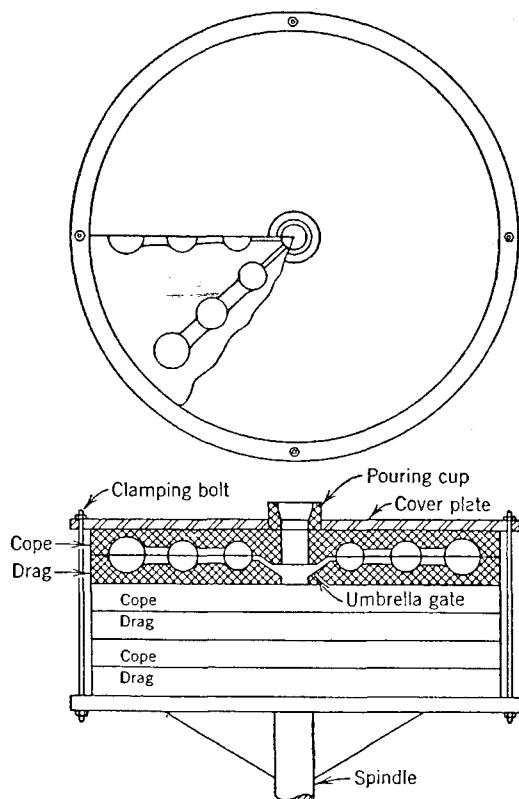


Fig. 3-25. Centrifuging process showing a dry sand stack of three molds.

### 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 at any angle in between. The essential features are that there are no sprues or runners, the metal being 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 various methods, and Figure 3-28 shows a casting being poured. 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

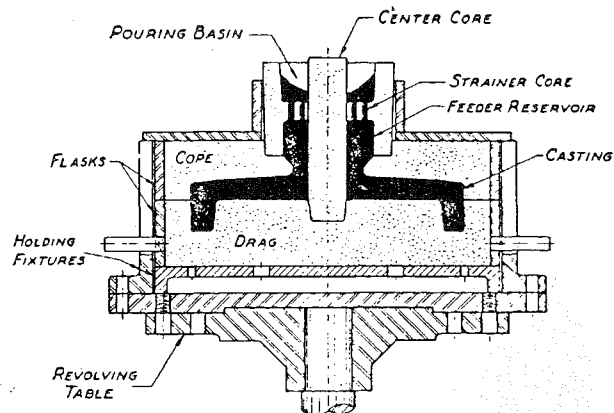


Fig. 3-26. Semi-centrifugal casting process

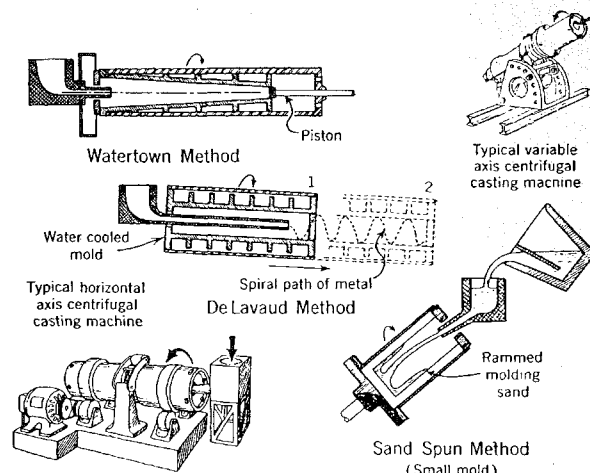


Fig. 3-27. Variations of true centrifugal casting process

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 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 on the mold 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.

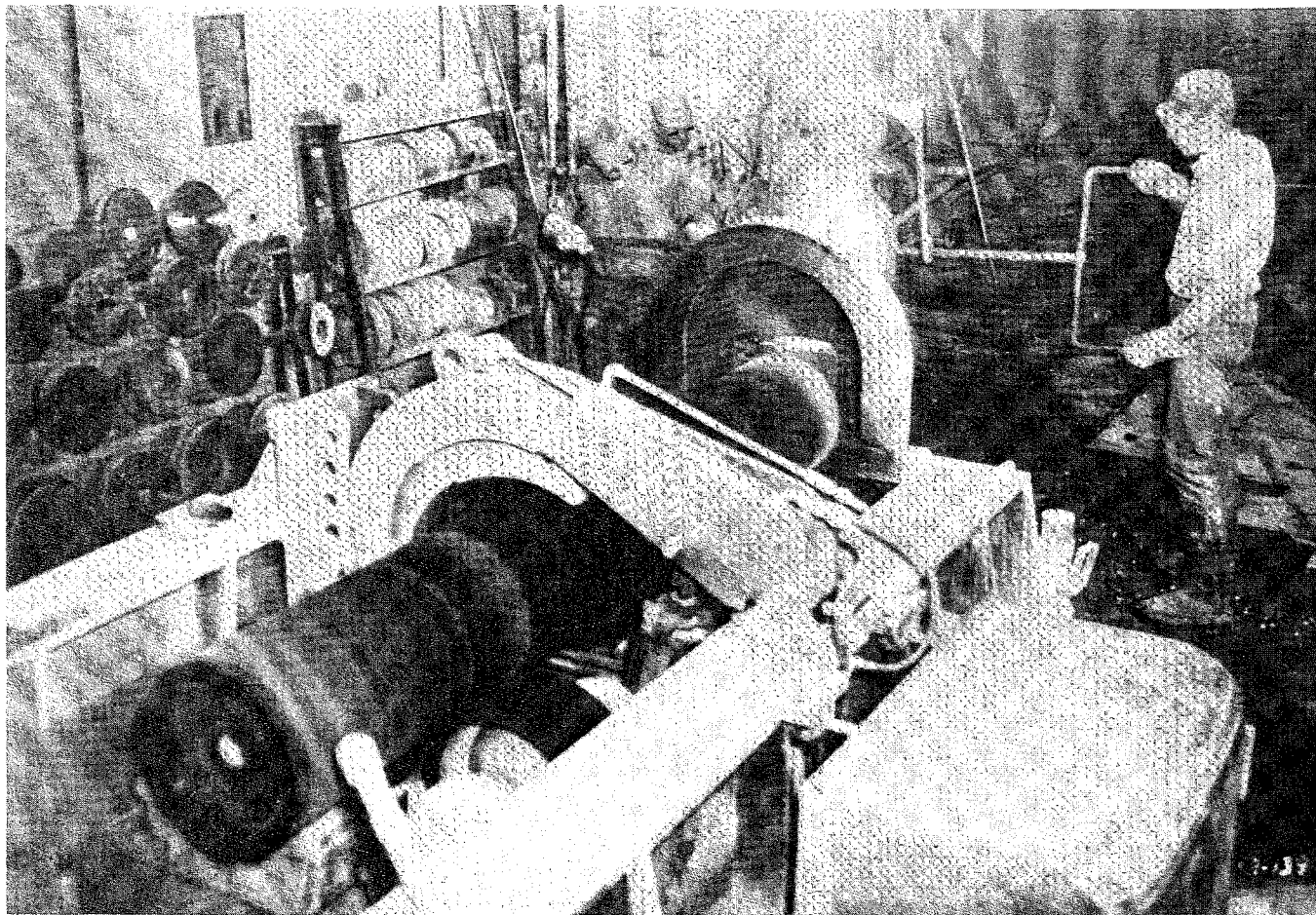


Fig. 3-28. Ten-foot tube being poured on a horizontal casting machine (Courtesy Wisconsin Centrifugal Foundry, Inc.)

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 “veining” (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 nonmetallics 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. 3-29. 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.

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.

**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.

### Theory, Structures & Properties

The mathematical theory governing the forces developed by mold rotation are 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.

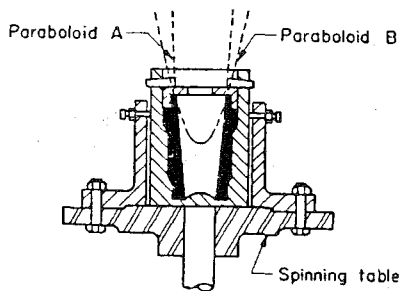


Fig. 3-29. Vertical centrifugal casting method showing effect of rotational speed on the shape of the inner surface.

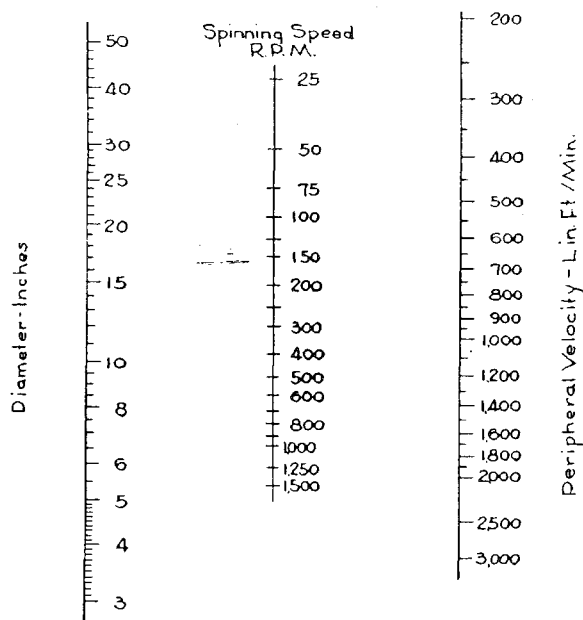


Fig. 3-30. Nomogram for calculating spinning speeds to constant peripheral velocity.

These assumptions are least valid for 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:

$$F = \frac{W 4\pi^2 N^2 R}{G \times 3600 \times 12}$$

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:

$$F = W N^2 R (.0000284) \text{ pounds}$$

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:

$$CA = N^2 R (.0000284)$$

$$CA = \text{Centrifugal acceleration in } G$$

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 *times gravity* 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:

$$P = 1.415 \times 10^{-5} d N^2 r^2 \text{ lb/sq. in.}$$

For copper alloys this reduces to:

$$P = .000004 N^2 r^2 \text{ lb/sq. in.}$$

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 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 14 psi, approximately), 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, and so on. 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. A wide variety of micro- and macrostructures 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

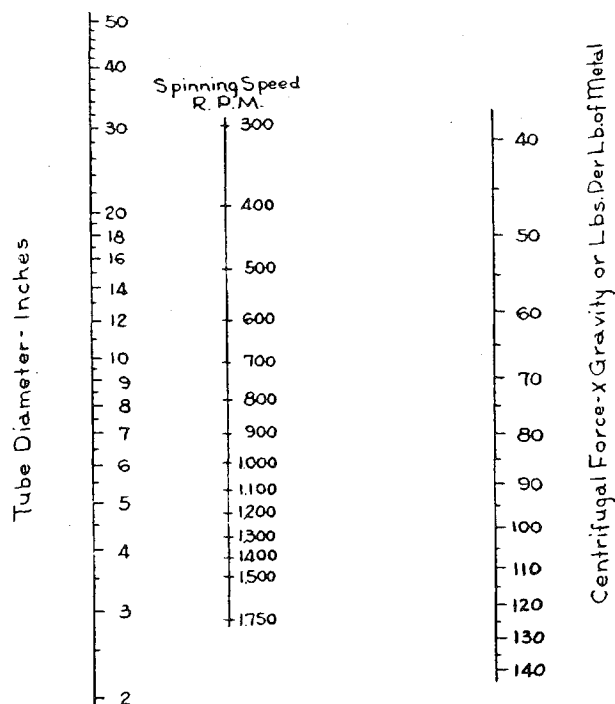


Fig. 3-31. Nomogram for calculating spinning speed to constant centrifugal force.

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 B271-73 are the same as in ASTM B584-79 "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 pro-

duction 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, and so on.

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.



Fig. 3-32. Pouring plaster slurry for plaster mold casting. (Courtesy Gorham Electronics, Providence, RI)

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% plaster of paris (gypsum), 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 (see Fig. 3-32).

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, since the presence of even minute amounts at the time of casting would possibly result in gas-related defects. 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 which 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/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

With plaster mold casting accurate reproduction of fine surface details is possible. 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 small 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:

- 1) Proper proportioning of plaster and water.
- 2) Proper mixing to insure uniformity.
- 3) Proper use of the right separating medium.
- 4) Proper gating and job set-up with gates, runner, and sprues cast into the plaster mold.
- 5) Complete dehydration of the mold in a proper type of oven for a sufficient time.
- 6) 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 burn-out temperature.

Foundries usually develop procedures and plaster-to-water ratios best suited to their individual requirements and equipment. Generally, 10 parts of metal casting plaster are mixed with 14 to 18 parts of water by weight (140–180 consistency).

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 too coated 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 complete elimination of pinholes and the production of uniform slurry. A 2- or 3-in., 3-blade standard pitch propeller

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. Mixing should be performed for 3 to 5 min after soaking, when hand mixing, 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 pinholes and produce smooth mold surfaces.

In order to remove the set-up plaster from the pattern, the pattern must be covered with a thin film of a separating medium. 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, with 0.1% wetting agent added.

Another widely used parting medium is made by shaving 6 oz. of stearic acid into 3 pts 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 nail 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:

- 1) Degree and volume of heat employed
- 2) Circulation of gases
- 3) Weight and thickness of mold and surface exposed

If an oil or gas oven which will attain a temperature of 1400F (760C) is available, 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

With plaster mold casting, in general, a dimensional tolerance of plus or minus 0.005 in. can be held. Where the dimension crosses the parting line the tolerance is increased to plus or minus 0.010 in., per inch. In particular portions of a casting, however, more exacting tolerances can be expected.

### 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, poleline 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, and so on.

In addition to the above-mentioned applications, this process is well suited for the production of hardware such as fittings, hinges, sprockets, and plumbing sup-

plies. Sparkproof tools such as wrenches, pliers, screwdrivers, and so on, 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.

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 archeological 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 its automation, have progressed to the point that investment casting is now a most important commercial process. Examples of high-precision, investment-cast parts are shown in Fig. 3-33.

There are two modifications of the investment casting process: 1) *investment flask casting*, which utilizes a

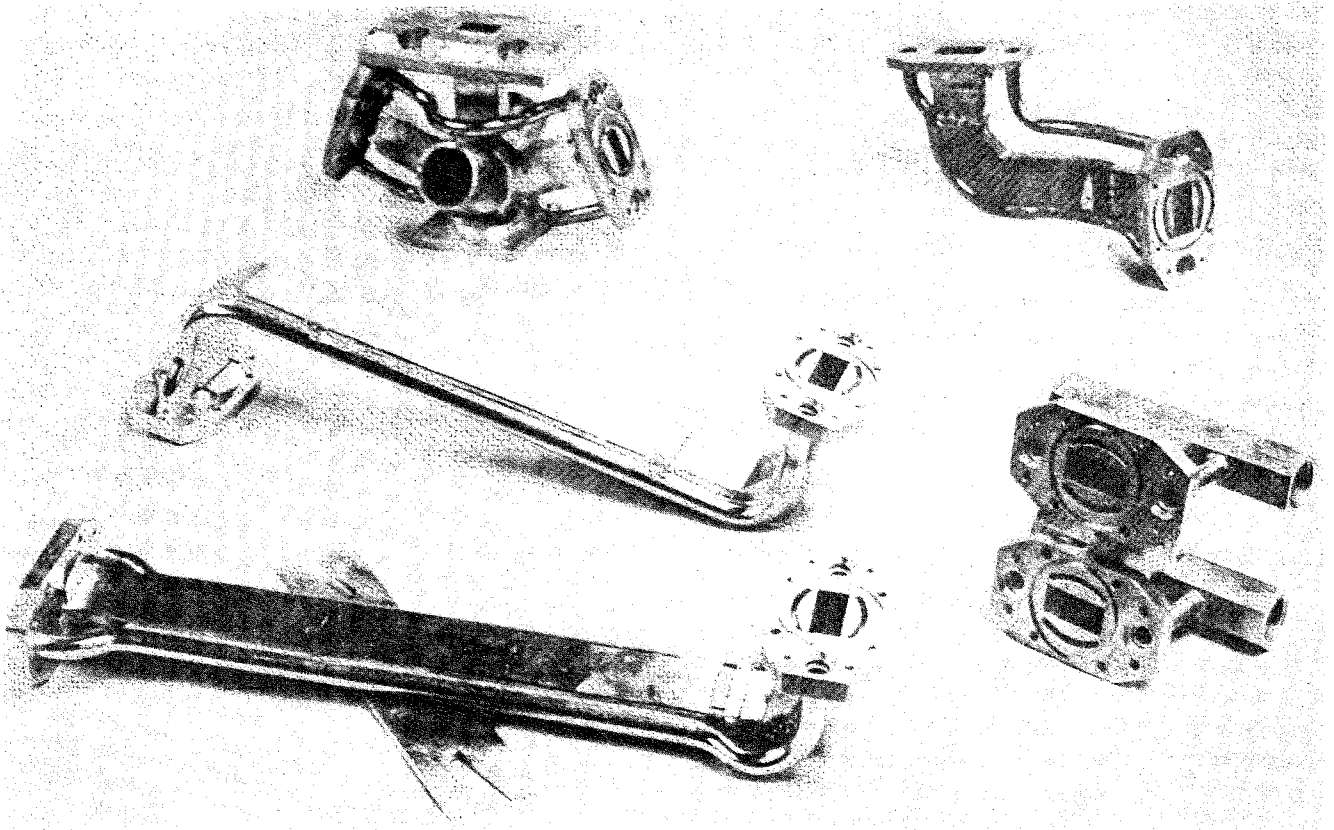


Fig. 3-33. Beryllium copper radar components produced from investment castings (Courtesy Gorham Electronics, Providence, RI)

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. 3-34.

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 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, and so on). As with pressure die casting 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 ap-

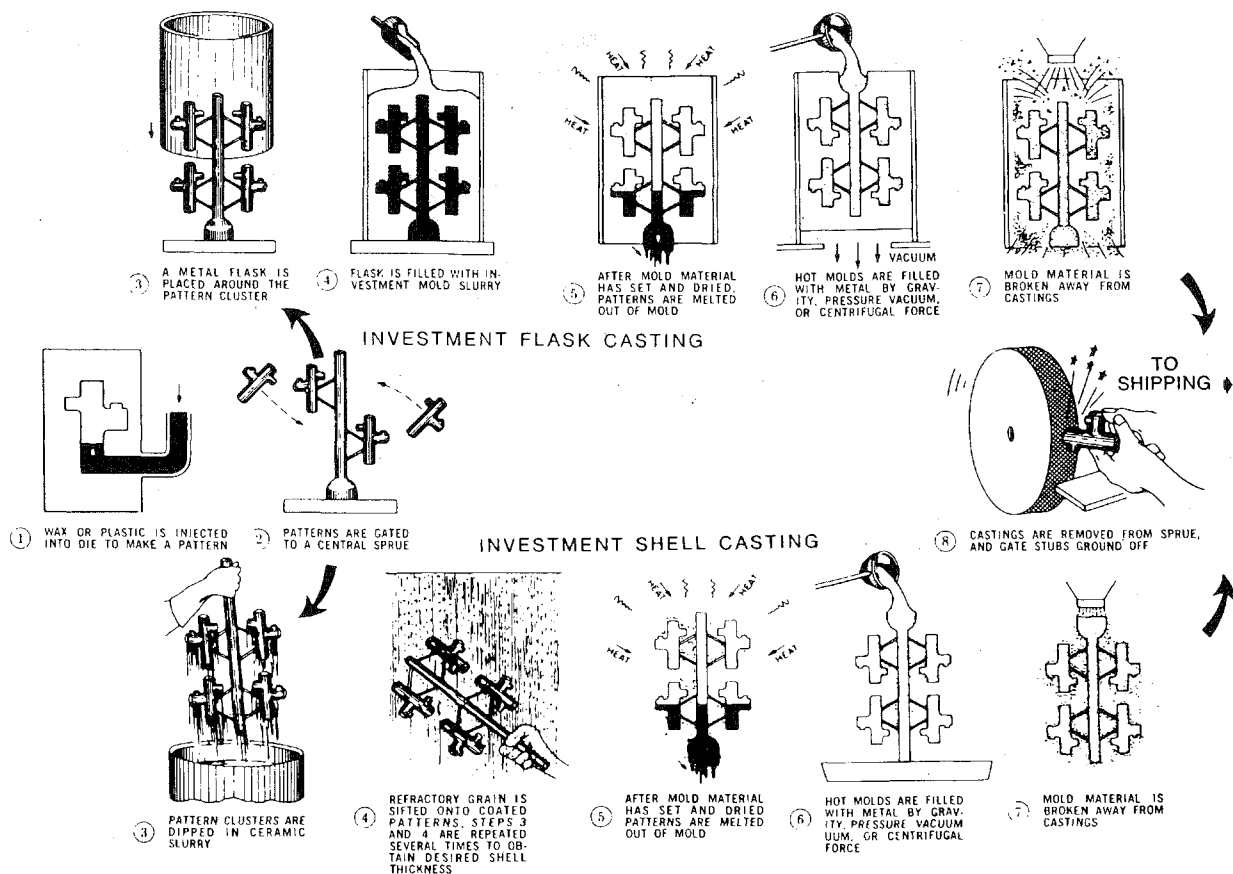


Fig. 3-34. Basic production steps for investment casting methods.

plied whether the patterns are made of wax or of plastic. This critical process, involving the heating of the entire pattern/mold assembly, involves the pattern material melting and draining from the mold with any residual material being 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 pressure in an autoclave. Following the low-temperature dewaxing cycle, molds are slowly heated for final firing at incandescent temperatures.

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  $\pm 0.005$  in. for dimensions up to one inch, with an

additional  $\pm 0.005$  in. for each inch thereafter. Closer tolerances are actually possible, depending on the alloy selected and the configuration of the part.

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

#### Shaw Process

In the Shaw process, a ceramic slurry is used as a molding aggregate in conjunction with conventional types of patterns and flasks. In this respect, the Shaw process is analogous to the Capaco process for plaster mold casting, which was described earlier. The Shaw process is not directly competitive with the lost-wax, investment casting process since the largest castings normally made by investment casting represent the smallest which are applicable to the Shaw process.

With this process, split molds are made by pouring a refractory slurry over a prepared pattern. In a matter of minutes the mold can be stripped from the pattern and then immediately flamed. Assembled molds are fired and can be poured while the mold is red hot or at lower temperatures.

This method may be used for castings of aluminum, magnesium, brasses and bronzes, cast iron, carbon steels, low and high alloy steels and super-alloys.

## Materials

The refractory slurry is composed of a mixture of coarse and fine sillimanite, 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. Crazeing is progressive throughout the mold mass producing a mold of high permeability and partial immunity to thermal shock.

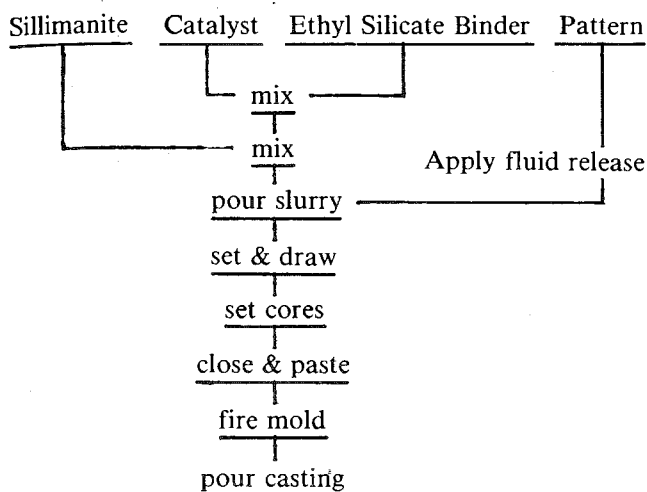
After the closing operation, the mold is fired at red heat for approximately 1/2 hr per inch of mold material thickness. This further strengthens the bond and produces an inert, gas-free, erosion-resistant, collapsible mold which can be poured hot or cold.

## Pattern Materials & Equipment

There have been a variety of pattern materials used for the Shaw process. These include wooden, metal, plaster and plastic patterns. 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.

Since the mold material is poured over the pattern rather than being rammed against it, there is negligible wear on patterns over a period of 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.

### FLOW CHART



## Shaw Process Advantages

The advantageous features of the Shaw process include the following:

- 1) Very thin sections can be cast since high mold and metal temperatures can be employed.
- 2) Castings with excellent surface finishes can be obtained. For instance, a finish of 125 micro-inch or better is obtained in the casting of steel.
- 3) 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.
- 4) Dimensional tolerances of  $\pm 0.003$  to  $\pm 0.015$  in. are obtainable, depending on section size and configuration. The process is good for prototype work.
- 5) Low pattern costs are significant when production rates are low.
- 6) Simplicity of pattern construction and molding procedure allows short lead times.
- 7) The process is adaptable to a wide range of casting sizes.
- 8) Due to the inert and erosion-resistant properties of the mold material, metal sections are unusually clean and free from gas defects—providing that furnace and ladle slag is not entrapped in the metal.

## Process 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 Shaw process:

- 1) Thin, flat, rangy components.
- 2) Designs necessitating large print areas.
- 3) 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

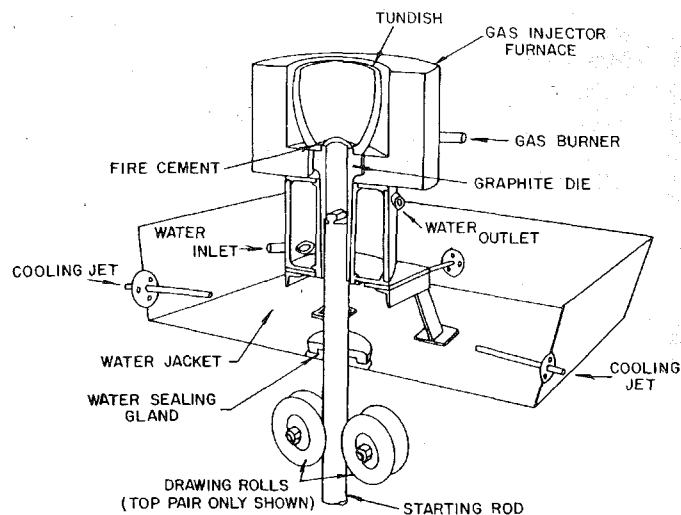


Fig. 3-35. Diagrammatic arrangement of original Tin Research Institute vertical casting system for bronze rod, with secondary water cooling.

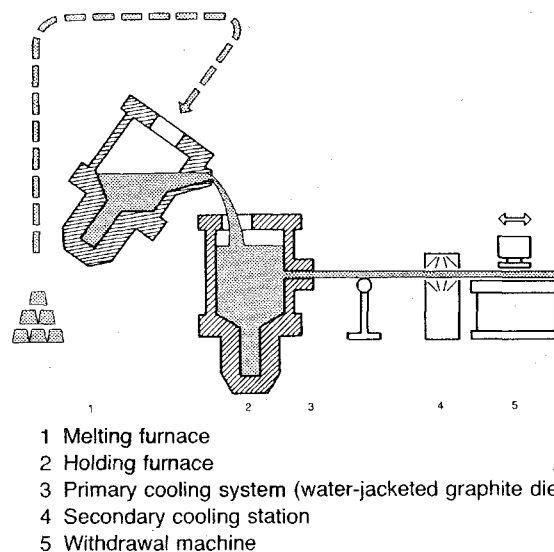


Fig. 3-36. Schematic layout of horizontal continuous casting equipment (Courtesy Alfred Werthli, Ltd., Winterthur, Switzerland)

Table 3-9 - 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<br>Gunmetal |               | 1.25         | 1200        | 2            | 5             | 24        | 7         |
|                           | 85-5-5-5      | 0.5          | 1210        | 4            | 4             | 10        | 5         |
|                           | 81-3-7-9      | 1.25         | 1170        | 2            | 2             | 24        | 12        |
| Tin Bronze                |               | 3.0          | 1150        | 2            | 4             | 13        | 4.3       |
|                           | 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         |
| Brass                     |               | 3.0          | 1120        | 2            | 4             | 12        | 4         |
|                           | 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  $t_{on}$   
 $v = \text{Casting rate} = \frac{t_{on} S}{t_{on} + t_{off}}$

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. 3-35, the basic equipment for continuous casting is comprised of a *tundish* for holding the molten metal, attached directly to a machined graphite mold of 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).

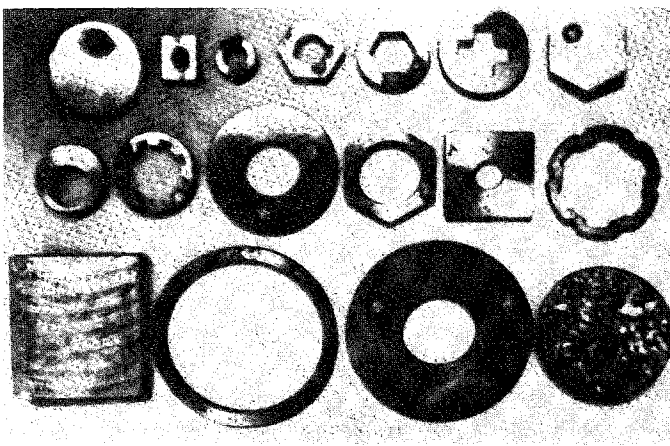


Fig. 3-37. Sections of cast shapes produced in a vertical, closed-head continuous casting system. Hollow shapes result from use of an uncooled graphite mandrel suspended in the mold.

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. 3-36. 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 3-9. Examples of cross-sectional shapes which can be cast are shown in Fig. 3-37.

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 to occur, 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 runout of molten metal from the furnace or mold must be channeled away from any wet surfaces.

## SAND CASTING PROCESSES

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# Chapter 4

## MELTING EQUIPMENT

### INTRODUCTION

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

The economics of melting have changed radically in the past ten years. The cost of energy has skyrocketed and will probably continue to do so for years to come. Natural gas, an almost ideal fuel for melting brass and bronze alloys, now costs ten times what it did ten years ago. The cost of fuel oil has increased nearly as much, and the cost of electric energy is increasing at the rate of 15% per year, or doubling approximately every five years. Capital costs of melting equipment have increased, as have installation costs and the effect of inflation on financing costs.

Environmental problems in handling molten metals have created another critical area which may even affect the foundry's survival. Requirements for removing particulate matter from the atmosphere and for controlling emissions of alloying elements like 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. 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 is another problem area. It has become increasingly difficult to recruit competent personnel for many areas in the foundry operation. Unless the job of melting brass and bronze can be made more attractive, the time may come when no one will want to work in this area.

One final important consideration is the ever-increasing demand for higher and more consistent quality in the castings produced in copper-base alloy foundries. With more castings being ordered to meet rigid ASTM and ASME specifications and federal regulations, metal quality must be dependable. The choice of melting equipment will be influenced by these increasing demands.

### TYPES OF EQUIPMENT

Equipment for melting brass and bronze alloys can be classified as either fuel-fired or electric. The advantages and disadvantages of each type of equipment are discussed in the section "Choosing Melting Equipment." Descriptions of the available equipment follow.

#### Fuel-Fired Furnaces

The most common fuels used in melting copper-base alloys are natural gas and fuel oil. 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 solid metal. Heat is added until the solid metal starts to become liquid; the metal is then sufficiently superheated 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 furnace is the simplest and 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 air blower; the volume and pressure of air and fuel are metered and automatically controlled to provide a constant melting atmosphere. Figure 4-1 shows a schematic of a crucible furnace. The crucibles are made either of clay-bonded graphite or carbon-bonded silicon carbide and vary in size from holding capacities of 5 pounds to about 700 pounds of brass—the usual maximum weight that can be safely lifted out of the furnace. Clay-bonded graphite crucibles are less expensive and more widely used, particularly in electric induction melting where the high elec-

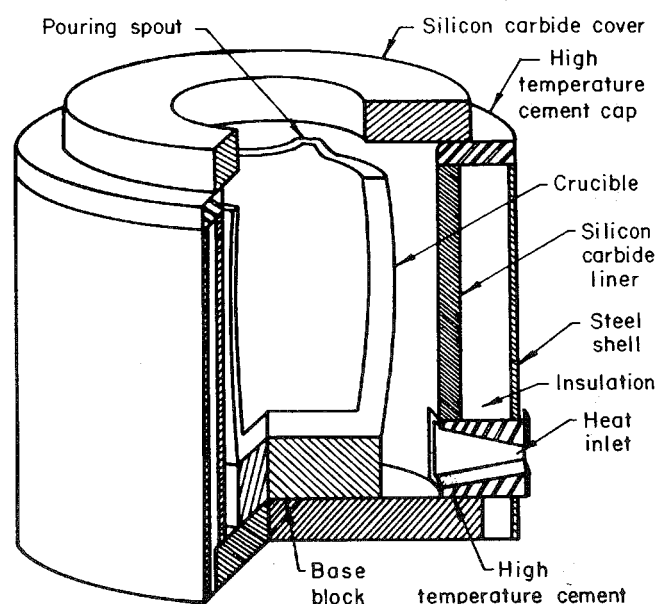
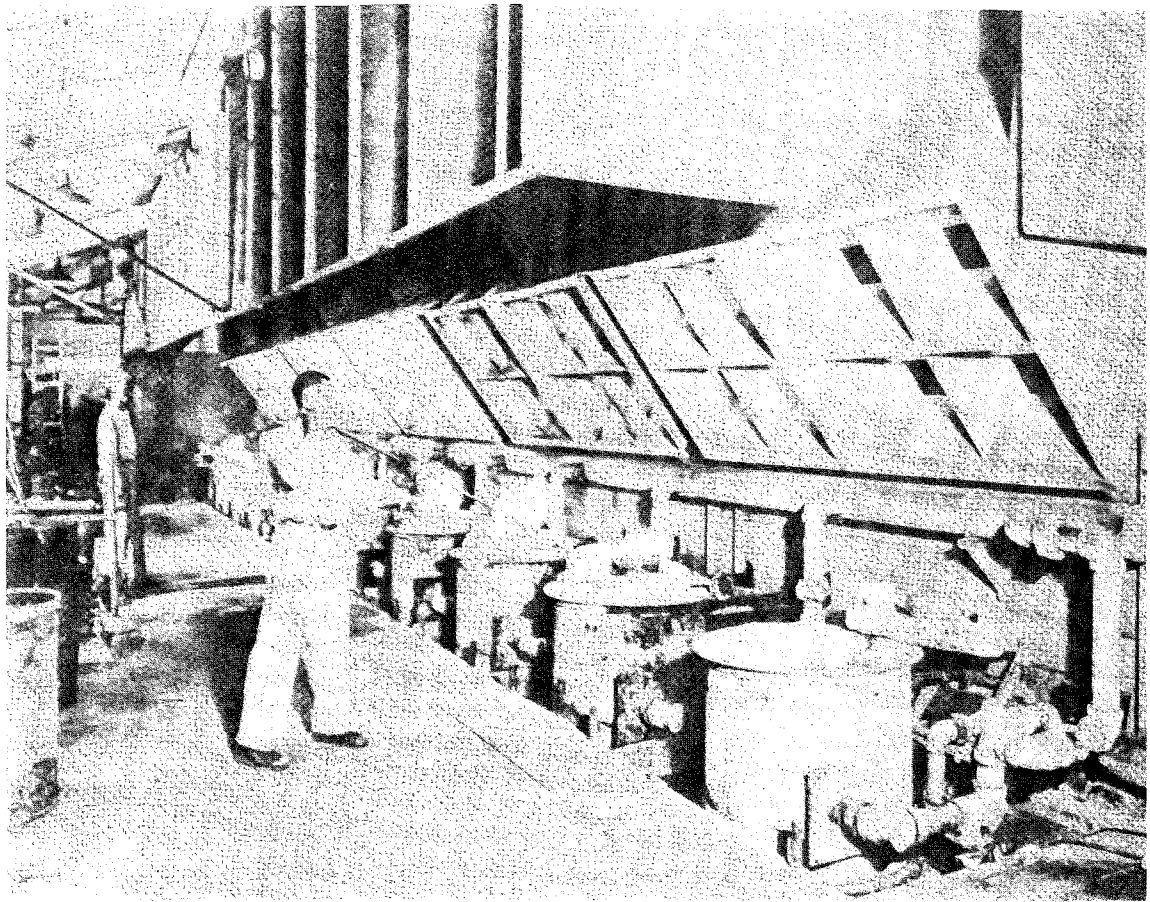


Fig. 4-1. Schematic of "lift-out" crucible furnace showing various components. Furnace may be either floor-mounted or installed in a pit, and may be fired with either gas or fuel oil.



*Fig. 4-2. Battery of gas-fired, lift-out crucible furnaces; note ingots preheating on furnace covers.*

trical 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 pounds of aluminum. Since copper is three times more dense than aluminum, a no. 50 crucible holding 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, a small crucible—no. 50 (150 lbs metal) or no. 80 (240 lbs of metal)—can be used. For larger castings, a no. 100 (300 lbs metal) or a no. 225 (675 lbs metal) can be used. In pro-

duction shops, a battery of crucible furnaces, either at floor level or in a pit, will 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 work day. The first charge of ingot, or ingot plus gates and risers, is placed into the crucible and melted. The heat is transferred from the flame to the refractory, to the crucible, and then to the metal. 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 pick-up from damp material. Also, 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 at the proper pouring temperature, the metal is poured.

Most foundries pouring a variety of alloys use separate crucibles for each class of alloy. Crucibles can last for 100 or more heats if care is taken in preheating, charging, pouring, and mechanical handling.

In simple burners, the ratio of air to fuel is constant and only 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. Melting atmosphere is important in controlling metal quality. In the melting of copper-base alloys, it is desirable to maintain a slightly oxidizing atmosphere (a slight excess of oxygen or CO<sub>2</sub> in the products of combustion). More sophisticated burner controls usually will maintain the proper melting atmosphere and reduce the influence of furnace operator adjustments.

### Tilting Furnace

When larger amounts of molten metal are needed for pouring brass and bronze alloys (such as in high-production shops or in making large castings), tilting furnaces are frequently used. 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, a hoist, or a hydraulic tilting mechanism. 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. 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 Chapter 5).

Since alloy changes may require relining 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 (1800 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 so as to make maximum use of the heat retained in the lining. Although melting times will vary with operators and conditions, tilting furnaces can melt approximately 500-600 lbs of brass or bronze per hour.

A recent 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 enhances the competitive position of fuel-fired furnaces as opposed to electric furnaces, it is too soon to determine whether these improvements along with the increased availability of natural gas will renew the interest of non-ferrous foundrymen in fuel-fired melting.

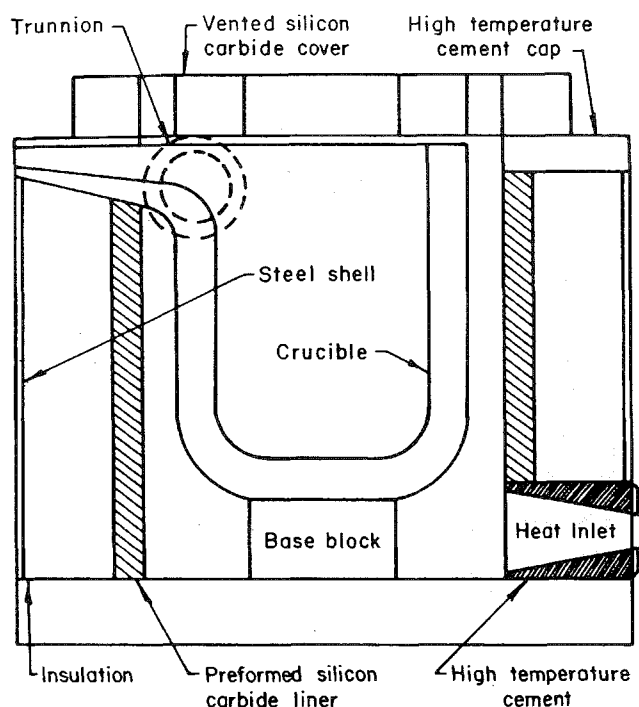


Fig. 4-3. Schematic of tilting-type, fuel-fired crucible furnace, showing melting crucible cemented in operating position.

### Rotary Furnaces

For pouring large volumes of molten metal—from 1000 lbs to as much as 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, almost always 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

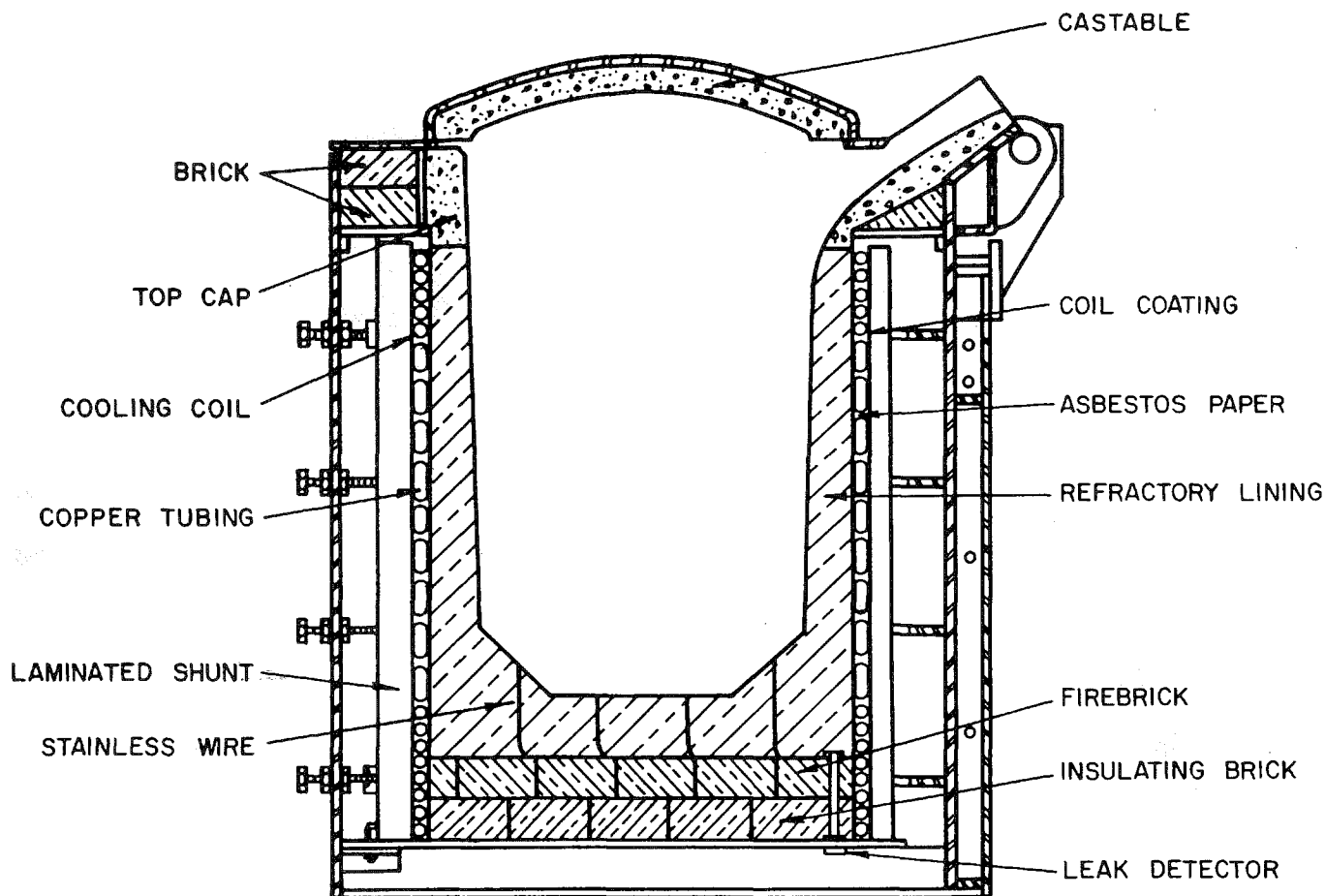


Fig. 4-4. Schematic of tilting-type, coreless induction furnace (nose tilt).

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 replacement.

### 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, has become the most popular and rapidly growing method for melting brass and bronze alloys. The principle of induction melting is analogous to that of a transformer wherein the metal charge (the secondary) is surrounded by a water-cooled coil (representing the

primary). When the coil is energized, electric energy is induced into the metal charge where it builds up heat in the metal until the metal melts and becomes superheated.

The recent transition from the older motor-generator sets to solid-state electrical conversion has greatly contributed to the increased use of induction furnace equipment. Today's induction power units basically draw 440-volt, 60-cycle power and by means of solid-state electronic devices convert the power to 440 volts, 180 cycles (180 hz), 540 cycles, 980 cycles or even 3000 cycles. This conversion can be accomplished in a number of ways; however, only the equipment most suitable for foundry melting of copper-base alloys will be considered here.

Most of the power units designed for use in non-ferrous foundries are medium- or high-frequency units—600 cycle (600 hz), 1000 cycle (1000 hz), or 3000 cycle (3000 hz). Induction furnaces are characterized by electromagnetic stirring of the metal bath. Because the amount of stirring is affected by both power input and power frequency, the power unit size and frequency should be coordinated with the furnace size in order to obtain the optimum-sized equipment for any specific operation. Most copper-base alloys are melted in 1000-cycle or 3000-cycle units, depending on the size of the furnace; larger melts are usually handled with 1000 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 3000–4000 lbs of metal are needed. Since melting rate is a function of power input, a foundry's molten metal requirements will dictate which equipment will be most efficient.

A coreless induction furnace is comprised essentially of a water-cooled copper coil in a furnace box made of steel and/or transite. 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 to the coil. Though a variety of designs are available, these furnaces are of two general types—tilting and stationary.

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 with a hoist or with a hydraulic lifting system. 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 (and box) is cantilevered from a center post and can move up and down vertically and swing horizontally about the post in a 90° arc. Since 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 furnace box is lifted (by hydraulic or air cylinders), pivoted to the side and lowered over the 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 in a pit. As shown in Fig. 4-5, the crucible stands on a refractory pedestal that can be raised or lowered by a hydraulic cylinder. This unit, called a “push-out” 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 metal falling into a pit will sometimes damage the hydraulic lifting equipment.

In an operating induction furnace, a power unit contains the solid-state components and necessary controls. Suitable power (usually 440V) is fed to the power unit by bus bar or cable. One or more furnaces of types previously described are attached to the power unit by bus bar and flexible water-cooled furnace leads. If more than one furnace is installed, switches are provided for transferring power to the selected furnace, since only one furnace can be run from one power unit at any given time. A water-

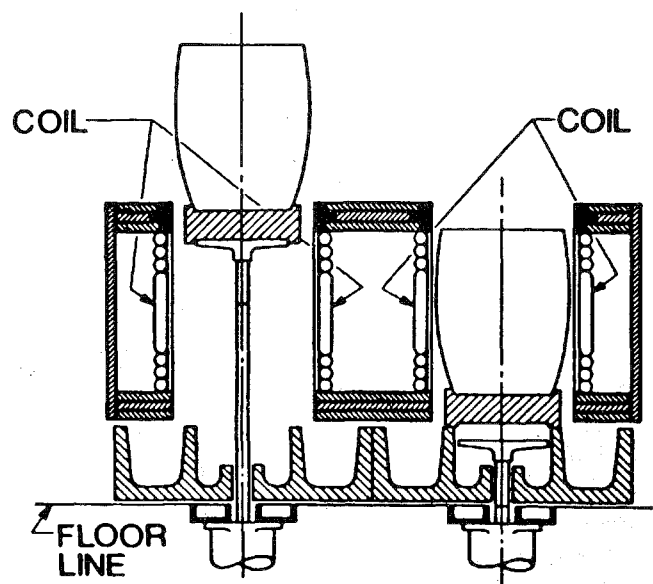


Fig. 4-5. Schematic of double pushout-type, coreless induction furnace (crucible in melting position in left-hand view).

cooling system circulates water through the electrical components (the furnace coils and the furnace leads), removing heat from those elements. The water is then cooled and recirculated continuously through the system. The waste heat in the cooling water may be recovered for space heating. Heat exchangers, however, can be expensive.

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, which is heated until the proper 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, because of electromagnetic currents, cause the molten metal to be stirred. This increases uniformity of both alloy composition and molten bath temperatures. Because of the rather vigorous stirring action, it is difficult to use any type of flux—and none is really necessary. Under most circumstances, gassing of the molten metal is unlikely because the atmosphere over the bath does not contain products of combustion (see Chapter 5). It is possible, however, to gas copper-base alloys in induction furnaces, especially if the water content of the ambient air is high, if the metal is excessively superheated, or if new crucibles or new linings are not thoroughly dry.

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 (no more than 85 db). Because there is no combustion, ventilation and space heating are under better control since makeup air is not needed to replace combustion air or air escaping up the hot stack as in the case of fuel-fired furnaces. 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.

Other types of coreless induction furnaces, such as line frequency (that is, 60-cycle) units are available. These furnaces are generally suitable only for ferrous melting and are widely used to substitute or supplement cupola melting.

Brass mills or large, high-production brass foundries, which use a single alloy and require a constant source of molten metal, use 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

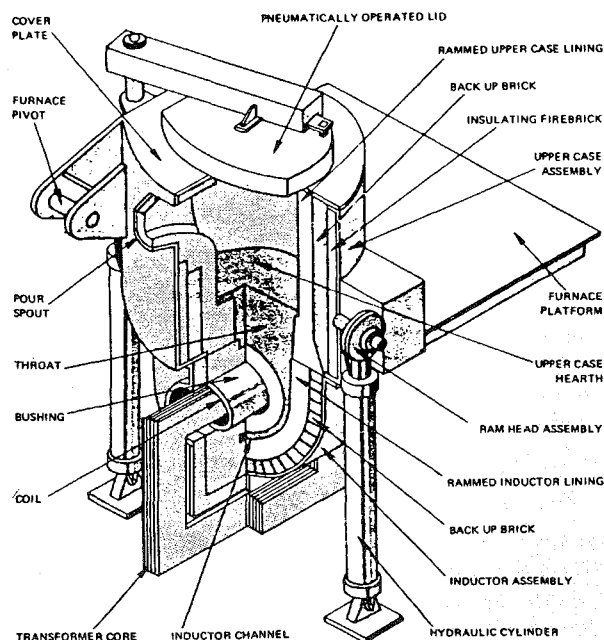


Fig. 4-6. A channel induction furnace is an attractive choice for melting a single copper-base alloy. Sectional view shows how inductor channel is joined to upper case.

located at the bottom of a cylindrical hearth. 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 shut-down. 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.

In view of its low cost, simplicity of operation, and ability to turn out good metal at high production rates, this furnace is best suited for continuous or long production runs with a single alloy. This type of furnace may be found in high-production, copper-base alloy foundries such as those which make castings for plumbing goods.

### Indirect-Arc Furnaces

The electric indirect-arc furnace, known as a "rocking-arc" furnace, enjoyed great popularity in production brass and bronze foundries before the advent of solid-state induction melting equipment. Its use has diminished in recent years.

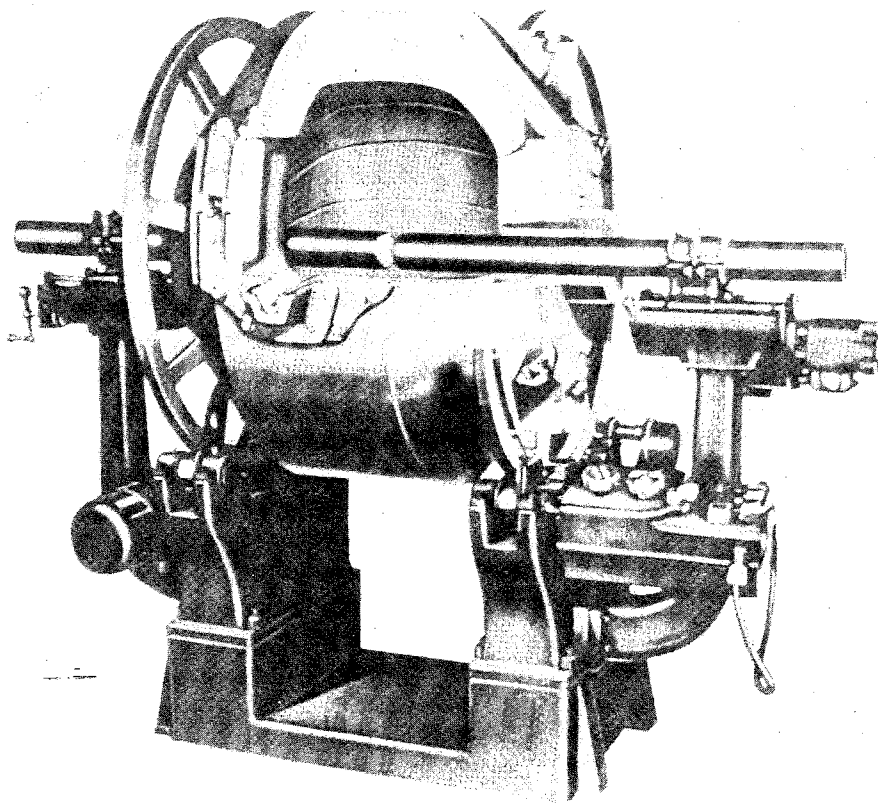
Rocking-arc furnaces (Fig. 4-7) consist of a refractory-lined steel shell which rests on power-driven rollers that rock the cylinder. One graphite electrode, supported by port blocks, enters the center of the shell from each end of the furnace.

Melting occurs when current from the secondary of a transformer passes through two electrodes, which strike an arc at the center of the melting chamber. Melting occurs both from the direct radiant heat of the arc and from heat absorbed from the radiant-heated lining. Rocking of the furnace helps transfer heat from the lining and also produces a more homogeneous melt.

Indirect-arc furnaces are generally noisy and may produce gassy metal unless air is allowed to flow through the electrode port to increase oxidation (which also increases electrode consumption). Indirect-arc furnaces are limited to melting batches of a single alloy, or alloys of similar compositions, since switching alloys may cause contamination from metal absorbed by the lining. Such furnaces handle borings efficiently and, if properly adjusted, provide good melting rates. Lining condition is an important factor in obtaining good productivity, and careful maintenance is essential.

### Resistance Furnaces

The newest type of electric melting furnace is based on very old electric heating technology involving passing a current through a material which can become 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 circuiting have resulted in new furnace designs which are claimed to be capable of melting copper-base alloys.



*Fig. 4-7. Cutaway drawing showing basic design and construction of indirect-arc (rocking) furnace.*

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 3000 F (1650 C) 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. Claims have been made, however, that resistance-furnace melting efficiency is higher than for fuel-fired or induction furnaces, that refractory life is excellent, that the furnace is non-polluting and does not require extra ventilation equipment, that it does not produce noise or smoke, and that oxidation losses are very small because the metal bath is not agitated during melting. 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 2000 lbs of brass or bronze (in a tilting-type furnace rated at 250 kw maximum input). The cost of resistance furnaces are about the same as for induction melting equipment; installation costs are comparable to or less than those for induction equipment.

## **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) the amount of metal production needed over a certain period of time (per shift, per day, and so on); 3) whether it is necessary to change quickly from one type of alloy melted to another; 4) whether production involves many molds of light-weight 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 tilter 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, 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 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 one manufacturer claims that its gas-fired tilter meets OSHA noise regulations. Most manufacturers of induction furnaces will warrant that their operating equipment will not exceed 85 db. Arc melting furnaces generate considerable noise that normally exceeds 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 which makes it necessary that furnace crews wear protective clothing.

Because, in induction-melting crucible furnaces, only the top of the metal bath is exposed, radiation losses are small and there are no exhaust gases to heat up 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.

### **Smoke and Fumes**

In gas or oil melting, since both flame and refractory temperatures are high and approximately 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 and lead both oxidize preferentially and create smoke and fume problems which require extensive furnace hooding and fume collection equipment.

Induction and resistance furnaces, while not fume-free, are considerably more so than are 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.

## **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 pound 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. Also, fuel consumption varies between foundries, depending on the equipment, melting practices, alloys, pouring temperatures, and shift lengths being used.

A very general comparison of melting-energy costs can be made from the following fuel consumption requirements, each based on melting one ton (2000 lbs) of alloy and raising it to its pouring temperature:

Gas-fired crucible: 5000 ft<sup>3</sup> natural gas @ 1000 Btu ft<sup>3</sup>

Oil-fired crucible: 35 gal fuel oil @ 180,000 Btu/gal

Electric induction crucible: 350 kwh

### **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 for the melting department. Also, 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.

### **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 fur-

naces 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 of 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 repairman 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 keep 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, 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 even build their own. 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

so as to become operator-proof. Although simple maintenance must be performed regularly, it requires no unusual 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. Installation costs can be as expensive as the equipment itself if 440-volt power must be made accessible to the foundry and the melting area, if water supply and drainage must be provided for, and if construction is required (such as below-floor excavations and concrete work).

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 non-ferrous foundry industry for most of its 6000-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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# Chapter 5

## 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 will focus primarily on the control of melt chemistry and dissolved gasses, other variables affecting melt quality are identified below along with the chapters which provide supplementary information on each.

1) *Furnace selection.* The type of furnace used influences melt quality control. Specific furnace types are discussed in Chapter 4. It should be noted that different liquid-metal processing procedures may be recommended depending upon the melting unit used.

2) *Fluidity.* The complexity of the casting and section size normally dictate the pouring temperature, as will be discussed in Chapter 6. However, higher pouring temperatures make chemistry and gas control more difficult to achieve.

3) *Mold materials.* Chapter 3 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."

4) *Gating.* Improper gating can result in gas pickup and porous castings. Recommended gating practice is discussed in Chapter 7.

5) *Solidification and shrinkage.* Since both gas porosity and shrinkage may occur in the portions of the casting which are the last to solidify, the defects are often indistinguishable. Chapter 8 discusses the solidification characteristics of the alloys.

6) *Mechanical properties.* Several chapters in this book, and specifically Chapter 17, deal with the mechanical properties of the 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.

All of the above topics will be discussed in this chapter only as they relate to melt control. The chapters cited will be helpful for a more complete understanding of these topics.

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 extremely difficult to control in everyday foundry 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

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 for use as input material.

a) *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 compound their own alloys from the raw materials, except for use in short-run specialty chemistries.

b) *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 at a later date.

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.

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.

c) *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.

*d) 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 how they are treated in melting. For examples, gates and risers from sand castings may not be completely clean of mold materials; turnings may be covered with cutting fluids; residual deoxidizers or impurities may be building up in the return materials. Each one of these can contribute to casting defects which can become more pronounced as the quantity of returns in the charge increases.

*e) 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 scrap castings. 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.

*a) 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 humid summer 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 produce 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 section on gases, the use of melt covers may show mixed results. Melt covers are used in attempt to exclude the atmosphere and thus reduce dross formation. Charcoal is one example of a melt cover; however, it cannot 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 application of melt covers or fluxes.

*b) Vapor losses.* Fortunately, the same techniques used for dross minimization will also reduce vapor losses. The most notable element loss in molten copper alloys takes place with 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 which contain zinc also contain lead in amounts which 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 Chapter 18.

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 are to 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 several chemical and physical principles which 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. Two important examples of the positive role of gases in copper alloys are their use in dispersing shrinkage and their use as degasifiers.

The purging of liquid metals with an inert gas is a potential method for removal of detrimental gases. An example would be a nitrogen purge of an aluminum bronze. This technique, as well as the use of other solid additions which produce inert gas at the liquid-metal temperatures, will be discussed in greater detail in a later section.

The use of gas for dispersal of shrinkage has been successful in producing discontinuous porosity in castings, which creates better pressure-tightness and surface quality.

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), which is why gas porosity is a problem in copper castings. During the solidification process, the solid rejects gas to the remaining liquid, due to the fact that hydrogen is less soluble in the solid state. Once the gas exhibits a pressure greater than the pressure of the surrounding atmosphere and metal head, a gas pore will be formed.

Since higher temperatures of the liquid result in higher gas solubility (Fig. 5-1), higher pouring temperatures produce 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  $H_2$ /100g. Dividing 3.5cc by 11.16cc gives 31 volume per-

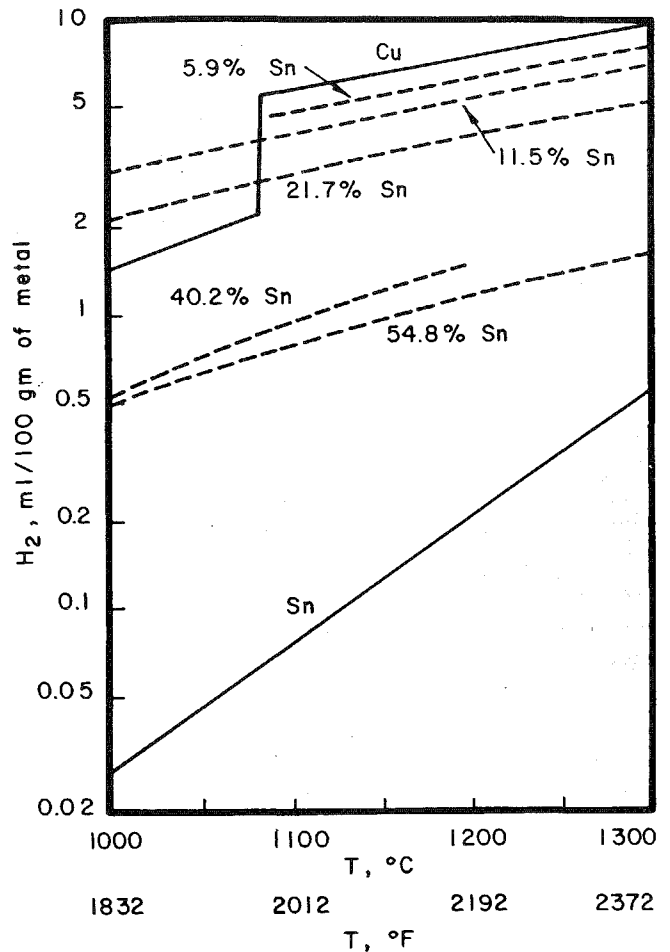


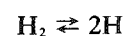
Fig. 5-1. The solubility of hydrogen at atmospheric pressure in pure copper, pure tin, and in copper-tin alloys.

cent of evolved hydrogen, which could easily result in porosity. Other units are used, 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 1.11cc/100g or 10 volume percent.

Furthermore, all of the gas contents are given at standard temperature and pressure (20°C 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, as follows.

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:

$$H \text{ (dissolved)} = K' \sqrt{pH_2} \text{ where } K' = \sqrt{K}$$

From Fig. 5-1, molten copper at 1083°C dissolves 5.5 cc/100g hydrogen when a pure hydrogen atmosphere is present.

Therefore:

$$5.5 \text{ cc/100g} = K' \sqrt{1 \text{ atm}}, \text{ or } K' = 5.5$$

Now, to be more realistic, assume we have a partial pressure of hydrogen of only 0.01 atm over the melt. 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.

It should be noted that Sievert's Law refers to equilibrium, a condition seldom achieved in casting. However, the concept of a reduction in partial pressure leading 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 greater 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. The interaction between dissolved gas species must also be considered; that is, the complex gases such as hydrogen-oxygen and carbon-oxygen must be studied.

### 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. During solidification, these dissolved gases combine to form molecular water vapor, thus creating gas porosity when the gas pressure exceeds 1 atm or 760 mm Hg.

This hydrogen-oxygen equilibrium interaction in pure copper at its melting point (1083°C) is shown in Fig. 5-2. 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:

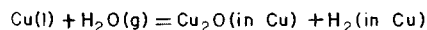
$$2 \text{ cc/100g} = 5.5 \sqrt{pH_2}, \text{ and } pH_2 = 0.132 \text{ atm}$$

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. 5-2 (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  $2 \times 10^{-5}$  wt% (0.00134 atm). In this case, 100 times less hydrogen (0.132 atm vs. 0.00134 atm) will cause gas porosity if oxygen is also present.

Although 0.39 wt% oxygen sounds high, it is possible to achieve this level even with low initial oxygen levels. The Cu-O phase diagram shown in Fig. 5-3 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).

The important point is that low hydrogen content can result in gas porosity when oxygen is also present. The enrichment of the liquid phase in both hydrogen and oxygen during solidification along with inadequate time for diffusion will only add 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.



$$[H] = 3.04 \times 10^{-7} \sqrt{PH_2O / [O]}, \text{ at } 1083^\circ\text{C}$$

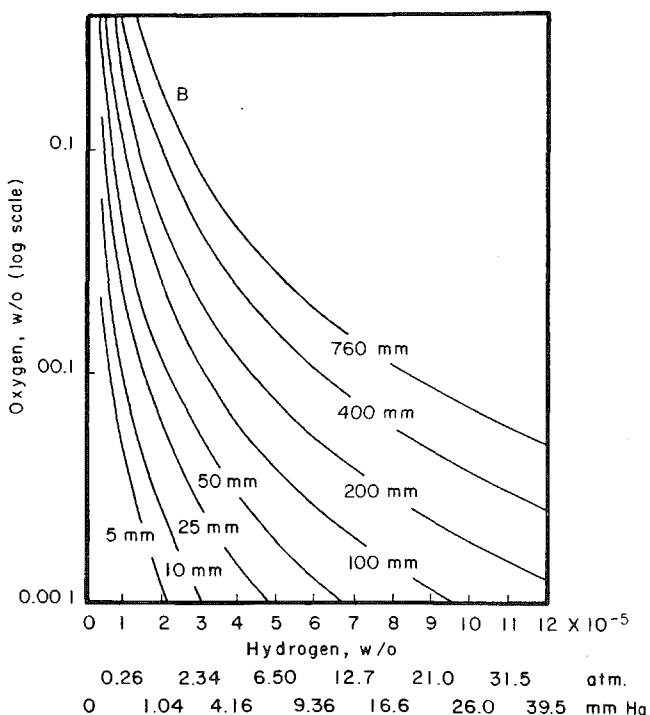


Fig. 5-2. Equilibrium of water vapor with molten copper at 1083°C (1481°F). Point B shows equilibrium between 0.39 wt% oxygen and  $2 \times 10^{-5}$  wt % hydrogen at 760 mm water vapor pressure.

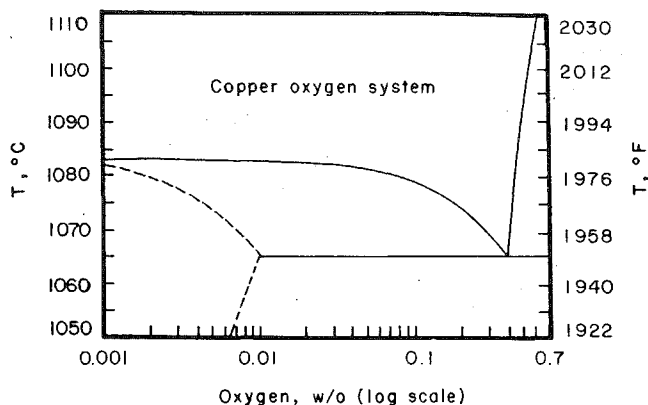


Fig. 5-3. Constitution diagram of the copper-oxygen system. The eutectic occurs at 0.39 wt% oxygen.

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 process. This is much less common today due to an increase in the use of electric melting. Low sulfur results in higher oxygen dissolved, while higher sulfur gives a lesser amount of oxygen dissolved. The evolved gas is  $\text{SO}_2$ .

With nickel-bearing copper alloys, carbon pickup occurs; the important equilibrium becomes carbon-oxygen rather than hydrogen-oxygen. The gas evolved upon solidification is  $\text{CO}$  rather than  $\text{H}_2\text{O}$ . Once 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.

#### Identification of Gas

Briefly, the gases most often found in porous copper-base alloys are  $\text{H}_2$ ,  $\text{H}_2\text{O}$ , and  $\text{CO}$ . The identification of these gases is important in order to determine the most

efficient degassing technique. Identification is also dependent upon the alloy family, as will be discussed later.

Although the heading of this section suggests merely that the type of gas be identified, an important basic question to ask is whether or not gas is really the cause of the defect in a casting. This is not always easy to determine 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. Under the microscope, the rough texture of dendrites can be identified.

Gas, on the other hand, 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 to gas.

Comparison of dendrites in defective areas poured with and without gassy metal will show subtle differences, as seen in Figs. 5-4 and 5-5. The presence of gas tends to blunt the somewhat sharp dendrites, possibly due to the pressure of the evolved gas.

This does not mean that gas will always be associated with shrinkage. For example, some wide-freezing-range copper alloys such as C83600 (85-5-5-5) tend to have interdendritic shrinkage 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.



Fig. 5-4. Close-up of a shrinkage cavity in a 1-in. chilled Y-block poured from degassed C95400 metal. Note the rough appearance characteristic of dendrites.



Fig. 5-5. Close-up of shrinkage from gassy C95400 alloy poured in a 1-in. chilled Y-block. In this case the cavity is smooth.

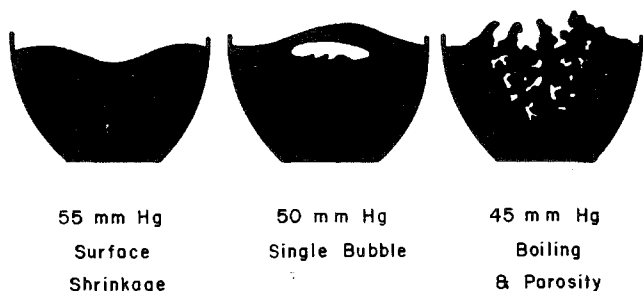


Fig. 5-6. These cut-away samples display the different responses of the same amount of gas dissolved in the liquid metal when exposed to different pressures in the test chamber of the reduced-pressure test.

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.

A simple solution to this defect identification problem is therefore not available. Although experience plays an important role, an absolute answer can be gained only with the aid of a reproducible gas test, as discussed below.

### Testing for Gas

There are several qualitative methods by which to estimate the gas content of wide-freezing-range, 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 these alloys tend to show relatively little localized shrinkage even when free of gas, AFS research was conducted<sup>1</sup> 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.

A more quantitative approach to measurement of the gas content of the metal was necessary, and research was therefore initiated in 1972. This work to develop another test was jointly sponsored by the International

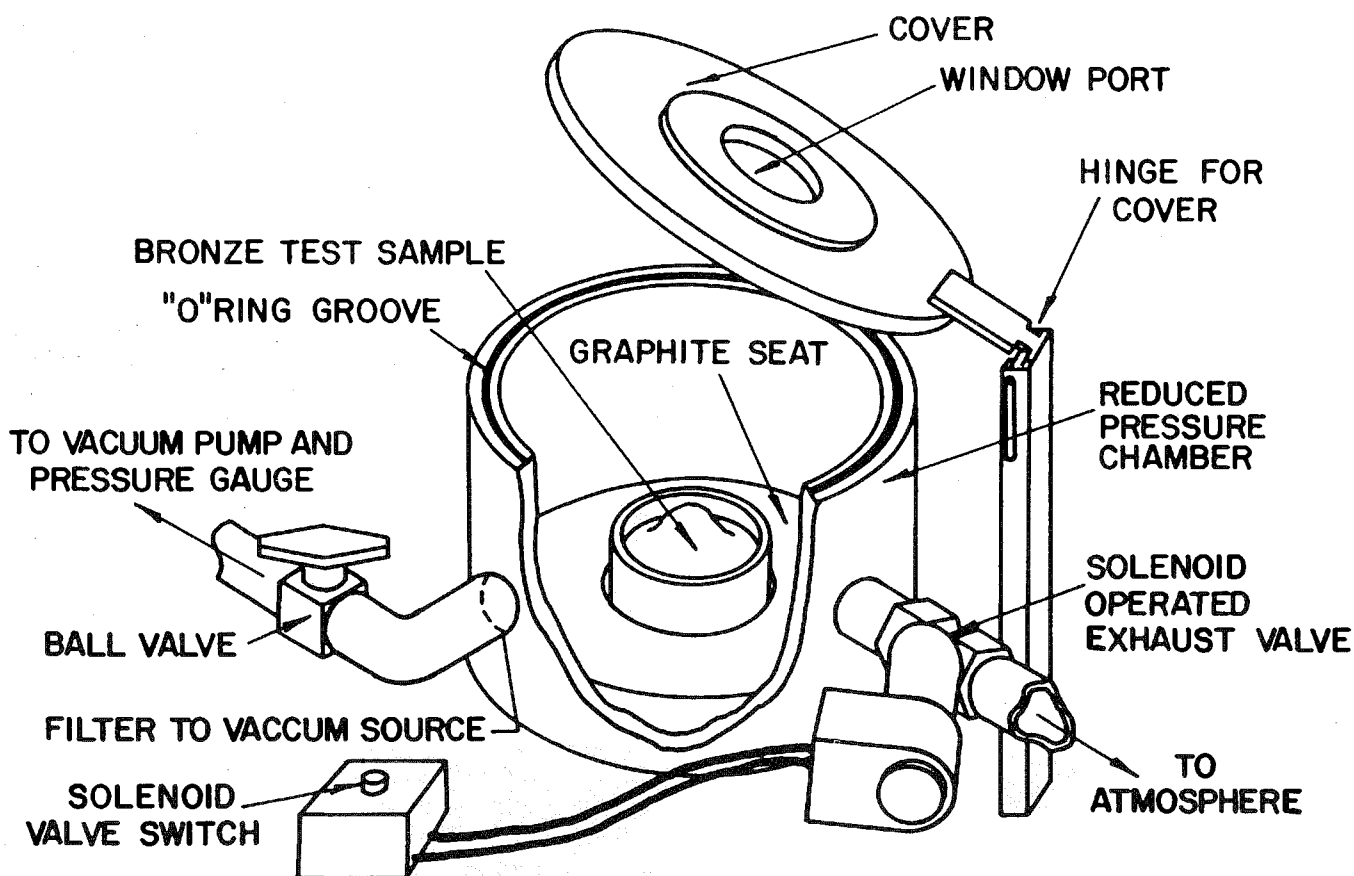


Fig. 5-7. The test chamber as used in the reduced-pressure test. The remainder of the apparatus is described in the literature.<sup>2,3</sup>

Table 5-1.  
Crucible and Seat Combinations for the Reduced-Pressure Test

| <u>Alloy Type</u>                    | <u>Crucible</u>        | <u>Seat (Graphite)</u>                  | <u>Time Before Exposure to Reduced Pressure</u> |
|--------------------------------------|------------------------|-----------------------------------------|-------------------------------------------------|
| Pure Copper<br>(ex. C81100)          | Preheated<br>Porcelain | Flat with small<br>depression           | 15-30 Sec.                                      |
| Short Freezing<br>Range (ex. C95400) | Preheated<br>Porcelain | Loose fitting to top<br>of crucible lip | 30-45 Sec                                       |
| Wide Freezing Range<br>(ex. C83600)  | Steel                  | Tight fitting to top<br>of crucible lip | 5-10 Sec                                        |

Copper Research Association and AFS. This effort resulted in the development of the reduced-pressure test.

### Reduced-Pressure Test

The aluminum industry has used a gas test—the Straube-Pfeiffer test—that 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 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 chamber used for the tests is diagrammed in Fig. 5-7. 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.<sup>2,3</sup>

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 of this are shown in Fig. 5-6.

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 (see Fig. 5-7).

There are essentially three combinations of crucibles

and seats that have proven successful (Table 5-1). 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. 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 inhibit affecting a tight seat.

Most copper alloys can be successfully tested by using one of the described methods. 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 alloy sensitivity to gases, and degassing effectiveness using the reduced-pressure test, will be discussed in later sections.

### Quantitative Analysis Methods

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 solidify-

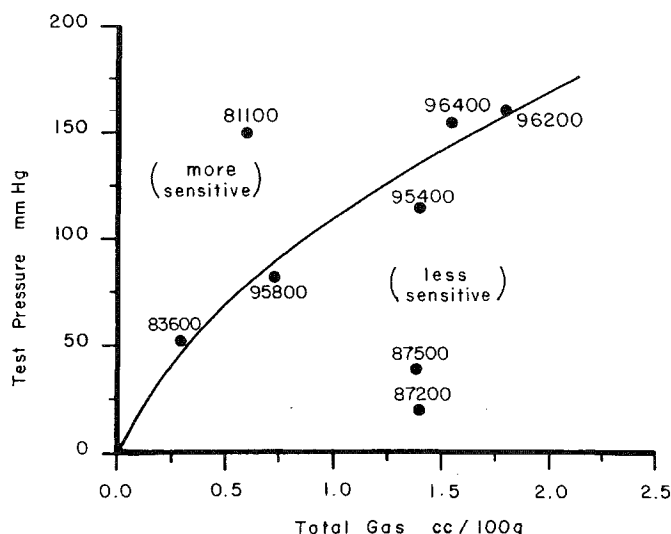


Fig. 5-8. The sensitivity of the reduced-pressure test shows good correlation with the total gas content of the melt. The data are for saturation in a gas furnace atmosphere at 300F superheat. The text discusses the anomalies with copper (C81100) and the silicon-bearing alloys (C87200, 87500).

ing alloys are very expensive. Although these analyses are important for the proper selection of degassing techniques, their interpretation is difficult. Therefore, the average foundry finds the reduced-pressure test more useful with respect to both cost and promptness of results.

The literature can provide specific numerical values for the quantities of gas species contained in alloys.<sup>4-7</sup> Table 5-2 summarizes some of the more important results; however, a few general comments are also necessary.

Water vapor is the most common gas evolved from solidifying copper alloys. The hydrogen combines with the available oxygen to form water vapor until the dissolved oxygen is depleted; 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.

Melting is commonly practiced under an oxidizing atmosphere in order to obtain higher dissolved oxygen and, hence, lower hydrogen (see Fig. 5-2). Residual oxygen is easily removed by standard deoxidation techniques.

The presence of nickel in copper-base alloys introduces CO gas when melting is done in a graphite crucible or with carbonaceous covers. Water vapor may also exist at low nickel contents. This provides the three gas species, CO, H<sub>2</sub>O and H<sub>2</sub>.

Although the identification of gas type is important, the total gas content and the sensitivity of the reduced-pressure test as a measure of total gas content minimize the necessity for precise gas analysis (Fig. 5-8). The correlation between total gas and reduced pressure is very good except in the case of C81100, 87200 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 is the standard surface-bubble test.

The silicon-bearing copper alloys C87200 and 87500 have been much discussed by foundrymen in regard to their gassing tendencies. Although Fig. 5-8 indicates that these alloys have a high gas content, with H<sub>2</sub> levels being higher than H<sub>2</sub>O levels, the reduced-pressure test is not very sensitive to the presence of these gases. There are possibly two reasons 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.

### Gas Removal

The removal of dissolved gases from molten copper alloys is accomplished by either mechanical or chemical methods. Mechanical methods depend upon the principle that the melt attempts to come to equilibrium with the surrounding atmosphere. For example, a melt's pickup of gas from a gas-fired furnace is due to the fact that the atmosphere is rich in combustion byproducts, essentially H<sub>2</sub>O, CO<sub>2</sub>, 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.

A second technique is vacuum degassing. This method is expensive, however, and requires a secondary treatment station.<sup>8</sup> The reduced-pressure test is a miniature version of a vacuum-degassing process.

The most common method for mechanical removal of gas is purging with a second gas. The introduction of a gas bubble beneath the melt surface creates an artificial atmosphere with which 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. An example of purging with an inert gas (dry nitrogen) in aluminum bronze (C95400) is shown in Fig. 5-9.

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

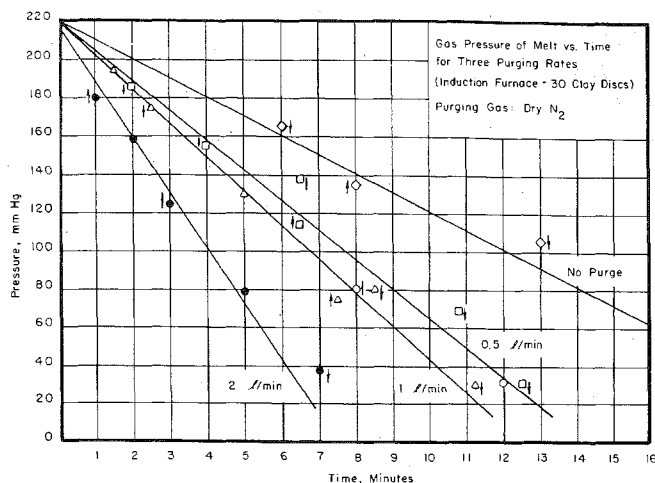


Fig. 5-9. The effect of nitrogen flow rate during purging on the residual gas pressure of a C95400 melt. At a constant temperature of 2250F, the magnetic stirring of the 100-lb melt reduces the gas on a low-humidity day even in the absence of purging.

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.

The effects of various purging gases on aluminum bronze is shown in Fig. 5-10. 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. If the purging time is too long, aluminum will be oxidized and abnormally large quantities of dross will be generated.

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. 5-2.

Purging can also be accomplished with solid addition agents that form gas bubbles at liquid-metal temperatures. One commercial product consists of a briquette form of polytetrafluoroethylene (Teflon) which produces a purging gas when plunged beneath the metal surface.

Another useful method for high-zinc alloys is to overheat the melt, thereby vaporizing some zinc (flare) and purging the bath of dissolved gas. This technique is shown in Fig. 5-11 for a melt produced in a gas furnace. The saturated reduced-pressure value represents equilibrium between the melt and the water-containing combustion byproducts of the gas furnace. This saturation

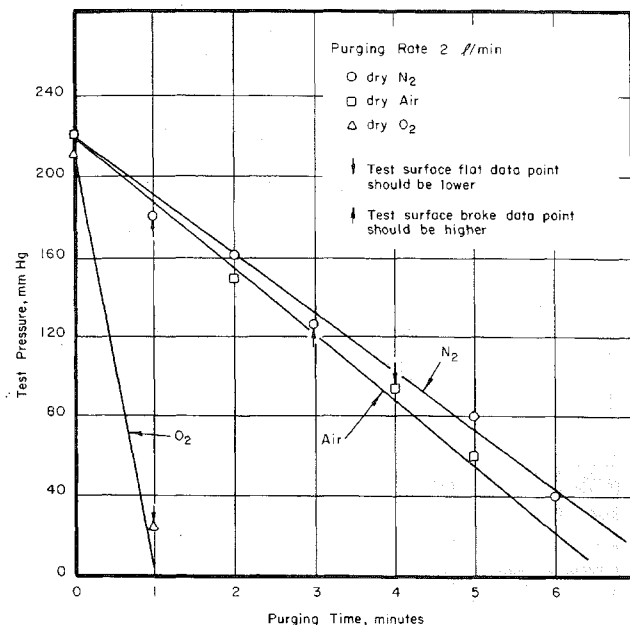


Fig. 5-10. The effects of different purging gases on the rate of gas removal in alloy C95400 (aluminum bronze) at 2250F in an induction furnace.

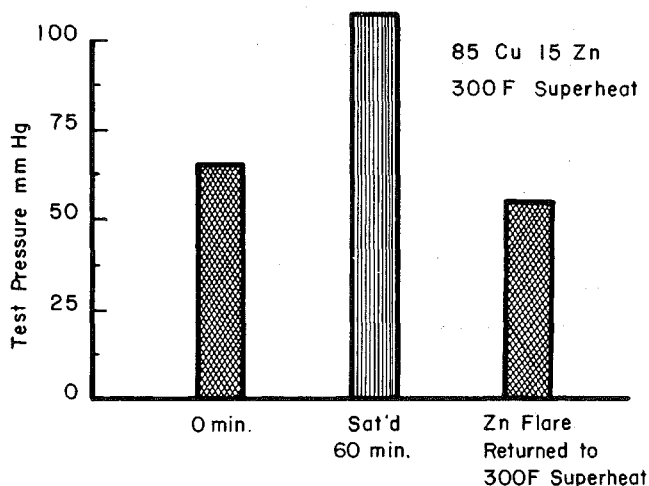


Fig. 5-11. A useful technique for reducing the gas content of zinc-bearing alloys is to overheat the metal and purge with the zinc vapors. The saturated value represents holding the gas-furnace-melted metal for 60 minutes at temperature.

value, which is reached in 60 minutes, indicates the disadvantage of holding the metal for an extended period of time at temperature.

Finally, an often overlooked technique is to allow gassy metal to solidify, thereby ejecting the gas. Remelting of this alloy will result in a lower dissolved-gas content as shown for 90Cu-10Ni alloy in Fig. 5-12. Again, high gas contents are achieved with a 60-minute hold time in a gas furnace. Solidification, remelting, and superheating to the desired 300F level produces a decrease in the gas level. Extended holding time would return the metal to undesirably high dissolved-gas levels.

*Chemical methods.* Here the objective is to tie up the dissolved gas chemically by the addition of an agent

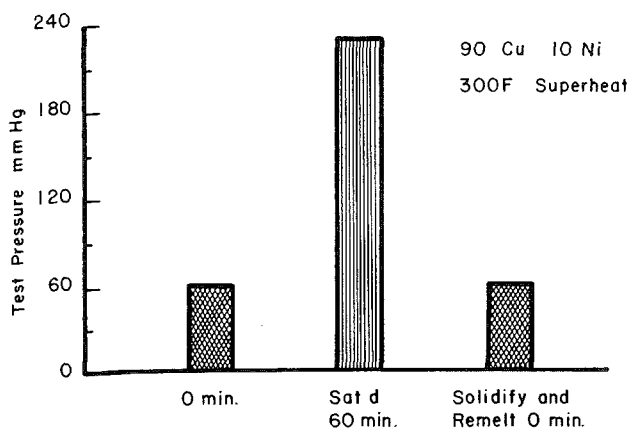


Fig. 5-12. A high gas content can be reduced by solidification and remelting of the alloy. The 60-minute saturation is the maximum melt gas pressure from the atmosphere of a gas-fired furnace.

which has a greater affinity for the gas than does the molten metal. Two examples will serve to show this effect.

In red brass, C83600, it is common practice to add phos-copper to deoxidize the melt. Figure 5-13 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. The absolute addition requirement is not fixed, since each foundry must determine the maximum amount of melt gas that can be tolerated and still allow production of marketable castings. The amount of deoxidizer added depends upon a number of variables which will be discussed later. However, unnecessary overadditions will lead to higher costs, potential problems with remelting of stock, and casting surface roughness.

When red brasses such as C83600 are deoxidized with P-Cu, 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 occur due to solubility change, as shown in Fig. 5-1. The only way to avoid high hydrogen levels is to maintain oxidizing conditions during melting.

In aluminum bronzes such as C95400, research has shown that significant levels of both hydrogen and oxygen may be present simultaneously. In such cases, 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. 5-14 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.

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 resulting from low-melting eutectics and from reaction between the phosphorus oxides and the sand-bonding agents.

Secondly, 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.

The importance of controlling residual phosphorus cannot be overemphasized since residual phosphorus is a major source of gassy castings. It is unfortunate that so few understand or pay close attention to their deoxidation practices. Most tend to make arbitrary additions of 15% 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. This results in fluctuating or persistent levels of scrap due to gassy casting conditions.

Each foundry should make a systematic effort to determine the maximum level of residual phosphorus which can be tolerated, commensurate with the production of sound, leak-free castings without visible porosity. 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.

Insufficient levels of residual phosphorus can also be troublesome, since the deoxidized metal is subject to re-oxidation 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.

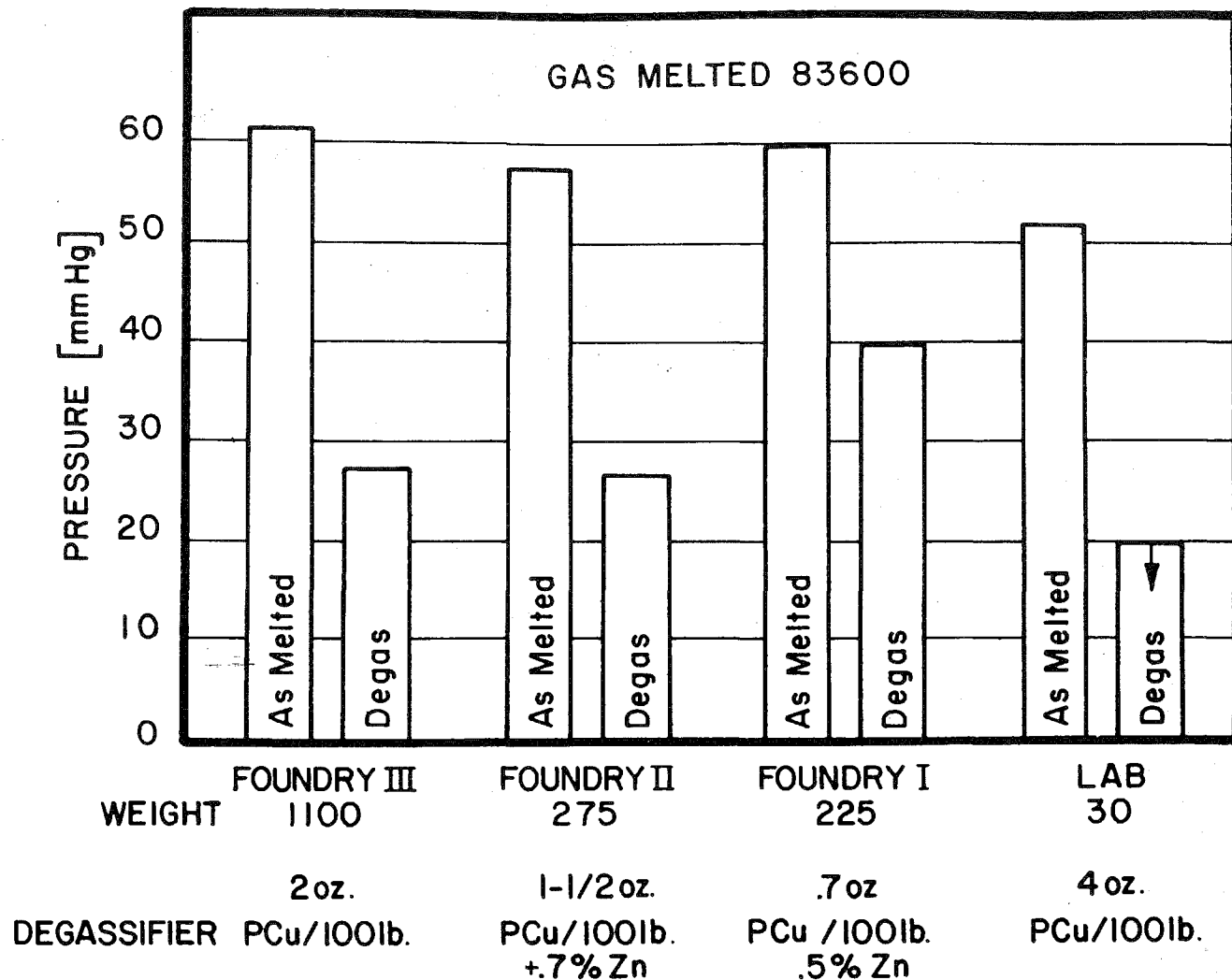


Fig. 5-13. The effect of quantity of phosphorus-copper (15% P) and zinc additions on the gas content of C83600 (red brass). The individual commercial foundries and laboratory data in the as-melted condition compare quite well.

The fact that residual phosphorus levels will vary may explain erratic losses due to gassy castings. 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 thicknesses 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.

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 is discussed in the following section, suggests successful deoxidation or degassing procedures for a number of commercial copper-base alloys.

#### Casting Variables Affecting Gas Content

Variables which may affect the gas content of castings are: alloy family, charge materials used, furnace type, temperature, 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 50 mm 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 so as to produce better quality castings.

*Alloy sensitivity.* Table 5-3 summarizes the gas content and the experimental deoxidation or degassing procedures used for several of the more common copper casting alloys. The anticipated gas species were summarized in Table 5-2. (The mechanical properties obtained for the alloys in their gassed and degassed conditions will be presented in the following section.)

The type of crucible used is the same as that which was used in the reduced-pressure test. All heats consisted of 30 lbs secondary ingot melted in a gas furnace. The saturation pressure and time provide an index of the sensitivity to gas pick-up.

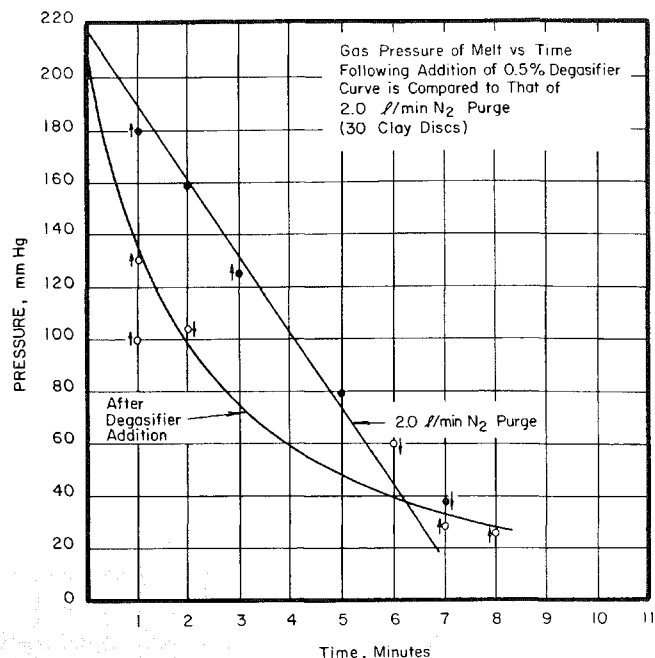


Fig. 5-14. A comparison of a high-nitrogen purging rate with a commercial degasifier. The metal is alloy C95400 (aluminum bronze) at 2250F. Note that the degasifier does not produce the minimum gas level immediately.

A high saturation value need not cause concern especially if it takes a long period of time 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 nor-

mally 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. For each alloy, effective deoxidation and/or degassing procedures were employed.

**Charge materials.** Aside from the question of high residual phosphorus, the use of returns should not be problematic since the dissolved gas is removed by solidification (see Fig. 5-12). However, this will be true only if the metal is not held for a long period of time upon remelting.

Figure 5-15 shows that a moderate addition of P-Cu to a charge consisting of 100% gating material is not as effective in removing gas from C83600 as it is when the charge is comprised of 100% ingot. In this example, the gates had not been blast-cleaned, and the desired oxidizing melting atmosphere may not have been effective due to heavy dross cover from dirty returns. 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 contained a high residual phosphorus level, this also may have prevented oxidation of the melt which resulted in higher hydrogen.

**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. 5-2), an oxidizing condition will help to minimize hydrogen. The dissolved oxygen is, generally, more readily removed. Figure 5-15 shows that a reducing atmosphere results in higher gas levels after deoxidation;

#### Summary of Gases Found in Copper-Base Alloys

| Alloy Family                | Gases Present                         | Remarks                                                                                                                                                                                                |
|-----------------------------|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| a) Pure Copper              | H <sub>2</sub> O, H <sub>2</sub>      | Approximate H <sub>2</sub> O/H <sub>2</sub> ratio of 1:0. Higher purity increases the H <sub>2</sub> O level and lowers H <sub>2</sub> .                                                               |
| b) Cu-Sn-Pb-Zn Alloys       | H <sub>2</sub> O, H <sub>2</sub>      | Pb does not effect the gases present. Increased Sn lowers the total gas. Increased Zn increases the H <sub>2</sub> , with a loss in H <sub>2</sub> O.                                                  |
| c) Aluminum Bronze          | H <sub>2</sub> O, H <sub>2</sub> , CO | The presence of 5 wt.% Ni in C95800 causes CO to occur rather than H <sub>2</sub> O. Lower Al leads to higher total gas.                                                                               |
| d) Silicon Brass and Bronze | H <sub>2</sub> O, H <sub>2</sub>      | Approximate H <sub>2</sub> O/H <sub>2</sub> ratio of 0:5. Increased Zn decreases the H <sub>2</sub> and increases H <sub>2</sub> O. (This is opposite to the effect when Sn is present as in b above.) |
| e) Cupronickels             | H <sub>2</sub> O, H <sub>2</sub> , CO | All three species present up to 4 wt.% Ni, beyond which only CO and H <sub>2</sub> are present. H <sub>2</sub> increases with Ni to 10 wt.% Ni. H <sub>2</sub> is decreased at 30 wt% Ni.              |

this is consistent with the inability of P-Cu to remove hydrogen.

Melting in an induction furnace, because of its magnetic stirring action, will result in lower gas levels (Fig. 5-16). However, after treatment with adequate amounts of P-Cu, the final gas content of the C83600 reaches the same level in both the induction and the gas-melted alloy. It is only when the melt is exposed to the gas combustion by-products for an extended period of time that this method 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 causes carbon to go into solution.<sup>9</sup> At higher carbon levels, the oxygen is low; at lower carbon levels the oxygen is high. Therefore, the carbon level of the furnace lining material must be considered when melting these alloys.

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 H<sub>2</sub>. This is important since degassing procedures must be able to remove both oxygen and hydrogen.

**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.

**Melt covers.** Melt covers are intended to control the atmosphere at the melt surface and to protect the melt from changing its characteristics. Several examples will serve to explain why the use of melt covers has both positive and negative aspects.

Table 5-3.  
Gas Content of Copper Alloys After Melting and After Degassing

| CDA No. | TYPE ALLOY             | TYPE CRUCIBLE | SATURATION PRESSURE (mmHg) | TIME REQ'D (Hours) | METAL TEMP., °F | DEOXIDATION METHOD     | PRESSURE AFTER DEGASSING |
|---------|------------------------|---------------|----------------------------|--------------------|-----------------|------------------------|--------------------------|
| 81100   | Cu                     | Porc.         | 150                        | 1.75               | 2300            | 6 oz. P-Cu per 100 lb. | <23                      |
| 81500   | 1 Cr                   | Porc.         | 57                         | 2.00               | 2300            | As Melted              | <23                      |
| 82500   | 2 Be                   | Steel         | 240                        | 1.50               | 2100            | N <sub>2</sub> Purge   | <23                      |
| 86300   | 25 Zn.                 | Porc.         | 85                         | 1.50               | 1900*           | Flared                 | 40                       |
| 86500   | 6Al, 3Mn<br>40Zn, 1 Al | Porc.         | 100                        | 1.00               | 1820*           | Flared                 | 55                       |
|         | <b>Sn Pb Zn</b>        |               |                            |                    |                 | 6 oz P-Cu/100 lb.      |                          |
| 83300   | 4 6 7                  | Steel         | 57                         | 1.00               | 2200            | "                      | <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            | —                      | —                        |
|         | <b>Al Fe Ni</b>        |               |                            |                    |                 | N <sub>2</sub> Purge   |                          |
| 95200   | 9 3 —                  | Porc.         | 120                        | 2.00               | 2250            | "                      | <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. #77½%            | <23                      |
|         | <b>Ni Fe Co</b>        |               |                            |                    |                 | Prop. #77½%**          |                          |
| 96200   | 10 1.5 1               | Porc.         | 160                        | 1.00               | 2450            | "                      | 30                       |
| 96400   | 30 1 1                 | Porc.         | 155                        | 1.00               | 2500            | "                      | 30                       |
|         | <b>Sn Pb Ni</b>        |               |                            |                    |                 | Prop. #77½%**          |                          |
| 97600   | 4 4 20                 | Steel         | 115                        | 1.50               | 2400            | "                      | <23                      |
|         | <b>Al Ni Co</b>        |               |                            |                    |                 | Prop. #77½%**          |                          |
| 99300   | 11 15 1.5              | Steel         | 76                         | 2.00               | 2300            | "                      | <23                      |
|         | <b>Si Zn</b>           |               |                            |                    |                 | None                   |                          |
| 87200   | 4 4                    | Steel         | 22                         | 2.00               | 2100            | As Melted              | <23                      |
| 87500   | 4 14                   | Porc.         | 40                         | 1.00               | 2000            | "                      | 23                       |

\*Lower temperatures because of zinc flare

\*\*Melted under charcoal; all others melted without covers

### FIELD TEST DATA (Foundry 1)

ALLOY CDA83600 85%Cu-5%Sn-5%Pb-5% Zn

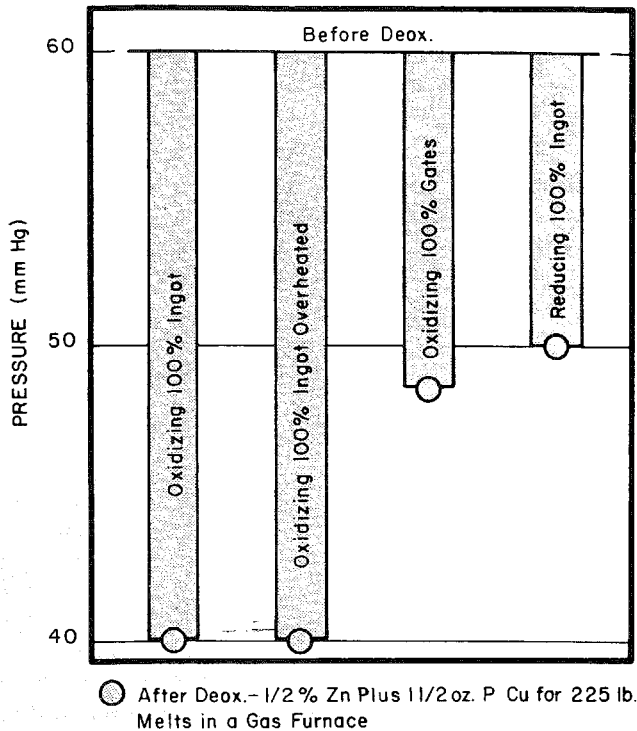


Fig. 5-15. The effect of gas melting-furnace atmosphere, type of charge, and deoxidation effectiveness on the dissolved gas content of alloy C83600. The detrimental effects of a reducing atmosphere and use of 100% revert is evident.

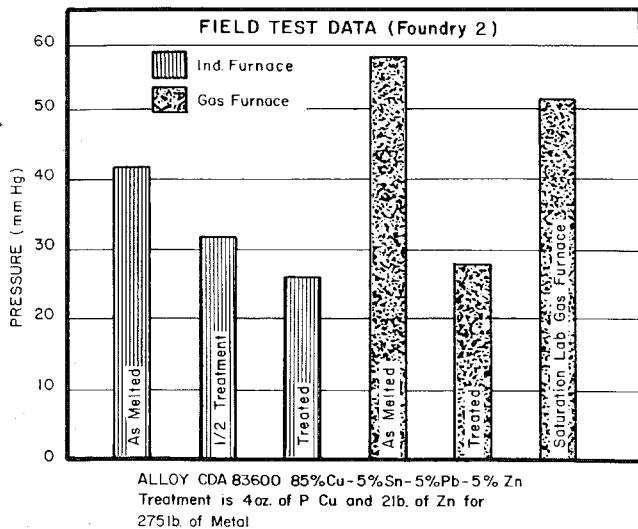


Fig. 5-16. The relationship of dissolved gas with melting furnace and deoxidation treatment for alloy 83600. The deoxidation is more efficient for the gas-melted metal (more dissolved gas removed) although the final gas content is not quite as low as for the induction-melted material.

### Example 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 determined 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.

### Example 2

Secondary ingot is induction-melted, and a charcoal cover is added immediately. Again, gassy metal is observed. Careful examination indicates that the charcoal was too green; hence, moisture was picked up by the melt. Gas also can be introduced by a carbon product that picked up moisture during outdoor storage.

### Example 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.** Mold materials can act in combination with metal to produce gas defects in castings. As an example, consider a 1-inch thick plate, 4 in. x 5 in. cross-section, with a 2 1/2 in. dia side-riser. The plate is cast of aluminum bronze (C95400). Pouring highly gassed metal with good directional solidification from chills on the three sides produces a density of 7.16 g/cc. This low value is an indication of the presence of gas in the casting. Table 5-4 summarizes the results from other combinations of mold materials and metal gas levels.<sup>10</sup> The following conclusions can be made:

- The use of chills produces directional solidification, which is intended to sweep some of the gas out of the casting.
- Chills are most effective when the mold material contains low gas (compare dry sand to green sand).
- Degassed metal shows little or no porosity for a wide variety of mold materials.
- Core sand (oil-bonded) adds more gas to the metal than does dry sand.
- Sodium silicate and alkyd-bonded sands add less gas to the metal than does dry sand.

In summary, 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

Table 5-4.  
Density Measurements of 5" x 4" x 1" C 95400 Castings

| Condition                                                            | Mold Material                  | Density |
|----------------------------------------------------------------------|--------------------------------|---------|
| Highly gassed metal;<br>chilled on three sides                       | Dry sand                       | 7.16    |
| Highly gassed metal;<br>chilled on three sides<br>and bottom         | Dry sand                       | 7.41    |
|                                                                      | Core sand (oil-bond)           | 7.28    |
|                                                                      | 4% H <sub>2</sub> O Green sand | 7.18    |
|                                                                      | 6% H <sub>2</sub> O Green sand | 7.12    |
| N <sub>2</sub> purged metal;<br>chilled on three sides<br>and bottom | Dry sand                       | 7.47    |
|                                                                      | Core sand (oil-bond)           | 7.46    |
|                                                                      | 4% H <sub>2</sub> O Green sand | 7.47    |
|                                                                      | 6% H <sub>2</sub> O Green sand | 7.47    |
| Lightly gassed metal;<br>chilled on one side                         | Sodium silicate                | 7.44    |
|                                                                      | Alkyd resin                    | 7.42    |
|                                                                      | Dry sand                       | 7.32    |

NOTE: Dry sand is water-bentonite bonded, then dried overnight at 375F.

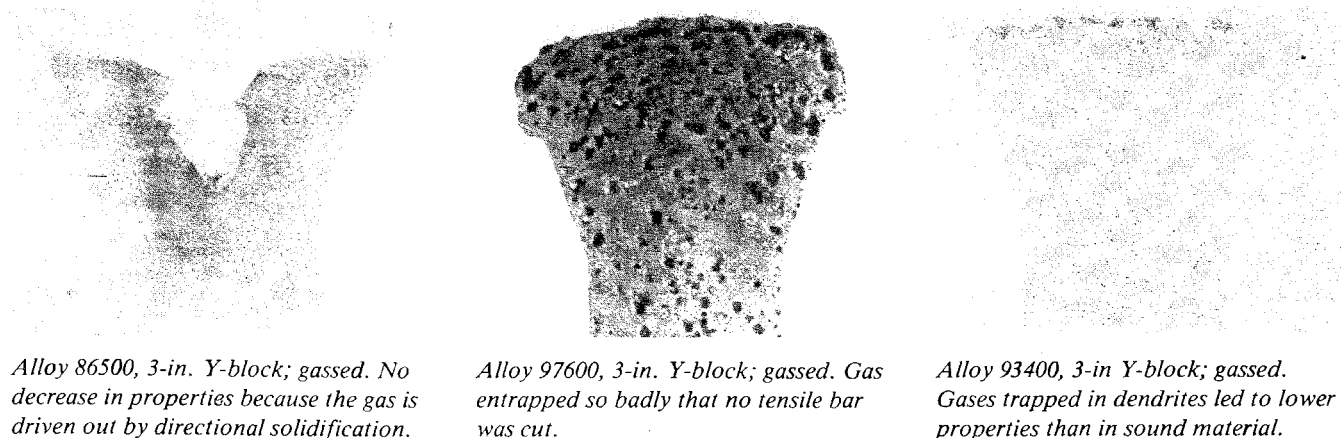


Fig. 5-17. Examples of progressive solidification in Y-blocks of three different alloys, showing the relation between gas retention and the degree of dendrite formation during freezing.

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 (as discussed in Chapter 7) becomes quite significant when dealing with borderline control in metal-gas equilibrium and with gas-producing agents in the mold material.

**Solidification rate.** The prior discussion of chills and their effectiveness in gas removal (Table 5-4) points out the significance of solidification rate, or thermal gradient control. The ease of pushing gas out is highly dependent upon the alloy system, due to the natural variation in dendrite formation among the alloys. In this sense, the problem is similar to that of feeding-distance control presented in Chapter 8. This concept is easily seen in Fig. 5-17 where large 3-in. Y-blocks provide normal, progressive solidification from the bottom

up to the riser. The three different alloys shown represent varying tendencies toward dendrite formation. The more extensive the dendrites, the more difficult it becomes to remove gas.

Although porosity will affect mechanical properties, it should be pointed out that the presence of some gas is useful in dispersing shrinkage. 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.

### Gas and Mechanical Properties

As-cast mechanical properties are dependent upon section size. As an example, consider the experimental data for aluminum bronze C95400 shown in Figs. 5-18 and 5-19. Both gassed and degassed tensile sample data are shown.

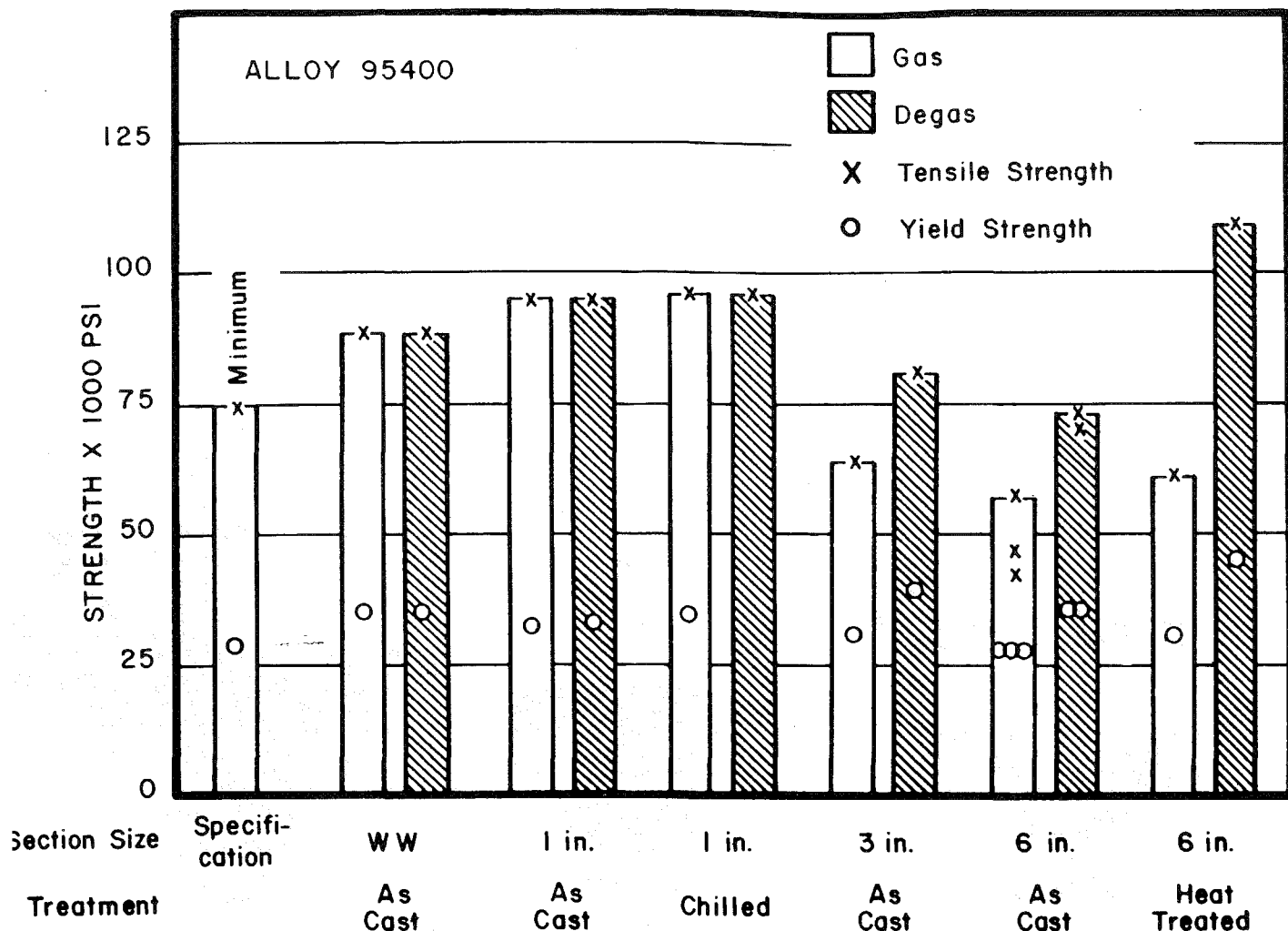


Fig. 5-18. The effect of section size on the tensile strength and yield strength of C95400 alloy when in the gassed and degassed conditions. (WW is standard Web-Webbert test bar while other sections are from the bottom of Y-blocks.)

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. section, the yields and tensile strengths are higher for the degassed metal (Fig. 5-18). In Fig. 5-19, the elongations of the degassed bars exhibit 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-in. 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 81100, 81500, 86300, and 86500, 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 90300, 92200, 92700, 93200, and 93700, 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,

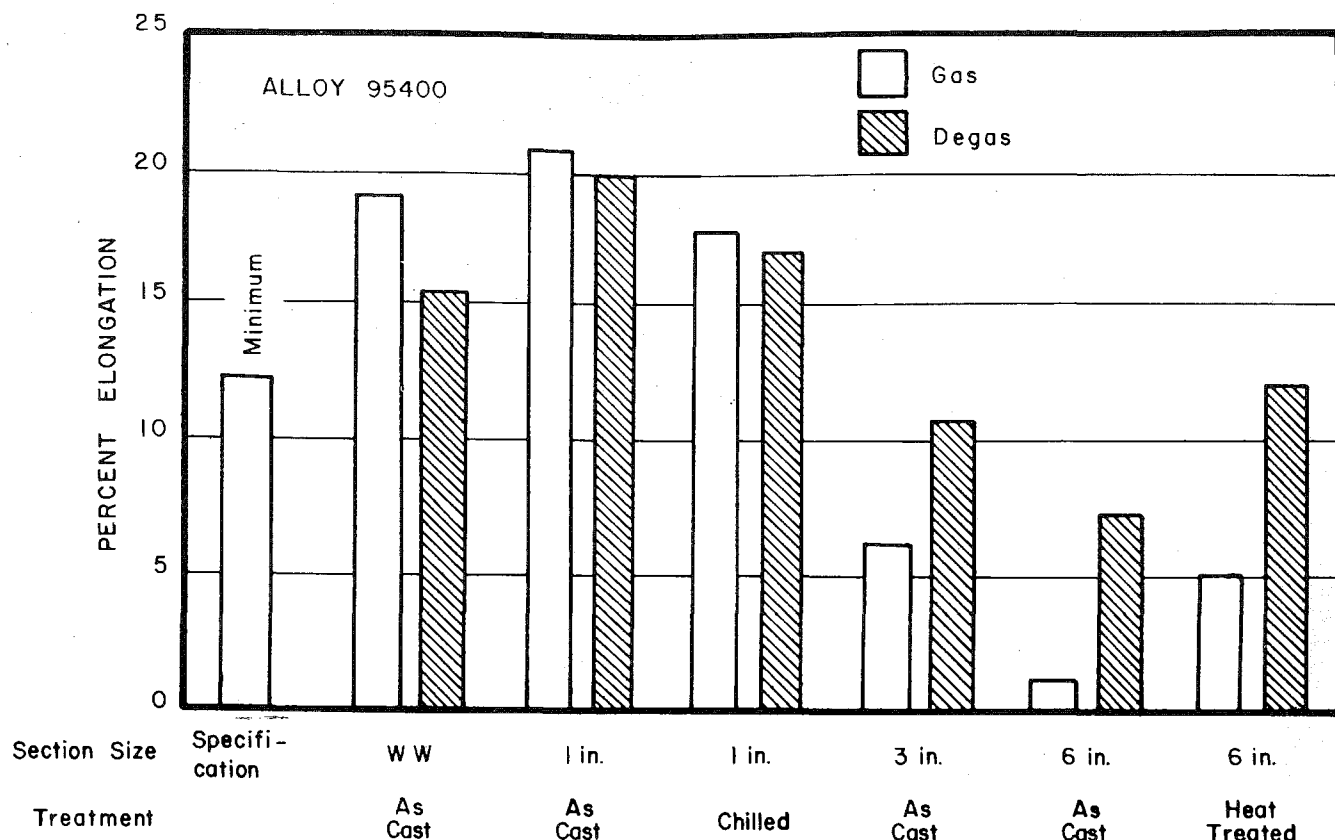


Fig. 5-19. Elongation of C95400 alloy as related to section size and gas content. The appearance of double bars indicates duplicate tests. (WW - Web Webbert; others are from Y-blocks.)

the properties of metal in the gassed condition are lower and the extent of property degradation varies with the alloy system.

## SUMMARY

Gas removal is an important factor in the production of castings. 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. It should be 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: Contain high water vapor levels in the products of combustion in contact with the melt, hence causing a strong tendency for gas pickup.

Induction: Furnace atmosphere (shop air) is generally low in water vapor content and high in oxygen; there-

fore, 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.

*Table 5-5.*  
*Mechanical Properties of 3-in. Y-Blocks*  
*(Gassed-Unchilled; Degassed-Chilled)*

| Alloy No. | Composition |           |           | Specification* |             |          | Degassed    |             |          | Gassed      |             |          |
|-----------|-------------|-----------|-----------|----------------|-------------|----------|-------------|-------------|----------|-------------|-------------|----------|
|           |             |           |           | Y.S.<br>ksi    | T.S.<br>ksi | el.<br>% | Y.S.<br>ksi | T.S.<br>ksi | el.<br>% | Y.S.<br>ksi | T.S.<br>ksi | el.<br>% |
| 81100     | Cu          |           |           | 6.5            | 19          | 20       |             |             |          |             |             |          |
| 81500     | Cr Cu       |           |           | —Not as Cast—  |             |          | 10          | 26          | 20       | 9           | 24          | 27       |
| 86300     | Cu Zn       |           |           | 60.0           | 110         | 12       | 15          | 31          | 39       | 14          | 32          | 33       |
| 86500     | Cu Zn       |           |           | 25.0           | 65          | 20       | 66          | 110         | 19       | 66          | 107         | 15       |
|           |             |           |           |                |             |          | 26          | 66          | 47       | 30          | 72          | 29       |
|           | <b>Sn</b>   | <b>Pb</b> | <b>Zn</b> |                |             |          |             |             |          |             |             |          |
| 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        | 42.0        | 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        | 22.0        | 45.3        | 35       | 16.6        | 21.1        | 6        |
|           | <b>Al</b>   | <b>Fe</b> | <b>Ni</b> |                |             |          |             |             |          |             |             |          |
| 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       |
|           | <b>Ni</b>   | <b>Fe</b> | <b>Cb</b> |                |             |          |             |             |          |             |             |          |
| 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       |
|           | <b>Sn</b>   | <b>Pb</b> | <b>Ni</b> |                |             |          |             |             |          |             |             |          |
| 97600     | 4           | 4         | 20        | 17             | 30          | 8        | 55.3        | 67.0        | 5        | Large holes |             |          |
|           | <b>Al</b>   | <b>Ni</b> | <b>Co</b> |                |             |          |             |             |          |             |             |          |
| 99300     | 11          | 15        | 1.5       | 55*            | 95*         | 2*       | 47.0        | 83.3        | 5        | 49.6        | 67.1        | 3        |
|           | <b>Si</b>   | <b>Zn</b> |           |                |             |          |             |             |          |             |             |          |
| 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/m<sup>2</sup>: 1 ksi = 6.9 MN/m<sup>2</sup>.

*Table 5-6.*  
*Treatment to Remove Gas from Copper Alloys*

| Yellow Brasses,<br>Silicon Brass and<br>Manganese Bronze<br>C85000-86000<br>and 87000 Alloys | Aluminum<br>Bronze and<br>Phosphor Bronze<br>C95000 and<br>91000 Alloys    | Pure Copper,<br>Copper-tin-lead<br>and Cupronickels<br>C80000, 90000,<br>92000 and 96000<br>Alloys | All others                                       |
|----------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|--------------------------------------------------|
| No degassing<br>treatment necessary<br>with high<br>zinc content.                            | Flush with dry<br>nitrogen at<br>55 °/min.<br>until gas<br>test is passed. | Melt under<br>strongly<br>oxidizing<br>conditions*.                                                | Melt under<br>mildly<br>oxidizing<br>conditions. |
| “Exotic”<br>deoxidizers?                                                                     | “Exotic”<br>deoxidizers?                                                   | Dexoidize<br>(PCu, etc.)                                                                           | Deoxidize<br>(PCu, 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 de-gas with nitrogen if the gas test is suspect.

### Degassing—

Alloys which do not dissolve oxygen (e.g., aluminum bronzes), should be purged with inert gas to remove dissolved hydrogen.

Alloys which dissolve oxygen readily (copper, red bronzes, 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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# Chapter 6

## POURING

### INTRODUCTION

To meet today's needs, many foundry 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 foundries, however, continue to experience casting losses due to improper pouring practices, 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 given to operating personnel in the area of pouring.

### INFLUENCE OF ALLOY TYPE ON POURING CONDITIONS

As will be noted in Chapters 7 and 8, the copper-base alloys may be divided into different categories on the basis of 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:

- 1) Stirring of the molten metal should be avoided in order to prevent oxide films from being thrust below the 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 is sometimes done to lower metal temperature for pouring. 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, an 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.

- 2) As will be noted later in Chapter 7, 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.
- 3) 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.
- 4) 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 Chapter 1, fortunately, comprise a second category of materials which 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, 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 which 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 during melting, much of this dross is dissolved to form a glass-like slag.

Under normal conditions, these drosses or slags 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 Chapters 5 and 16). The products of deoxidation (borates and phosphates) are fluid slags 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 so as 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 Chapter 7). Turbulence during transfer and pouring should be minimized, although these alloys are more tolerant and offer a 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. When we speak of pouring temperature we mean 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 range of temperature, 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 which 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 Hot

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 Chapter 5. 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 which 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 Chapter 15). 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.

### POURING RATE

The terms *pouring rate* and *pouring speed* are often used interchangeably and are usually expressed in terms of pounds of metal poured (into the mold) per second. The figure 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 back-pressure, 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,

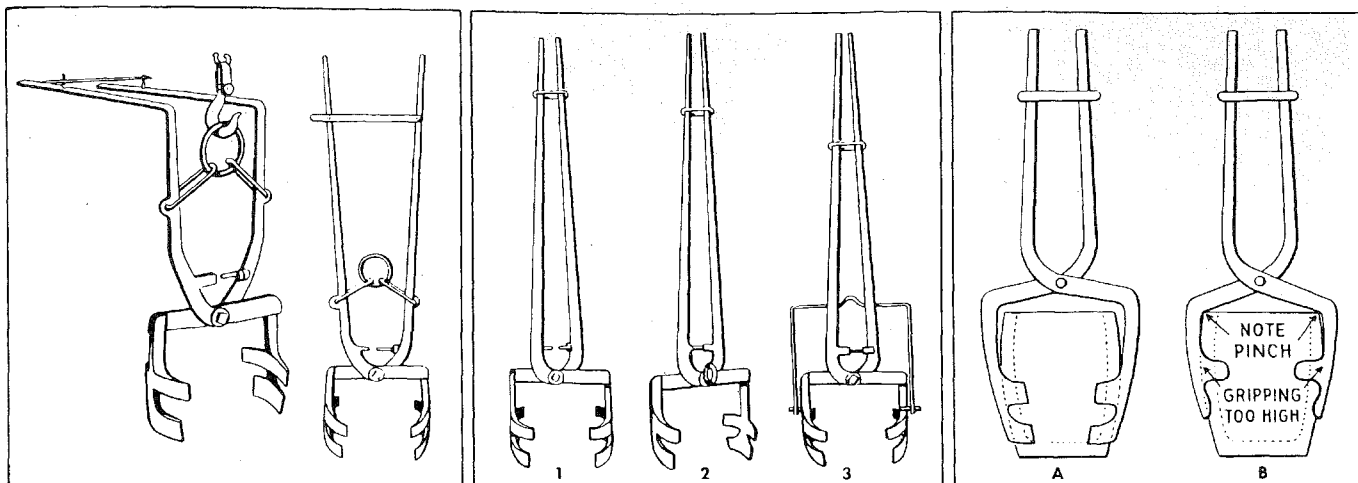


Fig. 6-1. Left: Side-operated and vertical lift-out tongs both equipped with stops limiting maximum pressure on the crucible. Center: (1) Hand lift tongs, (2) with eye bolt for mechanical hoist, (3) with side trunnions and bail for lifting. Right: Tongs that fit increase crucible life. Correct fit of tongs is shown at A. Crucible may be cracked by tongs pinching across the top, as shown at B.

is actually the overall average rate required to fill the mold completely.

Regardless of the gating system used (see Chapter 7), 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 Chapter 7, 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 which are fuel-fired, or in small, high-frequency induction furnaces of either the push-out or 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 provided 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 which 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.

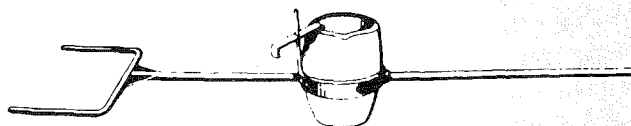


Fig. 6-2. Pouring shank with safety catch over top of crucible.

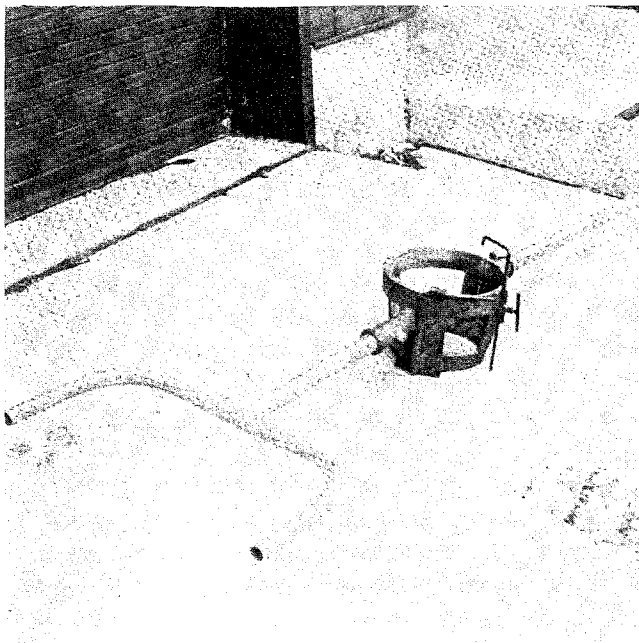


Fig. 6-3. Pouring shank with hinged support ring for use with crucibles in push-out or lift-coil induction furnaces.

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 which holds the crucible is actually hinged, permitting the ring to be opened and then 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 Chapter 4. Whether tapped by tilting of the furnace or by gravity run-out, 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.

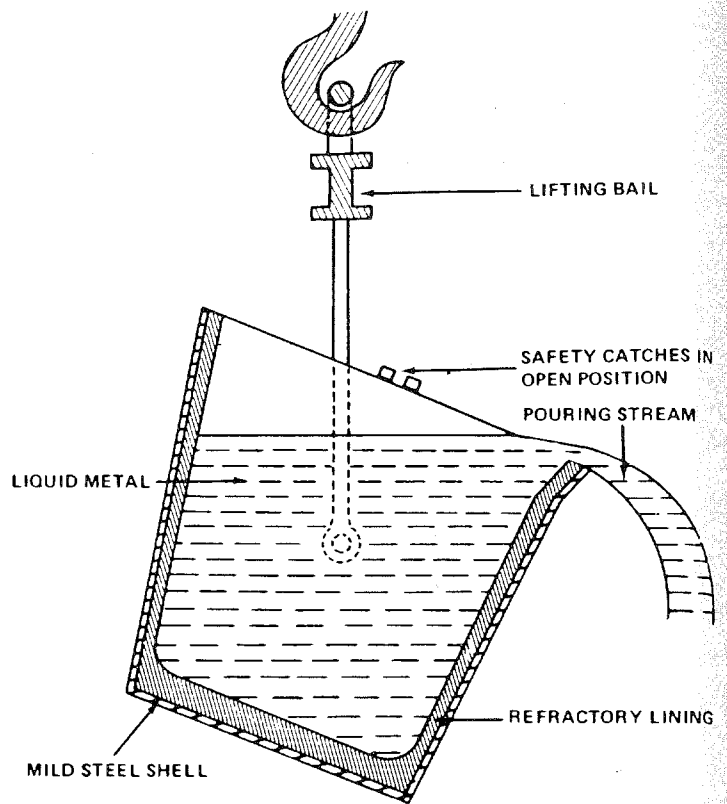


Fig. 6-4. Section through a lip pour ladle.

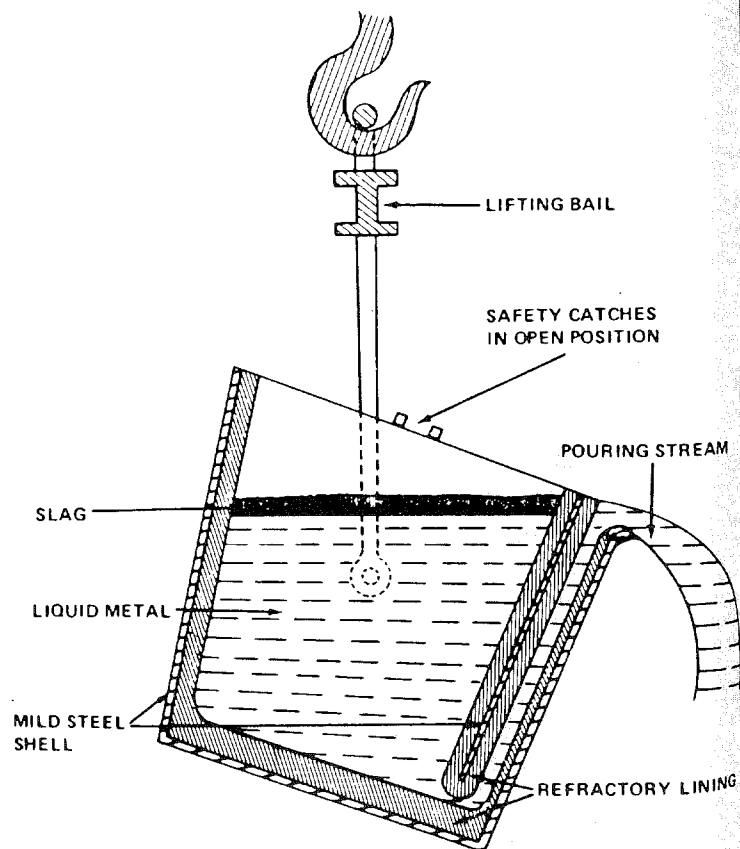
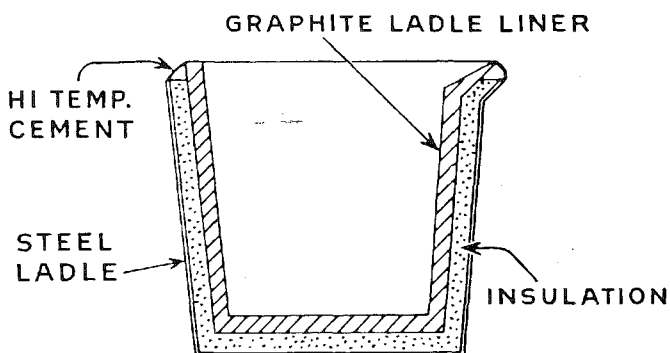


Fig. 6-5. Section through a teapot ladle.

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 which may be of either the ramming, castable or vibratable-plastic type. For handling aluminum bronzes, it may be advantageous to use



#### INSTALLATION - GRAPHITE LADLE LINER

Fig. 6-6. Diagram of installation of a graphite liner with insulation in a steel shell, lip-pour ladle.

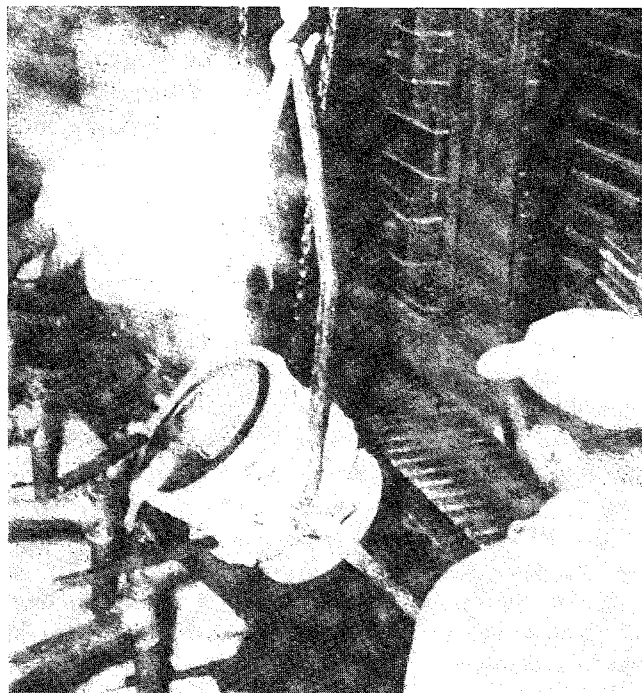


Fig. 6-7. Pouring bronze castings from a ladle shell lined with graphite; teapot-type liner providing skimmer and bottom-pour tube.

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.

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 which 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 handwheel-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:

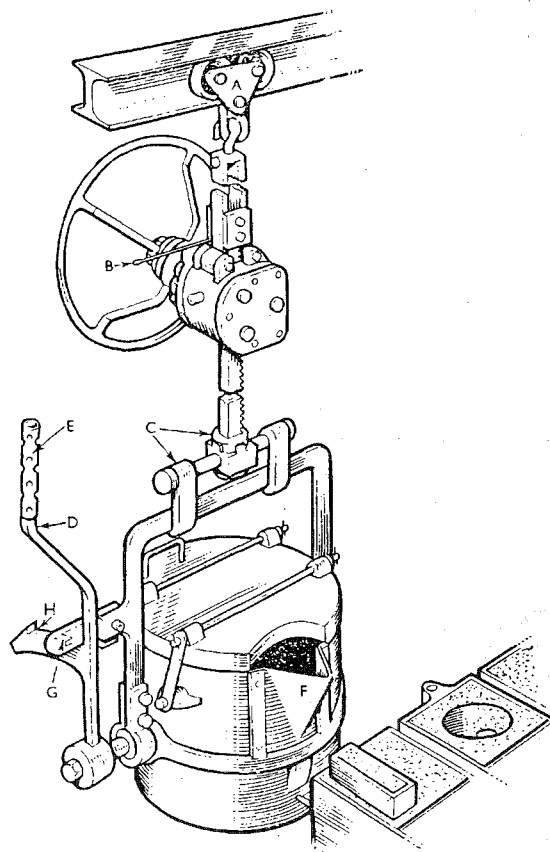


Fig. 6-8. One-man pouring ladle (with cover), provided with enclosed rack-and-pinion gearing and handwheel for height adjustment.

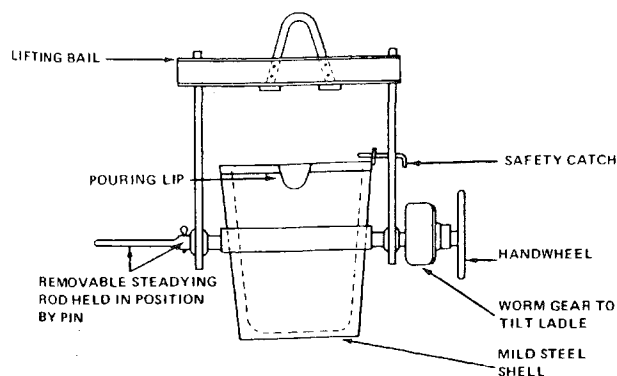


Fig. 6-9. Typical large lip-pour ladle with enclosed worm-gearing and handwheel for pouring.

### 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.
- 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, wherever they may be, 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 assure good visibility to 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. The relative

heights of conveyors, flooring, flasks, monorails, ladle trunnions, and so on, should all be considered with this in mind.

- Good ventilation in the pouring area is important not only to health but for improving operator visibility; hood and ducts, however, should be placed in such a way 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 is at the wrong 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 in. mold-to-mold (preferably less).
- In the case of automatic molding operations, every means should be considered to avoid pouring molds manually when they are moving continuously or intermittently along a mold conveyor.
- Lips and spouts of pouring ladles should be kept free from obstructions or accumulations which impede pouring.

Failure to consider or apply the above-mentioned ideas has resulted in substantial monetary and productivity losses for many foundries over the years. Observation 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 adopt 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 which 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 either 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.

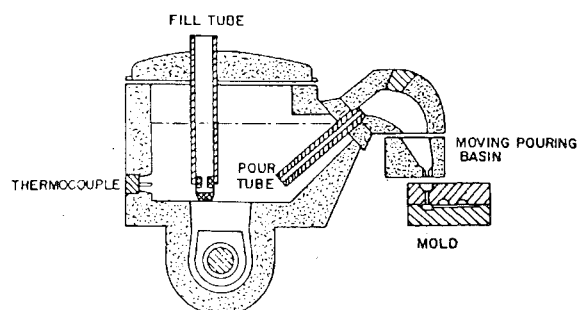


Fig. 6-10. Schematic view of channel-induction furnace with fill tube and pour tube, designed for automatic pressure-pouring.

### Pouring Moving Molds

The 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 provided at one end with a replaceable orifice. 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 which 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 which 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.

### 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  $\pm 10^\circ\text{F}$  ( $5.6^\circ\text{C}$ ), permitting selection of optimum pouring temperature for every mold poured. This compares with an average range of some  $100^\circ\text{F}$  ( $56^\circ\text{C}$ ) 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

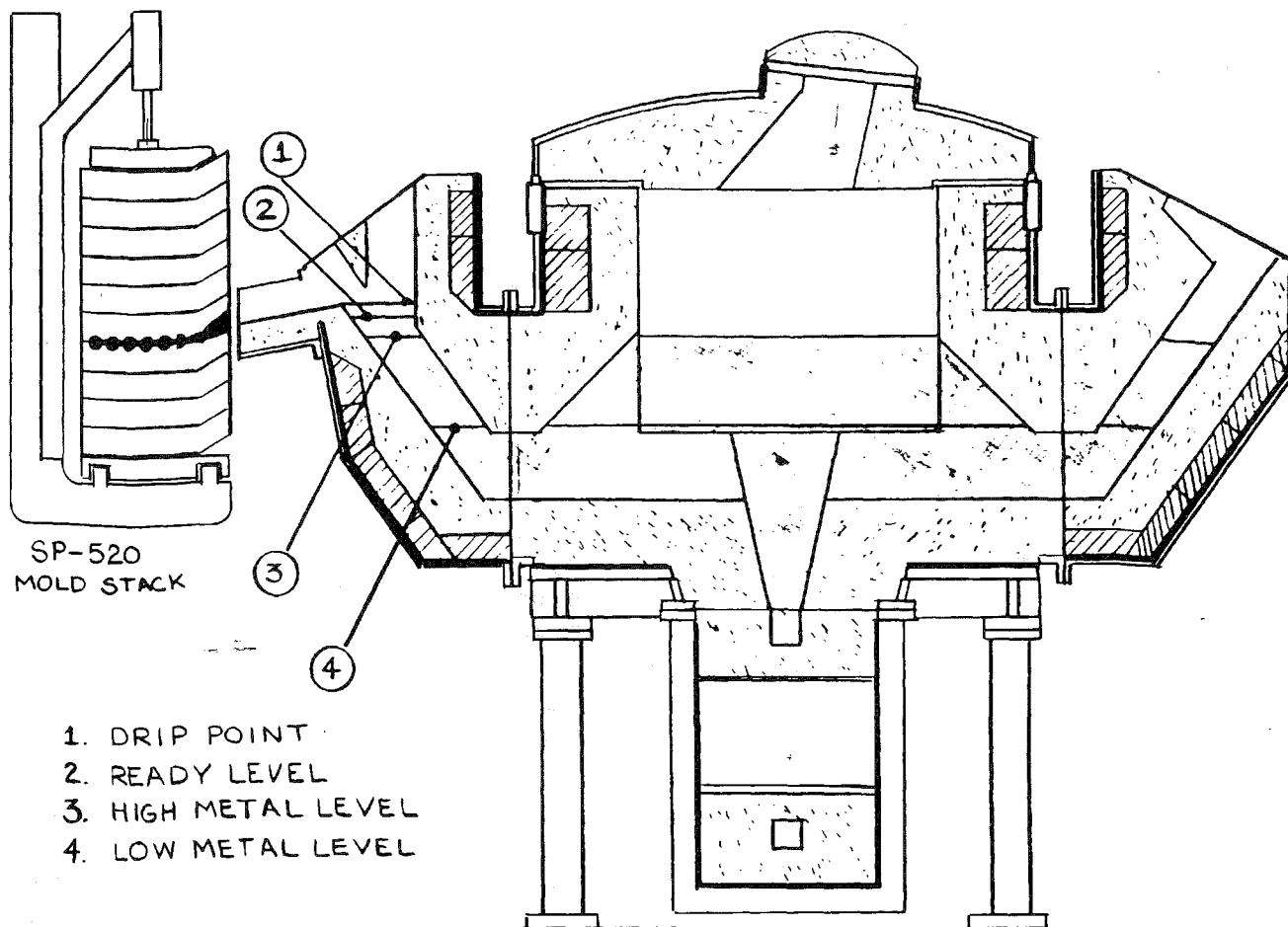


Fig. 6-11. Channel-induction furnace with extended pour spout, designed for automatic pressure-pouring of indexed, stack molds; ready-level in furnace maintained by controlled back-pressure. (Courtesy Inductotherm Corporation, Rancocas, NJ)

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 fur-

nace (dross and expended graphite should be skimmed away from time to time). 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 slightly reducing flame) at such locations as: 1) at the top of fill tube, 2) above launders, 3) at the top of the pour tube, and 4) 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 consistently matched by human skill.

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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## Chapter 7

# GATING OF COPPER-BASE ALLOYS

### 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 which 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 50C (90F) 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 which 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 Chapter 14).

The alloys having intermediate freezing ranges (Group II) have a range between liquidus and solidus points of about 50 to 111C (90 to 200F). 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 111C (200F) and often closer to 167C (300F). 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 327C (621F) 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

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

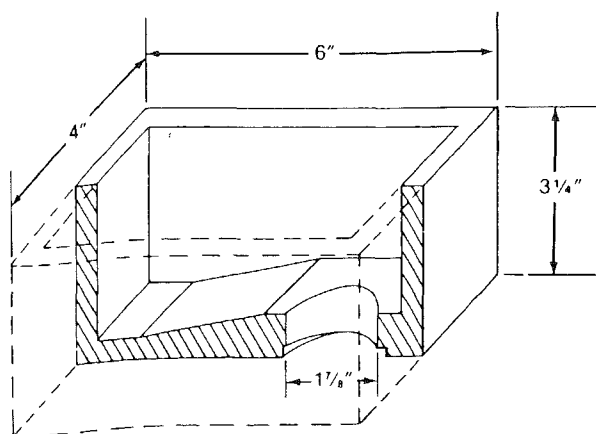


Fig. 7-1. Pouring basin

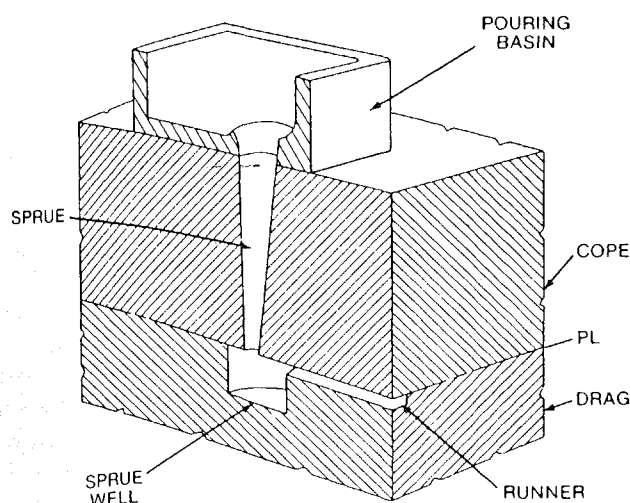


Fig. 7-2. Section of a typical sand mold with pouring basin.

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 which are placed on top of the sprue just after the mold reaches the pouring station. For squeezer 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 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 which delivers metal into the mold cavity. A wide-topped sprue will accomplish this with minimum spillage.

Since most high-production molds which 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  $\frac{1}{2}$  and  $\frac{7}{8}$  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.

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 minimum 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 addi-

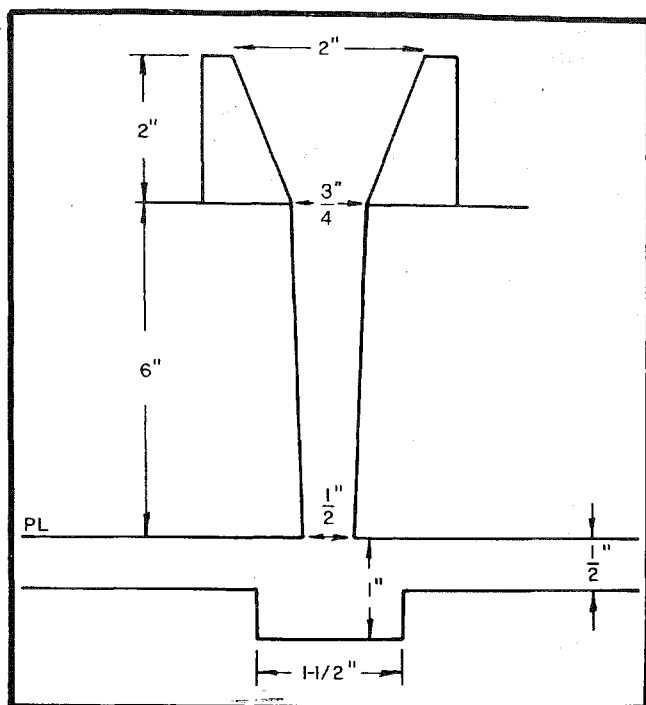


Fig. 7-3. Typical sprue design for reduced turbulence.

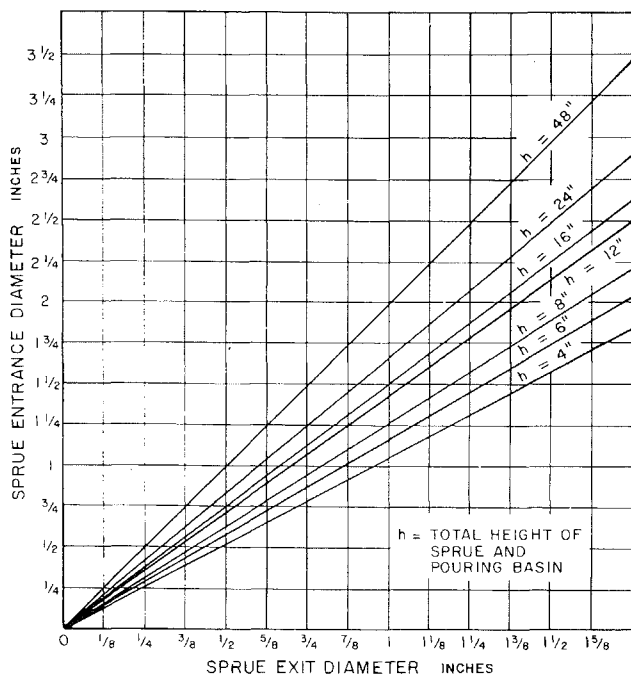


Fig. 7-5. Suggested entrance and exit diameters for sprues of various heights.

tion, 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 velocity of the stream is maximum 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

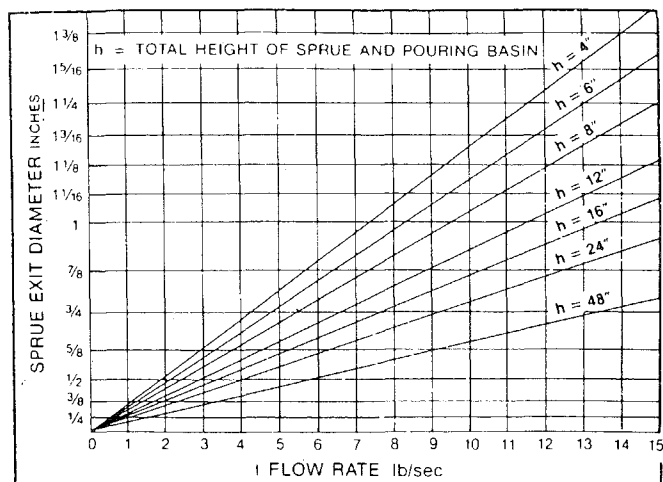


Fig. 7-4. Flow rates of copper-base alloys through tapered sprues of varying diameter and height.

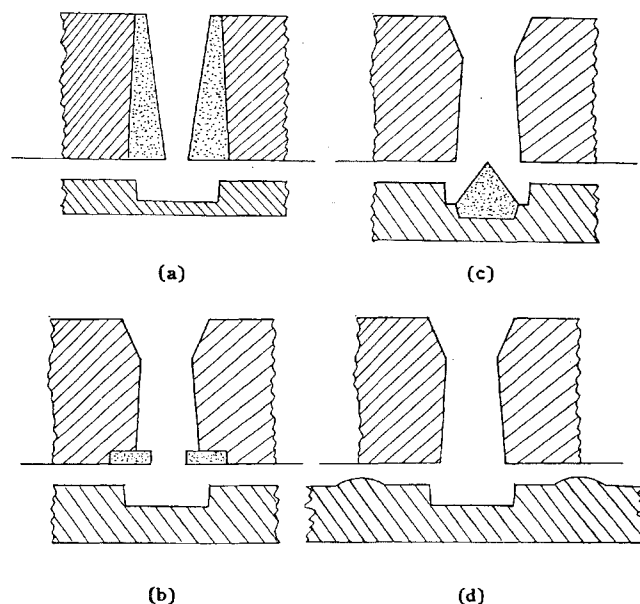


Fig. 7-6. Alternative methods for correcting the problem of a reverse-tapered sprue.

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 1 1/2 inches and a diameter of 1 1/2 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.

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 nonmetallics 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 which 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 which 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:

$$W = \sqrt{\frac{W_t}{0.86 + 1.09T}}$$

Where

W = Flow rate in lbs per second

W<sub>t</sub> = 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.

Table 7-1. Flow Rates of Copper-Base Alloys Through Tapered Sprues of Varying Diameter and Height

| Sprue Area<br>(In. <sup>2</sup> ) | Sprue Diameter<br>(In.) | Flow Rate (lbs/sec) for Sprue Height |       |        |        |        |
|-----------------------------------|-------------------------|--------------------------------------|-------|--------|--------|--------|
|                                   |                         | 4 in.                                | 6 in. | 12 in. | 24 in. | 48 in. |
| .2                                | 1/2                     | 1.8                                  | 2.0   | 3.0    | 4.0    | 6.0    |
| .3                                | 5/8                     | 2.8                                  | 3.3   | 4.5    | 6.0    | 9.0    |
| .44                               | 3/4                     | 4.0                                  | 4.5   | 6.5    | 9.0    | 13.5   |
| .60                               | 7/8                     | 5.5                                  | 6.5   | 9.0    | 12.5   | 18.0   |
| .785                              | 1                       | 7.5                                  | 8.5   | 11.5   | 16.5   | 29.5   |
| 1.0                               | 1 1/8                   | 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  
 3/4 as high as sprue x 1.3  
 1/2 as high as sprue x 1.2  
 1/4 as high as sprue x 1.1

However, large castings require large flasks and, therefore, higher sprues; thus, the effect is self-compensating. A 1-in. dia 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 3/4-in. sprue will fill the same casting in 43 seconds. Many large, high-grade castings have been produced using 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

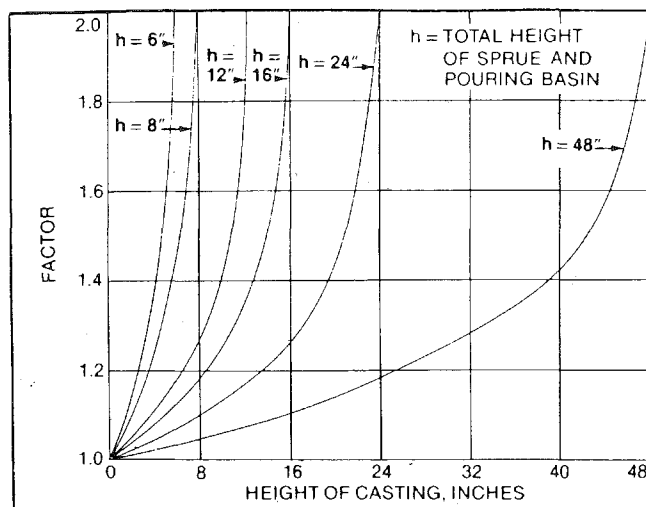
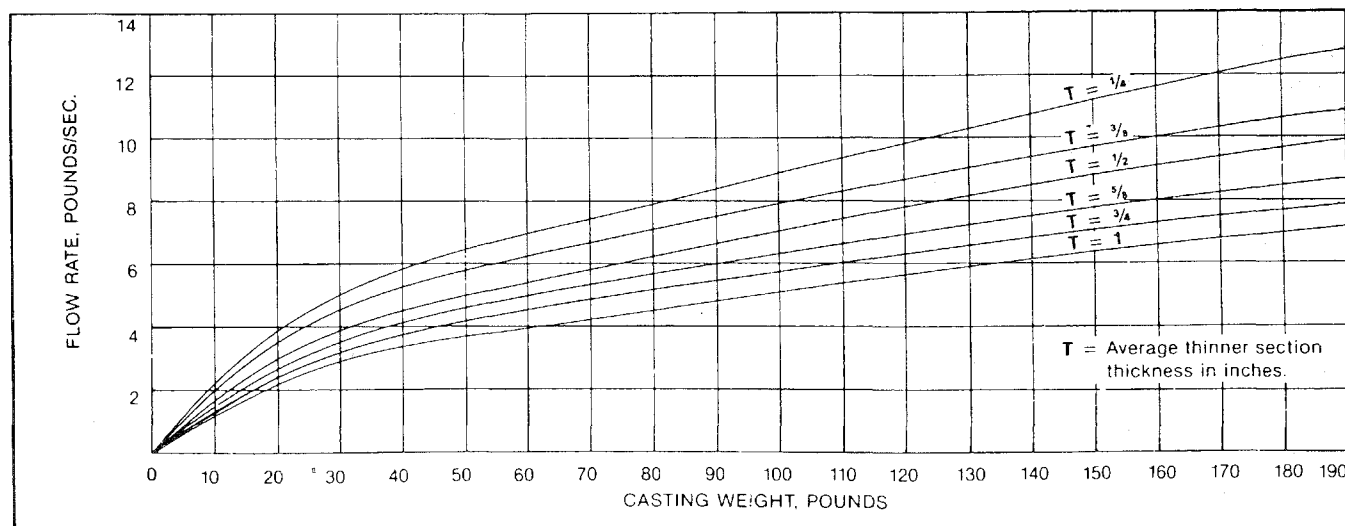


Fig. 7-7. Delivery factor for bottom-run castings which were of various heights.

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.

Fig. 7-8. Horizontal flow rate as a function of casting weight.



## 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 which 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 also 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 a  $\frac{7}{8}$ -in. dia sprue with a cross-sectional area of 0.6 in.<sup>2</sup> is used. The total runner area (four times

that of the sprue) would be 2.4 in.<sup>2</sup> 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.<sup>2</sup> and that of each gate would be  $\frac{(3.6)}{8}$ , or 0.45 square inches. Thus, with the  $\frac{7}{8}$ -in. dia sprue we might use two runners—each 1 in. x 1.2 in., and eight gates—each 0.375 in. x 1.2 inches. 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 which 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-step" runner design as shown in Fig. 7-9a for a single casting and in Fig. 7-10 for multiple castings.

As an example, suppose we were dealing with 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.<sup>2</sup> to 0.75 in.<sup>2</sup> after passing the first gate, from 0.75 to 0.50 in.<sup>2</sup> after passing the second, and from 0.50 to 0.25 in.<sup>2</sup> 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 so as 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.

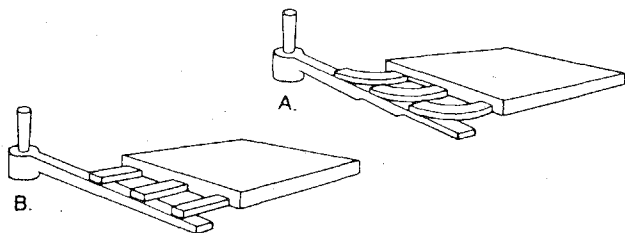


Fig. 7-9. Stepped vs. tapered runner for single cavity gating system.

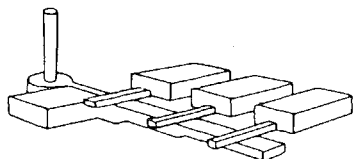


Fig. 7-10. Recommended multiple cavity gating system with stepped runner.

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 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 still 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

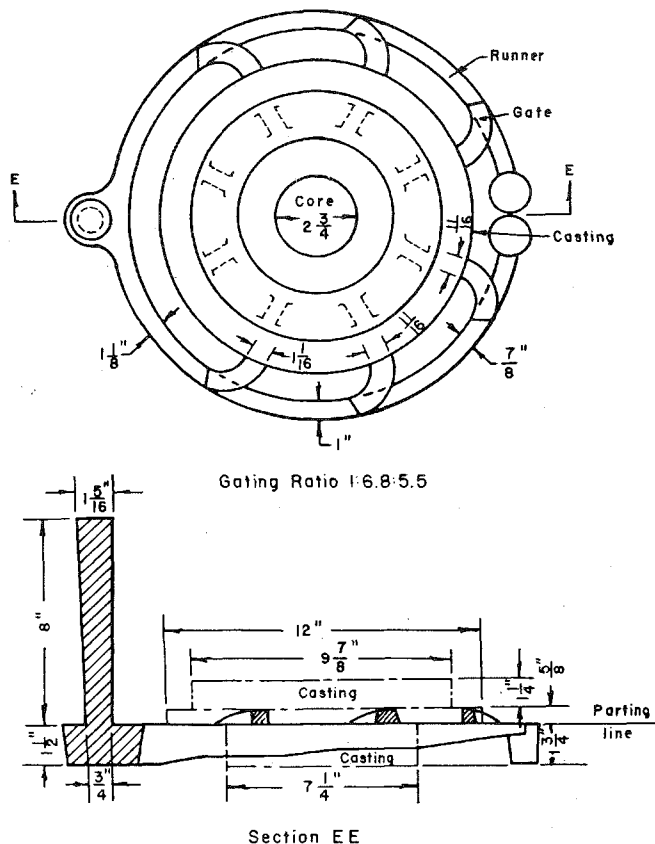


Fig. 7-11. Ring-gated suction head casting of 88-8-0-4 alloy.

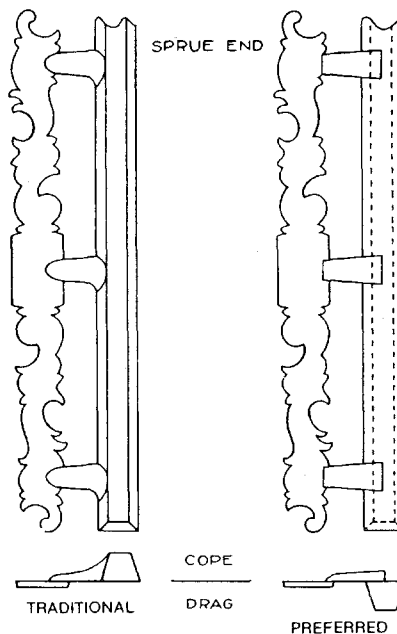


Fig. 7-12. Change in gating system that prevented misruns and roughness in yellow brass sand castings.

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 also 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 Chapter 8).

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

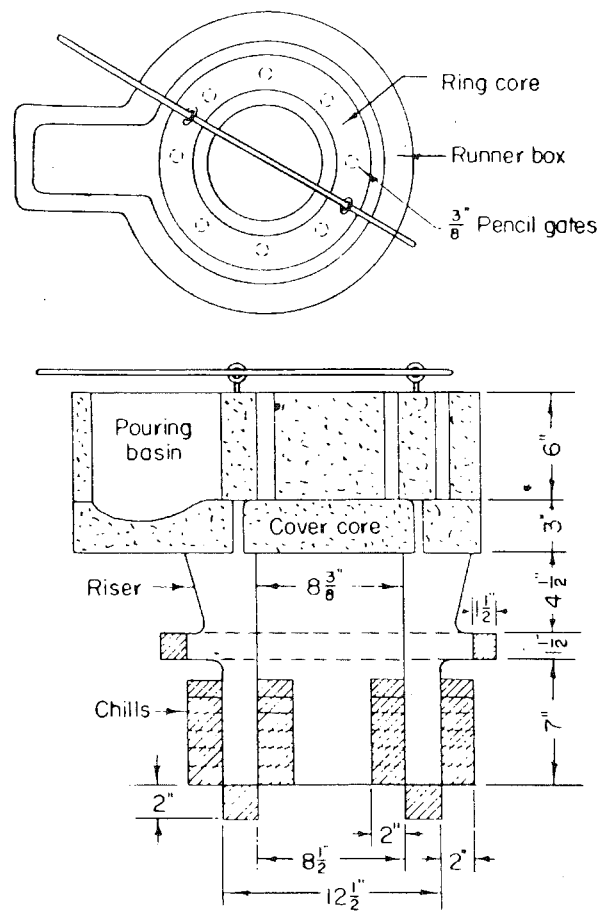


Fig. 7-13. Top pencil-gated flanged cylinder of 88-8-0-4 alloy.

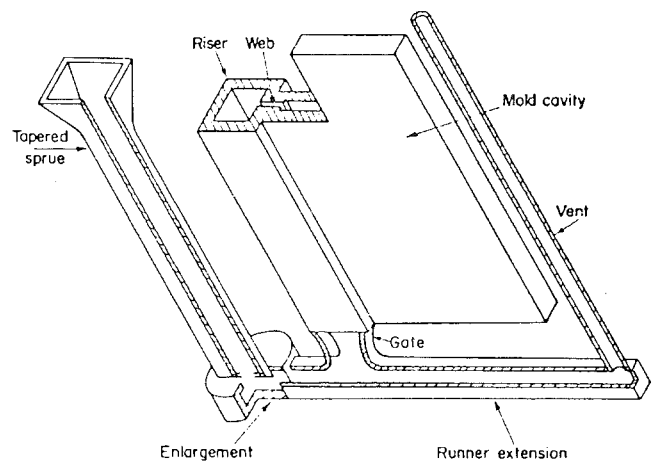


Fig. 7-14. A schematic sketch of an tentative improved vertical gating system.

the riser. This results in erratic and unfavorable temperature distributions which 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:run-

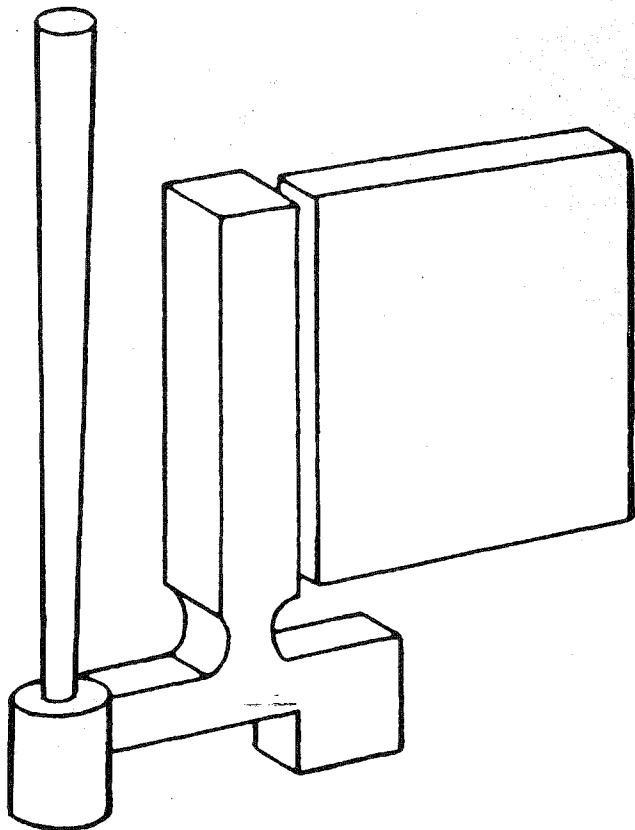


Fig. 7-15. Vertical system, single cavity. Web thickness —  $\frac{1}{4}$  in., gating ratio 1:4:4, tapered sprue,  $\frac{1}{2}$  in. choke.

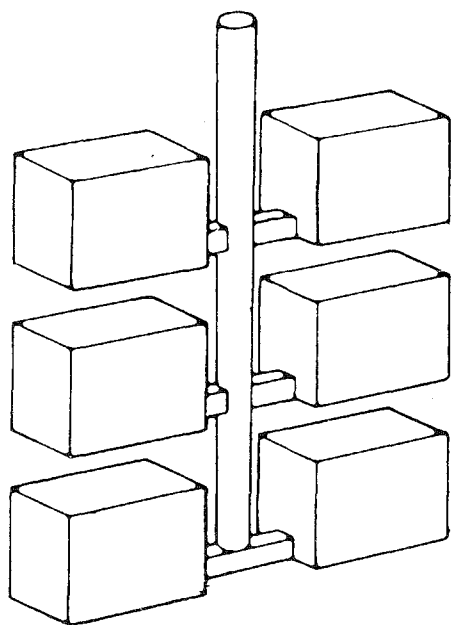


Fig. 7-16. Vertical system multiple cavity. Gating ratio 1:6 (1:2 at each level), tapered sprue —  $\frac{1}{2}$  in. choke.

ner: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.

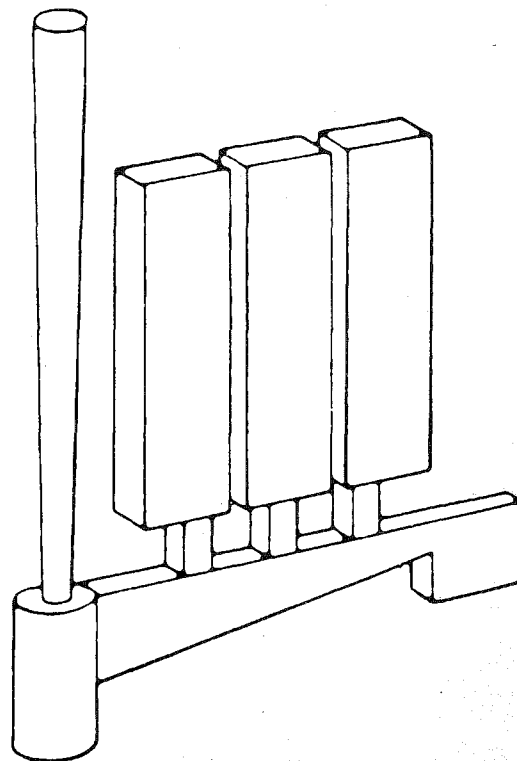


Fig. 7-17. Vertical system multiple cavity bottom runner. Gating ratio 1:4:4, tapered sprue —  $\frac{1}{2}$  in. choke

For the less sensitive, wide-freezing-range alloys of Group III which 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 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 which 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 stepping down the runner cross-section as previously described.

#### KNIFE-GATING AND KISS-GATING SYSTEMS

Special applications of 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 the use of special screens, or manual retrieval from mechanized systems. Figure 7-18 is a schematic representation of both kiss gating and knife 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  $\frac{1}{32}$  to  $\frac{3}{32}$  inch.

In knife gating, the castings are partially in the cope and partially in the drag. The runner which 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  $\frac{1}{32}$  to  $\frac{3}{32}$  inch. Figures 7-19 through 7-23 illustrate successful applications of knife gating and kiss 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 absolutely 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 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 down 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.

### 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 Chapter 15).

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

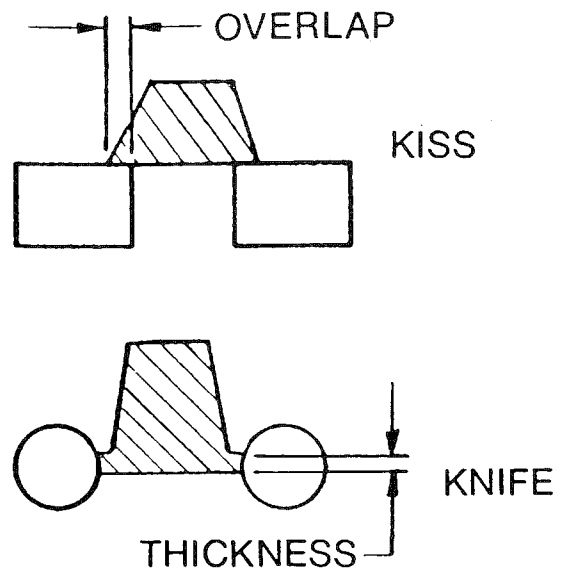


Fig. 7-18. Basic kiss and knife gates.

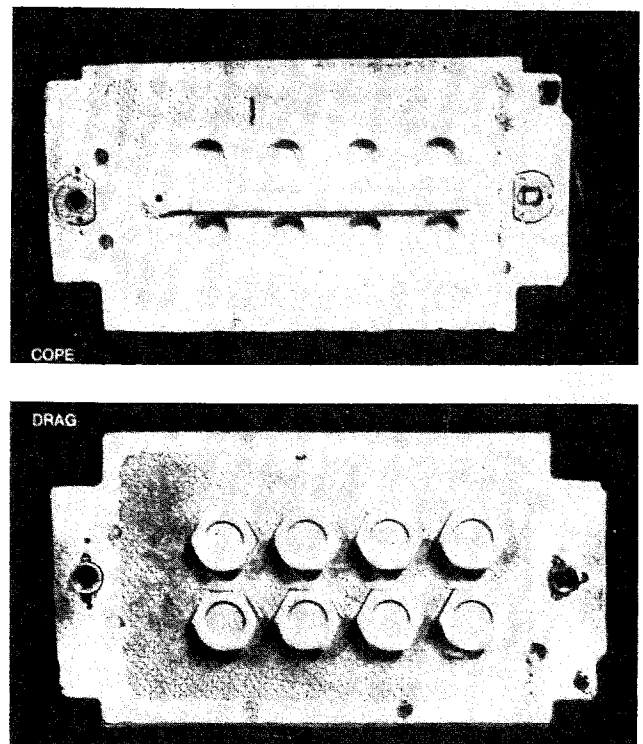


Fig. 7-19. Kiss gating system for union nut castings.

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

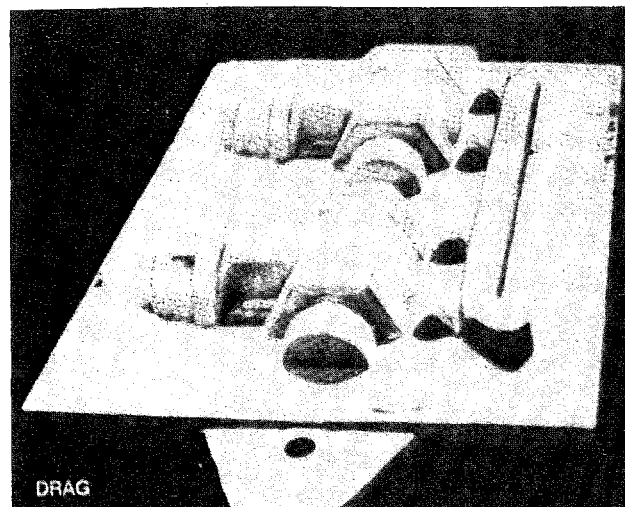
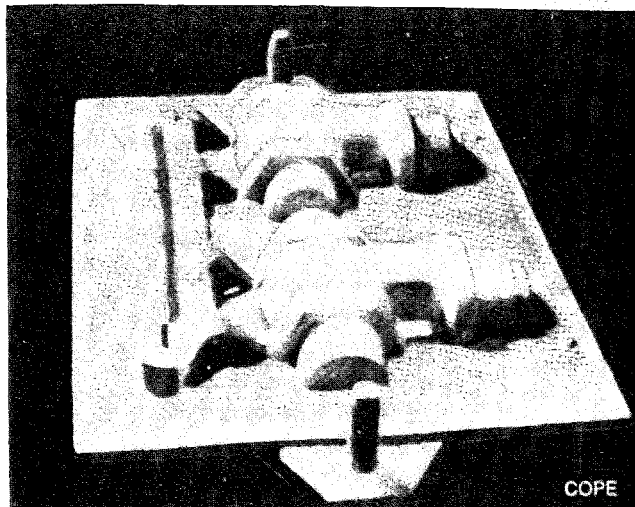


Fig. 7-20. Knife gating system for valve body.

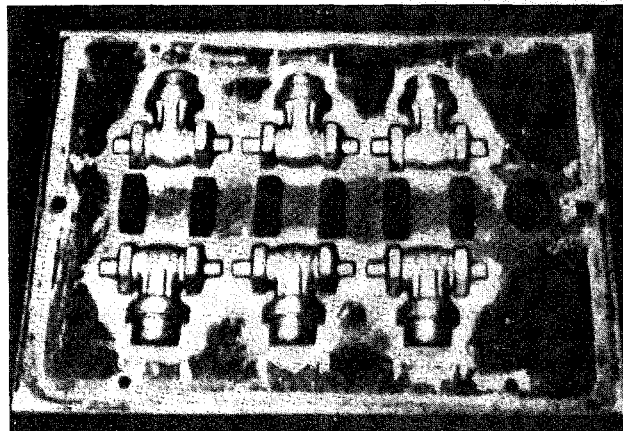
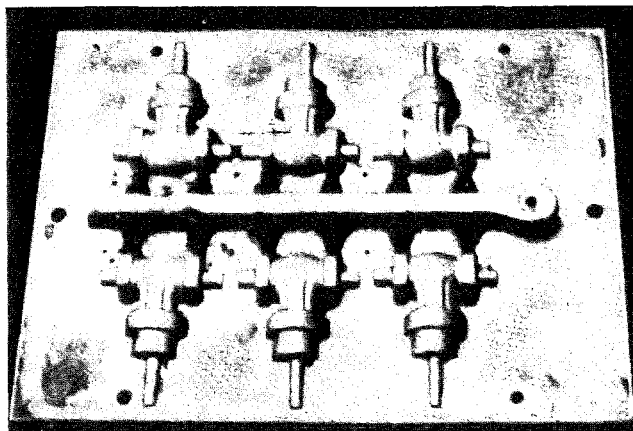
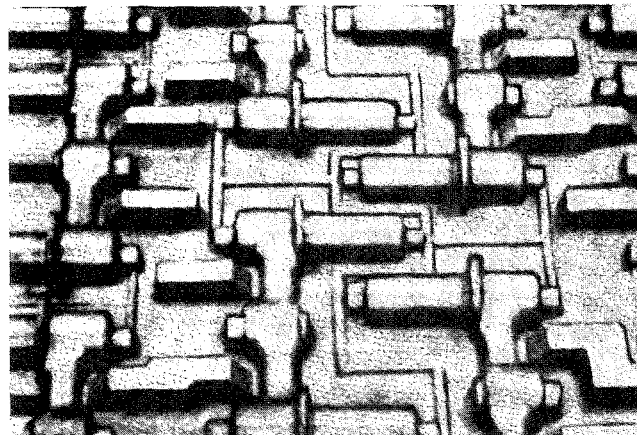
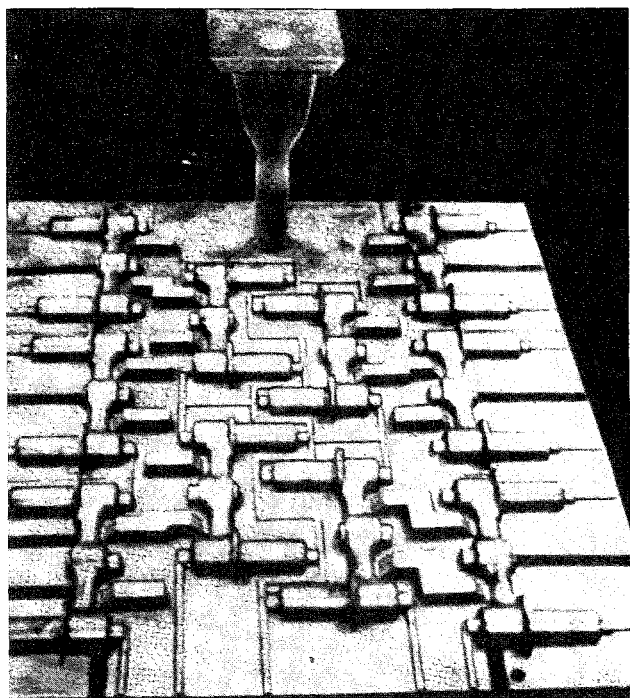


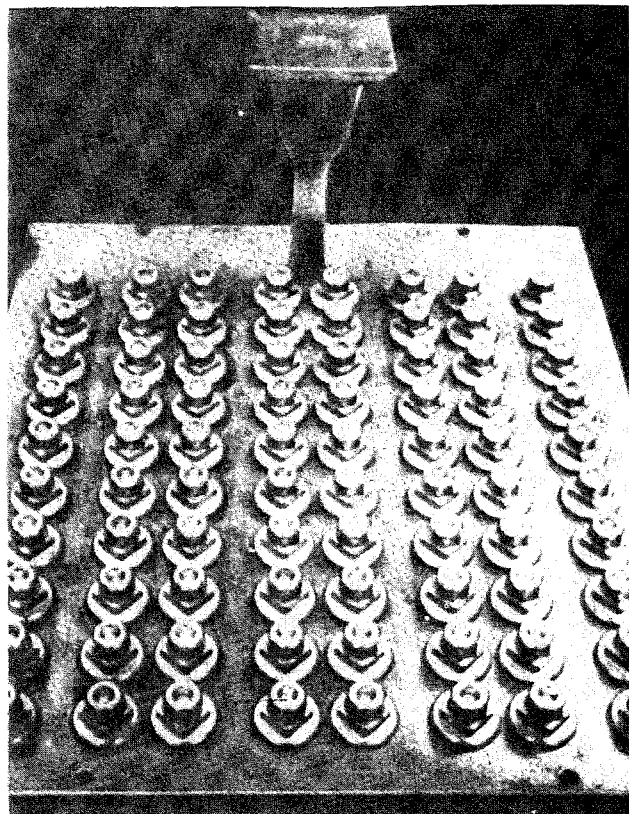
Fig. 7-21. Knife gating system—small valve body.

Fig. 7-22. Knife gating system—faucet body.

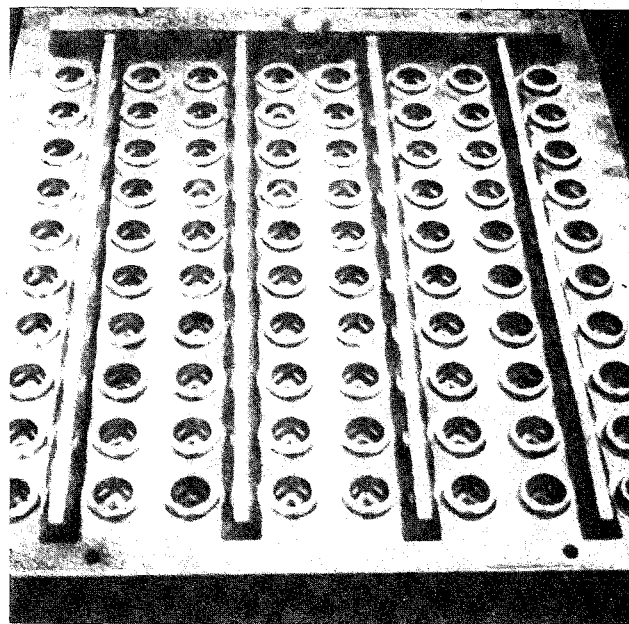


COPE

COPE



COPE



DRAG

Fig. 7-23. Kiss gating system—bonnet nuts.

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 Chapter 8). 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 foundrymen since this behavior controls the incidence of shrinkage porosity, the patterns which 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 certain risering and gating procedure when made in one alloy may require the use of a different procedure when made in another alloy. Therefore, the copper-base alloy foundryman is confronted frequently with the 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.

The purposes of this chapter are to provide foundrymen with an understanding of the basic mechanism of solidification; to indicate the connection between 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 which 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 extremes of behavior; 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 brasses. 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 their neighbors 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.<sup>1</sup>

This mode of freezing is shown in Fig. 8-2, which illustrates 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.

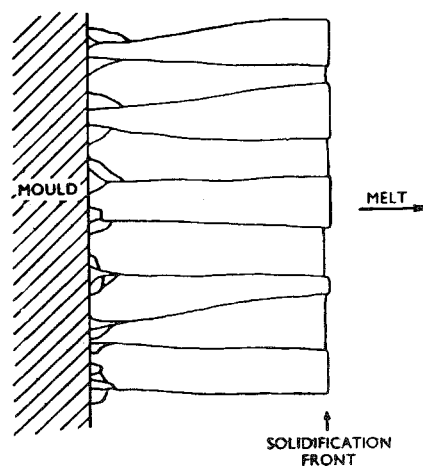


Fig. 8-1. The solidification front in copper of high purity.

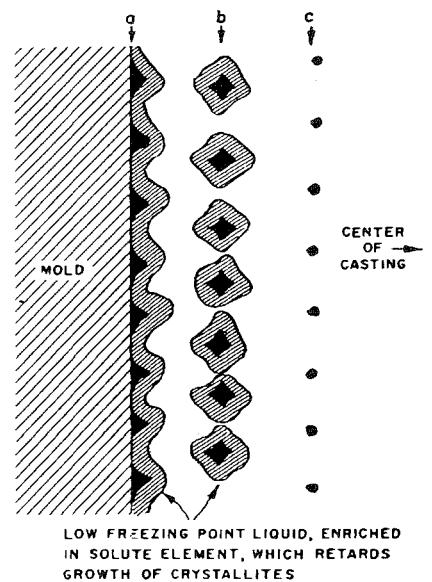
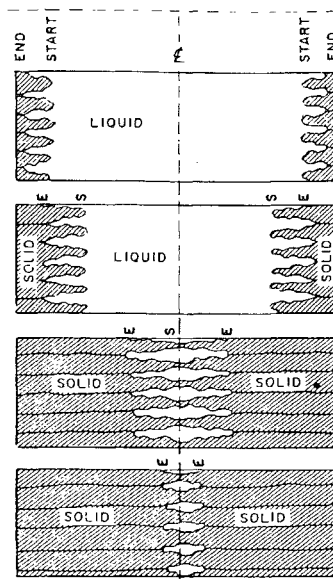
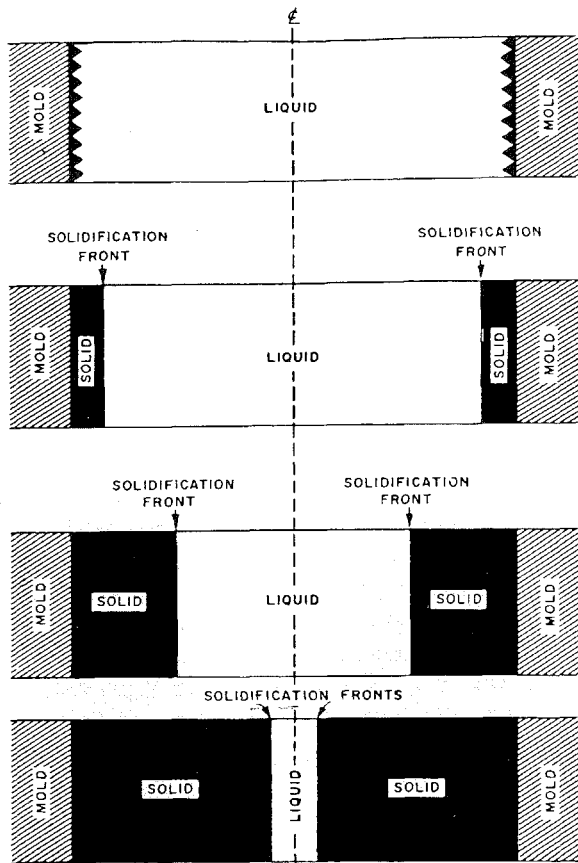


Fig. 8-2. Left: Stages in the freezing of copper of high purity.

Fig. 8-3. Center: Stages in the freezing of copper alloys of low alloying content. Freezing by skin formation.

Fig. 8-4. Right: Diagrammatic representation of restriction of crystal growth in the freezing of copper alloys of high alloy content.

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.

#### *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 of the 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.

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.

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 fall 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 still further towards the interior of the casting, just beyond the enriched region which now surrounds the second batch of crystallites. The process is repeated time and again until small crystallites have been nucleated throughout the entire casting in the manner indicated in Fig. 8-5. Freezing then 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. Bearing 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 be in Groups I or II.

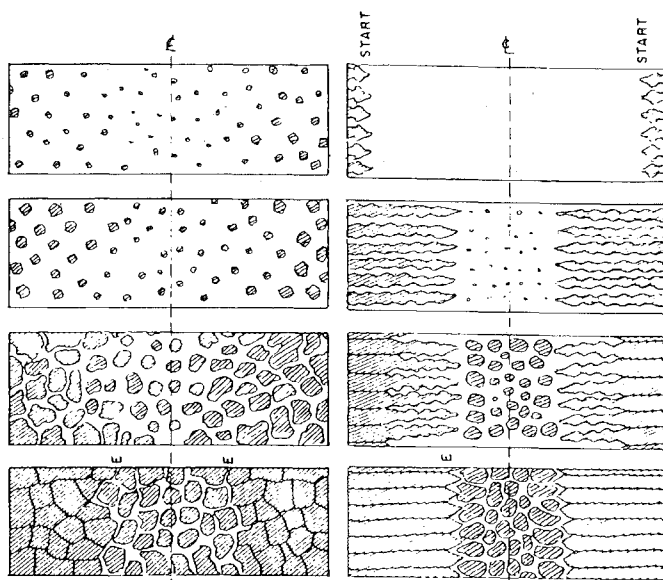


Fig. 8-5. Left: Stages in the freezing of copper alloys of high alloy content.

Fig. 8-6. Right: Stages in the freezing of a copper alloy in the intermediate manner.

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 peters out 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 which 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.

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.

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, when not fed, give rise to centerline shrinkage of the type indicated in Fig. 8-8. This kind of shrinkage arises because, toward the end of freezing, the tips of the crystals approaching the centerline of the section 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 castings made of these alloys give rise to pronounced, smooth-walled cavities as shown in Fig. 8-8.

#### Group II Alloys

In the early freezing stages of Group II alloys, the metal consists of a liquid in which are suspended tiny, solid crystallites. At this stage in freezing, the metal is still quite fluid and the shrinkage which takes place 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.<sup>2</sup> Thus, for an alloy whose total volumetric solidification shrinkage is 6%, we would expect some 4% to be due to mass feeding. This mechanism is illustrated in Fig. 8-9.

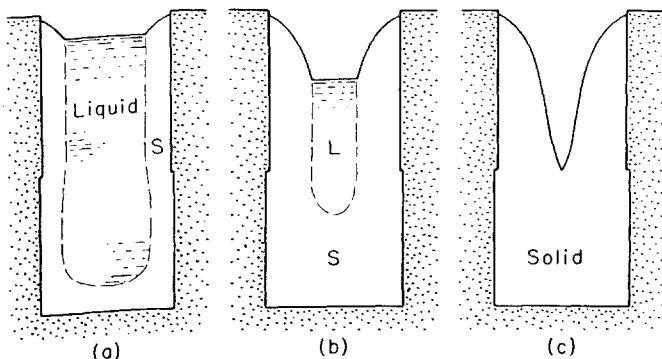


Fig. 8-7. Formation of pipe in copper alloys freezing by skin formation.

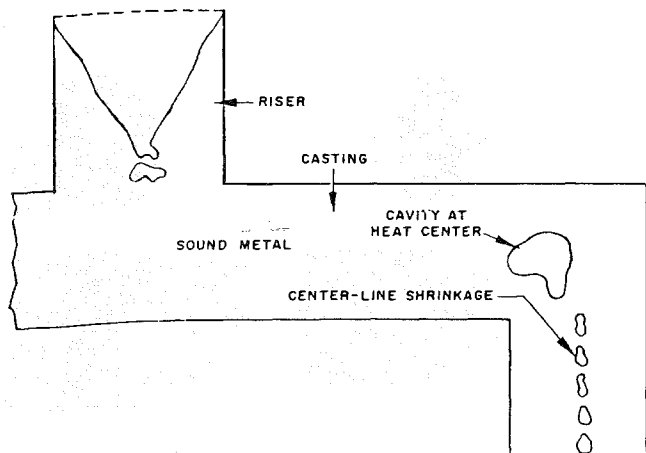


Fig. 8-8. Diagrammatic representation of shrinkage in castings made in copper alloys freezing by skin formation.

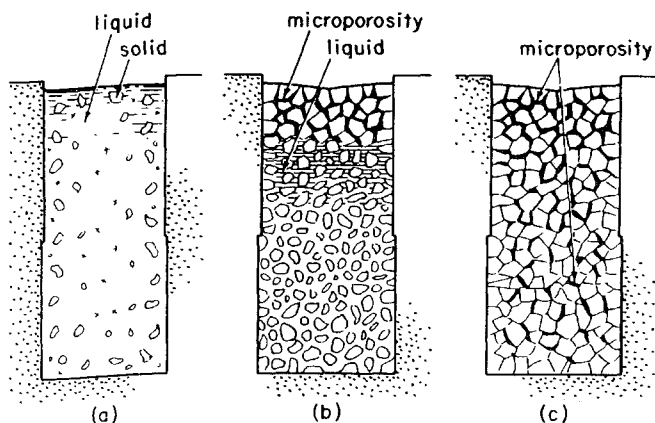


Fig. 8-9. Mass feeding in copper alloys of long freezing-range.

The process of mass feeding is normally aided by atmospheric pressure which 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 to the casting of a tall, small-diameter riser

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 still growing dendrites compete with each other for the remaining liquid metal which is now isolated in numerous little pools scattered throughout the alloy (see Fig. 8-9). It is not difficult to see how this mode of freezing gives rise to finely dispersed microporosity since, when each of the isolated pools of liquid eventually freezes, it gives 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 more coarse—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 both 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 (under  $\frac{3}{8}$  in.) sections, or are chill-cast, they freeze quickly enough to form a dense skin or surface layer which 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 areas which have been machined, 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

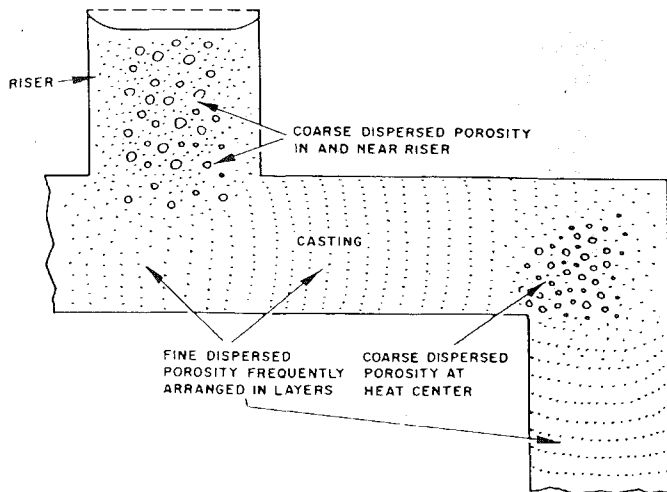


Fig. 8-10. Diagrammatic representation of shrinkage found in castings made in copper alloys of long freezing range.

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  $0.27 \text{ in./min}^{1/2}$ , according to reference 3.

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 which 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

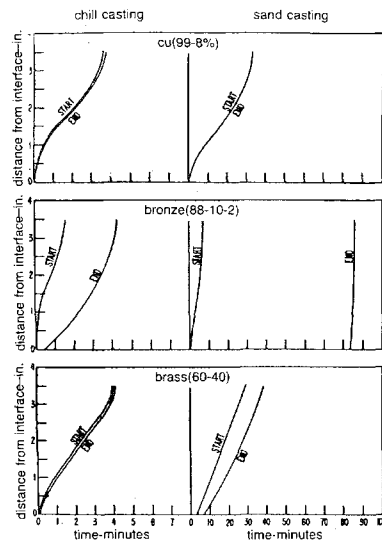


Fig. 8-11. Comparison of freezing of copper alloys in sand molds and in chill molds.

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.

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 gun metals 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.<sup>6</sup>

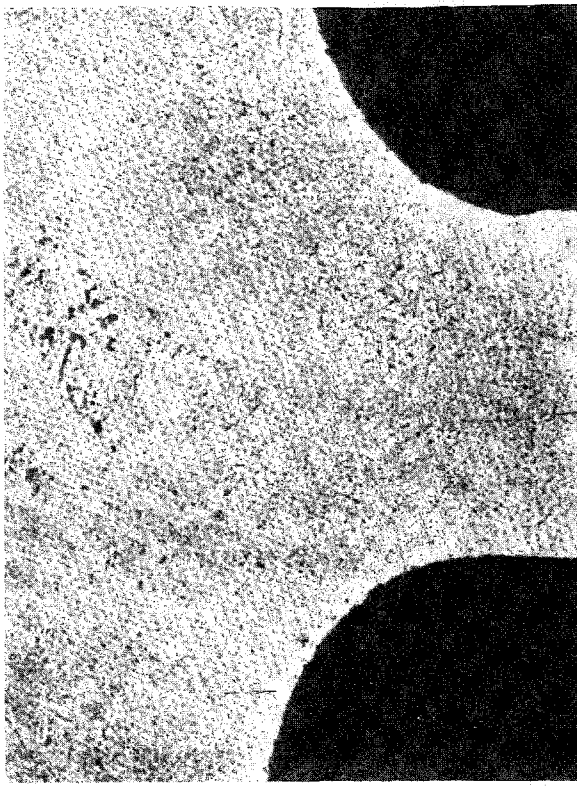


Fig. 8-12. Microstructure of coarse-grained red brass casting.

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 castings made in them is normally fairly fine. The iron-free aluminum bronzes and beta bronzes 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.<sup>7</sup>

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 gun metals 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.<sup>6</sup> 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-

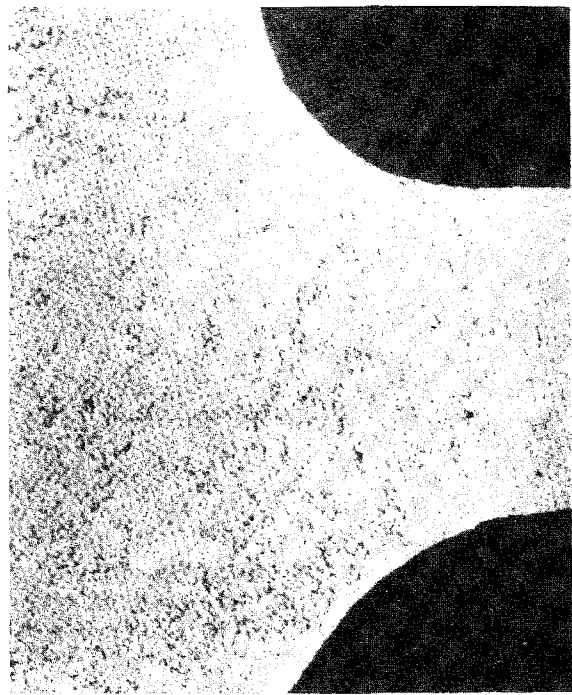


Fig. 8-13. Microstructure of fine-grained red brass casting showing layer porosity.

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 side wall 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.

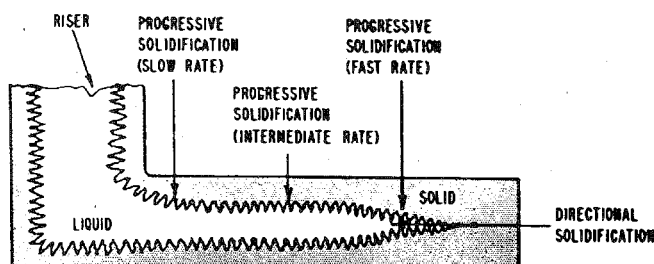


Fig. 8-14. Features of progressive and directional solidification.

Solidification from the side wall 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.

The discussion of directional solidification so far pertains to the freezing of pure metals, low-carbon steel, aluminum bronze, and other alloys which solidify in an essentially skin-forming manner. Unfortunately, most copper-base alloys have a mushy mode of freezing. As foundrymen 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 to foundrymen 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 which have been developed for carbon steels. The following approximate values for feeding ranges have been quoted in the literature and should be used with caution:

| Alloy            | Shape       | Feeding Distance in Terms of Thickness (T)    |
|------------------|-------------|-----------------------------------------------|
| Manganese bronze | Square bars | $4T$ to $10\sqrt{T}$ , depending on thickness |
|                  | Plates      | $5.5T$ to $8T$ , 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, blind side-risers with a hemispher-

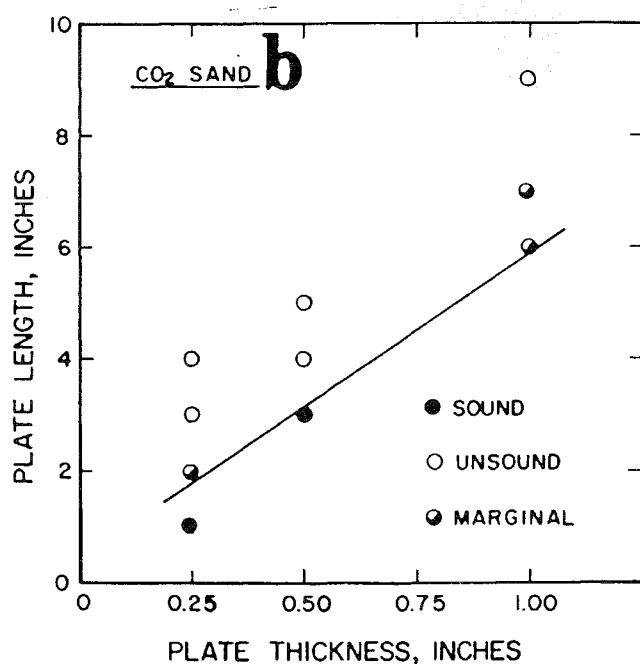
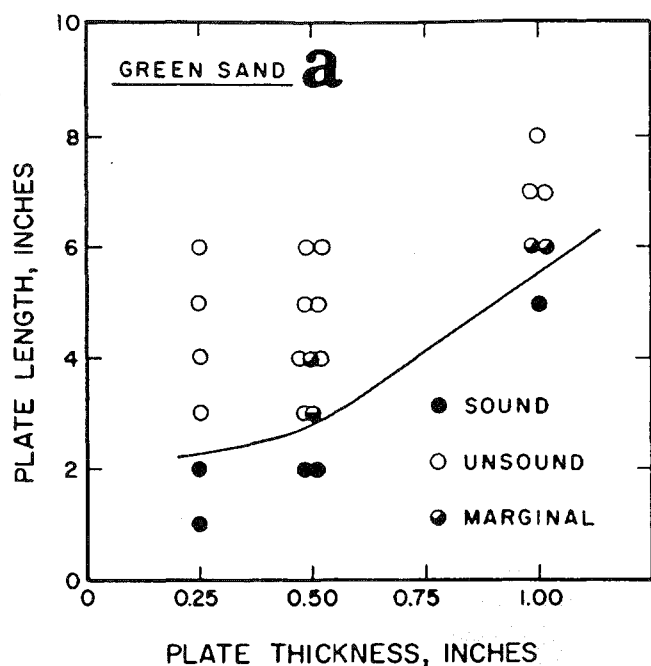


Fig. 8-15. Feeding distance in manganese bronze plates, (a) cast in green sand, (b) cast in sodium-silicate bonded sand.

ical 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 which 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

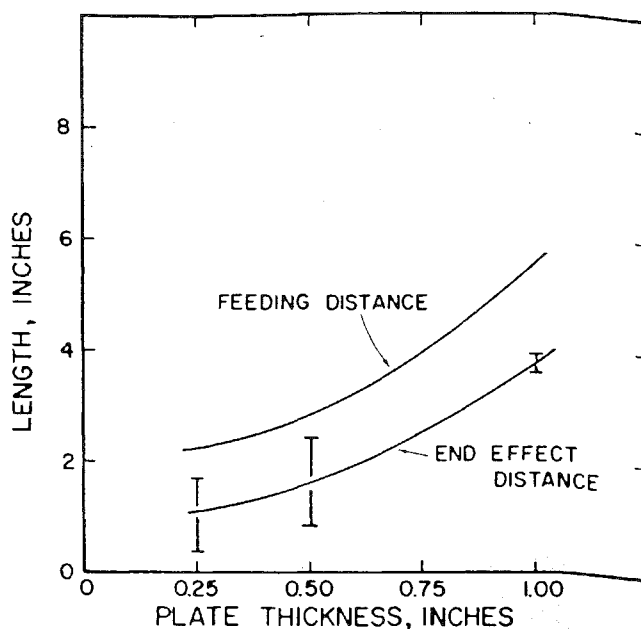


Fig. 8-16. The end effect distances compared to the feeding distances in manganese bronze plates. The range of values observed for the end effect distances is also shown.

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 which are more economical to use and cause fewer problems. Substantial savings can, however, 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

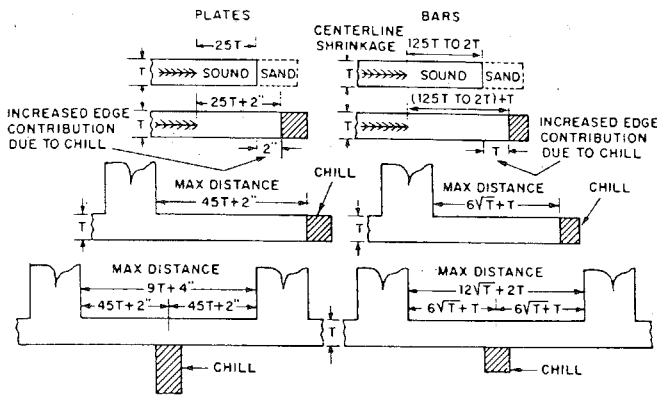


Fig. 8-17. Effect of chills in increasing feeding-range of risers.<sup>7</sup>

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,<sup>8</sup> and empirical relationships were established between *volume ratio* and *shape factor*, where:

$$\text{Volume ratio (Casting volume/Riser volume)} = \frac{V_c}{V_r}$$

$$\text{Shape factor} = \frac{L + W}{T}$$

( $L$ ,  $W$  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,<sup>10-12</sup> 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<sup>4</sup> 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 us 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, let us 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.  $\times$  10 in. square plate, 2½ 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 8-2. 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, indeed, 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.  $\times$  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

Table 8-2. 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.<br>Cubes, etc.<br>Dimensions in ratio<br>1:1.33:2* | 32                    | 40        | 140         | 198       |
| 2. Chunky.<br>Dimensions in ratio<br>1:2:4*                        | 26                    | 32        | 106         | 140       |
| 3. Average.<br>Dimensions in ratio<br>1:3:9*                       | 19                    | 22        | 58          | 75        |
| 4. Fairly Rangy.<br>Dimensions in ratio<br>1:10:10*                | 13                    | 15        | 30          | 38        |
| 5. Rangy.<br>Dimensions in ratio<br>1:15:30 or larger<br>ratio*    | 8                     | 9         | 12          | 14        |

\*Ratio of thickness:width:length

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.*

$$\text{Therefore: } A_c = 4 (2 \text{ in.} \times 9 \text{ in.}) + (2 \text{ in.} \times 2 \text{ in.})$$

$$A_c = 76 \text{ in.}^2$$

$$M_c = V_c/A_c = 36/76$$

$$M_c = 0.474 \text{ in.}$$

#### 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.

$$V_r = H \times \pi D^2/4; \text{ since } H = D, V_r = \pi D^3/4$$

$$A_r = H \times \pi D + \pi D^2/4, \text{ or } A_r = \pi D(D + D/4)$$

$$M_r = \frac{\pi D^3/4}{\pi D(D + D/4)}$$

$$M_r = D/5$$

Therefore  $D/5 = 0.616$  in., and  $D = 3.08$  in.,  $H = 3.08$  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.  $\times$  2 in.  $\times$  9 in. bar.

$$V_r = \pi D^3/4 = 0.785 \times 27$$

$$V_r = 21.2 \text{ in.}^3$$

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 8-2, we 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 we see that its volume should be at least 58% of that of the casting. Our calculated riser should therefore be adequate. Had it not been, we would have increased its volume by extending its height.

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 which compensate for differences in the rate of heat transfer. Good riser design also involves consideration of the geometry of the neck which attaches it to the casting. These subjects are treated in further detail in several references cited. 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 ware, 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. The foundryman has 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 chills 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 which 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 which are pressure tight and visibly sound without any deliberate attempt at feeding. The use of simple ingates, or even "kiss gating" (see Chapter 7), 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, Chapter 15). 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).

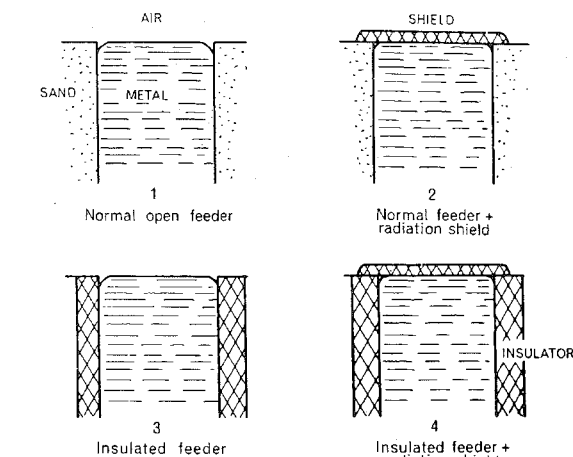
Risering of moderate and heavy-section castings, with proper design and application, can be beneficial,

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, Chapter 15). These defects consist of localized depressions on the casting surface, varying in severity from shallow areas to rather deep pockets which extend into the casting interior. Sinks occur at hot spots which 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.

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. Also, 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 metalostatic 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 general rule, the risers should be as small in diameter and as tall as is practical. This means a diameter not much greater than  $1\frac{1}{2}$  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



| Time (minutes) for total solidification of 4 × 4 inch cylindrical feeders |      |      |      |      |
|---------------------------------------------------------------------------|------|------|------|------|
|                                                                           | 1    | 2    | 3    | 4    |
| Steel                                                                     | 5 0  | 13 4 | 7 5  | 43 0 |
| Copper                                                                    | 8 2  | 14 0 | 15 1 | 45 0 |
| Aluminum                                                                  | 12 3 | 14 3 | 31 1 | 45 6 |

Fig. 8-18. Effect of various heat insulating techniques on the efficiency of feeders for aluminum, copper, and steel castings.

al.<sup>11</sup> have summarized the results of an extensive research program, conducted under the sponsorship of the American Foundrymen's 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 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 60F (33C) 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 Figure 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 3  $T$  to 4  $T$ , 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.

### 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

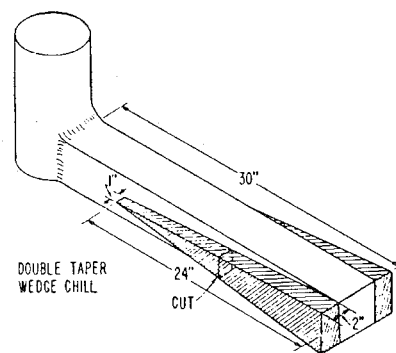


Fig. 8-19. Arrangement of wedge chills on gun-metal bar castings. This method of chilling avoids warpage.

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 the foundryman and the casting designer. The need for consultation at an early stage in design cannot be overemphasized. The foundryman 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:<sup>15</sup>

- 1) 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.
- 2) 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.
- 3) 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. They can, for example, 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).

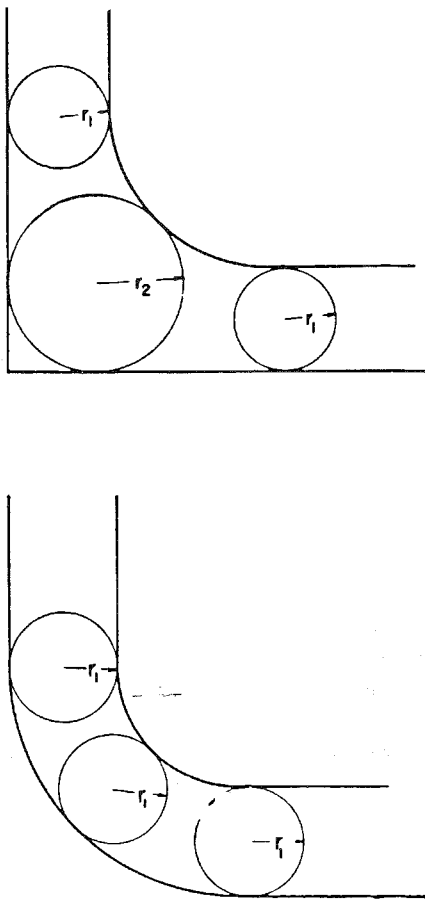


Fig. 8-20. L section redesigned to eliminate hot spots.

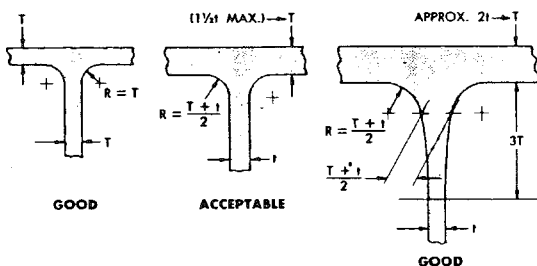


Fig. 8-21. Recommended fillet radii and blending practice for walls intersecting at 90 degrees.

- 4) 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.
- 5) 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.

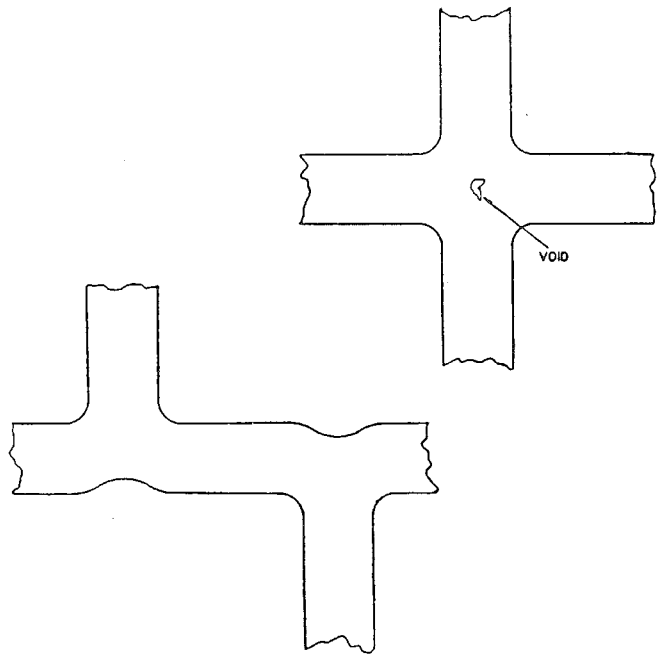


Fig. 8-22. Casting X section redesigned to avoid shrinkage defects.

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 patternmaking and foundry production.

Although such a procedure might seem to delay the design process, the potential for cost savings and quality enhancement certainly justify these suggested steps.

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## Chapter 9

# 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. Most of the individual alloys included here have, in the past, been designated by various commercial or colloquial names. These have now been largely superseded by the United Numbering System (UNS) designations listed in Chapter 1. These designations will, therefore, 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 sequence: copper, tin, lead, zinc.

For the benefit of those 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

These families are interrelated in that each 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 (85-5-5-5) is considered as 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" due to the fact that 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 have 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.

Since 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.

As shown in Table 9-1 (lower left), increasing zinc levels yielded alloys which came to be known as leaded "semi-red" brasses, typified by the alloys presently designated as C84400 (81-3-7-9) and C84800 (76-2½-1½-15). Note that alloy C83800 (83-4-6-7) as well as C83600 (85-5-5-5) have been designated in the past as leaded "red" brasses. Beyond about the 15% zinc level, the alloys fall in the family known as "yellow" brasses, which are included in the group covered in Chapter 10.

A second family of alloys (Table 9-1, lower right) which evolved because of certain engineering property requirements utilizes the excellent strengthening effects and load-bearing properties conferred by increased tin content in combination with the lubricity and bearing qualities imparted by high levels of lead. These materials comprise the 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), C93800 (78-7-15-0) and C94100 (71-6-22-0).

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).

### METALLURGY

As a group, the copper-tin-lead-zinc alloys exhibit very wide freezing ranges (Table 9-2), varying from about 150° to 300°F. Consequently, all solidify in a mushy, dendritic manner (as described in Chapter 8) 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 or processes such as inoculation which are intended to enhance properties by structural modification or grain refinement. Hence, 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

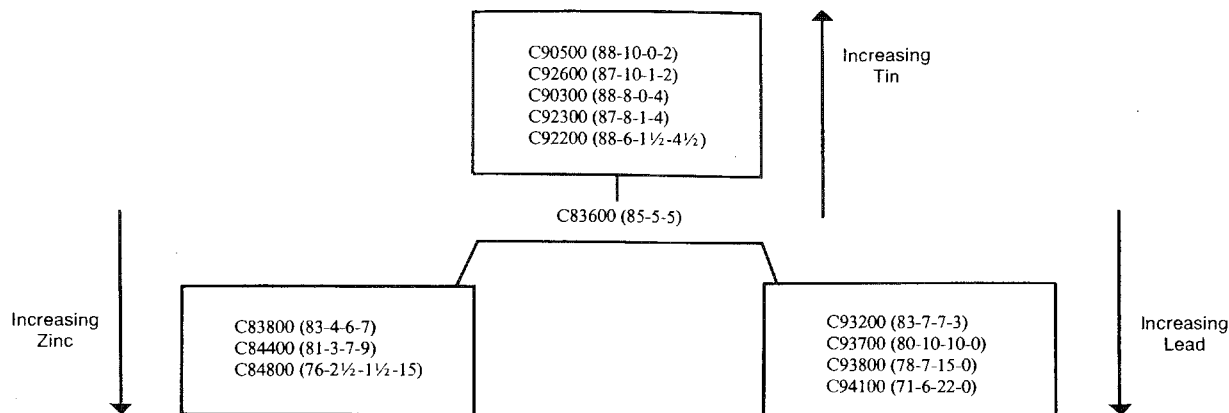


Table 9-1. Families of the Copper-Tin-Lead-Zinc Alloy Group.

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 shortly, however, 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 we can therefore consider the alloys of this group as binary or ternary, with or without lead being present as an insoluble additive.

Even though 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

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" ( $\alpha$ ) 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, we begin to encounter a second, intermediate solid solution ( $\beta$ ). (This "beta" phase will be discussed in more detail in Chapter 10 under yellow brasses.)

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. Zinc has a high vapor-pressure in the molten alloys, and is readily lost

Table 9-2. Solidification Ranges and Recommended Pouring Ranges for Copper-Tin-Lead-Zinc Alloys.

| Alloy  | Freezing Range <sup>1</sup> |            | Pouring Range Classification <sup>2</sup> |
|--------|-----------------------------|------------|-------------------------------------------|
|        | Celsius                     | Fahrenheit |                                           |
| C83600 | 1010-854                    | 1850-1570  | A                                         |
| C83800 | 1004-843                    | 1840-1550  | A                                         |
| C84400 | 1004-843                    | 1840-1550  | 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                                         |

<sup>1</sup>Data from CDA Standards Handbook, Part 7 (1974)

<sup>2</sup>See Table 9-3.

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  |

by evaporation and oxidation. This explains the need to replenish 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 is zinc, since less tin is required for an equivalent increase in strength. Unlike zinc, tin also improves corrosion resistance. As may be 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 above. However, because of 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 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” ( $\delta$ ) 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 520°C (968°F) to room temperature. Also, the “epsilon” ( $\epsilon$ ) phase shown to form at 350°C (662°F) 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 (its solubility being less than 0.005% in solid copper). At the copper-rich end of the diagram, alloy solidification begins with the crystallization of

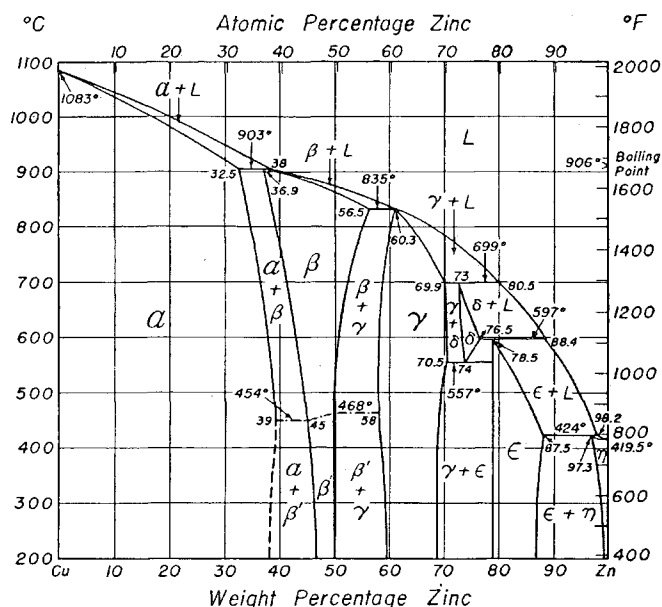


Fig. 9-1. Copper-zinc phase equilibrium diagram.

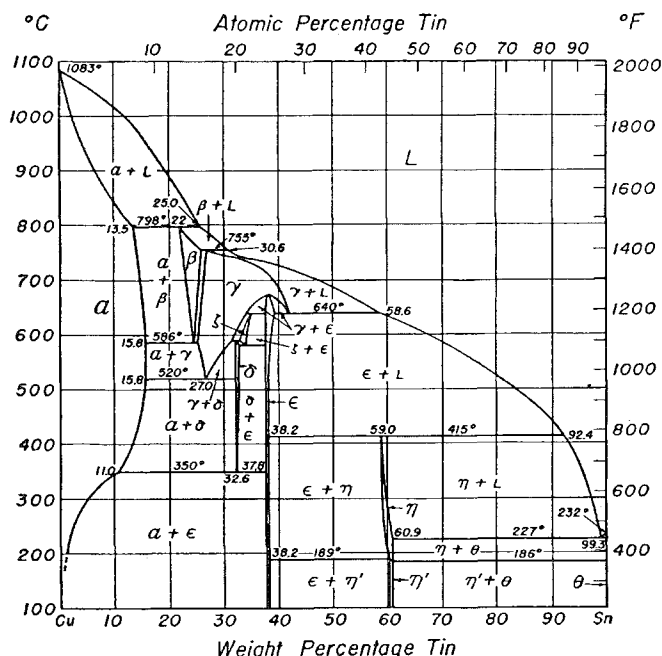


Fig. 9-2. Copper-tin phase equilibrium diagram.

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 41% at the monotectic temperature of 953°C (1747°F).

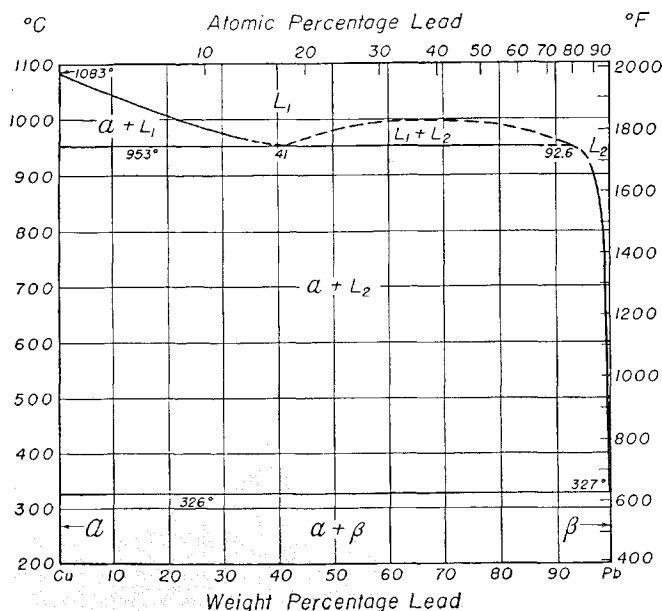


Fig. 9-3. Copper-lead phase equilibrium diagram.

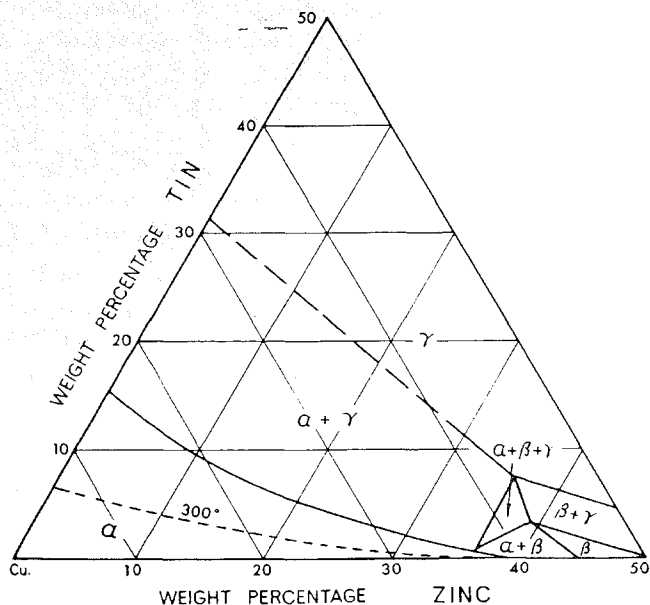


Fig. 9-4. The 500C (932F) isothermal section of the Cu-Sn-Zn ternary equilibrium diagram.

At the monotectic temperature, precipitation of additional copper from the melt occurs isothermally until the liquid eventually attains a composition of 92.6% lead. Next, an extended cooling period follows with little change occurring until, at 326C (619F), 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 Chapter 8). 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 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 500C (932F) 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.

The principal phase occurring in all the commercial alloys is that designated as "alpha" ( $\alpha$ ) 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'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 which 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 exhibit finer grain size and, consequently, finer distribution of the lead particles than do 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 of Fig. 9-4, note that the alpha field is bounded by a two-phased region of compositions consisting of alpha plus gamma ( $\gamma$ ). 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 which 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 brasses. 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.

### MICROSTRUCTURAL VARIATIONS

Since all the alloys of this group exhibit microstructures consisting of 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.

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 so as to extend through the wall of a pressure vessel and allow leakage to occur at isolated locations. These two types of microshrinkage are illustrated in Figs. 9-7 and 9-8. In these photomicrographs the voids appear as black areas which 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

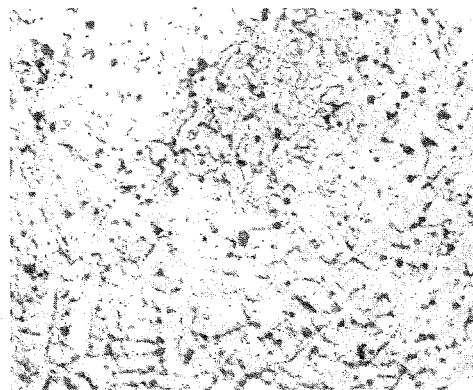


Fig. 9-5. "Coring" in a sand-cast leaded red brass. Ferric chloride etch,  $\times 50$ .

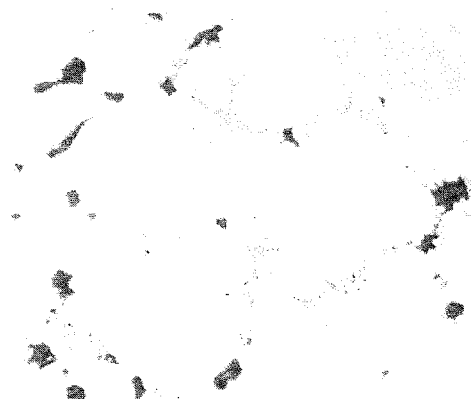


Fig. 9-6. Distribution of lead and alpha-delta eutectoid phases in sand-cast leaded red brass,  $\times 250$ .

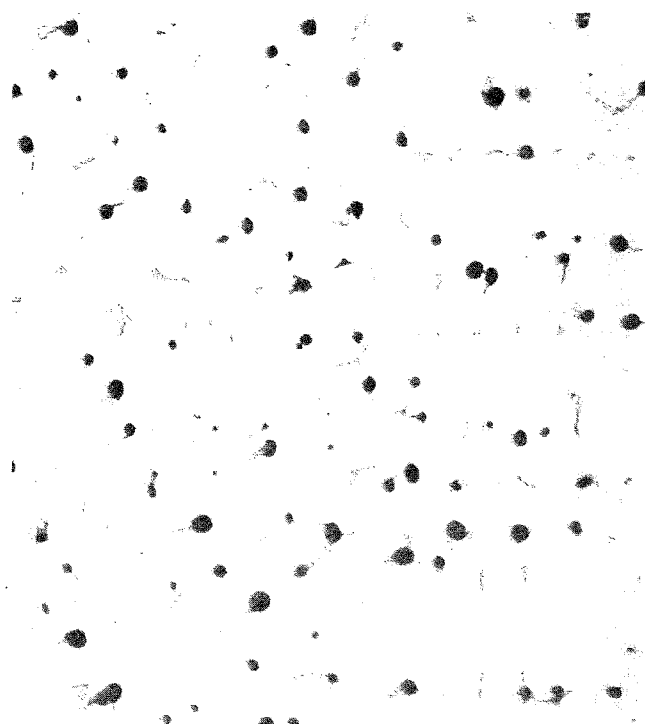
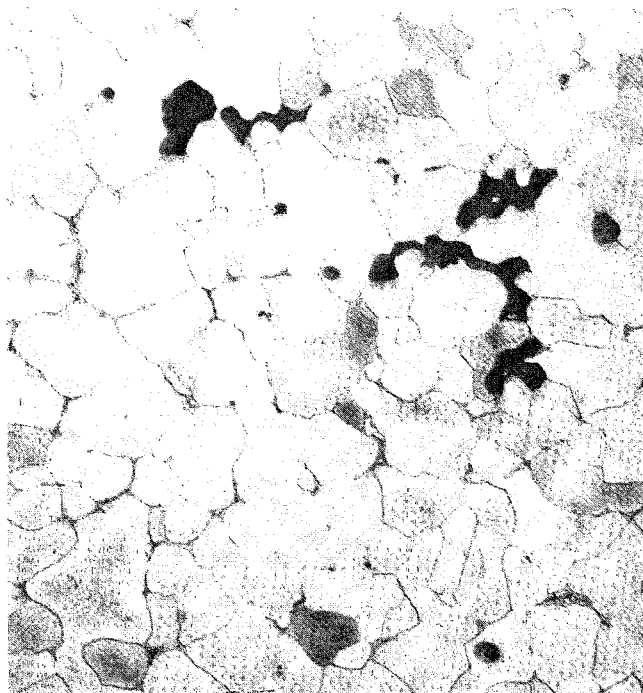


Fig. 9-7. Evenly distributed microshrinkage in C90500 alloy sample having an average density of 8.6 g/cc,  $\times 100$ .



*Fig. 9-8. Localized, interconnected microshrinkage in C90500 alloy sample having an average density of 8.75 g/cc. Despite its higher average density, this sample is much less pressure-tight than that shown in Fig. 9-7. (x50)*

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 as regards 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 induction melting furnaces. When fuel-fired furnaces are used, close atmosphere control (slightly oxidizing conditions) must be maintained, followed by proper deoxidation. Evaluation of the level of dissolved gases is best made by the reduced pressure test described in Chapter 5. Alternatively, one can use the fracture test comparison discussed in Chapter 16, although this is a much less sensitive method.

The proper degree of deoxidation with phosphorus-copper must be established empirically by each foundry, according to its melting practice and product mix. Residual phosphorus levels must be monitored to pre-

vent wide variations, and should normally be targeted and held in the range of about 0.015 to 0.030% (for the reasons explained in Chapters 5 and 16).

In melting, scrap returns should be watched carefully to avoid contamination with undesired elements. Excessive amounts of iron in the melt (from shot blasting, skimming tools, wire, etc.) will cause hard inclusions damaging to cutting tools. Small amounts of either silicon or aluminum (about 0.010% of either) are known to cause serious problems of casting leakage. It is not clear whether these elements do their damage by forming entrapped oxide films in the melt or by permitting the absorption of hydrogen. Excessive superheating and prolonged holding in the melting furnace should be avoided since both lead to excessive zinc loss and gas absorption.

### Gating and Risering

Small castings of uniform section thickness (about ¼ inch or less) can be kiss-gated successfully, using the techniques described in Chapter 7. 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 Chapter 8. Feeding from risers is extremely limited and directional solidification can be achieved only by conditions which produce thermal gradients of 60F/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 Chapter 8. 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.

## 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, is used for valves, pipe fittings, water pump and meter housings and impellers, small gears, high-quality plumbing goods, statuary and plaques. These applications are possible due to the 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)* are the "workhorse" alloys 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 and other pressure vessel applications operating at temperatures 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), the leaded material being the easier to machine.

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# Chapter 10

## 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 lower-strength, leaded yellow brasses; and the high-strength yellow brasses.

The family of leaded yellow brasses has been defined by the American Society for Testing and Materials 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, their 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 and C85700, whose nominal compositions and typical properties are listed in Table 10-1.

Table 10-1. Nominal Composition and Properties of Leaded Yellow Brasses\*

|        | Nominal Composition |        |        |
|--------|---------------------|--------|--------|
|        | C85200              | C85400 | C85700 |
| Copper | 72                  | 67     | 63     |
| Tin    | 1                   | 1      | 1      |
| Lead   | 3                   | 3      | 1      |
| Zinc   | 24                  | 29     | 35     |

| Mechanical Properties (Typical) |    |    |    |
|---------------------------------|----|----|----|
| Tensile str., ksi.              | 38 | 34 | 50 |
| Yield str., ksi                 | 13 | 12 | 18 |
| % Elongation                    | 35 | 35 | 40 |

|            | Freezing Range |             |             |
|------------|----------------|-------------|-------------|
|            | (941-927)      | (940-927)   | (940-913)   |
| Celsius    | (941-927)      | (940-927)   | (940-913)   |
| Fahrenheit | (1725-1700)    | (1725-1700) | (1725-1675) |

\*Copper Development Association. *Standards Handbook*. Part 7 (1974).

The second family in this group, often called *manganese bronzes*, have much higher tensile strengths and are, in fact, the strongest of all the copper-base alloys in the as-cast condition. The term "manganese bronze" is inaccurate and somewhat confusing, since some alloys in this category actually contain very little

manganese. For this reason, these alloys are more properly called *high-strength yellow brasses*. These alloys find application where relatively high strength is required in combination with good corrosion resistance and moderate cost. 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 which are lower in the above elements but higher in zinc content.

Table 10-2. Nominal Composition and Properties of High-Strength Yellow Brasses\*

|           | Nominal Composition |        |        |        |
|-----------|---------------------|--------|--------|--------|
|           | C86200              | C86300 | C86400 | C86500 |
| Copper    | 65                  | 62     | 58     | 58     |
| Aluminum  | 4                   | 6      | 1      | 1      |
| Iron      | 3                   | 3      | 1      | 1      |
| Manganese | 3                   | 3      | 0.5    | 0.5    |
| Lead      | —                   | —      | 1      | —      |
| Zinc      | 25                  | 26     | 38.5   | 39.5   |

| Minimum Mechanical Properties |        |         |        |        |
|-------------------------------|--------|---------|--------|--------|
| Tensile str.                  | 90 ksi | 110 ksi | 60 ksi | 65 ksi |
| Yield str.                    | 45 ksi | 60 ksi  | 20 ksi | 25 ksi |
| Elongation                    | 18%    | 12%     | 15%    | 20%    |

| Freezing Range |           |           |           |           |
|----------------|-----------|-----------|-----------|-----------|
| Fahrenheit     | 1725-1650 | 1693-1625 | 1616-1583 | 1616-1583 |
| Celsius        | 941-899   | 923-885   | 880-862   | 880-862   |

\*Copper Development Association. *Standards Handbook*. Part 7 (1974).

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 ( $\alpha$ ) solid solutions. The alpha phase is relatively soft and ductile, deriving

Table 10-3. Tensile Strengths of Annealed  
Cu-Zn Binary Alloys

| % Zinc | Nominal Tensile Strength, ksi |
|--------|-------------------------------|
| 0      | 32                            |
| 15     | 40                            |
| 20     | 44                            |
| 30     | 47                            |
| 35     | 48                            |
| 40     | 54                            |

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 consist essentially of single-phase ( $\alpha$ ) 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.

### High-Strength Yellow Brasses

As the zinc content of Cu-Zn alloys is increased significantly beyond 32.5% (as for alloys C86400 and C86500), the microstructures of the alloys begin to show increasing amounts of a second, "beta" ( $\beta$ ) phase. The beta phase has significantly greater hardness and strength (and lower ductility) than does the alpha phase, and hence it has a marked strengthening effect on the alloys. The beta phase or, more precisely, the "beta-prime" ( $\beta'$ ) 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.

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% 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 microstructure shown in Fig. 10-1. Note here that the alpha phase, which appears as an acicular structure, has formed by precipitation from a single, beta phase which 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 which 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 microstructures of alloys C86200 and C86300 are shown in Figs. 10-2 and 10-3, respectively. The high beta content of these structures accounts for their 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



Fig. 10-1. As-cast (sand) microstructure of alloy C86500 (58% Cu, 0.5% Sn, 39.5% Zn, 1% Fe, 1% Al). Light, acicular alpha phase in beta matrix. (100x)

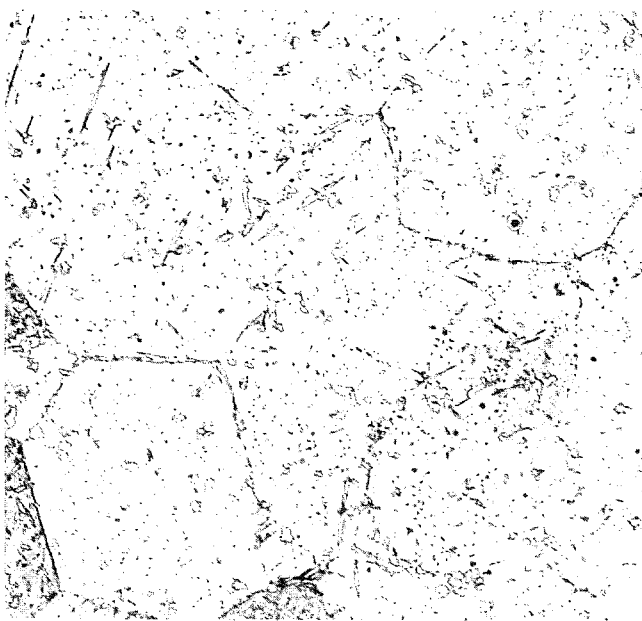


Fig. 10-2. As-cast (sand) microstructure of alloy C86200, showing matrix structure of beta phase with relatively small, acicular particles of alpha phase at grain boundaries and within grains. (200x)

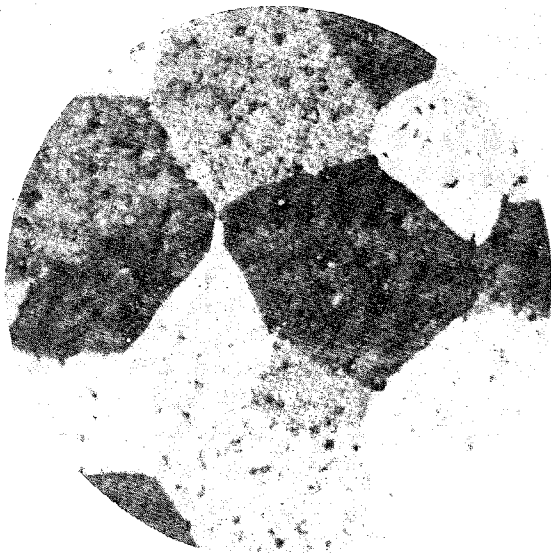


Fig. 10-3. As-cast (sand) microstructure of alloy C86300 (63% Cu, 25% Zn, 3% Fe, 6% Al, 3% Mn). Constituents are the same as in Fig. 10-2 except that very little alpha phase is present. Black specks are iron-rich particles of intermetallic phase (see Fig. 10-4). (100x)

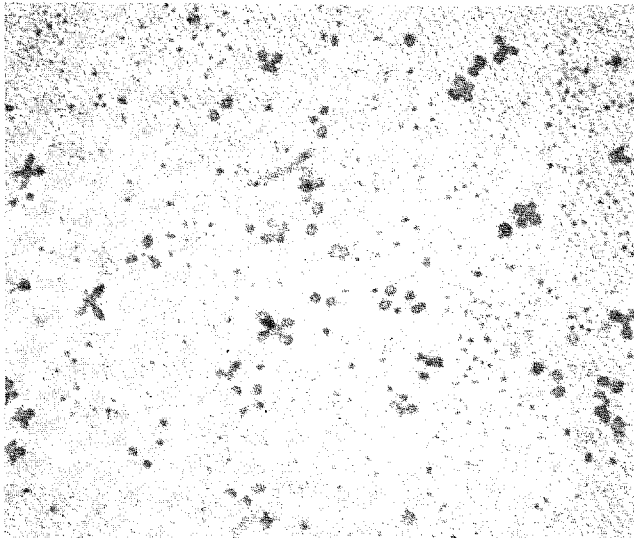


Fig. 10-4. Unetched microstructure of alloy C83600 showing rounded and rosette-shaped inclusions of iron-rich intermetallic phase precipitated along grain boundaries and within grains. (400x)

refinement. This is particularly important for castings containing both thin and thick sections. In the absence of iron additions, heavy sections which 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 as shown in Fig. 10-4 at (400x magnification). 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 alloys.

The role of manganese in the high-strength yellow brasses remains obscure. Although it has a low zinc equivalent (0.5), it will slightly increase strength 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 relatively 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 properties, 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" ( $\gamma$ ) phase at the grain boundaries, resulting in severe brittleness of the castings.

It should be noted that the "all-beta" alloys generally have good hot-toughness (unless contaminated by lead). However, these materials have a reputation for being "hot short" at about 400C (752F) and require care in shake-out.

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 casting 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, acts as a grain refiner in the leaded yellow brasses and increases strength and hardness to some degree. Nickel likewise refines the grain size. Aluminum is sometimes added in small amounts to control flaring and to produce smooth casting surfaces. No more than 0.2% aluminum should be used for this purpose, and aluminum should be avoided entirely for castings which must be pressure-tight. To attain better fluidity in casting thin 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.

## 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 metal(s) 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 which may inadvertently be introduced into heats of high-strength yellow brasses. In the case of alloys C86500 and C86400, 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 corrosion 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 thus 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. 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. Also, 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 melting losses when added as protective covers. Fluxes are ordinarily found to be 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 so as 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 to chill-cast a finger bar (approximately  $\frac{1}{2}$  x  $\frac{1}{2}$  x 8 in.) which 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.

Good temperature control must be maintained in order 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 (1121 to 1193C) and, for heavy castings, 1900 to 2050F (1038 to 1121C). 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 15).

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 (1066C). 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 (954 to 1121C). 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 Chapter 7. 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 Chapters 7 and 6.)

## 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, for 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.

Outstanding strength, in combination with corrosion resistance and moderate cost are the principal attributes of the high-strength yellow brasses. As already 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 all-beta alloys C86200 and C86300, because of their low levels of tin and lead, are weldable; alloys C86400 and C86500 are not. When welding is done, the casting should be stress-relief annealed as described in the section of this chapter dealing with 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 somewhat better corrosion resistance and find applications as gears, valve stems, and some marine fittings. Their resistance to dezincification in seawater is somewhat 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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# Chapter 11

## ALUMINUM BRONZE

### 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 B148-78. The alloys listed in Table 11-1 include aluminum bronze, nickel-aluminum bronze, silicon-aluminum bronze, and manganese-nickel aluminum bronze. For more detailed information on specific alloys and processes, refer to the references at the end of this chapter.

### 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 600-750F (316 to 399C), valve components, spark-resistant tools, forming dies, rolls and shoes used in metal shaping.

### METALLURGY

#### Aluminum and Nickel-Aluminum Bronze

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 an introduction to this literature. What follows is a simplified treatment.

Copper-aluminum alloys containing up to about 9.25% aluminum should exhibit a single phase alpha ( $\alpha$ ) structure according to the equilibrium phase diagram shown in Figure 11-1 (a). However, due to the presence of the alloying elements nickel and/or iron, the microstructures of commercial alloys always contain the kappa ( $\kappa$ ) nickel- or iron-rich phase. The structures for alloys containing aluminum and 4% each of iron and nickel are shown in the pseudo-binary equilibrium diagram of Figure 11-1 (b). In addition, because of non-equilibrium solidification and cooling which characterize the casting process, the alloys with more than about 8.5% aluminum contain substantial beta ( $\beta$ ) phase at higher temperatures. This transforms to alpha plus gamma<sub>2</sub> ( $\alpha + \gamma_2$ ) as the casting cools to room temperature, and additional kappa is also formed in this reaction.

Thus it is common to find a microstructure consisting of an alpha matrix in which are embedded particles of kappa, and an intimate mixture of alpha + kappa + gamma<sub>2</sub> in the areas formerly occupied by the high-temperature beta phase. The gamma<sub>2</sub> phase is detrimental to both ductility and seawater corrosion resistance. The amount of this phase in the microstructure increases with the aluminum content; therefore, the

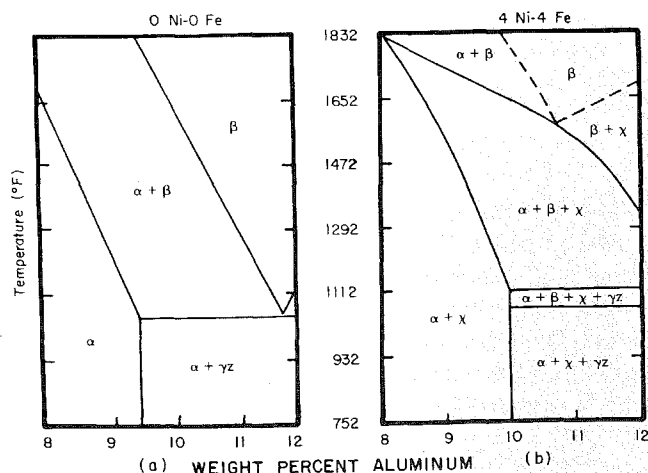


Fig. 11-1. Equilibrium phase relationships for (a) aluminum bronze, and (b) nickel-aluminum bronze.

Table 11-1. Nominal Composition of Aluminum Bronze Sand Casting Alloys, ASTM B148-78

| Copper Alloy No. (CDA)                  | Old Designation | Commercial Designation | Nominal Composition, percent |        |      |          |         |           |
|-----------------------------------------|-----------------|------------------------|------------------------------|--------|------|----------|---------|-----------|
|                                         |                 |                        | Copper                       | Nickel | Iron | Aluminum | Silicon | Manganese |
| Aluminum bronze C95200                  | 9A              | Grade A                | 88.0                         | —      | 3.0  | 9.0      | —       | —         |
| Aluminum bronze C95300*                 | 9B              | Grade B                | 89.0                         | —      | 1.0  | 10.0     | —       | —         |
| Aluminum bronze C95400*                 | 9C              | Grade C                | 85.0                         | —      | 4.0  | 11.0     | —       | —         |
| Aluminum bronze C95500*                 | 9D              | Grade D                | 81.0                         | 4.0    | 4.0  | 11.0     | —       | —         |
| Silicon-aluminum bronze C95600          | 9E              | Grade E                | 91.0                         | —      | —    | 7.0      | 2.0     | —         |
| Manganese-nickel aluminum bronze C95700 | 9F              | Grade F                | 75.0                         | 2.0    | 3.0  | 8.0      | —       | 12.0      |
| Nickel-aluminum bronze C95800           | —               | —                      | 81.3                         | 4.5    | 4.0  | 9.0      | —       | 1.2       |

\*These grades respond to heat treatment.

Table 11-2. Chemical Composition Requirements for Aluminum Bronze Sand Castings, ASTM B148-78<sup>a</sup>

| Classification       | Aluminum Bronze |          |           |           | Silicon-Aluminum Bronze | Manganese-Nickel-Aluminum Bronze | Nickel-Aluminum Bronze |
|----------------------|-----------------|----------|-----------|-----------|-------------------------|----------------------------------|------------------------|
| Copper Alloy Number  | C95200          | C95300   | C95400    | C95500    | C95600                  | C95700                           | C95800                 |
| Composition, percent |                 |          |           |           |                         |                                  |                        |
| Copper, min          | 86.0            | 86.0     | 83.0      | 78.0      | 88.0                    | 71                               | 79.0                   |
| Aluminum             | 8.5–9.5         | 9.0–11.0 | 10.0–11.5 | 10.0–11.5 | 6.0–8.0                 | 7.0–8.5                          | 8.5–9.5                |
| Iron                 | 2.5–4.0         | 0.75–1.5 | 3.0–5.0   | 3.0–5.0   | —                       | 2.0–4.0                          | 3.5–4.5 <sup>b</sup>   |
| Manganese            | —               | —        | 0.50 max  | 3.5 max   | —                       | 11.0–14.0                        | 0.8–1.5                |
| Nickel               | —               | —        | 2.5 max   | 3.0–5.5   | 0.25 max                | 1.5–3.0                          | 4.0–5.0 <sup>b</sup>   |
| Silicon              | —               | —        | —         | —         | 1.75–3.25               | 0.10 max                         | 0.10 max               |
| Lead                 | —               | —        | —         | —         | —                       | 0.03 max                         | 0.03 max               |
| Total named elements | 99.0            | 99.0     | 99.5      | 99.5      | 99.0                    | 99.5                             | 99.5                   |

<sup>a</sup> Analysis shall regularly be made for all the elements designated in this table.

<sup>b</sup> Iron content shall not exceed the nickel content.

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 gamma<sub>2</sub> phase in the casting microstructure. Both nickel and iron combine with the aluminum to form complex kappa phases and thus increase the amount of aluminum necessary to introduce the gamma<sub>2</sub> phase. Figure 11-1 (b) is considered representative of the equilibrium diagram for alloy C95800. The addition of manganese to the aluminum-bronze is reported to slow down the transformation of beta phase to the alpha-plus-gamma<sub>2</sub> eutectoid. The effects of an additional 4% nickel, 3% iron and 1% manganese on the as-cast microstructure of a 9% aluminum alloy are illustrated in Figure 11-2.

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 beta phase to the alpha-plus-gamma<sub>2</sub> 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.

The specified chemical composition requirements of ASTM B148-78 for the aluminum bronzes are presented in Table 11-2. In addition to the elements listed, impur-

ity elements can significantly alter properties. The addition of lead, which is virtually insoluble and forms isolated interdendritic particles, has a beneficial influence on machinability. Additions over 1% are necessary for significant changes. Lead also can be added to improve bearing properties where lubrication is poor, but such aluminum bronze alloys have reduced strength and ductility. For castings to be welded or heat-treated, the lead content should be below 0.1% 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, exceed to 1%. Zinc is not considered to have a harmful effect on either mechanical properties or corrosion resistance unless amounts greater than 1% are present. Generally, small amounts of tin up to approximately 0.2% are not considered harmful. Magnesium has been recommended as a deoxidant, but even 0.01% is said to have a harmful effect on ductility. Phosphorus is reputed to be a harmful impurity, but does not alter the usual mechanical properties until more than 0.8% is present; however, hot shortness may be encountered during welding at levels as low as 0.01%.

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



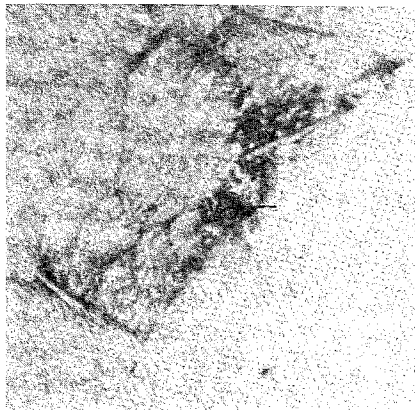
(a-1) 3Fe - 1Mn



(b-1) 4Ni - 1Mn



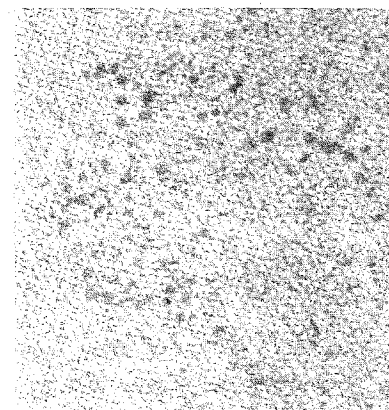
(c-1) 3Fe - 1Mn



(a-2) 3Fe - 3Mn  
Effect of manganese on as-cast structure of a 9% Al-4% Ni alloy (500x).



(b-2) 5Ni - 1Mn  
Effect of nickel on as-cast structure of a 9% Al, 3% Fe alloy (500x).



(c-2) 5Fe - 1Mn  
Effect of iron on as-cast structure of a 9% Al-4% Ni alloy (500x).

Fig. 11-2. Effects of composition on microstructure of aluminum bronze. Basic composition 9% Al, 4% Ni, 3% Fe, and 1% Mn.

are normally subjected to two-step thermal treatments: a solution treatment in the range of 1450 to 1700F (788 to 927C) followed by rapid cooling plus a temper in the range of 1100 to 1250F (593 to 677C), also followed by quenching in water or oil. 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 11-3. Alloy C95800, when intended for seawater service, is normally given a temper anneal heat-treatment at 1200 to 1300F (650 to 700C) to dissolve any gamma phase, and is still required to meet the minimum tensile properties specified in Table 11-3 for non-heat-treated material.

#### Manganese-Nickel Aluminum Bronze

The C95700 alloys are reported to solidify with an all-beta structure, but below approximately 1560F (850C) some beta phase transforms to alpha phase resulting in an alpha-plus-beta microstructure in which are embedded a number of iron-manganese, and nickel-rich intermetallic compounds. Aluminum has the greatest effect on mechanical properties, 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 resistance but has little effect on tensile properties. Tin additions of about 0.25% reportedly improve 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 to 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 1050F (565C) or at 1200F (650C) has been reported to improve the seawater corrosion resistance of weldments. Slow cooling below about 1000F (550C) increases magnetic permeability

Table 11-3. Mechanical Property Requirements for Aluminum Bronze Sand Castings, ASTM B148-78

| Classification                                   | Aluminum Bronze |             |             |              | Silicon-Aluminum Bronze | Manganese-Nickel-Aluminum Bronze | Nickel-Aluminum Bronze |
|--------------------------------------------------|-----------------|-------------|-------------|--------------|-------------------------|----------------------------------|------------------------|
|                                                  | As-Cast         |             |             |              |                         |                                  |                        |
| Copper Alloy Number                              | C95200          | C95300      | C95400      | C95500       | C95600                  | C95700                           | C95800                 |
| Tensile strength, min, ksi (MPa)                 | 65<br>(450)     | 65<br>(450) | 75<br>(515) | 90<br>(620)  | 60<br>(415)             | 90<br>(620)                      | 85<br>(585)            |
| Yield strength <sup>a</sup> , min, ksi (MPa)     | 25<br>(170)     | 25<br>(170) | 30<br>(205) | 40<br>(275)  | 28<br>(195)             | 40<br>(275)                      | 35<br>(240)            |
| Elongation in 2 in. (50.8 mm) percent            | 20              | 20          | 12          | 6            | 10                      | 20                               | 15                     |
| Brinell hardness No. <sup>b</sup> (3000 kg load) | 110             | 110         | 150         | 190          | —                       | —                                | —                      |
| Heat-Treated                                     |                 |             |             |              |                         |                                  |                        |
| Copper Alloy Number                              | —               | 953         | 954         | 955          | —                       | —                                | —                      |
| Tensile strength, min, ksi (MPa)                 | —               | 80<br>(550) | 90<br>(620) | 110<br>(760) | —                       | —                                | —                      |
| Yield strength <sup>a</sup> min, ksi (MPa)       | —               | 40<br>(275) | 45<br>(310) | 60<br>(415)  | —                       | —                                | —                      |
| Elongation in 2 in. (50.8 mm), percent           | —               | 12          | 6           | 5            | —                       | —                                | —                      |
| Brinell hardness no. <sup>b</sup> (3000 kg load) | —               | 160         | 190         | 200          | —                       | —                                | —                      |

<sup>a</sup> Yield strength shall be determined as the stress producing an elongation under load of 0.5 percent, that is, 0.01 in. (0.254 mm) in a gage length of 2 in. (50.8 mm).

<sup>b</sup> For information only.

and reduces ductility and impact resistance due to low-temperature precipitation of manganese-rich compounds.

## MECHANICAL PROPERTIES

The minimum tensile and hardness properties as specified in ASTM B148-78 are listed in Table 11-3. For additional information on the physical and/or mechanical properties of these copper-base casting alloys, the reader should see references 2 and 3 at the end of this chapter, and also refer to Chapter 17.

## 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 Chapter 3.)

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 in recent years have also been produced by continuous casting.

### 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.

In most cases, for light castings of nonuniform 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 so as to reduce the likelihood of turbulence.

The general practice of using several small gates should be avoided, as should 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 which 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 so as to feed the portions of the casting that solidify last.

Typical gating and risering systems are shown in Figs. 11-3 through 11-9, and modern practice is also described in Chapter 7. Molds are often tilted to ensure progressive solidification. Tilting machines similar to those used for large aluminum permanent molds are sometimes used.

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. In Europe, select compositions of aluminum bronze are widely used in permanent mold casting.

### Melting and Pouring

Practically all equipment suitable for other brasses 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.

Fluxes can be used advantageously with aluminum bronze for the purpose of providing a cover over the molten metal and thereby preventing gas absorption, and for preventing the formation of oxides. Also, 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 actual practice, fluxes should be used with caution as the slag which is formed may be difficult to remove and can attack crucibles and furnace linings.

Induction melting is satisfactory provided the power input is reduced to avoid turbulence and thus prevent the surface oxide skin from being broken and stirred into the melt. 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:

1) Preheat a clean crucible to normal operating temperature.

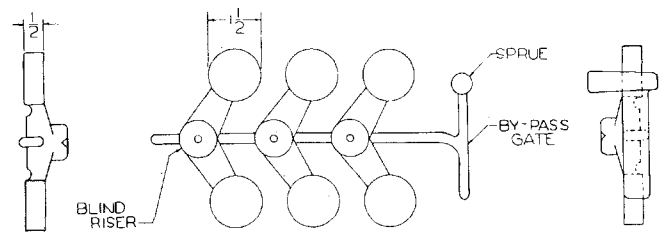


Fig. 11-3. Typical gating and risering system for matchplate casting.

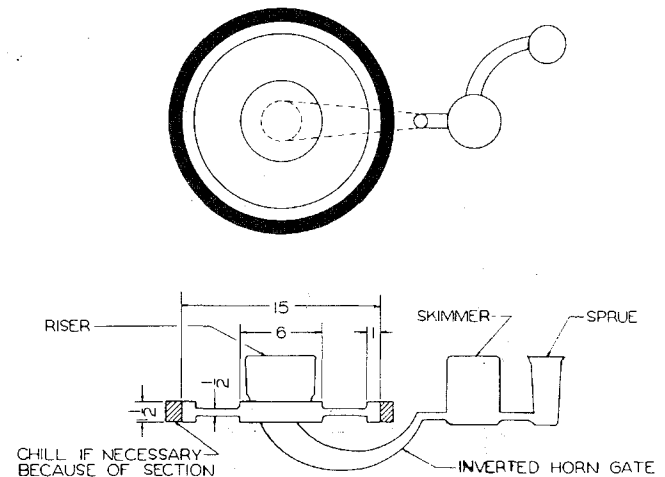


Fig. 11-4. An example of conventional chilling, gating, and risering technique.

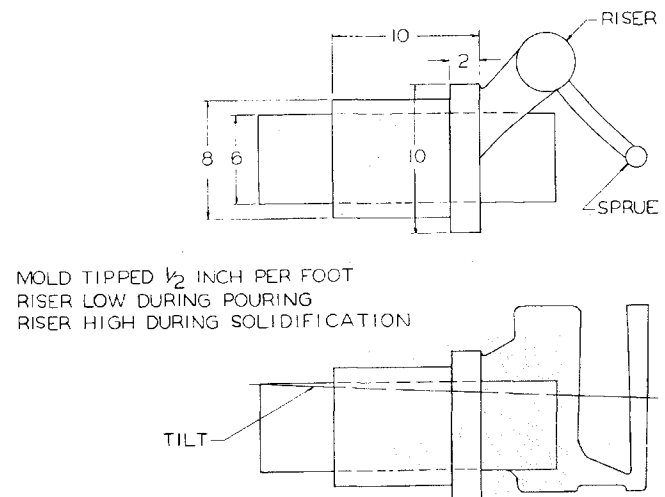


Fig. 11-5. An example of tilt-pouring and feeding.

- 2) 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.
- 3) The remainder of any metal to be charged into the crucible should first be preheated by the exhaust gases leaving the furnace.
- 4) Add the balance of the charge while the metal in the crucible is still in the semi-solid state.

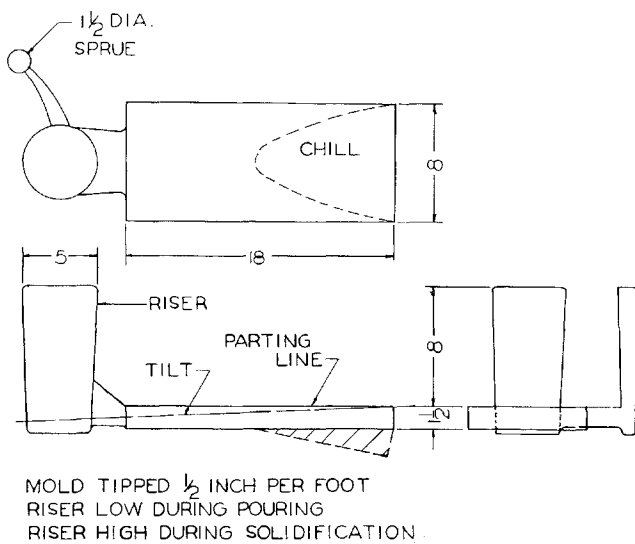


Fig. 11-6. Another example of tilt-pouring and feeding.

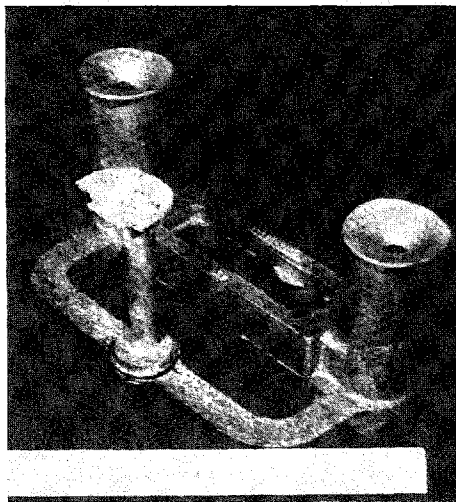


Fig. 11-7. An aluminum bronze casting with tapered round sprue, drag runner, and screens under the combination gate-risers.

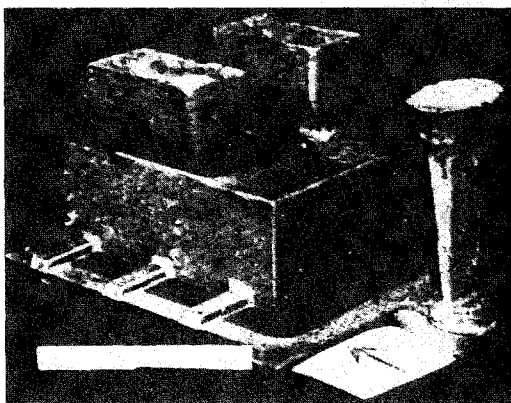


Fig. 11-8. A gating system for aluminum bronze showing a tapered rectangular sprue, choked (arrow) drag runners, and cope gates.

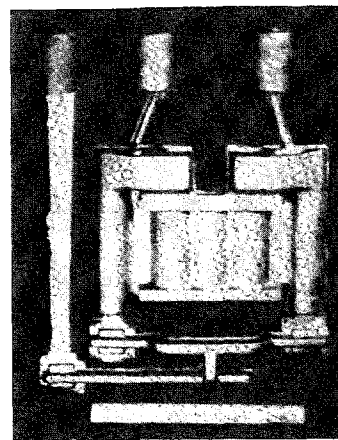


Fig. 11-9. An aluminum bronze casting utilizing the principles of vertical gating with screens and web gates.

- 6) Before pouring make a gas-check determination using the shrink bar or, preferably, the vacuum 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.
- 7) 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 be dissolved and the melt be homogeneous in all respects.

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 (28-55C) 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. However, as rapid cooling from 1100F (600C) to room temperature in-

- 5) 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.

hibits kappa and alpha-gamma<sub>2</sub> transformation, early shakeout of larger castings may enhance corrosion resistance. 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 subsolidus 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.<sup>13,14</sup>

### 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 Chapter 15. 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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## Chapter 12

# COPPER-SILICON ALLOYS

### INTRODUCTION

This chapter covers two families of alloys, the *silicon bronzes* and the *silicon brasses*. By definition, the distinction between the two families is a matter of zinc content—the *bronzes* containing not over 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,” and differed principally in zinc content. Today, the cast versions of these two alloys are both encompassed in a single UNS designation number and constitute the only members of this family.

The silicon brasses, which were developed somewhat later, possess the fluidity and castability of the silicon bronzes, and also have the advantage of lower melting points as a result of their higher zinc contents. This makes the silicon brasses particularly well-suited for both pressure die casting and permanent-mold casting. Although several commercial compositions exist (see Chapter 1), only two representative alloys are covered in this chapter.

The popular usage of silicon bronzes reached a peak 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.

### PROPERTIES AND APPLICATIONS

#### Silicon Bronze

As shown in Chapter 1, alloy C87200 is the only alloy listed which qualifies as a silicon bronze, by virtue of the limitation on zinc content (5% max.):

|                            | Min. | Max. | Nominal |
|----------------------------|------|------|---------|
| Al                         |      | 1.5  |         |
| Cu                         | 89.0 |      |         |
| Fe                         |      | 2.5  |         |
| Pb                         |      | 0.50 |         |
| Mn                         |      | 1.5  |         |
| Si                         | 1.0  | 5.0  | 4       |
| Sn                         |      | 1.0  |         |
| Zn                         |      | 5.0  |         |
| Tensile strength: 45.0 ksi |      |      |         |
| Yield strength: 18.0 ksi   |      |      |         |
| Elongation: 20%            |      |      |         |

In practice, two compositions continue to be produced and used, one being essentially zinc-free and the other containing a nominal 4% zinc:

|                 | Nominal Compositions, C87200 |    |    |    |
|-----------------|------------------------------|----|----|----|
|                 | Cu                           | Si | Zn | Mn |
| “Herculoy”-type | 92                           | 4  | 4  | —  |
| “Everdur”-type  | 95                           | 4  | —  | 1  |

It can be seen that both alloys fall within the chemical composition limits of 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.

Many have observed that the zinc-containing alloy seems less prone to gas pick-up during melting, being less temperature-sensitive in this regard. Conversely, the zinc-free composition has somewhat better corrosion resistance in certain environments. In general, however, both compositions are 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 Chapter 17).

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

Although several different alloy compositions exist within the family of silicon brasses, two have been selected for the purpose of discussion as being representative.

## Nominal Composition

|                       | C87500                     | C87900                     |
|-----------------------|----------------------------|----------------------------|
| Cu                    | 82                         | 65                         |
| Si                    | 4                          | 1                          |
| Zn                    | 14                         | 34                         |
| Tensile strength, ksi | 60 min.                    | 70 typ.                    |
| Yield strength, ksi   | 24 min.                    | 35 typ.                    |
| Elongation, %         | 16 min.                    | 25 typ.                    |
| Freezing range        | (916-821C)<br>(1680-1510F) | (926-899C)<br>(1700-1650F) |

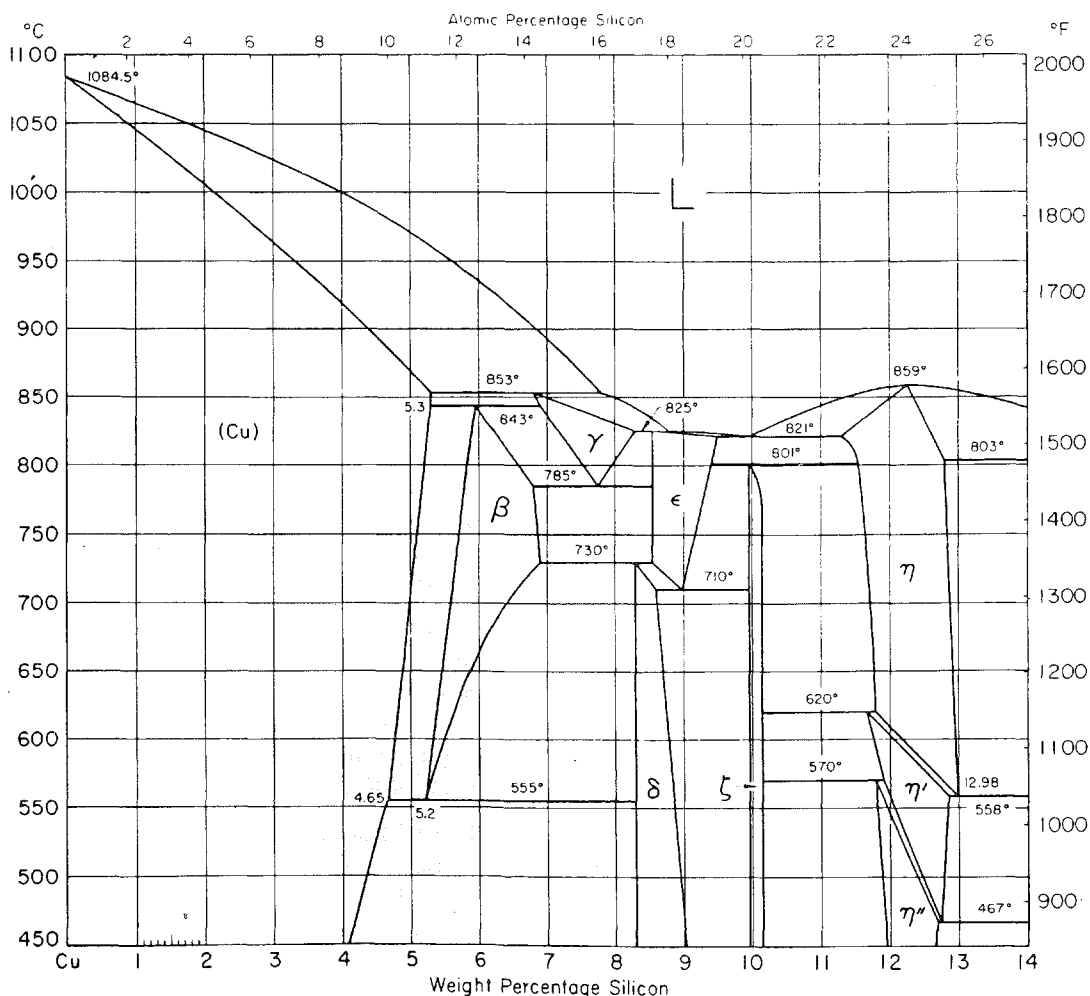
The mechanical properties listed for C87500 are minimum values, per ASTM B584, for test bars separately cast from sand molds. Alloy properties can vary widely, depending on the actual levels of silicon and zinc within the specification limits; close control of composition must therefore be exercised 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.

Alloy C87900 is actually a yellow brass (34% zinc) with 1% silicon added to impart fluidity and to control drossing. This alloy likewise has a rather low melting temperature and is used extensively for the production of pressure die castings where moderate strength is required. Addition of aluminum up to the maximum allowed by the specification (0.15%) is most necessary in order to obtain good fluidity and to suppress zinc flaring during casting. This alloy is used very little for sand castings because of its drossing tendency and susceptibility to gas pickup. The mechanical properties listed above are typical values for die-cast parts made in accordance with ASTM B176.

## METALLURGY & EFFECTS OF IMPURITIES

The copper-silicon phase equilibrium diagram shown in Fig. 12-1 indicates that binary alloys containing less than 4% silicon should solidify as single-phase, "alpha" ( $\alpha$ ) solid solutions. This is essentially the case for the low-zinc (Everdur) version of C87200, whose normal microstructure is shown in Fig. 12-2 at 100x magnification. Here, the most distinctive feature is the dendritic pattern seen within the grains (coring), resulting from micro-segregation during solidification. The presence of other elements within the permissible limits, and particularly iron and manganese, causes the

Fig. 12-1. Copper-silicon phase-equilibrium diagram.



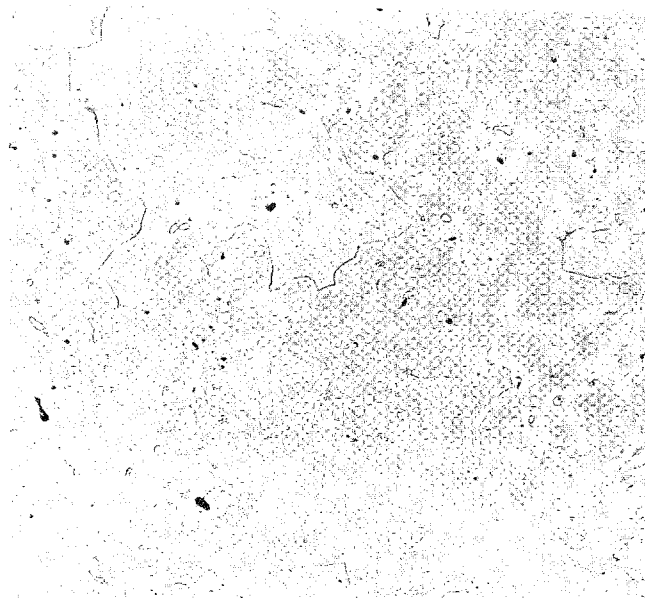


Fig. 12-2. Microstructure of "Everdur" (low-zinc) version of C87200 (3.5% Si, 1.5% Fe), showing cored alpha matrix with a few small, white beta islands. Black areas are porosity. (Ferric chloride etch, 100x)

formation 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" ( $\beta$ ) phase at the grain boundaries of the alpha matrix. Figure 12-3 shows the same microstructure as Fig. 12-2, but at a magnification of 500x. At this magnification one can readily see the precipitated particles of the iron-manganese-silicon intermetallics as well as a few isolated colonies of the beta phase. Note that this phase, in the earlier literature dealing with the copper-silicon phase-equilibrium diagram, was formerly identified as the "kappa" ( $\kappa$ ) phase. The phase-equilibrium diagram indicates that the beta phase, below 555C (1031F), should decompose to form an alpha-delta ( $\delta$ ) eutectoid. The sluggishness of this reaction is such that the delta phase is seen only in slowly cooled sections.

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 "Herculoy" (4% zinc) version of C87200 and also of alloy C87500, 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. 12-4,

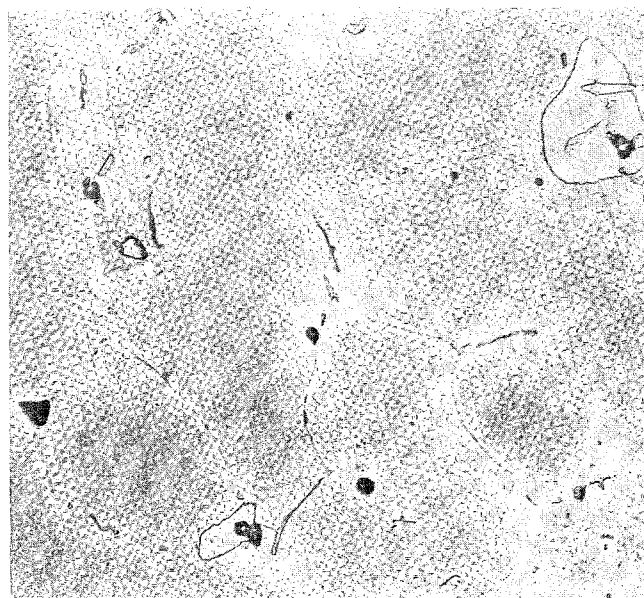


Fig. 12-3. Same as Fig. 12-2, showing evidence of fine precipitates in the cored, alpha structure plus larger (gray) intergranular particles of Fe-Mn-Si intermetallics. Light areas are islands of beta. (500x)

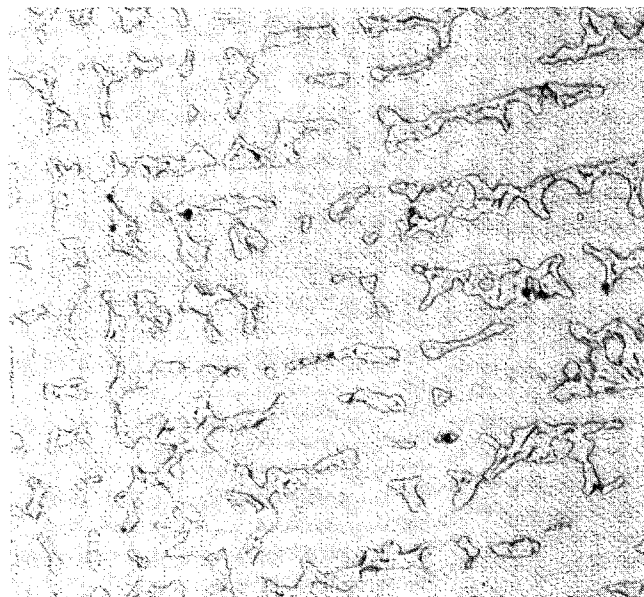


Fig. 12-4. Microstructure of "Herculoy" (high-zinc) version of C87200 (3.75% Si, 4.75% Zn), showing alpha matrix with large amounts of beta phase located in interdendritic areas. (100x)

the beta phase occurs within the interdendritic areas of the alpha matrix. At higher magnification (Fig. 12-5) 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.

The high zinc content (34%) of alloy C87900, together with its low (1%) silicon content, causes it to more nearly resemble a yellow brass. Its microstructure is essentially single-phased (alpha), explaining its



Fig. 12-5. Same as Fig. 12-4, showing alpha phase free of precipitates with striation marks surrounding the large islands of beta. The acicular particles within the beta phase are probably the silicon-rich delta phase. (300x)

relatively high ductility. Its excellent tensile strength results from solid-solution strengthening, plus the very fine grain size due to the rapid cooling rates of the die casting process.

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. Conversely, the specification for alloy C87200 allows maximum values of 1.0% Sn, 0.5% Pb, 2.5% Fe, 1.5% Al, and 1.5% Mn. This is because practically all of these have been used as alloying elements (rather than "impurities") in commercial variations of C87200.

The effects of the foregoing elements on alloy C87200 are twofold. First, because of their respective effects on the solubility limits of silicon, their presence will influence the amount of beta in the microstructure, similar to the effect of zinc and aluminum in the high-strength yellow brasses (Chapter 10). For example, increased aluminum in the alloy increases the percentage of beta formed (with commensurate increases in strength and hardness and decrease in ductility). Second, these elements affect diffusion rates during solidification and subsequent cooling, causing variations in the degree of coring and the tendency of the beta phase to transform to the equilibrium, alpha-delta eutectoid structure at lower temperatures.

It is obviously necessary, therefore, to exert close control on alloy composition limits and impurities in order to achieve consistent mechanical properties for alloy C87200. 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 reported that homogenization of a cored struc-

ture by soaking 8 hours at 700C (1292F) 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 Chapter 5. Tests with alloys C87200 and C87500 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. The following are suggested pouring temperature ranges:

| C87200                  | C87500                  |
|-------------------------|-------------------------|
| Thin sections           |                         |
| 2050-2250F (1121-1232C) | 1900-2100F (1038-1140C) |
| Heavy sections          |                         |
| 1900-2050F (1038-1121C) | 1800-1900F (982-1038C)  |

Alloys C87200 and C87500 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). The intermediate freezing ranges of these alloys, as explained in Chapter 8, require feeding techniques which utilize high thermal gradients in the mold in order to achieve directional solidification and subsequent freedom from shrinkage porosity.

Alloy C87900, because of its higher zinc content, has a much greater drossing tendency. This explains the earlier statement that the maximum allowable aluminum content is often added to suppress flaring. Alloy

C87900 has a rather narrow freezing range; as noted, however, the alloy is used almost exclusively for pressure diecasting where the usual principles of gating and risering do not apply.

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## Chapter 13

# 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 and military specifications. Table 13-1 gives the chemical composition and tensile properties for these two alloys in ASTM B369. Conforming specifications and additional properties can be found in Chapters 2 and 17.

A considerable amount of work has been done on a chromium-modified 70/30 cupronickel alloy (IN-768)<sup>3,11</sup> and on beryllium<sup>7</sup> and silicon-beryllium<sup>8</sup> 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 can the tin bronzes and 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 (columbium), 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. 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 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

The nickel silver alloys are characterized by a pleasing white appearance. These alloys are 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. These alloys contain from 12 to 25% nickel, 2 to 20% zinc, up to 5% tin, and up to 9% lead. ASTM B584 covers the 12%, 20% and 25%-nickel, leaded nickel silver alloys. The nominal compositions and properties are shown in Table 13-2. The most commonly used casting applications are relatively low in zinc, and also contain tin and lead.

### Nickel-Tin Bronzes

The nickel-tin bronzes provide a useful combination of high strength, corrosion-resistance, and good wear

Table 13-1. Chemical composition and tensile properties for 70/30 and 90/10 cupronickel alloys.

| Copper Alloy<br>UNS No. | ASTM<br>Spec. |               | Cu           | Ni          | Fe           | Si       | Mn        | Pb*      | Nb           | C | Yield Strength<br>min. ksi | Tensile Strength<br>min. ksi | Elong. in 2 in.<br>min. % |
|-------------------------|---------------|---------------|--------------|-------------|--------------|----------|-----------|----------|--------------|---|----------------------------|------------------------------|---------------------------|
| C96200                  | B369          | min.<br>max.  | 84.5<br>11.0 | 9.0<br>1.8  | 1.0<br>0.30  | —<br>1.5 | —<br>0.03 | —<br>1.0 | —<br>0.10    | — | 25                         | 45                           | 20                        |
| C96400                  | B369          | min.<br>max.* | 65.0<br>32.0 | 28.0<br>1.5 | 0.30<br>0.50 | —<br>1.5 | —<br>0.03 | —<br>1.5 | 0.50<br>0.15 | — | 32                         | 60                           | 20                        |

\*Weldability test requirements may not be attained if the lead content exceeds 0.01%.

Table 13-2. Nominal chemical composition and minimum tensile properties of nickel silver alloys—ASTM B584.

| Copper Alloy<br>UNS No. | Commercial<br>Designation                   | Cu | Sn | Pb | Zn | Ni | Yield<br>Strength<br>Minimum, ksi | Tensile<br>Strength<br>Minimum, ksi | Elongation<br>% in 2 in.<br>Minimum, ksi |
|-------------------------|---------------------------------------------|----|----|----|----|----|-----------------------------------|-------------------------------------|------------------------------------------|
| C97300                  | 12% leaded nickel<br>silver (nickel bronze) | 57 | 2  | 9  | 20 | 12 | 15                                | 30                                  | 8                                        |
| C97600                  | 20% leaded nickel<br>silver (nickel bronze) | 64 | 4  | 4  | 8  | 20 | 17                                | 40                                  | 10                                       |
| C97800                  | 25% leaded nickel<br>silver (nickel bronze) | 66 | 5  | 2  | 2  | 25 | 22                                | 50                                  | 10                                       |

Table 13-3. Nominal chemical composition and minimum tensile properties of nickel-tin bronze and leaded nickel-tin bronze (ASTM B584).

| Copper Alloy<br>UNS No. | Commercial<br>Designation        | Composition |    |    |    |    | Minimum Mechanical Properties |                   |                        |
|-------------------------|----------------------------------|-------------|----|----|----|----|-------------------------------|-------------------|------------------------|
|                         |                                  | Cu          | Sn | Pb | Zn | Ni | Tensile<br>Strength           | Yield<br>Strength | Elongation<br>in 2 in. |
| C94700                  | Nickel-Tin Bronze Gr A           | 88          | 5  | —  | 2  | 5  | 45 ksi                        | 20 ksi            | 25                     |
| C94700 H.T.             | Age-hardened                     |             |    |    |    |    | 75 ksi                        | 50 ksi            | 5                      |
| C94800                  | Leaded Nickel-Tin<br>Bronze Gr B | 87          | 5  | 1  | 2  | 5  | 40 ksi                        | 20 ksi            | 20                     |
| C94900                  | Leaded Nickel-Tin<br>Bronze Gr C | 80          | 5  | 5  | 5  | 5  | 38 ksi                        | 15 ksi            | 15                     |

Table 13-4. Nominal composition and properties of Monel castings.<sup>19</sup>

| Material  | Condition        | Composition |       |      |      |      |      |       |    | Yield<br>Point,<br>1000 psi | Tensile<br>Strength,<br>1000 psi | % Elongation<br>in 2 in. | Brinell<br>Hardness,<br>3000 kg | Impact Strength    |                      |
|-----------|------------------|-------------|-------|------|------|------|------|-------|----|-----------------------------|----------------------------------|--------------------------|---------------------------------|--------------------|----------------------|
|           |                  | Ni          | Cu    | Fe   | Mn   | Si   | C    | S     | Cr |                             |                                  |                          |                                 | Std. Izod<br>ft-lb | Std. Charpy<br>ft-lb |
| Monel     | as cast          | 63.00       | 32.00 | 1.50 | 0.75 | 1.60 | 0.15 | 0.015 | —  | 32-40                       | 65-90                            | 45-25                    | 125-150                         | 80-65              | 70                   |
| "H" Monel | as cast          | 63.00       | 31.00 | 2.00 | 0.75 | 3.00 | 0.10 | 0.015 | —  | 60-80                       | 90-115                           | 20-10                    | 175-250                         | 45-35              | 40                   |
|           | age-hardened     |             |       |      |      |      |      |       |    | 80-115                      | 110-145                          | 4-1                      | 275-350                         | 9-3                | 4                    |
|           | annealed         |             |       |      |      |      |      |       |    | —                           | —                                | —                        | 225-260                         | —                  | —                    |
| "S" Monel | annealed         | 63.00       | 30.00 | 2.00 | 0.75 | 4.00 | 0.10 | 0.015 | —  | 80-115                      | 110-145                          | 4-1                      | 300-375                         | 5-1                | —                    |
|           | and age-hardened |             |       |      |      |      |      |       |    |                             |                                  |                          |                                 |                    |                      |

properties. ASTM B584 covers two leaded nickel-tin bronze alloys and the nickel-tin age-hardenable 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 nominal compositions and properties of Monel castings; the most widely used alloy is specified in ASTM A494,<sup>17</sup> and additional data are given in ASM's *Metals Handbook*.<sup>20</sup>

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.

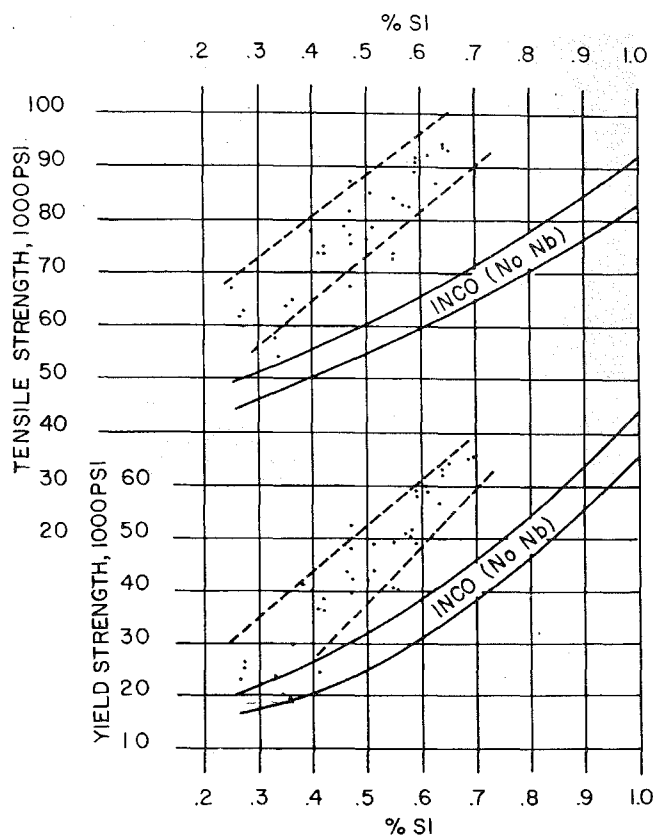


Fig. 13-1. Influence of Si and Nb on strength of 70/30 cupronickel. Heats contain major elements within the percent range of: Cu 65.7–68.4; Ni 28.8–31.6; Mn 0.83–1.41; Fe 0.50–0.94 (except one with 1.07% designated by dot inside box); Cb 0.33–0.83.<sup>4</sup>

## 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 which 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,<sup>4</sup> silicon was utilized to increase the strength. With over about 0.40% silicon, tensile properties of MIL-C-20159 could be met; however, visible weld cracks oc-

curred 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<sup>4</sup> 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.<sup>9</sup>

Table 13-5 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 increase in yield strength but low elongation may result.<sup>11</sup>

While the niobium and silicon content 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 13-6.

The cooling rate effects discussed above explain the results given in Table 13-7, which show the influence of test-bar design and early shakeout. Clearly, slower cooling gives higher strength and lower ductility.

The strength of small castings usually can be improved by a so-called homogenization heat treatment.<sup>4</sup> (This involves heating to 1200F, holding for 1 hour at temperature, and furnace cooling to 500F.) The effect of this treatment is illustrated in Table 13-8<sup>4</sup> for separately cast test bars (small castings) as well as for

Table 13-5. Effect of Si and Nb content on mechanical properties of specimens machined from the modified keel blocks.<sup>11</sup>

| Melt No.        | Wt % Si | Wt % Nb | 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    |         |         |               | 60 min   | 32 min  | 20 min |
| 0.7 max 1.5 max |         |         |               |          |         |        |

\*Do not meet the ASTM B369-72 mechanical property requirement.

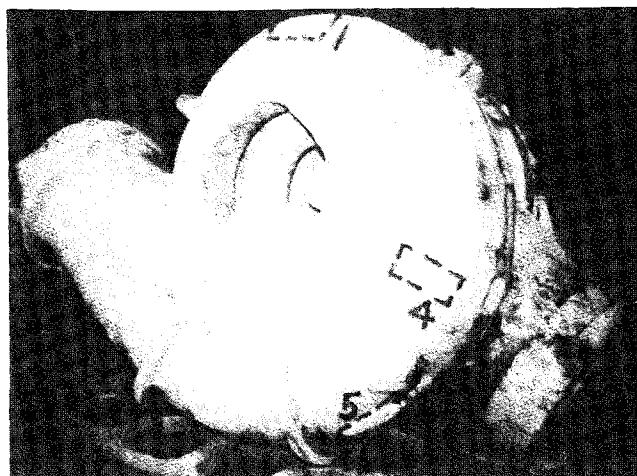


Fig. 13-2. 70/30 Cupronickel alloy. Location of test bars removed from casting. Cleaned casting weight is 3950 pounds. See Table 13-8 for tensile properties of specimens.<sup>4</sup>

Table 13-6. Tensile properties and hardness of 70/30 cupronickel with various cooling and aging conditions.<sup>9</sup>

| Condition                                            | Y.S.<br>0.5% EUL<br>ksi | Tensile<br>Strength<br>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                       |
| 1600F-O.Q. + 1100F 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. + 1200F A (15 hours)                      | —                       | —                          | —        | 185                       |
| ASTM B369 (C96400 alloy minimum)                     | 32.0                    | 60.0                       | 20       | —                         |

O.Q. = oil quench

A = aging temperature °F, furnace cooled to 500F after aging.

#### 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 |

those removed from a large casting. Figure 13-2<sup>4</sup> illustrates the type of casting and location of test bars. The casting shown in the figure weighed 3950 lbs (cleaned weight). The homogenization treatment 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<sub>3</sub>Nb, Ni<sub>3</sub>Si, or Nb<sub>2</sub>Ni<sub>3</sub>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.

#### 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.<sup>7,8</sup> However, environmental constraints and potential health hazards when dealing with beryllium have prevented these alloys from becoming popular.

Table 13-7. Effect of test-bar type on tensile properties, vertically cast 1 in. keel block vs. 1 in. full Web-Webbert. Test-bar molds were made in dry oil sand.<sup>9</sup> (See ASTM B208 for test-bar design.)

| Nb   | Si   | Y.S.<br>0.5% EUL |       | Tensile<br>Strength |       | % Elong. |     | BHN (3000kg) |     |
|------|------|------------------|-------|---------------------|-------|----------|-----|--------------|-----|
|      |      | ksi              |       | ksi                 |       |          |     |              |     |
|      |      | 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 |

All above test results were obtained on specimens cooled in the 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\*\*

W = 1 in. full Web-Webbert

K = 1 in. keel block

Table 13-8. Influence of homogenization (aging) heat treatment on tensile properties.<sup>4</sup>

| Type of<br>Test Bar*        | 0.5% Yield Strength |      | Tensile Strength |      | Elongation % |      | BHN (3000 Kg) |      |
|-----------------------------|---------------------|------|------------------|------|--------------|------|---------------|------|
|                             | ksi                 |      | ksi              |      |              |      |               |      |
|                             | As-cast             | Homo | As-cast          | Homo | As-cast      | Homo | As-cast       | Homo |
| 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 |

**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 having 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 a deoxidant prior to pouring. Figure 13-3<sup>11</sup> 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 *spinodal decomposition*.<sup>3</sup> This type of strengthening occurs as the casting cools to room temperature. Since spinodal decomposition is insensitive to cooling rates, it is this factor which gives the alloy remarkably uniform properties over a wide range of section thicknesses. 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 reheat-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 Figure 13-4, the Cr-Si hardened 70/30 alloy contains a fine Cr silicide precipitate in the interdendritic regions.

In addition to the good mechanical properties and unique retention of properties after welding, the alloy also has exceptional impingement-resistance to flowing seawater.<sup>3,11</sup>

### 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. Mechanical properties are also improved as the nickel content increases (Table 13-2). Zinc, in the presence of sufficient nickel, also exerts a definite though less effective influence on whiteness. Tin and lead content exert only a secondary effect. Tin helps to improve corrosion-resistance and castability, while increasing hardness and strength. Lead is added to these alloys for improved pressure-tightness and machinability. Lead is insoluble in the copper-nickel-zinc matrix.

Tin and lead 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

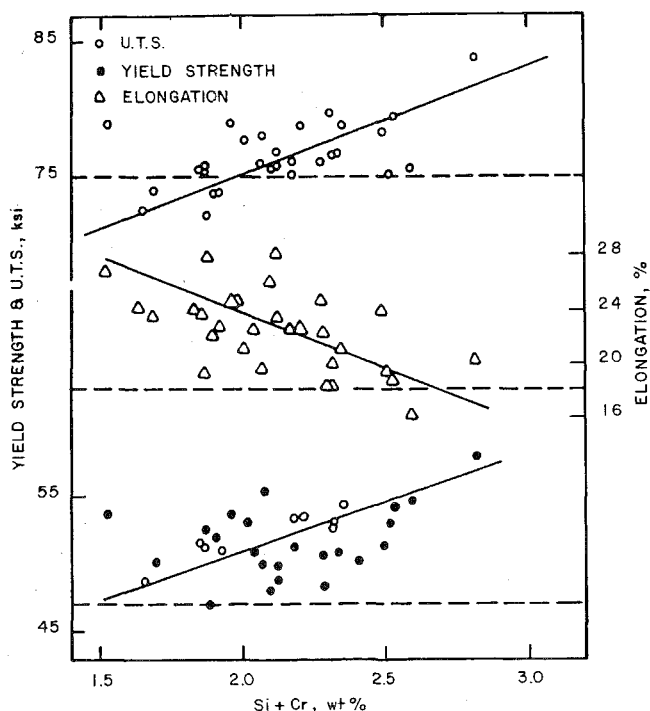


Fig. 13-3. Cumulative effect of Si plus Cr on UTS, yield strength, and elongation of Cu-Ni casting alloys.<sup>11</sup>

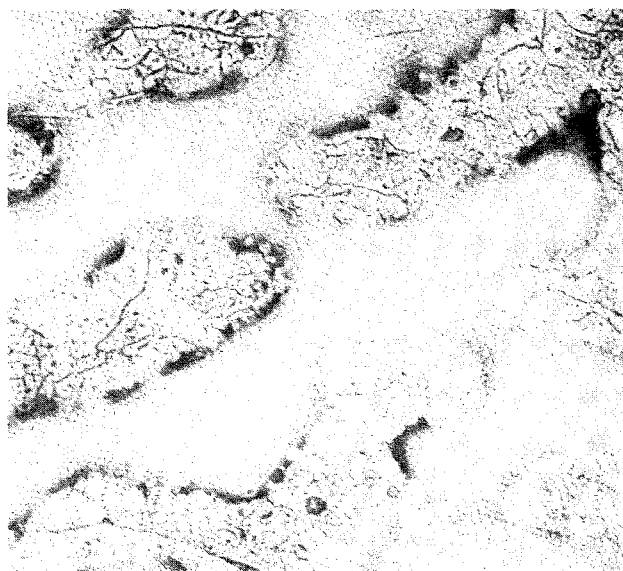


Fig. 13-4. Microstructure of 70/30 Cu-Ni alloy containing 0.26% Si and 1.4% Cr. Shows nickel-rich primary dendrites (white). Vein-like nickel silicides and particles of chromium silicide are precipitated in the interdendritic regions.<sup>11</sup> Etched in alcoholic ferric chloride (x500).

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 (say 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. As little 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 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 Figure 13-5.

Manganese and magnesium are added as deoxidizers and desulphurizers. Both have little effect on strength, although manganese is said to improve the foundry characteristics. Iron is traditionally present in amounts of about 2%, and slightly increases strength by reducing silicon solubility. Iron may also have a beneficial effect on grain size and corrosion-resistance. 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 hard-

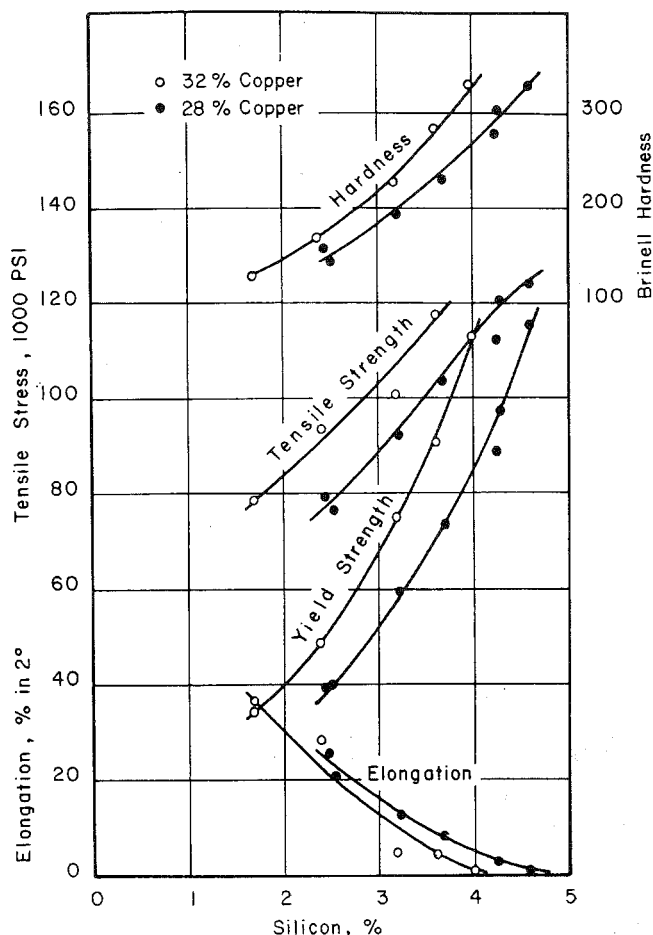


Fig. 13-5. Effect of copper and silicon on properties of cast Monel induction furnace heats.<sup>18</sup>

ness and reducing the impact properties as shown in Table 13-9. For the normal 1.5% Si Monel, a carbon content in the range of 0.15-0.20% is usually preferred.

### MELTING PRACTICE

The general foundry characteristics of the copper-nickel alloys are given in Table 13-10. 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-

Table 13-9. Effect of carbon content on the mechanical properties of 28% copper, 1.25% silicon Monel metal.

| %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   | 90     | 70     | 63     | 58     | 58     | 50     |
| BHN      | 118    | 125    | 140    | 148    | 150    | 149    |

(Courtesy Victor T. Popp, Union Carbide Corp.)

Table 13-10. Casting characteristics.<sup>14</sup>

| Alloy Designation              | Drossing       | Gassing        | Fluidity | Shrinkage | Casting Yield | Effect of Section Size on Soundness and Mech. Properties | Melting Range °F |
|--------------------------------|----------------|----------------|----------|-----------|---------------|----------------------------------------------------------|------------------|
| <b>Cupronickel Alloys</b>      |                |                |          |           |               |                                                          |                  |
| 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)  |
| CuNiSiBe 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)   |
| <b>Nickel Silvers</b>          |                |                |          |           |               |                                                          |                  |
| 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)   |
| <b>Ni-Sn Bronzes</b>           |                |                |          |           |               |                                                          |                  |
| 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)  |

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 Chapters 5, 6, 9 and 10). 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 Chapter 5 and Reference 6). 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 Chapters 5 and 6.

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 they 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 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, then thoroughly deoxidized 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 inert gas, such as by 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 melt-down, using nickel or iron tubes depending on the iron content of the melt.

Besides the effect of carbon as a gas former, 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 melting practice for a Nb-Si modified 70/30 cupronickel is detailed below.

#### *Induction Practice—Nb-Si Modified 70/30<sup>9</sup>*

- 1) Place electrolytic copper at the bottom of the furnace and pack revert around it to create a high-density charge. Add nickel next.
- 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 references 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.

#### **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:

- 1) 5 oz of 70/30 copper manganese shot, added about 3 minutes before pouring.
- 2) 1 oz of stick magnesium after treating with the manganese alloy.
- 3) 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 in 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 fuels, 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.

## **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 the alloys.

The CO<sub>2</sub>-silicate process has been quite successful in small to very large molds for all of the alloys. However, some trouble has been encountered with CO<sub>2</sub>-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 nobake sand binders can be utilized for casting production with these alloys as discussed in Chapter 3.

## **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 burn-on are more critical than they are for casting 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 gate systems.

The cupronickel and Monel families are often produced to very stringent quality control standards, requiring radiography, and 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 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 so 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 dross readily at the high pouring temperatures. Besides careful gating practice involving non-pressurized, non-turbulent systems, it is desirable to use the lowest possible pouring temperature. 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 only causes more dross formation.

### **Monels**

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-slagging” 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 260F (145C), 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 ther-

mal gradients where maximum soundness is required. Figure 13-6 shows a typical rigging.

### Cupronickels and Monels

While the cupronickel and Monel alloys are classified as having a narrow solidification range, the literature indicates that some researchers<sup>8,11</sup> have found the cupronickels to be intermediate when compared to narrow-freezing-range alloys such as aluminum bronzes (6-30F, 3-16C) and manganese bronzes (30-75F, 16-46C). For example, the solidification range of CuNiSiBe is reported to be 170F (96C). 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. 13-7.

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 microshrinkage. Figure 13-8 is an example of a suc-

cessful practice. The Monel alloys, having a narrower freezing range (50F, or 30C), are somewhat easier to feed.

Table 13-10, cited previously, illustrates the general foundry 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 Chapter 15. However, because of the particular characteristics of these alloys, special care is needed in the following areas.

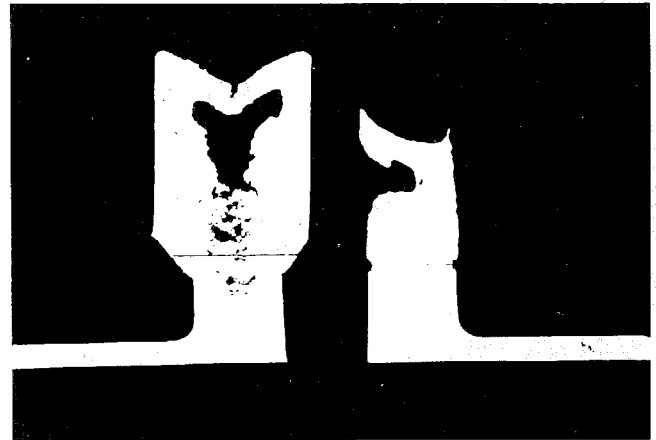


Fig. 13-7. Illustrated are two types of shrinkage characteristics of the cupronickel alloys: piping and interdendritic.

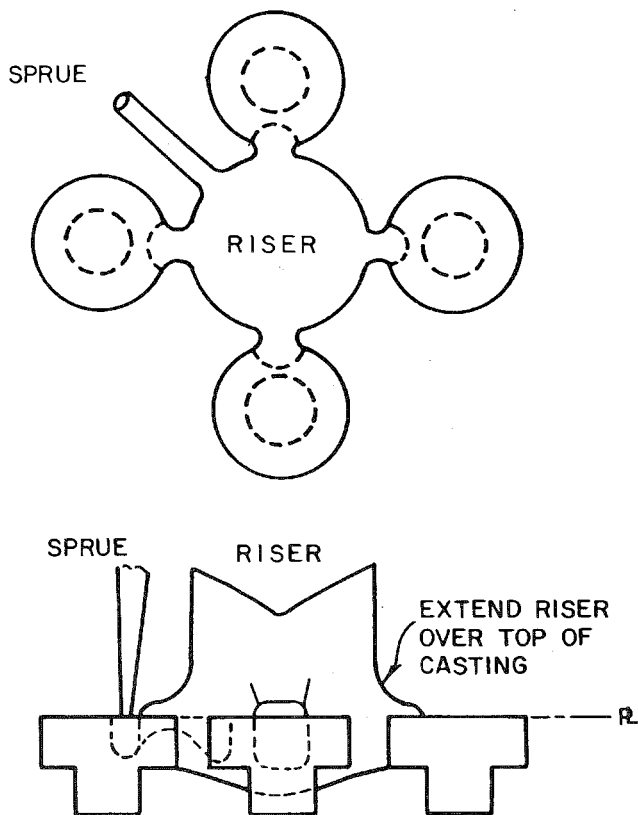


Fig. 13-6. Method of gating small gears and similar castings.

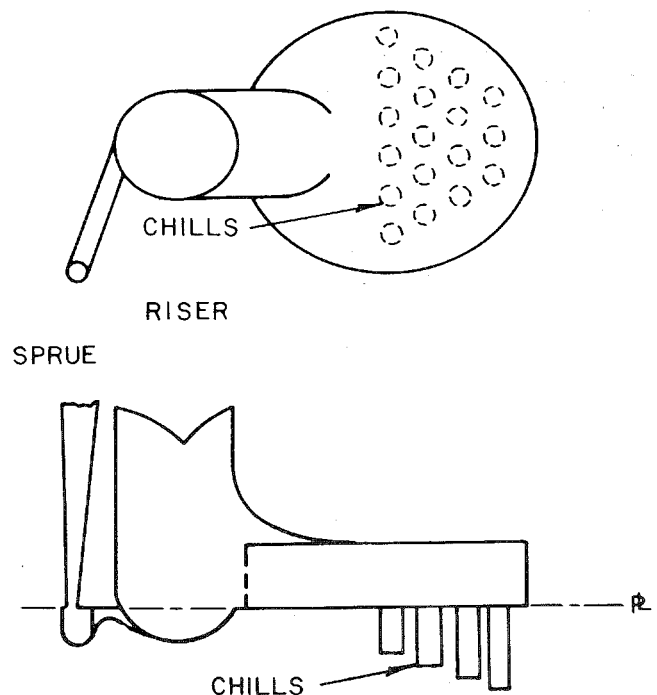


Fig. 13-8. Method of gating and risering disk castings. Note the use of chills to promote directional solidification.

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—about 2700F (1480C)—generate sand defects such as wash, scab, buckle and metal-mold reaction defects.

The high-nickel alloys are sensitive to certain impurities which 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.

## FINISHING

The nickel-containing alloys produce good dense structures when properly handled, and attain a high finish by 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 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 Class 5.6 ECuNi filler metals are available for welding these alloys.

## Effect of Composition

While the cupronickels are considered to be 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 additions of niobium. It is desirable to restrict the silicon level to about 0.40% maximum, with niobium over 0.50% (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 13-11. 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 specifications. 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.

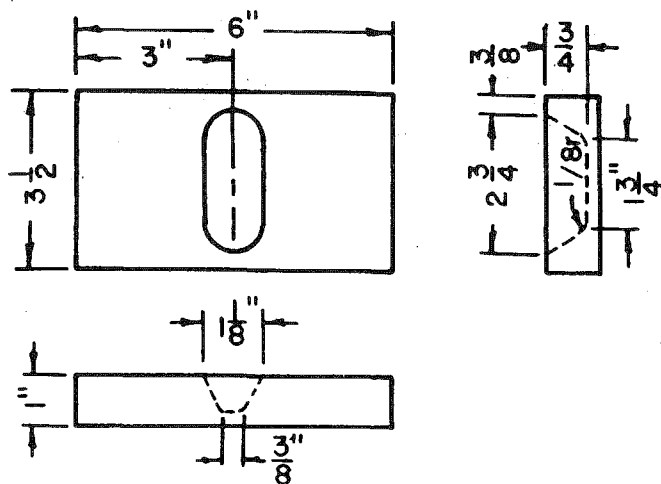
In the chromium-modified 70/30 alloy, it is desirable to limit the silicon content between 0.30 to 0.50% to enhance weldability. Filler metals have been developed to produce tensile and yield strengths which equal or exceed those of the parent casting, and these welds have been successfully bend-tested in accordance with the ASTM B369.

Table 13-11. All-weld metal deposit tensile properties (AWS A5.6 ECuNi).

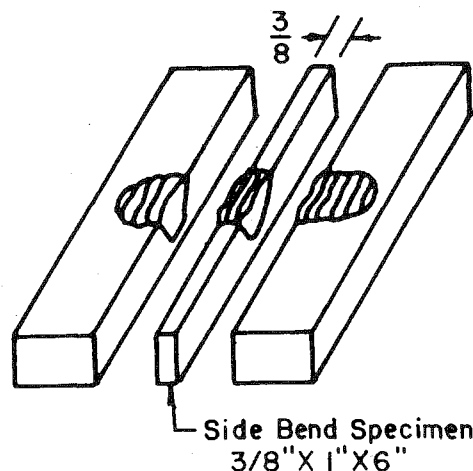
| Condition | Y.S.<br>0.5% Offset,<br>ksi | Tensile<br>Strength<br>ksi | Elong. %<br>in 2 in. | BHN  |
|-----------|-----------------------------|----------------------------|----------------------|------|
| As-welded | 25.5                        | 51.5                       | 49.0                 | 85.5 |

## Chemical Analysis of Weld Deposit

| Cu    | Ni   | Mn   | Si   | Fe   | Pb    | Si   | Al     | Cr    | Ti    | Cb   | S     |
|-------|------|------|------|------|-------|------|--------|-------|-------|------|-------|
| 66.94 | Bal. | 0.81 | 0.01 | 0.57 | 0.007 | 0.16 | 0.0006 | 0.003 | 0.044 | 0.05 | 0.009 |



**Cast Block for  
Weldability Test**



**Weldability Test Block**

*Fig. 13-9. Cast block for weldability test (left), and weldability test block (right).<sup>16</sup>*

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 chemical 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. 13-9. 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<sup>13</sup> 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 con-

stituents 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.

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<sup>2</sup> 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 not amendable to welding.

### 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. 13-10.<sup>11</sup> 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 (spinodal hardening coupled with silicide precipitation).

The high-silicon Monels can be softened by annealing for 1 hour at 1600F (870C), air cooling to 1200F (650C), and then quenching to suppress the precipitation of silicides. Rapidly cooled material can be hardened by aging at 1100F (590C) for 4 to 6 hours, followed by air- or furnace-cooling.

### EFFECT OF IMPURITIES

The effect of impurities on 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.

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

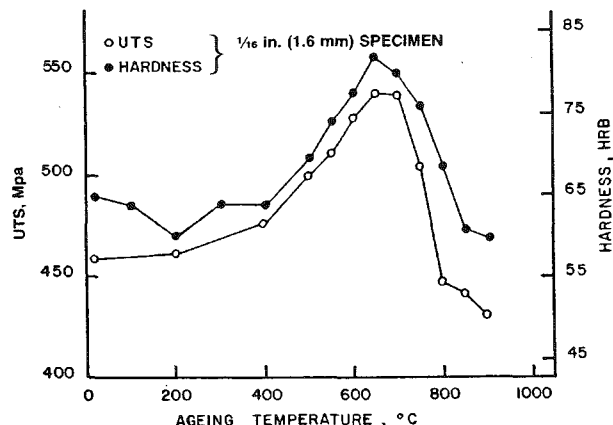


Fig. 13-10. Effect of aging temperature on UTS and hardness of 1.6 mm thick Cu 30%, Ni 0.46%, Si 1.73% Cr (water-quenched after 1 hour at 975C).<sup>11</sup>

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 to be 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.

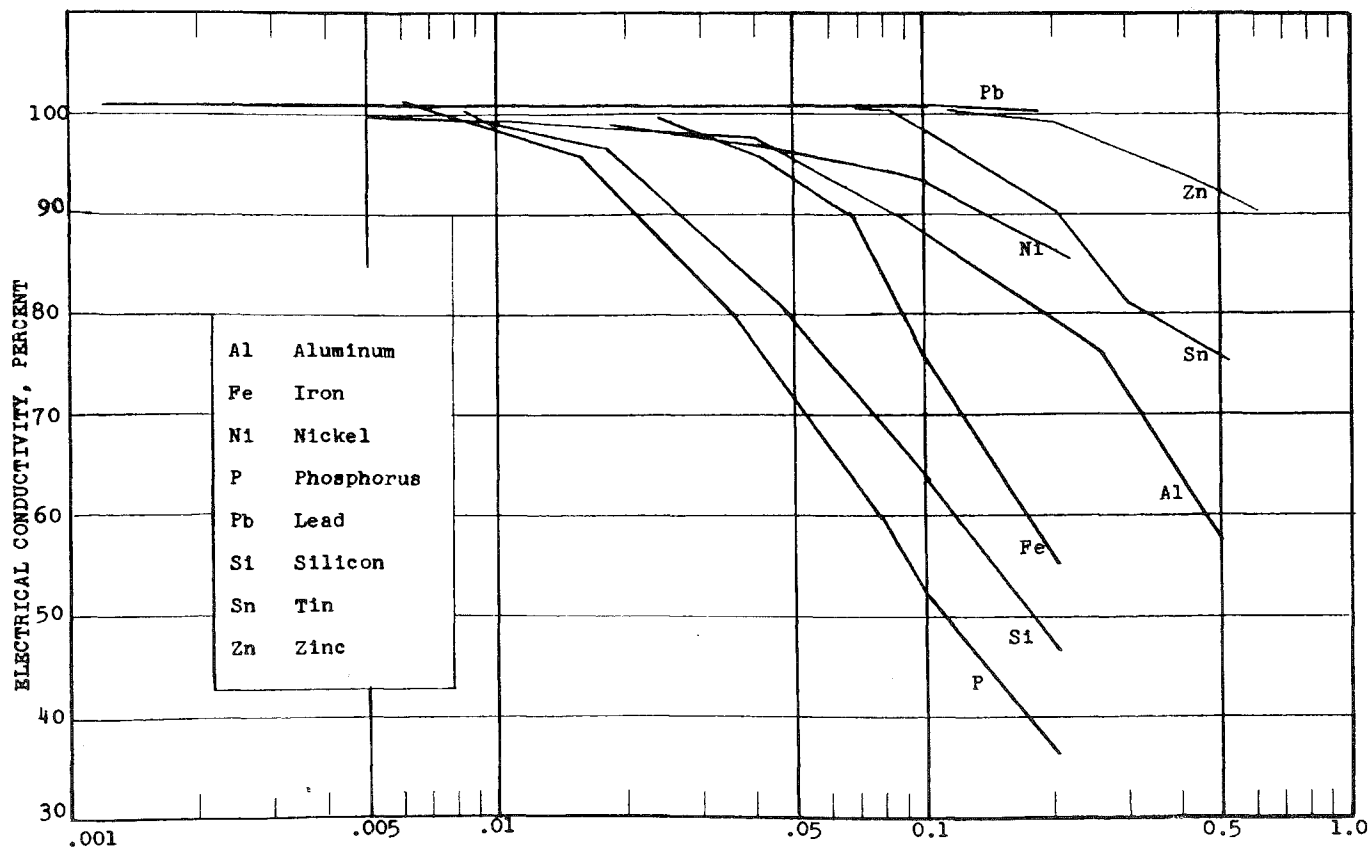
Much of the difficulty in producing pure copper castings has been caused by unsoundness due to gas

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 which 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

Fig. 14-1. The effect on electrical conductivity of small percentages of elements entering into solid solution with copper.



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.

## 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

**Sand.** Sands which 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.** 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. However, a graphite wash may be used on the runner and gate areas of large copper and chromium copper castings to prevent burn-in, which can occur because of the high pouring tempera-

tures and the large volume of metal which passes through these sections of the molds.

**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. Use of a silica sand bonded with a good 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 burn-in and will help minimize gas formation at the core/metal interface.

CO<sub>2</sub> 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 which 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 noncritical 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, a high oxygen content is deliberately induced into the melt to limit the pickup of hydrogen and to oxidize impurities which 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 Chapter 5.) 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 as possible to 2200–2250F (1200–1230C). During melting, a 1 to 1 1/2 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 (1200C), 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 (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.<sup>1</sup>

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.

A relatively simple procedure for evaluating the degree of deoxidation consists of pouring a 3-in. dia x 3-in. 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.<sup>1-3</sup> 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.<sup>1</sup>

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 Chapter 5.

#### *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 which 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 Chapter 5). 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.<sup>5</sup> 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 which 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 may create a health hazard. Appropriate environmental control agencies should be contacted for specific regulations and for guidance in establishing proper procedures. (See also Chapter 18.)

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 so as to minimize loss of beryllium and absorption of gas. The

Table 14-1. Recommended Pouring Ranges

| Material               | Pouring Temperature Range |           |
|------------------------|---------------------------|-----------|
|                        | °F                        | °C        |
| Copper C81100          | 2100-2350                 | 1149-1290 |
| Chromium Copper C81500 | 2200-2300                 | 1204-1260 |
| Beryllium Coppers      |                           |           |
| C82000 (10 C)          | 2050-2250                 | 1121-1232 |
| C82500 (20 C)          | 1850-2050                 | 1010-1121 |
| C81800 (50 C)          | 2050-2250                 | 1121-1232 |
| C81400 (70 C)          | 2150-2300                 | 1177-1260 |
| C82400 (165 C)         | 1900-2050                 | 1038-1121 |
| C82600 (245 C)         | 1850-2000                 | 1010-1095 |
| C82800 (275 C)         | 1850-1975                 | 1010-1079 |

prealloyed ingot (preheated) should then be added and the melt 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.<sup>5</sup>

### 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 such a 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.<sup>6,7</sup>

Solution annealing may be performed in any suitable furnace where the temperature can be maintained within  $\pm 15^\circ\text{F}$  ( $\pm 8^\circ\text{C}$ ). 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

Table 14-2. Heat-Treating Cycles for Beryllium Copper and Chromium Copper Alloys\*

| Alloy                   | Solution Annealing |             | Precipitation Hardening |          |
|-------------------------|--------------------|-------------|-------------------------|----------|
|                         | Time, hr           | Temperature |                         | Time, hr |
|                         |                    | °F          | °C                      |          |
| Beryllium Copper Alloys |                    |             |                         |          |
| C82000 (10 C)           | 1                  | 1675-1700   | 913-927                 | 3        |
| C81800 (50 C)           |                    |             |                         |          |
| C82400 (165 C)          | 1                  | 1475-1500   | 802-816                 | 3        |
| C82500 (20 C)           |                    |             |                         |          |
| C82600 (245 C)          |                    |             |                         |          |
| C82800 (275 C)          | 1                  | 1800-1850   | 982-1010                | 2        |
| C81400 (70 C)           |                    |             |                         |          |
| Chromium Copper         | 1                  | 1800-1850   | 982-1010                | 2        |
| C81500                  |                    |             |                         |          |

\*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

| Alloy          | Treatment* | Tensile Strength, ksi | Elongation, % in 2 in. | Rockwell Hardness | Electrical Conductivity |
|----------------|------------|-----------------------|------------------------|-------------------|-------------------------|
| C82000 (10 C)  | B          | 60 to 70              | 10 to 20               | B70 to 80         | 35 to 45                |
| C82500 (20 C)  | A          | 95 to 110             | 7 to 15                | C20 to 28         | 17 to 22                |
| C82800 (275 C) | A          | 110 to 125            | 4 to 12                | C25 to 30         | 16 to 21                |

\*Treatment A: Heated 4 hours at 600F (316C)

Treatment B: Heated 4 hours at 900F (482C)

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                             |

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 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 will 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 Chapter 15 for other copper-base alloys.

The most common defects found in high-copper alloys are as follows:

- 1) Gas porosity in cast copper due to lack of proper deoxidation.
- 2) 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.
- 3) Excessive drossing due to turbulence caused by improper gating or excessive agitation during melting.
- 4) Shrinkage cracks and cavities due to lack of proper filleting and feeding.
- 5) Low physical and mechanical properties resulting from improper alloying and/or heat treatment.

## Effects of Impurities

**Beryllium Copper Alloys.** 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.

## 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 ASTM Metals Handbook and the Beryllium Corporation's bulletin.<sup>6,7</sup> Rigid control of the principal alloy constituents as well as 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 which require high electrical conductivity; however, it is also widely used for heat transfer purposes. Its use is limited to applications which 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 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 which require maximum strength and wear resistance.

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# Chapter 15

## COMMON DEFECTS IN SAND-CAST COPPER-BASE ALLOYS

### INTRODUCTION

Defective castings can be caused by a variety of conditions which may arise from time to time in the foundry. The purpose of this chapter is to provide guidelines for recognizing and correcting the common types of defects.

The first and most important step in correcting a defective casting problem is proper diagnosis, or identification, of the defect. To assist in the proper identification of defects, an international system<sup>1</sup> has been devised which classifies the defect based upon visual appearance, nature, size and location on or within the casting. This system recognizes seven categories of defects:

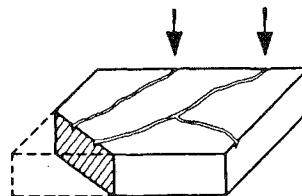
- A—Metallic projections
- B—Cavities
- C—Discontinuities
- D—Defective surfaces
- E—Incomplete casting
- F—Incorrect dimension or shape
- G—Inclusions or structural anomalies

Each category is further divided into subgroups which 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 *AFS International Atlas of Casting Defects*. It is recommended that this reference be utilized for regular diagnosis of defective castings in the foundry.

The *Atlas*<sup>1</sup> 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<sup>2,3</sup> dealing with causes and cures of defective castings. Chapters 3, 5 and 16 of this book contain valuable, detailed information on quality and process control in the brass foundry.

Special attention will be given to the problems of structural unsoundness and leakage under pressure, which occur 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—relatively small variations in production conditions can cause problems to appear and disappear quite suddenly without apparent reason. (This is discussed in detail in Chapters 5 and 8, as well as in reference 4.)

### DEFECT A 112—VEINING OR FINNING



This defect occurs as projections in the form of veins which are generally perpendicular to the casting surface, occurring either singly or in networks, and not situated along parting lines (Fig. 15-1).

In green sand molding, these projections often appear at fillets in conjunction with defect D 230 (scabs) or A 211 (swells).

#### Possible Causes

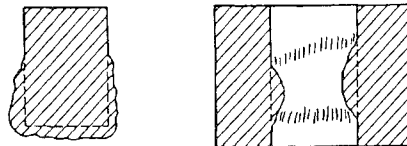
Defect A 112 may be caused by mold surface cracks occurring during drying when there is excessive shrinkage tendency of the sand, due to: a) too rapid heating, b) too high a baking temperature, or c) too much sand binder or moisture.

Or, this defect may 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

Depending upon the assumed causes, 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. 15-2), generally rough and extended, and often in combination with defects D 121 (roughness), D 122 (penetration), and A 112 (veins and fins).

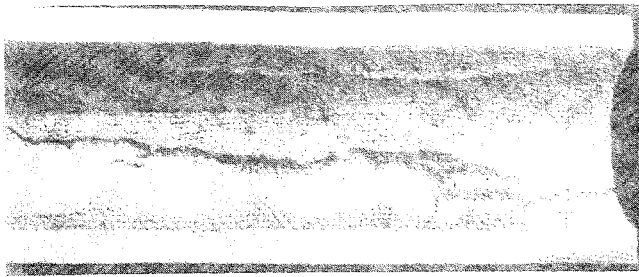


Fig. 15-1. Bronze bushing showing veins caused by core cracks, which disappeared when proper core baking was observed.

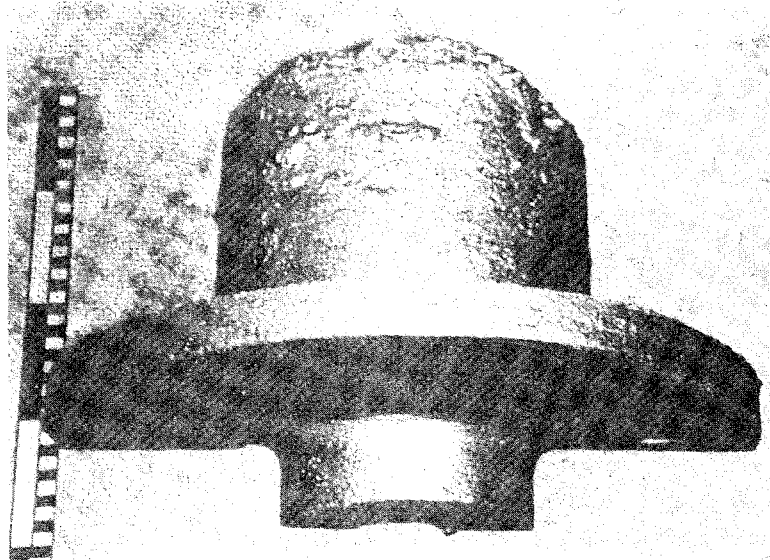


Fig. 15-2. Flanged bushing showing swells resulting from soft-rammed mold.

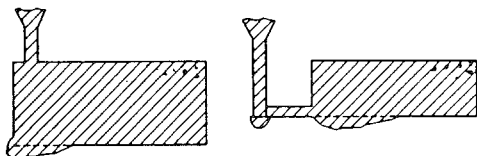
### Possible Causes

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 ex-

tending along the course of metal flow into the mold cavity (Fig. 15-3). Sand inclusions are often found in other regions of the casting.

### 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.

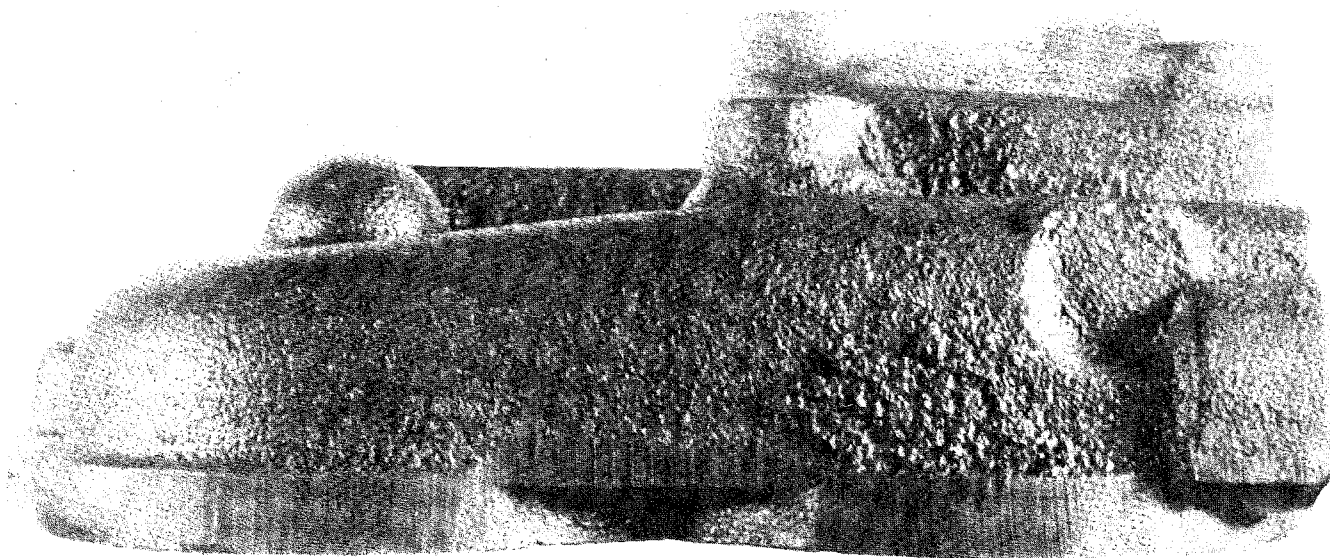
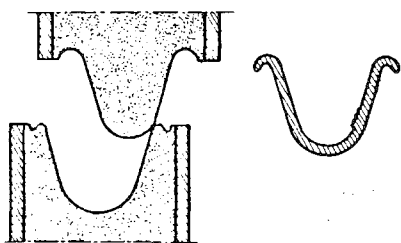


Fig. 15-3. Typical wash or cut in the gate area.

## 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.

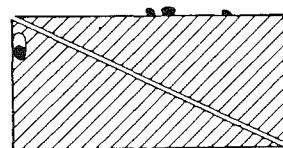
### Remedies

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 during the closing of the mold; and c) using caution in closing the mold to verify that rubbing has not occurred.



Fig. 15-4. Tin sweat. This sprue from a leaded tin bronze shows defect A 311 (sweating or, more precisely, tin-sweat). Casting analysis: 85% Cu, 13.79% Sn, 0.17% Pb, 1.04% Zn. Exuded material analysis: 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.

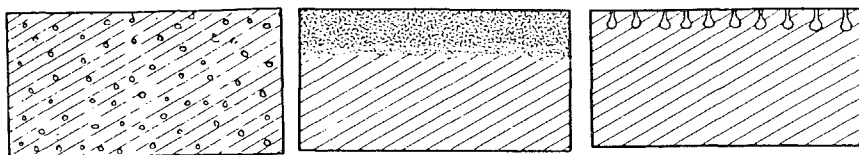
## Defect A 311—TIN SWEAT AND LEAD SWEAT



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,

## Endogenous Blowholes and Pinholes

(Internal Origin)



## Exogenous Blowholes and Pinholes

(External Origin)

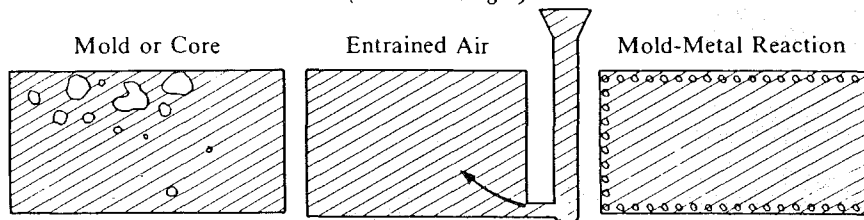


Fig. 15-5. Endogenous and exogenous blowholes and pinholes.

sometimes the size of peas (Fig. 15-4). This is usually encountered only with tin bronzes and high-lead tin bronzes.

### Possible Causes and Remedies

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.

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.

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. 15-5, 15-6, 15-7).

### 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) increasing 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-colored or reddish brown (Fig. 15-8).

### Possible Causes and Remedies

Blows may be caused by: a) sand properties, b) core practice, c) molding techniques, or d) the use of chills.

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 a permeability and lack of adequate venting may also cause blows. Cores should be thoroughly dried after assembly and application of core washes.

Hard and uneven ramming of sand adjacent to the pattern may also cause blows. Even though sand has relatively high permeability, venting the mold at the parting line and above high portions of the casting in 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 reentrant angles of the casting, cores, gates or risers. This defect is most

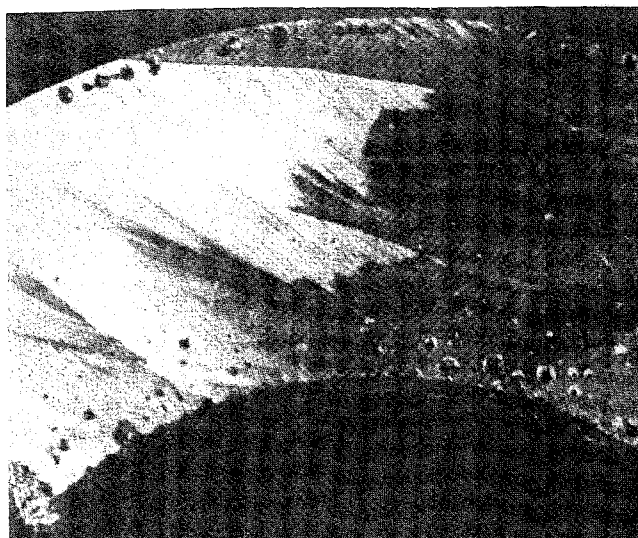


Fig. 15-6. Gas porosity is marked by small, spherical, bright-walled cavities usually segregated near the surface but underneath the skin of heavy sections of the casting.

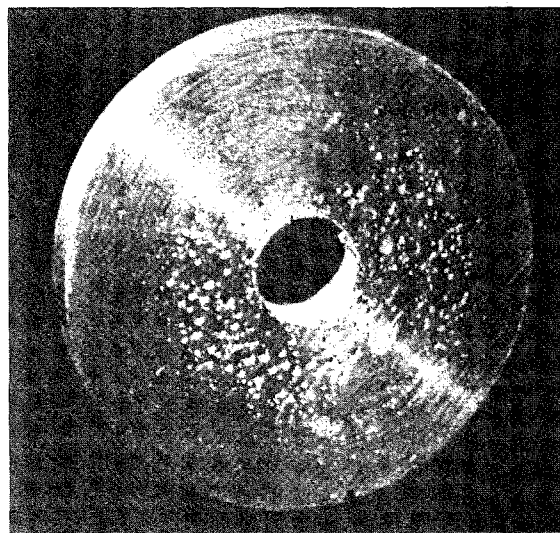


Fig. 15-7. Nozzle of 180 mm (7.2 in.) diameter cast in 10% tin bronze. Blowholes are due to gas absorbed during melting.

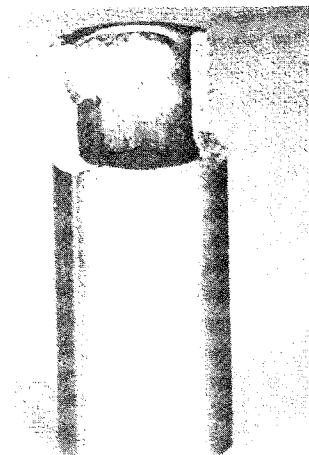


Fig. 15-8. A small bushing cut in half to show blow.

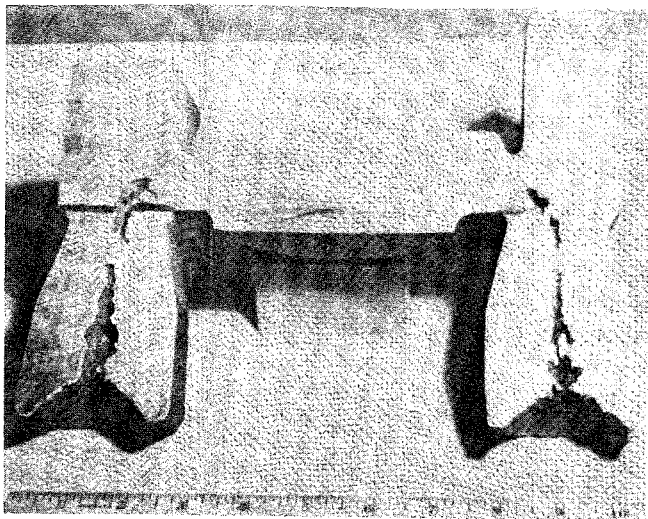


Fig. 15-9. Insufficient cope height prevented adequate riser height to feed the sections involved. Sectioning through both the risers and the casting demonstrates the need for additional feed metal height.

pronounced with alloys of narrow freezing range—such as yellow brasses, manganese bronzes, aluminum bronzes, and pure copper (Fig. 15-9).

### 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 deformation caused by expansion due to elevated mold temperature or metal pressure (static pressure or solidification expansion).

### 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 which may, if necessary, be removed by machining.

#### Pouring

- So far as possible, limit the pouring temperature in order to minimize liquid metal contraction.

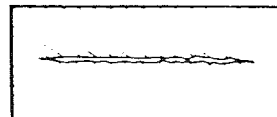
#### Gating and Riser

- 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.
- 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 which are plate-like in shape (Fig. 15-10).

### Possible Causes

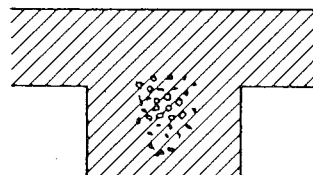
Centerline or axial shrinkage may be caused by the layer of metal in contact with the mold rapidly solidifying, especially in the case of green sand or a metal mold, with the metal at the centerline of the casting taking somewhat longer to freeze. The metal at the centerline is subject to the effects 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.

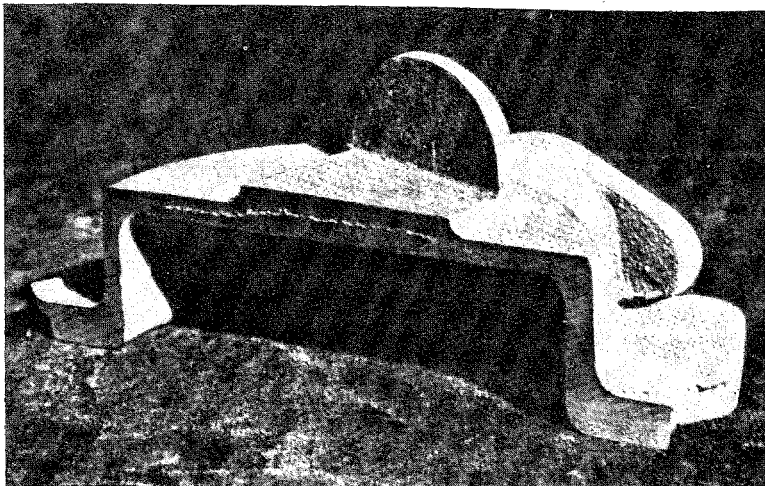
### Remedies

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.

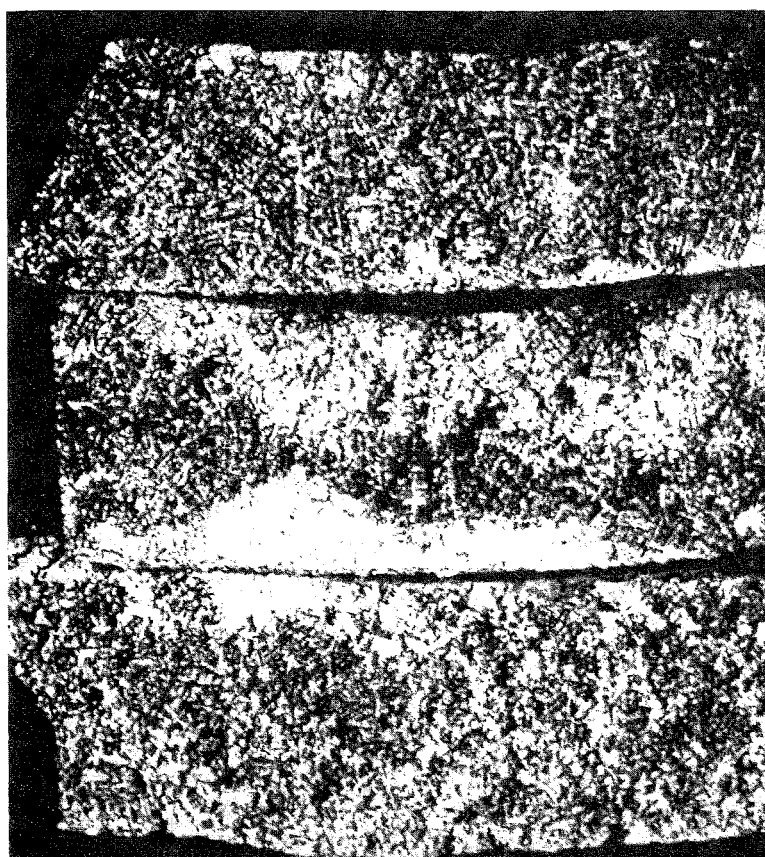
### DEFECT B 311—MACROSHRINKAGE, MICROSHRINKAGE, SHRINKAGE POROSITY, AND LEAKERS



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



*Fig. 15-10. Brass sand casting, 150 mm (6 in.) diameter. The centerline shrinkage crack (B 222) is located in a zone of porous metal. The defect disappears upon lowering the iron and tin content, increasing riser size, and pouring at a lower temperature.*



*Fig. 15-11. Weak, discontinuous or open structures, as shown by fractures, are caused by the presence of aluminum or silicon in the alloy, excessive pouring temperatures, or small amounts of gases such as hydrogen.*

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. 15-11, 15-12).

#### **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

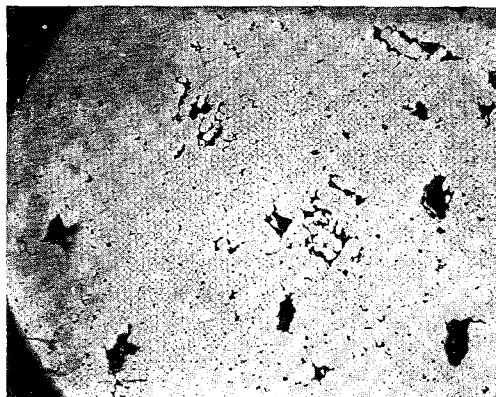
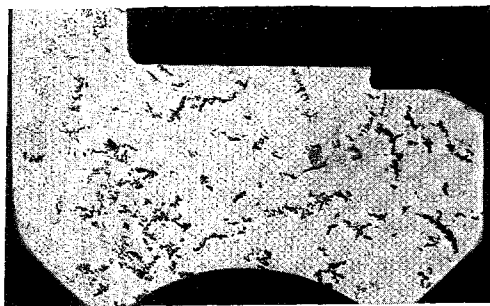


Fig. 15-12. Macroporosity in a bronze casting, photographed unetched.

or chemical effects of the liquid metal may also cause this defect.

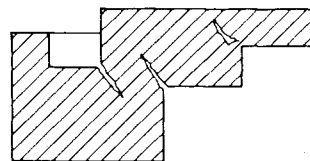
### Remedies

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 Chapter 5 on melt quality control) and both the deoxidation and degassing treatments should be controlled so as 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 so as to avoid gas contamination of the melt during pouring.
- 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 Chapter 8).

### DEFECT C 221—HOT TEARING



Defect C 221 consists of more or less deep inter-crystalline fissures of irregular outline (Fig. 15-13). 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 many branching, connected sections.

Contraction may also be 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



Fig. 15-13. Casting of 85-5-5-5 bronze. 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.

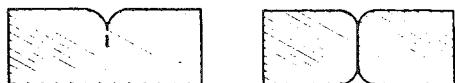
strength in stressed areas; or b) the alloy contains lead or another low-melting phase which remains liquid at grain boundaries.

#### 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. 15-14).

#### DEFECT C 311—COLD SHUT OR COLD LAP



Defect C 311 consists of a linear discontinuity with rounded edges (Fig. 15-15). This defect has a characteristic appearance and may vary in depth, exten-

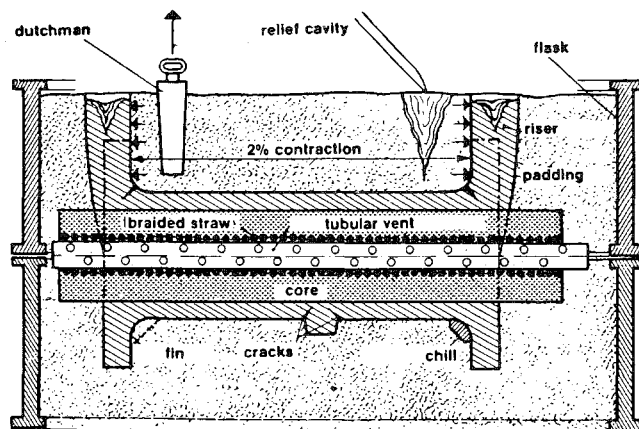


Fig. 15-14. Schematic representation of the formation of hot tears and of various corrective measures possible in the case of a flanged, cast tube.

ding 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.

Cold shut occurs on wide surfaces of the casting, in thin sections which are difficult to fill, or where two streams of metal converge in the mold because of the sequence of filling.

#### Possible Causes

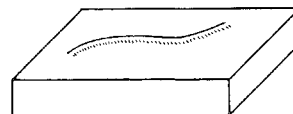
Cold shuts or laps may be caused by: a) insufficient fluidity and oxidized metal; b) slow or interrupted pouring; c) insufficient venting; or d) incomplete fusion of two streams of metal in die casting (the two often showing different structures due to differences in cooling rates).

#### 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—RAT TAIL



Defect D 132 consists of a shallow, groove-like defect which 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.

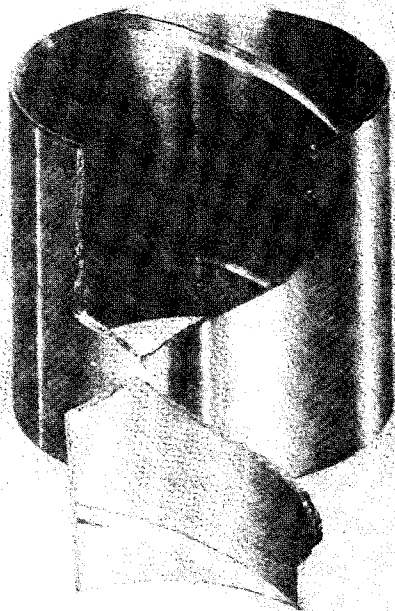


Fig. 15-15. Crack from a cold shut in a bushing.

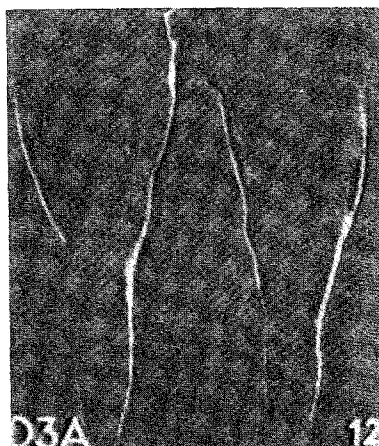


Fig. 15-16. Rat tails

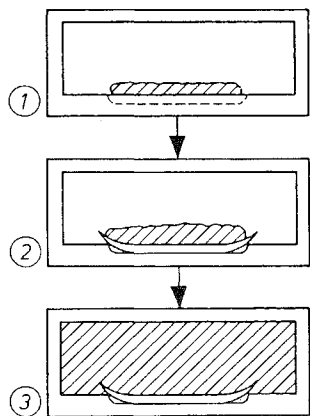


Fig. 15-17. The formation of a rat tail.

Rat tails 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. 15-16. For sands with a strong tendency toward this type of defect, rat tails may also be accompanied by more severe sand-expansion defects such as buckles and scabs (see defect D 231).

#### Possible Causes

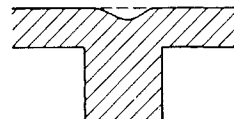
Heat from the stream of molten metal causes the formation of a wet condensation zone in the sand just below the surface. Expansion of the silica causes buckling and detachment of the crust of sand at the wet layer. Because of its increased volume, the crust extends inward at the edges of the stream (1 and 2 of Fig. 15-17).

Since the edges of the projecting scale of sand are not flattened by the metal after the mold fills, they form grooves known as rat tails (Figs. 15-16, 15-17).

#### Remedies

To avoid the formation of rat tails, 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. 15-18).

These depressions most often appear at thickened sections of the casting and sometimes at the bottom of an internal shrinkage cavity or porous area.

#### Possible Causes

Solidification contraction (surface collapse) at locations such as heavy sections which 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.

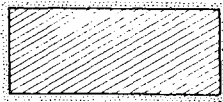
In die casting, defect D 141 may occur as a result of low metal and/or mold temperature together with insufficient metal pressure.

#### 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; or d) in die casting, 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. 15-19).

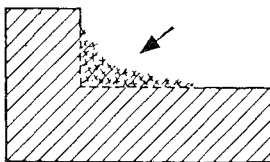
##### Possible Causes

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).

#### 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. 15-20). 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 D 221). Metal penetration represents extreme conditions and often results in parts which cannot be economically salvaged, if at all. Metal penetration is most prevalent with alloys

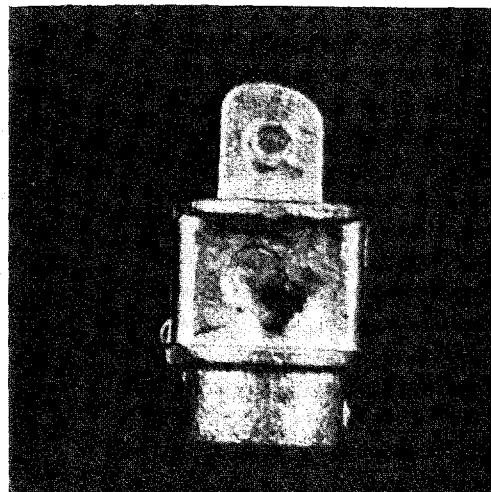


Fig. 15-18. Defect D 141—sink marks.



Fig. 15-19. Castings with burn-on.

high in lead and/or phosphorus, cast in heavier sections (Fig. 15-21).

##### Remedies

To prevent metal penetration from occurring, use the same remedies as those used for the prevention of defect D 221.

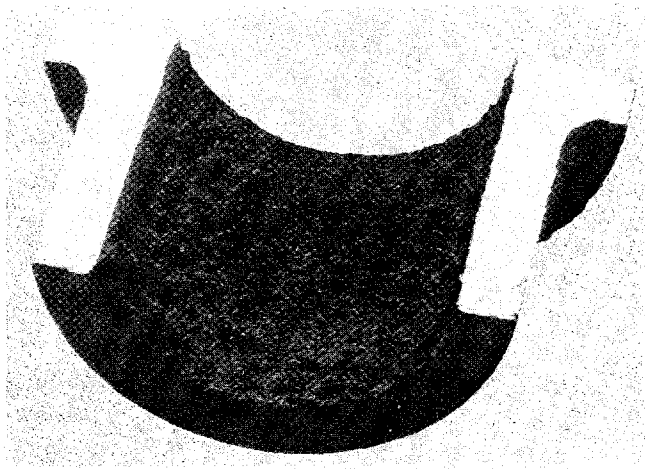
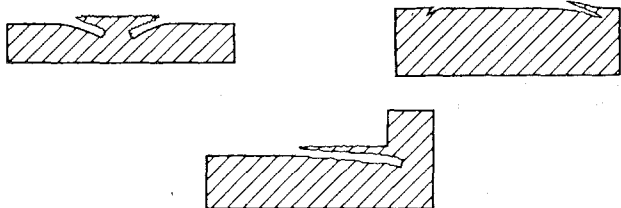


Fig. 15-20. Sand-cast bronze half-bearing showing defect D 223 (penetration). Low surface-tension of the liquid metal was directly responsible for the defect. To avoid this defect, a graphite wash should be used on the core. Normal precautions should be taken for the casting of phosphor bronze. A more dense sand having good thermal conductivity (iron oxide addition to the sand) should be used.

#### 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 which 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 (sketch 1 of Fig. 15-22), followed by formation of a crust of dry sand whose expansion is restrained by compression stresses in the mold wall (sketch 2 of Fig. 15-22). The pressure forcing this crust against the backup sand, caused by the arrival of the liquid metal,

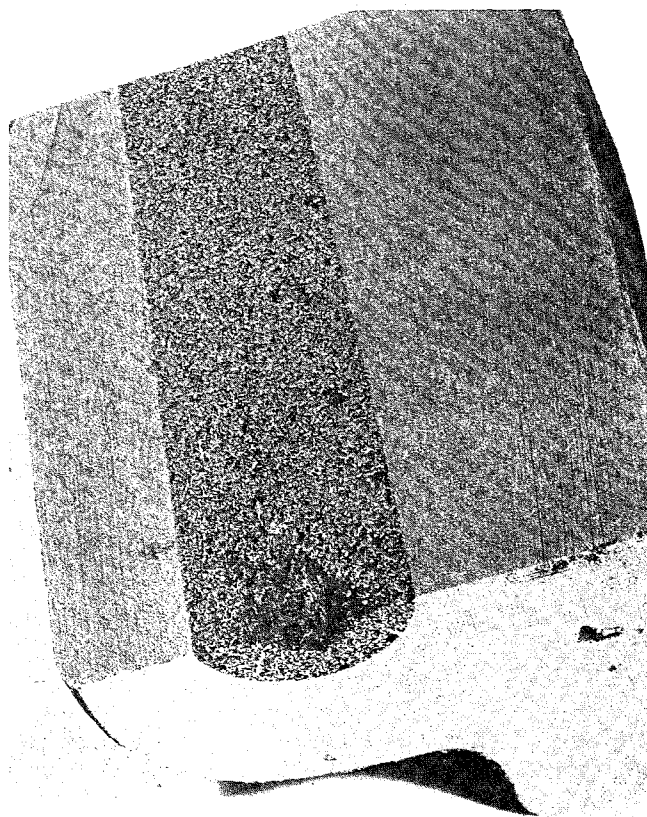


Fig. 15-21. Cross-section of a bronze pillow block with a 20 mm (0.8 in.) diameter cast hole formed by a silicate/ $\text{CO}_2$  core. Total penetration of the core by the liquid metal has occurred. The use of an alumina core wash reduced, but did not prevent penetration. Elimination of the core is 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.

causes the crust to break (sketch 3). The liquid metal infiltrates the space behind the crust forming a thin layer of metal which comprises the scab (Fig. 15-23). If such infiltration does not occur, the defect will instead be a buckle.

A fillet scab may also form by the appearance of a low-strength condensation zone (sketch 1 of Fig. 15-24), 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 (sketch 1 of Fig. 15-25). 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.

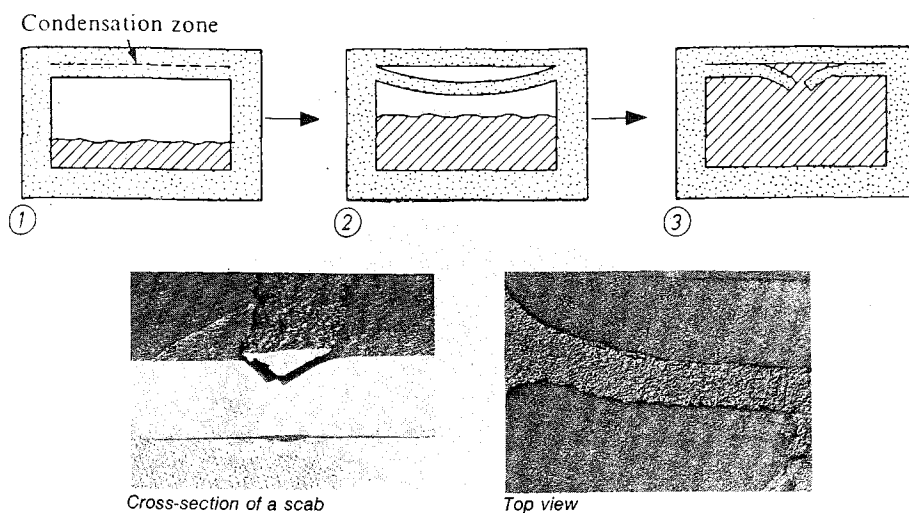


Fig. 15-22. The formation of a scab.

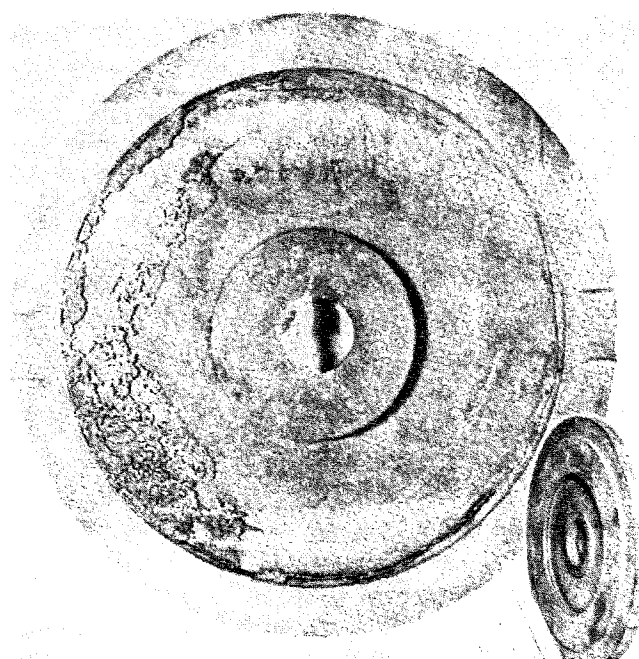


Fig. 15-23. Typical expansion defect (scab) on cope surface.

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 (sketch 2 of Fig. 15-25). The edges of the crust are raised, causing the formation of rat tails (R) or, if the edges raise 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 (sketches 1 and 2 of Fig. 15-26), 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).

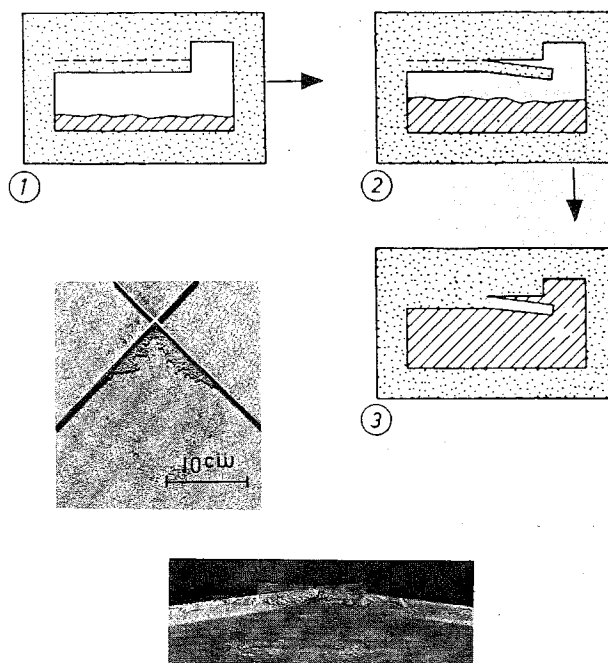


Fig. 15-24. The formation of a fillet scab.

## 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.

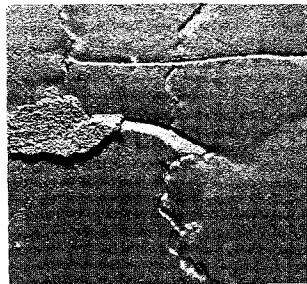
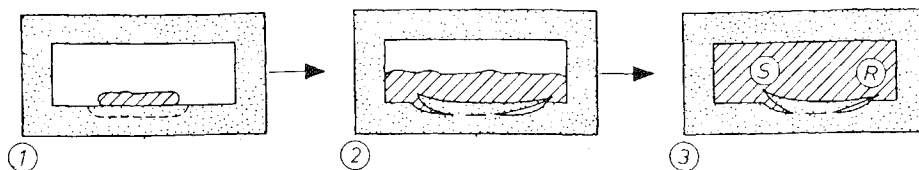


Fig. 15-25. One type of drag scab.

sion; d) substituting sand minerals (olivine, zircon) having lower coefficients of expansion than does silica; and e) where possible, suggesting 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. 15-27). The edges surrounding the missing portion are rounded. Adjacent surfaces are generally shiny.

##### 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 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.

#### 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 seen 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.

##### 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.

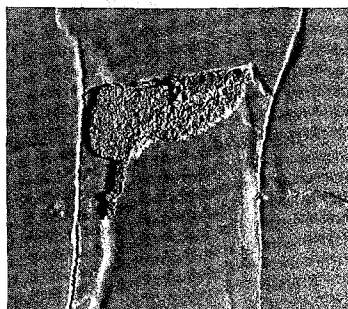
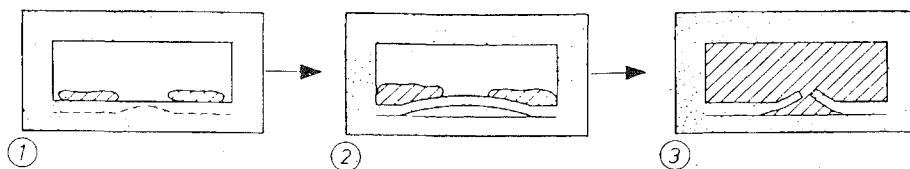


Fig. 15-26. Another form of drag scab.

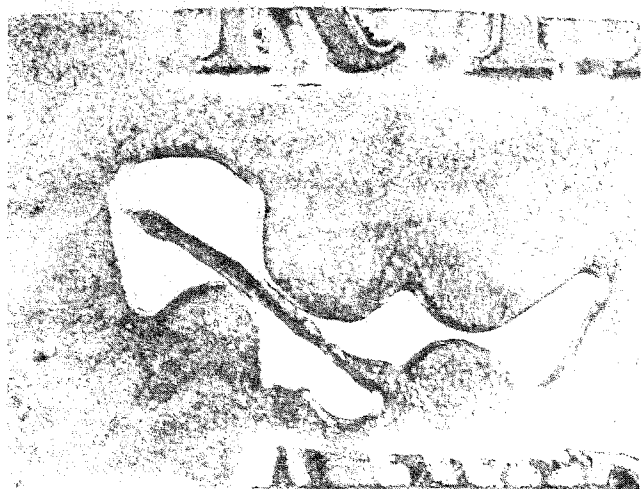


Fig. 15-27. Illustration of a misrun in a marker.

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; c) 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" pour-

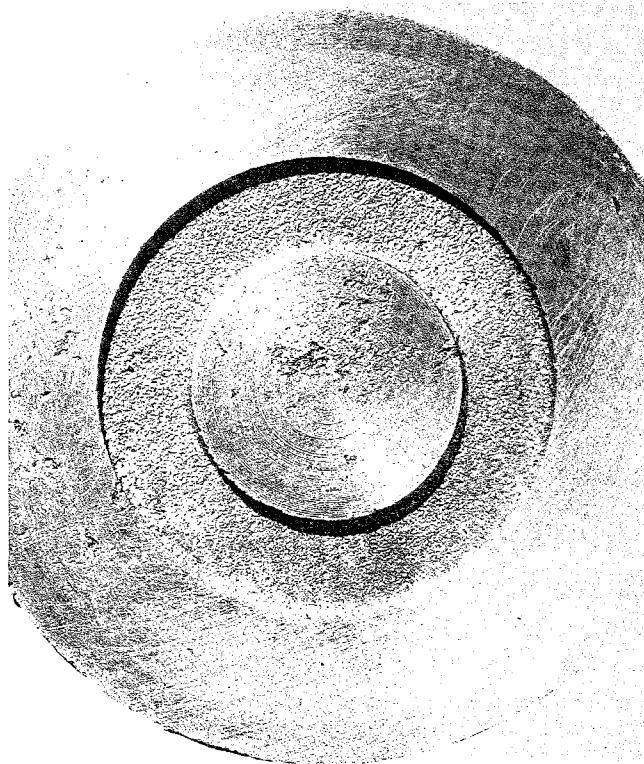


Fig. 15-28. Brass disc, 200 mm (8 in.) in diameter, containing dross inclusions.

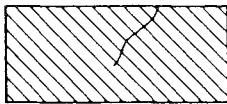
ing spouts; e) keeping pouring basins and sprues filled during pouring; f) using nonpressurized gating systems with suitable chokes; and g) locating machined surfaces in the drag half of the mold.

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.



Fig. 15-29. Casting with oxide film inclusions. The metal entered the mold with turbulence, and aluminum oxide skins were trapped in the casting wall.

#### 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. 15-29).

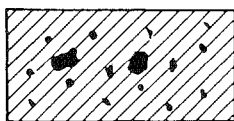
##### Possible Cause

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 Chapter 7).

##### 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 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 pick-up of silicon from sand and refractories, particularly in the presence of active flux covers such as those containing boron.<sup>6,7</sup>

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.

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# Chapter 16

## QUALITY CONTROL OF COPPER-BASE ALLOYS

### INTRODUCTION

The term *quality control* signifies an effort to assure that the manufactured product being shipped from the foundry meets the customer requirements in all respects, and at a cost which is mutually satisfactory to both supplier and user. 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 requirements and somewhat lower standards of quality. Before a foundry can establish a quality control program which is both effective and economical, it is essential that 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. Defective castings should be rejected immediately by the foundry, as opposed to being discovered after machining or assembly has taken place. 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 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 proportion of castings made in this country utilize charges containing *composition*, or pre-alloyed, 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. It is impossible to make high-quality castings from poor-quality ingot.

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 E-88-58, "Sampling Nonferrous Metals in Cast Form 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 E-88-58 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 is 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 in-

gots 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 deep-etch test, usually consisting of the immersion of an ingot cross-section in a nitric-hydrochloric acid solution, indicates relatively little regarding ingot quality and is therefore not recommended as a quality-control procedure.

The general requirements and tests for copper-base alloy ingots are given in ASTM Specification B30—"Standard Specifications for Copper-Base 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.

Foundrymen are often reluctant to incur the additional expense involved in including routine or periodic chemical analysis 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 on the basis of 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 even 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, 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.

Trial samples of castings should be used as an aid in the determination of quality for any new lot of purchased ingots. One or two molds of castings being produced by the foundry, preferably of typical section

thickness and geometry, can be poured and tested for various levels of whatever quality. All such trial castings should be poured from the same heat of metal; a separately cast test bar should also be poured for correlation with mechanical property values.

This sample casting evaluation procedure can be used as a guide for the acceptability of ingot shipments; the standards required for acceptance should be established by mutual agreement between the ingot supplier and the foundry.

## SCRAP

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 remeltings 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 find their way into 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 remeltings. 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 the machining

of 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.

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 on metal quality in Chapter 5 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 which 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.

#### *Arc Furnaces*

Although once rather popular, arc furnaces find relatively little use in copper-alloy foundries today. Whether direct-arc or indirect-arc, these furnaces melt within a closed chamber. Air can find its way into the furnace through the taphole or around the electrode openings, although the rate of circulation of air is not great. The intense heat of the arc causes combustion of the graphite electrodes to occur by reaction with any oxygen present in the furnace atmosphere. This results in an atmosphere consisting essentially of nitrogen, carbon monoxide, and any residual moisture from incoming air.

Suppressing hydrogen absorption in arc furnaces by flushing in excess air has been tried. This method, however, has the disadvantage of greatly increasing the rate of electrode consumption. The more common practice has been to seal off the taphole with a refractory cement so as to minimize the flow of air into the furnace. This practice depends upon keeping atmospheric moisture out of the furnace as much as possible and is naturally most effective on days of low humidity. Should significant hydrogen absorption occur, the only remedy would be flushing the heat with dry nitrogen or an inert gas.

#### *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 foundrymen 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 figure should be something like 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 smokey 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 100F (55C) and might well be as great as 150 to 200F (83 to 111C). 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, to be useful, 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, the foundryman has 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 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. 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 give 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 the foundryman has 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.

A variation of fracture testing, as applied to high-strength yellow brasses (narrow freezing range) has been described by the U. S. Buships in its publication, *Melting and Molding of Ferrous and Non-Ferrous Metals and Alloys*, as follows:

"A cup sample should be taken by pouring the metal into a finger mold, which consists of a flat plate of cast iron or steel with half-round grooves approximately 1 1/4 in. wide and 12 in. long. At a dull red color the solidified metal should be placed over a compressed air line by means of tongs, and the sample slowly cooled from the bottom to the top until most of the heat is radiated. The test sample should then be immersed in water and bent in a vise with a heavy hammer until it breaks. The test bar should not fracture at an angle of less than 90 degrees and the

fractured surface should have a pink tinge with a slight sparkle."

### Reduced-Pressure Test

Within the past few years a rapid, sensitive, and highly reproducible test has been developed which gives a quantitative measurement of gases dissolved in a heat of copper-base alloy. The test procedures are the result of extensive research at the University of Michigan-Ann Arbor, under the joint sponsorship of the American Foundrymen's Society, the International Copper Research Association and the Brass & Bronze Ingot Institute. This test involves the carefully controlled solidification of a small sample of molten metal under a partial vacuum. The pressure at which a bubble forms during freezing, but fails to burst from the surface of the sample, is taken as a measure of the gas content of the sample.

For the first time in history, the brass foundry industry now has a tool available with which it is possible to obtain a quick and accurate measure of the level of dissolved gases in a melt before it is poured. This permits corrective treatment prior to casting the metal, by methods discussed in Chapter 5.

### 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%. 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 ½ to 2 ½ 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/scrap 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 to the bottom of the ladle immediately before tapping. 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 quickly 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 pre-weighed 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 indeed conform with such requirements. As an example, we may consider the requirements listed in ASTM B584-79, "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 under 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; Chapter 3 has 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,

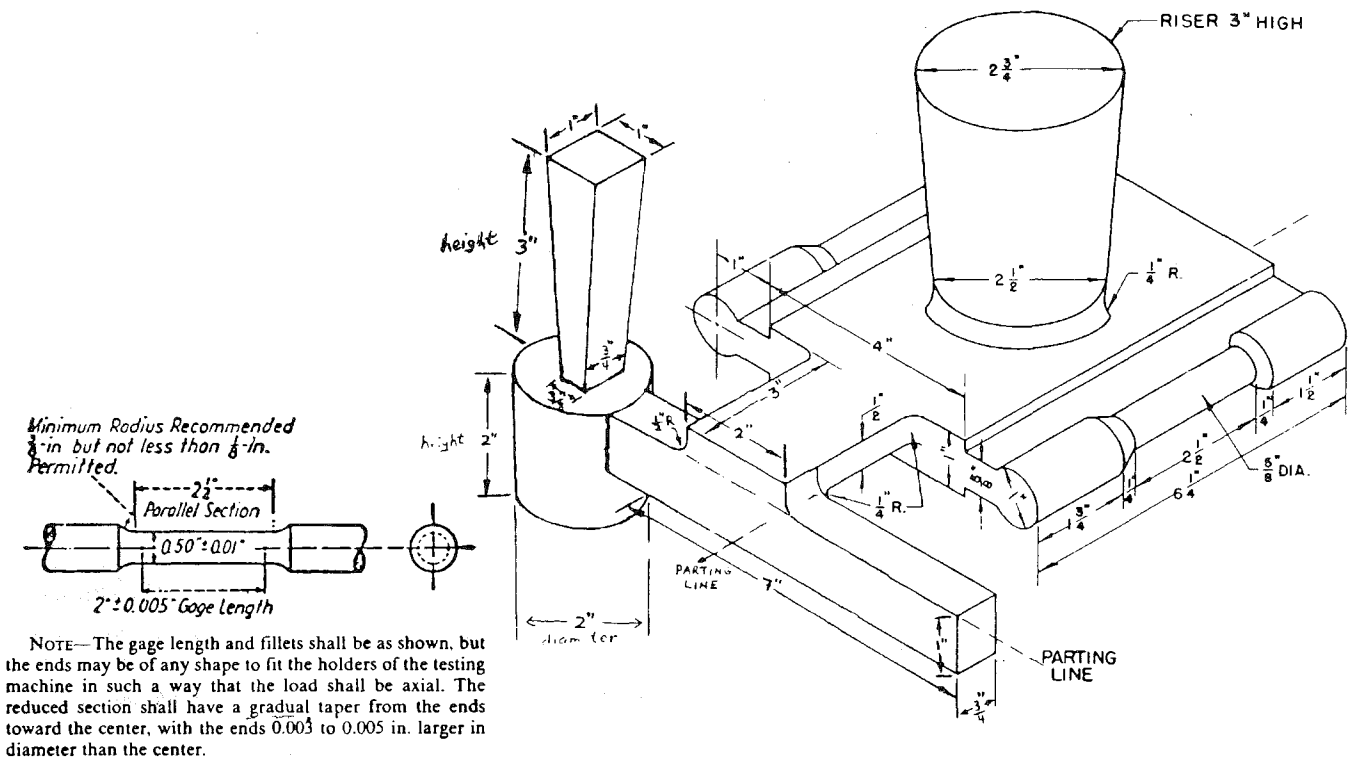


Fig. 16-1. Double, horizontal full-web type test bars.

depends somewhat on the solidification characteristics of the individual alloy. The specification most commonly used in the United States is ASTM B208-81, "Standard Practice for Preparing Tension Test Specimens for Copper-Base Alloys for Sand Castings." Included in this specification are three test-bar mold designs. 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.

Note that the foregoing standards apply only to sand castings. There are at present no comparable ASTM standards for test bars to be used for permanent molded, pressure die cast, centrifugally cast or continuously cast parts.

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 struc-

ture 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 B208-81 as follows:

"1.2 The test bar or bars poured in accordance with this recommended practice should be considered as representing the potential properties of the metal going into the castings poured from the same melt, but these properties are not necessarily the same as the corresponding properties of the castings because of the effect of varying size, section and design."

Although less prevalent than was once the case, some casting purchasers insist that test bars be cast as appendages to the castings themselves. This practice perpetuates the myth that the properties of such test bars reflect those of the casting. Actually, the attachment of the test bar to the casting could easily detract from the soundness of the casting at that location by disrupting the pattern of solidification. For large parts, the pour-

ing temperature may be unnecessarily high in order to permit the smaller test bar to fill without misruns. This could easily damage casting properties in the case of wide-freezing-range alloys. As regards the test bar itself, its location and method of attachment are usually dictated by casting and mold geometry, making it prone to all manner of defects associated with poor gating practice. For these reasons, the stipulation that test bars be poured as attachments to the castings should be avoided whenever possible.

#### *Other Requirements*

As a quality control tool, fracture tests made on the castings themselves can provide information to supplement that derived from fracture testing of melt specimens. Fracture locations for test castings should be chosen selectively so as to study not only the more representative areas of the part but also the critical locations, particularly those which are last to solidify and are therefore prone to show shrinkage or internal gas porosity. The latter include sections adjacent to gates and risers, or isolated heavy walls and bosses. The soundness of areas which are to be machined is particularly important.

Fractures are most easily controlled by making saw cuts, from one or both ends, in the desired plane of fracture and then bending the casting while it is firmly held in a vise.

Many foundries use the fracture test routinely for evaluating the effectiveness of gating and risering systems on new or revised patterns, or in the establishment of proper pouring-temperature ranges. The same test can be used to evaluate or diagnose the cause of defects in castings rejected by visual inspection or other quality tests. For example, parts which show leakage during pressure-testing should be fractured as closely as possible through the exact point (or area) of leakage. If sand or slag inclusions are found, the remedial action to be taken is rather obvious. The same is true when a smooth, unfused surface is exposed, indicating the presence of a cold shut. If, however, the fracture is porous or discolored at the location of leakage it is best to examine the fractures of adjacent areas before reaching a decision. If adjacent areas are homogeneous and sound in structure, and of uniform color, it is likely that the porosity is a localized condition which results from solidification shrinkage—perhaps the most common cause of leakers in copper-tin-lead-zinc alloys. Paradoxically, localized shrinkage in these alloys is more apt to occur with metal which is quite low in dissolved gases—in other words, with melts of high quality. Leakers caused by shrinkage porosity, in unmachined areas of the casting, are often associated with hot spots such as re-entrant angles and fillets. Most often, leakage occurs at machined surfaces. 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.

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*

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 B369-78, "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:

E 478 - "Chemical Analysis of Copper Alloys"

E 54 - "Chemical Analysis of Special Brasses and Bronzes"

E 75 - "Chemical Analysis of Copper-Nickel and Copper-Nickel-Zinc Alloys"

E 88 - "Sampling Non Ferrous Metals and Alloys in Cast Form 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, x-ray fluorescence, and atomic absorption analysis. 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 comes into contact with 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 at the present time 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 Part 42 of the *ASTM Annual Book of Standards*.

## **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 was also emphasized.

In nearly all cases, copper alloy test-bars require machining before testing. (Machining dimensions are given in ASTM Standard B208-81.)

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 Methods of 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.

### **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 which 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.

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.

Hardness readings should be taken on a clean, flat casting surface which has been suitably ground for the purpose. The location should be such that the underside of the casting can be firmly supported by the anvil of the testing machine to avoid any movement during application of the load. Testing of thin sections ( $\frac{1}{4}$  in. or less) is risky when dealing with soft materials because of the possible interference of the supporting anvil with the travel of the indenter, thereby giving false readings. In selecting the location of hardness testing on sample castings, consideration should also be given to whether

the hardness indentation will mar or otherwise damage the casting for its intended use.

### **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 either an x-ray tube, designed to produce radiation of the desired wavelength and intensity, or may consist of a radioactive isotope which 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 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 Annual Book of Standards*, Part 11, "Metallography and Non Destructive Testing":

- E 142 - "Controlling Quality of Radiographic Testing"
- E 272 - "High Strength Copper Base and Nickel-Copper Alloy Castings (Reference Radiographs)"
- E 310 - "Tin Bronze Castings (Reference Radiographs)"
- E 94 - "Recommended Practice for Radiographic Testing"

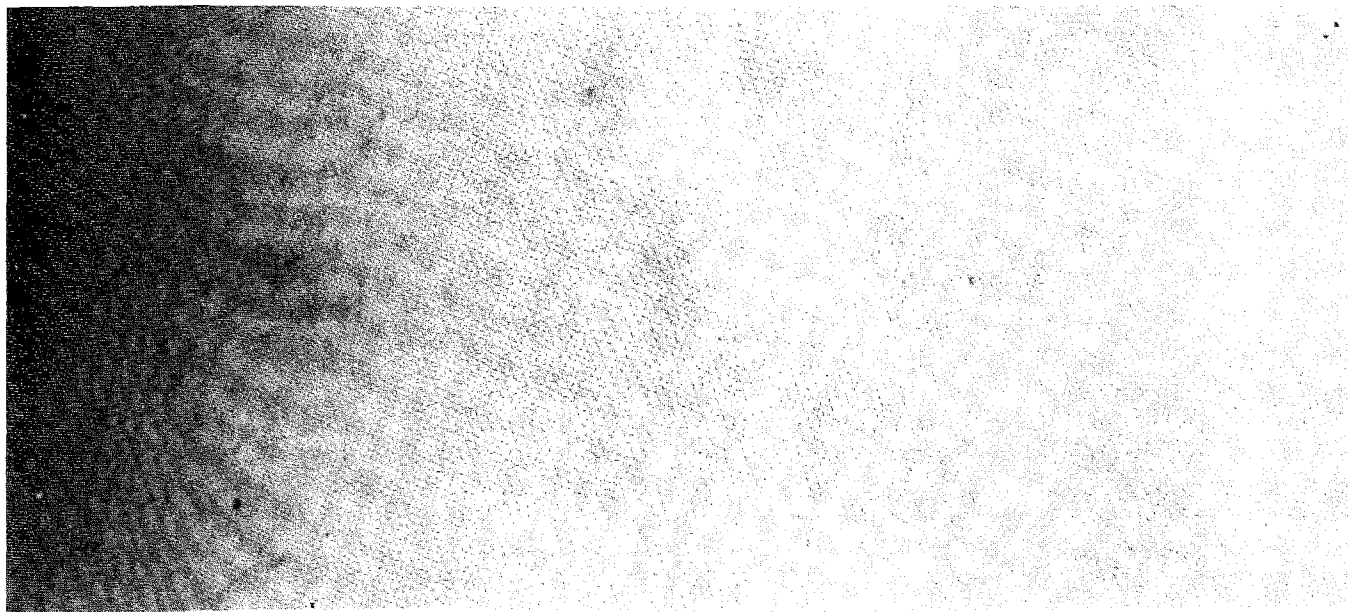
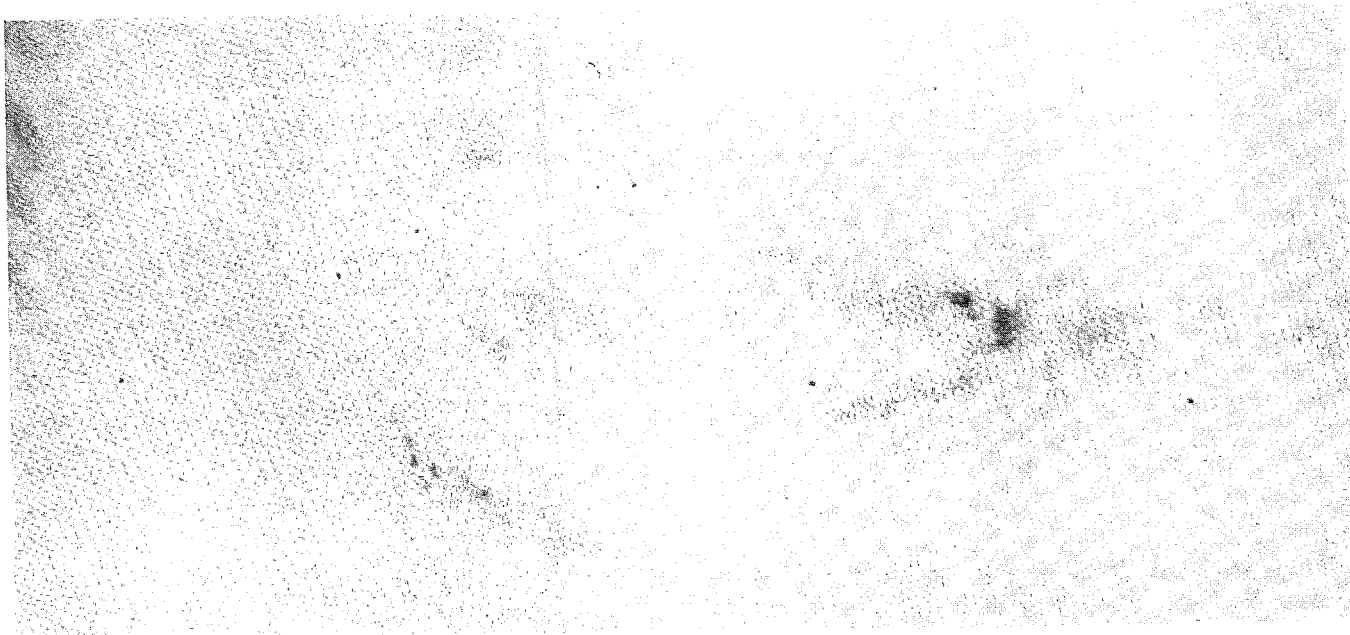
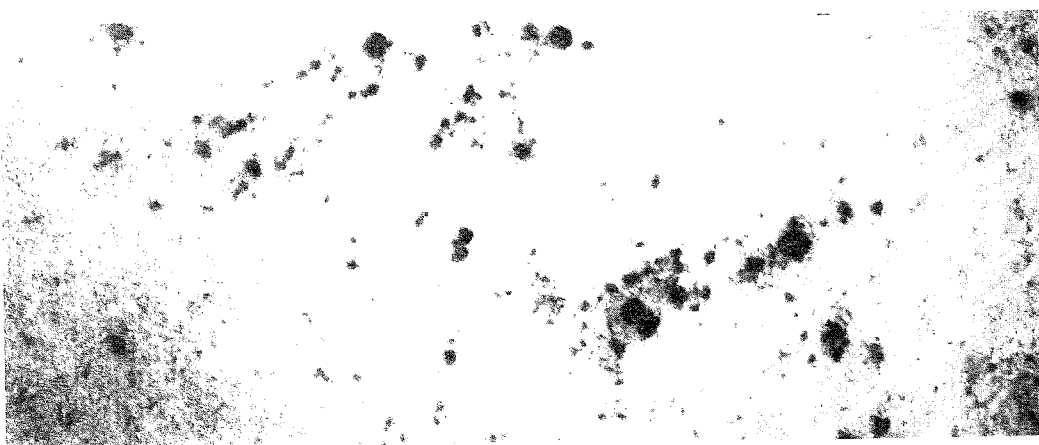


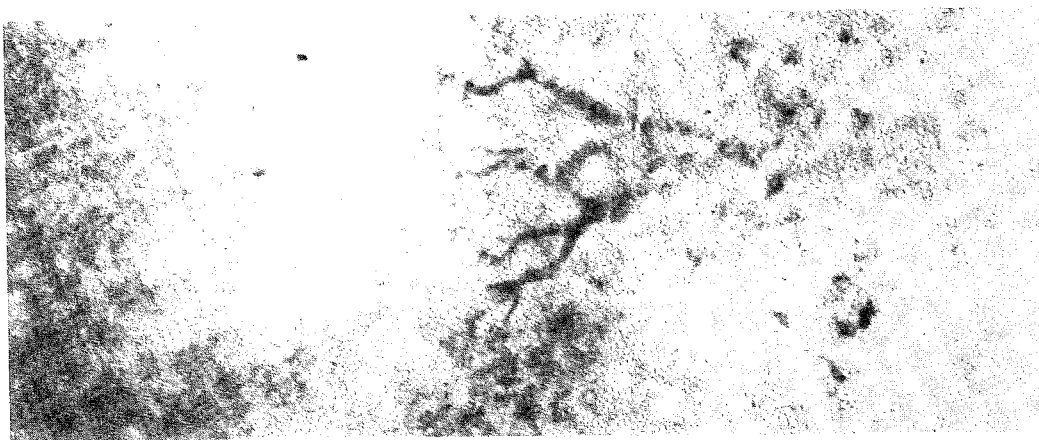
Fig. 16-2. Radiograph of manganese-aluminum-bronze showing feathery shrinkage.



*Fig. 16-3. Radiograph of manganese-aluminum-bronze showing spongy shrinkage.*



*Fig. 16-4. Radiograph of tin bronze showing porosity.*



*Fig. 16-5. Radiograph of tin bronze showing 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 ASTM Standard E 2, "Preparation of Micrographs of Metals and Alloys" and E 3, "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 Chapter 3.

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# Chapter 17

## 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 Chapters 1 and 2, are dealt with here.

Covered in this chapter are such mechanical and physical properties as tensile and yield strengths, modulus of elasticity, Brinell hardness, compression strength, impact 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

| NOMINAL CHEMICAL ANALYSIS |                        |      |     |     |     |    |    |            | TENSILE PROPERTIES |         |           |                          |
|---------------------------|------------------------|------|-----|-----|-----|----|----|------------|--------------------|---------|-----------|--------------------------|
| UNS Number                | Alloy Name             | Cu   | Sn  | Pb  | Zn  | Fe | Al | Others     | UTS, ksi           | YS, ksi | Elong., % | E, psi x 10 <sup>6</sup> |
| 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                    |                        | 62   |     |     | 25  | 3  | 6  | 4 Mn       | 120                | 69      | 16        | 14                       |
| C86400                    |                        | 58   |     | 1   | 38  | 1  | 1  | .5 Mn      | 69                 | 26      | 23        | 13                       |
| C86500                    |                        | 58   |     |     | 39  | 1  | 1  | .5 Mn      | 72                 | 30      | 37        | 15                       |
| C87200                    | Silicon bronze         | 92   |     |     | 4   |    |    | 4 Si       | 60                 | 25      | 40        | 17                       |
| 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                    |                        | 70   | 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                    |                        | 86   |     |     |     | 4  | 10 |            | 90                 | 35      | 15        | 18                       |
| C95500                    |                        | 81   |     |     |     | 4  | 11 | 4 Ni       | 102                | 43      | 11        | 19                       |
| C95800                    |                        | 81.5 |     |     |     | 4  | 9  | 4.5Ni, 1Mn | 96                 | 38      | 25        | 19                       |
| C96400                    | Cupronickel 30%        | 67   |     |     |     | 1  |    | 30Ni, 1Nb  | 70                 | 40      | 25        | 21                       |
| 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                       |

Table 17.1, continued

| UNS Number | Alloy Name                | COMPRESSION STR. |                 | Bhn  | Impact*<br>ft. lbs. | Fatigue**<br>str., ksi. | Spec.<br>gravity | Thermal<br>cond. %<br>of copper | Electrical<br>cond.<br>% IACS |
|------------|---------------------------|------------------|-----------------|------|---------------------|-------------------------|------------------|---------------------------------|-------------------------------|
|            |                           | .001 in.<br>set  | .010 in.<br>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<br>brass  |                  |                 | 55   |                     |                         | 8.7              | 18                              | 16.6                          |
| C84800     |                           | 13               | 16              | 58   | C-12                | 11                      | 8.8              | 18                              | 16.5                          |
| C85200     | Leaded yellow<br>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                          |
| C87200     | Silicon bronze            | 19               |                 | 87   | I-30                |                         | 8.3              | 7                               | 6.1                           |
| 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<br>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 | 18                  | 8.9                     | 8                | 8.9                             |                               |
| C97300     | Leaded nickel<br>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

| UNS. No. | Alloy Name        | Temperature |    |    |             |    |    |             |      |      |             |    |    |             |     |      |
|----------|-------------------|-------------|----|----|-------------|----|----|-------------|------|------|-------------|----|----|-------------|-----|------|
|          |                   | 80F (27C)   |    |    | 250F (121C) |    |    | 300F (149C) |      |      | 350F (177C) |    |    | 400F (204C) |     |      |
|          |                   | 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   |
| C83600   | 85-5-5-5          | 35          | 15 | 31 | 32          | 14 | 27 |             |      |      |             |    |    |             | 30  | 12   |
| 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   |
| C86300   | Manganese bronze  | 118         | 68 | 19 |             |    |    |             |      |      | 105         | 67 | 22 |             | 91  | 63   |
| C95400   | Aluminum bronze   | 95          | 36 | 18 |             |    |    |             |      |      |             |    | 90 | 32.5        | 16  |      |
| C97600   | 20% Nickel silver | 48          | 26 | 20 |             |    |    |             |      |      |             |    | 35 | 20          | 16  |      |
| C87200   | Silicon bronze    | 42          | 15 | 27 |             |    |    |             |      |      |             |    |    |             |     |      |
| C87500   | Silicon brass     | 68          | 30 | 19 |             |    |    |             |      |      |             |    |    |             | 68  | 30   |
| C95700   | Mn-Al bronze      | 105         | 46 | 25 |             |    |    | 102         | 49   | 25   |             |    |    |             | 97  | 47   |

| UNS. No. | Alloy Name      | 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, ksi  
YS - Yield strength, ksi  
%E - Elongation, percent

Table 17-3. Low Temperature Properties of Cast Copper-Base Alloys

| UNS No. | Alloy Name        | Temperature |      |      |             |    |    |              |      |    |              |      |      |               |    |    |
|---------|-------------------|-------------|------|------|-------------|----|----|--------------|------|----|--------------|------|------|---------------|----|----|
|         |                   | 80F (27C)   |      |      | -40F (-40C) |    |    | -107F (177C) |      |    | -310F (190C) |      |      | -424F (-253C) |    |    |
|         |                   | 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  | 76-2½-6½-15       | 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, ksi  
YS - Yield strength, ksi  
%E - Elongation, percent

Table 17-4. Limiting Creep Strength of Cast Copper-Base Alloys

| UNS No. | Alloy Name                  | Creep Strength, ksi<br>(for creep rate of 0.1% per 10,000 hr) |                |                |                |                |                |                |                |                |
|---------|-----------------------------|---------------------------------------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
|         |                             | 250F<br>(121C)                                                | 350F<br>(177C) | 450F<br>(232C) | 500F<br>(260C) | 550F<br>(288C) | 600F<br>(316C) | 700F<br>(371C) | 800F<br>(427C) | 900F<br>(482C) |
| C92200  | Navy M                      |                                                               | 16.0           | 11.2           |                | 6.2            |                |                |                |                |
| C93700  | 80-10-10                    |                                                               | 10.4           | 7.4            |                | 1.8            |                |                |                |                |
| C83600  | 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            |                |

Creep Strength, ksi  
(for creep rate of 1.0% per 10,000 hr)

| UNS No. | Alloy Name       | 250F<br>(121C) | 350F<br>(177C) | 450F<br>(232C) | 550F<br>(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<br>rating (a), % |
|--------------------------------------|---------------------------------------|--------------------------------|
| Group 1—Free-cutting Alloys          |                                       |                                |
| C83600                               | 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 |                                       |                                |
| C86400                               | 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       |                                       |                                |
| C86300                               | High-strength manganese bronze        | 20                             |
| C95200                               | 9% aluminum bronze                    | 20                             |
| C95400                               | 11% aluminum bronze                   | 20                             |
| C95500                               | Nickel-aluminum bronze                | 20                             |

(a) Machinability rating expressed as a percentage of the machinability of C36000, free-cutting brass. The rating is based on relative speed for equivalent tool life. For instance, a material having a rating of 50 should be machined at about half the speed that would be used to make a similar cut in C36000.

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 |                  |                            |                               |                             |                                                               |                                                      |                                               |
| Leaded Tin Bronzes                           | C94300     | 70                   | 5      | 25      |    | 48               | 14,000                     | 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 |
|                                              | 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                     |                               |                             |                                                               |                                                      |                                               |
| Non-Leaded Tin Bronzes                       | C92700     | 88                   | 10     | 2       |    | 70               | 32,000                     |                               |                             |                                                               |                                                      |                                               |
|                                              | 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<br>C90500                               | Tin bronze                | B                                  | B                                    | B                         | B                      | B                     | A            | A             |
| C92200<br>C92300                               | Leaded tin bronze         | B                                  | B                                    | B                         | B                      | B                     | A            | A             |
| C93200<br>C93500<br>C93700<br>C93800<br>C94300 | High-leaded tin bronze    | C                                  | C                                    | C                         | C                      | C                     | A            | A             |
| C83600<br>C83800                               | Leaded red brass          | C                                  | C                                    | C                         | C                      | B                     | A            | A             |
| C84400<br>C84800                               | Leaded semi-red brass     | C                                  | C                                    | C                         | C                      | B                     | A            | A             |
| C85200<br>C85400                               | Leaded yellow brass       | C                                  | C                                    | C                         | C                      | C                     | B            | A             |
| C86400                                         | Leaded Mn bronze          | C                                  | C                                    | C                         | C                      | C                     | B            | A             |
| C86200<br>C86300<br>C86500                     | Manganese bronze          | A                                  | A                                    | A                         | A                      | A                     | A            | A             |
| C95200                                         | Aluminum bronze           | A                                  | A                                    | B                         | B                      | A                     | C*           | C*            |
| C95300<br>C95400<br>C95500                     | Aluminum bronze (as cast) | A                                  | A                                    | A                         | A                      | A                     | C*           | C*            |
| C97300<br>C97400<br>C97600<br>C97800           | Leaded Ni silver          | C                                  | C                                    | C                         | C                      | C                     | B            | A             |
| C87200                                         | Silicon bronze            | B                                  | B                                    | A                         | B                      | B                     | B            | C             |
| 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             |
| Acetic acid                   | A      | C          | B                 | C                      | B                | C                     | C                   | C                                 | C                          | A               | C                   | A                    | A              | B             |
| 20%                           | A      | C          | B                 | C                      | B                | C                     | C                   | C                                 | C                          | C               | A                   | C                    | B              | A             |
| 50%                           | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | A                   | B                    | A              | A             |
| Glacial                       | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | A               | B                   | A                    | A              | A             |
| Acetone                       | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | A               | A                   | C                    | A              | A             |
| Acetylene (a)                 | A      | C          | C                 | C                      | A                | A                     | C                   | C                                 | C                          | A               | A                   | C                    | A              | A             |
| Alcohols (b)                  | A      | C          | C                 | C                      | A                | A                     | C                   | C                                 | C                          | B               | C                   | C                    | C              | C             |
| Aluminum chloride             | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Aluminum sulfate              | B      | B          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Ammonia, moist gas            | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Ammonia, moisture-free        | A      | C          | A                 | C                      | A                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| 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                | B                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Ammonium tetrachloride        | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Aniline and aniline dyes      | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| 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                          | C               | A                   | A                    | A              | C             |
| Barium sulfide                | C      | A          | C                 | B                      | C                | C                     | C                   | C                                 | C                          | B               | C                   | C                    | C              | B             |
| Beer (b)                      | A      | A          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | A               | A                   | A                    | B              | B             |
| Beet sugar syrup              | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Benzene                       | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Benzol                        | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Boric acid                    | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | 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                | B                     | C                   | C                                 | C                          | A               | C                   | A                    | A              | B             |
| Calcium chloride (acid)       | B      | B          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | A               | C                   | A                    | 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                          | C               | C                   | C                    | C              | C             |
| Calcium hypochlorite          | C      | C          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | B               | C                   | C                    | C              | C             |
| Cane sugar syrups             | A      | A          | B                 | A                      | B                | A                     | C                   | C                                 | C                          | A               | A                   | C                    | A              | B             |
| Carbonated beverages (b)      | A      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | A               | A                   | C                    | A              | A             |
| Carbon dioxide, dry           | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Carbon dioxide, moist (b)     | B      | A          | B                 | A                      | C                | B                     | C                   | C                                 | C                          | A               | C                   | A                    | A              | B             |
| Carbon tetrachloride, dry     | A      | B          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | A               | A                   | A                    | A              | A             |
| Carbon tetrachloride, moist   | B      | B          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | B               | A                   | A                    | A              | A             |
| Chlorine, dry                 | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Chlorine, moist               | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Chromic acid                  | C      | C          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Citric acid                   | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Copper sulfate                | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | B               | B                   | A                    | A              | A             |
| Cottonseed oil (b)            | B      | B          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | A               | B                   | A                    | A              | B             |
| Cresosote                     | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | A               | B                   | A                    | A              | 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                | A                     | B                   | B                                 | B                          | A               | B                   | B                    | B              | C             |
| 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             |
| Furural                       | 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             |
| Glycerin                      | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Hydrochloric or muriatic acid | C      | B          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | B                   | C                    | C              | B             |
| Hydrofluoric acid             | B      | B          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | B                   | C                    | C              | B             |
| Hydrofluosilicic acid         | B      | B          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | C               | A                   | A                    | A              | A             |
| Hydrogen                      | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| 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                          | C               | C                   | C                    | C              | C             |
| Hydrogen sulfide, moist       | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | 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                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Linseed oil                   | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Liquors                       | B      | B          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | C               | B                   | C                    | C              | B             |
| Black liquor                  | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | B             |
| Green liquor                  | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | B             |
| White liquor                  | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | B             |
| Magnesium chloride            | A      | A          | B                 | A                      | B                | A                     | C                   | C                                 | C                          | C               | A                   | C                    | C              | B             |
| Magnesium hydroxide           | B      | B          | A                 | B                      | A                | B                     | C                   | B                                 | C                          | C               | A                   | C                    | B              | B             |
| Magnesium sulfate             | A      | A          | A                 | A                      | A                | B                     | C                   | C                                 | C                          | C               | A                   | C                    | B              | A             |
| 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             |
| Nickel chloride               | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | B                   | C                    | C              | C             |
| Nickel sulfate                | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Nitric acid                   | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Oleic acid                    | A      | A          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | C               | A                   | C                    | A              | B             |
| Oxalic acid                   | A      | A          | B                 | B                      | B                | B                     | C                   | C                                 | C                          | C               | A                   | C                    | A              | B             |
| Phosphoric acid               | A      | A          | C                 | A                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | A              | A             |
| Picric acid                   | A      | A          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | A              | A             |
| Potassium chloride            | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Potassium cyanide             | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Potassium hydroxide           | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Potassium sulfate             | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Propane gas                   | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Seawater                      | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | A                   | C                    | C              | B             |
| Soap solutions                | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | A             |
| Sodium bicarbonate            | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | A                   | C                    | C              | B             |
| Sodium bisulfate              | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | A                   | C                    | C              | A             |
| Sodium carbonate              | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Sodium chloride               | C      | A          | A                 | A                      | A                | A                     | B                   | C                                 | C                          | A               | C                   | C                    | C              | A             |
| Sodium cyanide                | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | B                   | C                    | C              | C             |
| Sodium hydroxide              | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Sodium hypochlorite           | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Sodium nitrate                | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Sodium peroxide               | B      | B          | B                 | B                      | B                | B                     | B                   | B                                 | B                          | B               | B                   | B                    | B              | B             |
| Sodium phosphate              | B      | B          | B                 | B                      | B                | B                     | B                   | B                                 | B                          | B               | B                   | B                    | B              | B             |
| Sodium sulfate, silicate      | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Sodium sulfide                | A      | A          | A                 | A                      | A                | A                     | B                   | B                                 | B                          | B               | B                   | B                    | B              | B             |
| Thiosulfate                   | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | B                   | C                    | C              | C             |
| Stearic acid                  | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | A                   | A                    | A              | A             |
| Sulfur, solid                 | A      | A          | A                 | A                      | A                | A                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Sulfur chloride               | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | C               | C                   | C                    | C              | C             |
| Sulfur dioxide, dry           | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Sulfur dioxide, moist         | A      | A          | A                 | A                      | A                | A                     | B                   | B                                 | B                          | B               | B                   | B                    | B              | B             |

|                         | 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 |
|-------------------------|--------|------------|-------------------|------------------------|------------------|-----------------------|---------------------|-----------------------------------|----------------------------|-----------------|---------------------|----------------------|----------------|---------------|
| Sulfur trioxide, dry    | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Sulfuric acid           | B      | B          | B                 | B                      | B                | C                     | C                   | C                                 | C                          | A               | C                   | C                    | B              | B             |
| 78% or less             | C      | C          | C                 | C                      | C                | C                     | C                   | C                                 | C                          | B               | C                   | C                    | C              | C             |
| 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             |
| Tanic 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             |
| Trichlorethylene, dry   | A      | A          | A                 | A                      | A                | A                     | A                   | A                                 | A                          | A               | A                   | A                    | A              | A             |
| Trichlorethylene, 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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## Chapter 18

# HEALTH AND SAFETY ASPECTS OF COPPER-BASE ALLOY FOUNDRY PRACTICE

### ATMOSPHERIC CONTAMINANTS

#### Metals

Many metals are used in the manufacture of copper-base alloys, and excessive exposure to some of these metals can present a health hazard. The effects of the different metals are considered individually in the following paragraphs.

#### Beryllium

Beryllium (Be) is a silvery-white, brittle, extremely toxic metallic element similar in appearance to magnesium and is usually encountered in the foundry in copper alloys. It has a melting point of 1284C (2343F) and a boiling point of 2780C (5036F). 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 OSHA Permissible Exposure Limits). Exposure to airborne beryllium or a beryllium compound can cause a disease called beryllosis, which 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 do not appear for long periods following exposure.

#### Copper

Copper (Cu) is a reddish-brown, ductile, malleable metal which occurs in nature as free copper or as a sulfide ore. It has a melting point of 1083C (1981F) and a boiling point of 2595C (4703F). 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, and electrical wires, tubes, 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 cause irritation. Excessive airborne concentrations of copper dust can cause nose bleeds.

There is no evidence that exposure to copper fume or dust can cause 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), a low melting point of 327C (621F), and a relatively low boiling point of 1725C (3137F). It is added to copper-base alloys to improve free machining qualities. 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.

#### 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 1245C (2275F) and a boiling point of 1962C (3563F).

Table 18-1.

## OSHA Permissible Exposure Limits (PEL) (1981)

|                                                 |                                                                                                                                  |
|-------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Acrolein                                        | 0.1 ppm                                                                                                                          |
| Ammonia                                         | 50 parts per million (ppm) based on exposure over the 8-hour day                                                                 |
| Beryllium                                       | 0.002 mg/m <sup>3</sup>                                                                                                          |
| Carbon Dioxide                                  | 5000 ppm                                                                                                                         |
| Carbon Monoxide                                 | 50 ppm                                                                                                                           |
| Copper                                          |                                                                                                                                  |
| Fume                                            | 0.1 mg/m <sup>3</sup>                                                                                                            |
| Dusts & mists                                   | 1.0 mg/m <sup>3</sup>                                                                                                            |
| Dimethylethylamine                              | no established limit                                                                                                             |
| Ethyl Alcohol                                   | 1000 ppm                                                                                                                         |
| Formaldehyde                                    | 3 ppm based on exposure over the 8-hour day; 5 ppm acceptable ceiling concentration; 10 ppm acceptable peak for 30 minute period |
| Furfuryl Alcohol                                | 50 ppm                                                                                                                           |
| Isopropyl Alcohol                               | 400 ppm                                                                                                                          |
| Hexamethylenetetramine                          | (no established limit) liberates formaldehyde and ammonia on decomposition                                                       |
| Isocyanate (MDI type)                           | 0.02 ppm                                                                                                                         |
| Lead                                            | 0.05 mg/m <sup>3</sup>                                                                                                           |
| Manganese                                       | 5.0 mg/m <sup>3</sup> C                                                                                                          |
| Methyl Alcohol                                  | 200 ppm                                                                                                                          |
| MDI Methylene Bisphenyl                         | 0.02 ppm (ceiling)                                                                                                               |
| Nuisance or Inert Dust                          |                                                                                                                                  |
| Respirable Fraction                             | 5 mg/m <sup>3</sup>                                                                                                              |
| Total Dust                                      | 15 mg/m <sup>3</sup>                                                                                                             |
| Phenol                                          | 5 ppm                                                                                                                            |
| Phosphoric Acid                                 | 1 milligram per cubic meter (mg/m <sup>3</sup> ) of air                                                                          |
| Silica                                          |                                                                                                                                  |
| Crystalline                                     |                                                                                                                                  |
| Quartz (respirable)                             | $\frac{10 \text{ mg/m}^3}{\% \text{SiO}_2 + 2}$                                                                                  |
| Quartz (total dust)                             | $\frac{30 \text{ mg/m}^3}{\% \text{SiO}_2 + 2}$                                                                                  |
| Cristobalite (respirable)                       | $\frac{10 \text{ mg/m}^3}{\% \text{Quartz} + 2(\% \text{Cristobalite}) + 2}$                                                     |
| Cristobalite (total)                            | $\frac{30 \text{ mg/m}^3}{\% \text{Quartz} + 2(\% \text{Cristobalite}) + 2}$                                                     |
| Tridymite                                       | (same as Cristobalite)                                                                                                           |
| Amorphous, including natural diatomaceous earth | $\frac{80 \text{ mg/m}^3}{\% \text{SiO}_2}$                                                                                      |
| Silicones                                       | (no established limits)                                                                                                          |
| Sodium Silicate                                 | (no established limit)                                                                                                           |
| Sulfuric Acid                                   | 1 mg/m <sup>3</sup>                                                                                                              |
| Tin (inorganic compounds—except oxide)          | 2.0 mg/m <sup>3</sup>                                                                                                            |
| Tin oxide (nuisance)                            | 10.0 mg/m <sup>3</sup>                                                                                                           |
| Toluene - 2, 4 Diisocyanate (TDI)               | 0.02 ppm ceiling                                                                                                                 |
| Triethylamine                                   | 25 ppm                                                                                                                           |
| Urea                                            | (no established limit) liberates ammonia on decomposition                                                                        |
| Zinc oxide fume                                 | 5 mg/m <sup>3</sup>                                                                                                              |

It is used as a constituent of copper alloys, such as manganese bronze and high-manganese aluminum bronzes which may contain up to 14% manganese—special alloys may contain more.

Inhalation of the dust, in plants processing manganese ore or ferromanganese alloy, 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.

Manganese poisoning (Manganism) is predominantly a chronic disease occurring after repeated heavy exposure to dust or fumes. The chief symptoms are related to central nervous system damage—headaches, 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 232C (450F) and a high boiling point of 2270C (4118F). 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 nondisfiguring and nondisabling 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 in cases of stannosis may be confused with the fibrotic nodules of silicosis.

### **Zinc**

Zinc is a silvery metal of low to intermediate hardness. It has a melting point of 419.4C (787F) and a low boiling point of 907C (1665F). 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 metal poisonings often display the same or similar symptoms.

The occurrence of “brass chills” indicates the potential for metal poisoning by 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 principle 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.

Table 18-2 lists potential exposures from some of the binder systems at various work locations in the foundry, such as the mixing and pouring areas. The effects of the different resinous binder systems and their chemical components are considered individually in the following paragraphs.

### **Acrolein**

Acrolein ( $C_3H_4O$ ) is a colorless to yellowish liquid with a pungent, disagreeable odor. It is an ingredient of one variety of tear gas.

In foundries, acrolein vapor may be formed by the thermal decomposition of the vegetable oils which 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 used.

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**

Amines are used most often in foundries as catalysts for organic binder systems. The amines most commonly used are triethylamine (TEA), dimethylethylamine (DMEA) and hexamethylenetetramine (HEXA). TEA or DMEA is used as a catalyst for the phenolic-urethane (cold-box) binder. TEA is also used as a catalyst for the alkyd oil-urethane (nobake) binder. HEXA is used as a combination catalyst and co-reactant in the shell sand (resin-coated) process. Less frequently encountered

amines include triethylenediamine, aryl-substituted pyridine, ammonia, and those amines used as epoxy hardeners. Triethylenediamine is used as a catalyst for the alkyd oil-urethane (nobake) binder. Aryl-substituted pyridine is used as a catalyst in the phenolic-urethane (nobake) binder. Ammonia is a by-product of the curing reaction from HEXA in the shell sand process.

TEA and DMEA are liquids at 20C (68F) and are highly flammable. TEA has a flashpoint of 20F (-6.7C), and DMEA has a flashpoint of -37F (-38.3C). Both of these amines are irritating to the eyes and to the upper respiratory tract. Contact with the eyes can cause severe chemical burns. Skin contact with TEA and DMEA can also cause chemical burns.

TEA and DMEA are known to cause corneal edema, which results in a foggy vision and the appearance of a bluish halo around lights. TEA and DMEA can be absorbed through the skin. Fortunately, both of these amines have a strong odor that is apparent at levels far below the current OSHA exposure limits, so adequate warning of their presence is given.

Hexamethylenetetramine is a powdery crystalline solid at 20C (68F). Prolonged skin contact with HEXA can cause skin irritation, and continued exposure may lead to sensitization. The fine powder can also present a dust explosion hazard.

HEXA can decompose, in the presence of water, to formaldehyde and ammonia, especially when acids or heat are also present. Ammonia is a gas which 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 also has a strong odor and is an irritant with other side effects.

Aryl-substituted pyridines are usually liquids at 20C (68F). They are irritating to the eyes and skin and have a strong odor.

Triethylenediamine is a solid crystal at 20C (68F). It has a strong odor and is irritating to the eyes, the upper respiratory tract, and the skin. It may also be sensitizing to the skin.

### **Epoxy Resins**

Epoxy resins are most likely found in the pattern shop and generally consist of a resin and an amine hardening or curing agent. The two component agents are mixed together shortly before use and cure by chemical polymerization.

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 these agents in uncured or partially cured resins can sensitize the individual, causing serious skin irritation or asthmatic-like reactions. There can also be asthmatic-like reactions

to some types of amine hardeners or catalysts or to airborne contaminants generated at cutting or grinding of cured resins. Dermatitis may occur on handling, grinding, or cutting cured resins which contain fillers such as fiberglass.

### **FURAN NOBAKE RESINS**

Furan resins are synthetic, thermosetting resins used to bond sand for the production of cores and molds. They are based on furfuryl alcohol. Toluenesulfonic acid (TSA), or benzene sulfonic acid (BSA), as aqueous and/or alcoholic solution, and phosphoric acid as a 75-85% solution, are the usual catalysts. Furan resins are usually modified with phenol and/or urea and/or formaldehyde.

Resins, especially nobake catalysts, are potential eye and skin irritants.

Exposures to furfuryl alcohol, phenol vapors, and formaldehyde gas, all eye and respiratory system irritants, can occur during sand mixing and coremaking. The degree of exposure increases significantly as the temperature of the sand rises above 25C (76F).

Exposure to thermal decomposition products such as carbon monoxide can occur during pouring and shakeout.

### **HOT BOX RESINS**

Hot box resins are liquid, synthetic, thermosetting resins used in combination with liquid or dry catalysts to produce hot box cores. 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.

All of these resins and catalysts in their uncured forms can cause skin and eye irritation. Those containing phenol are more hazardous in this respect because of their free phenol content. Phenol can be absorbed through the skin.

Liberation of formaldehyde, phenol, furfuryl alcohol, and ammonia may occur during mixing and heat curing of hot box resins. Carbon monoxide, phenol, and other gases and vapors are generated during pouring, casting, cooling, and shakeout.

### **Nobake Resins**

Nobake resins are used to bond sand for the production of cores and molds used in casting all types of metals. The resins are 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 furan, phenolic, urethane (isocyanate-based), phosphate-based, and sodium silicates. Furan and phenolic resins are cured with acid catalysts such as phosphoric, sulfonic, and other mineral acids. Urethane resins are cured with "driers" such as cobalt naphthenate and with nitrogen compounds such as triethylamine. The sodium

silicates are cured with a variety of materials such as glycerin acetates, silicon metal powders, and various slags. Phosphate-based binders are cured with alkaline earth oxides, such as magnesium oxide.

Contact with or exposure to liquids, gases, or vapors from any of these binders may be hazardous. Precautions should be taken at sand mixing, coremaking, core baking or torching, metal pouring, casting cooling, and shakeout stations.

### Phenolic Resins

Phenolic resins are synthetic resins used to bond sand for the production of cores and molds. They are used in baking applications, in the hot-box process, as nobake binders, in the shell sand process, and in the cold-box process. Phenolic resins are made from phenol and formaldehyde and are sometimes modified with urea and furfuryl alcohol. A variety of catalysts can be used with phenolic resins, depending upon the application.

**Baking Application**—Excessive exposure to phenol and formaldehyde will cause irritation of the eyes, nose, and respiratory tract. Contact with the resin may cause skin irritation.

**Hot-Box Process**—Liquid or powdered acid catalysts are used. These catalysts are skin irritants and, when used in the dry powdered form, 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 serious skin irritation.

**Nobake Process**—Phenolic resins are used alone or in combination with furan resins or polymeric isocyanate in this application. When used alone or in combination with furan resins, acid catalysts are required. Strong acids such as phosphoric, toluenesulfonic, benzene sulfonic, and sulfuric acids are used. Curing is chemically activated and occurs at room temperature. Serious skin irritation can result from contact with these acids. Exposure to phenol and formaldehyde can cause eye and respiratory irritation, and contact with the resin can cause serious skin irritation.

Combinations of the polymeric isocyanates and phenolic resins are used to produce one of the urethane nobake binders. Pyridine-like catalysts are used with these binders. These catalysts are alkaline, and skin contact can cause irritation. Excessive exposure to phenol, formaldehyde, polymeric isocyanate, and solvent vapors from the resins can cause eye and respiratory irritation. MDI (Methylene bisphenyl isocyanate), the specific polymeric isocyanate used in foundry sand binders, has not been known to cause the asthma-like attacks associated with TDI.

Since solvent components of phenolic resin systems vary widely, information should be obtained from the supplier concerning the potential for excessive solvent exposure associated with specific trade name products.

**Shell Process**—In this application, hexamethylenetetramine is used as a catalyst, and waxes and calcium stearate are used as lubricants. Hexamethylenetetramine is a skin sensitizer, and physical contact can cause severe irritation. Although most of the resins now used for coating sand are solids, solvents may sometimes be used. These solvents are often flammable and potentially explosive and can cause eye and respiratory tract irritation, dizziness, etc. Exposure to phenol and formaldehyde from the resin, and formaldehyde and ammonia from the hexamethylenetetramine, can cause eye and respiratory tract irritation. On heating, hexamethylenetetramine liberates formaldehyde and ammonia. Physical contact with liquid phenol resins can cause skin irritation.

**Cold-Box Process**—Phenolic resins are used in combination with polymeric isocyanates to produce one of the nobake binders. Amines carried in air, carbon dioxide, or nitrogen are used as catalysts. The amines are highly flammable and excessive exposure can cause eye and respiratory tract irritation. As noted, the specific isocyanate used in foundry sand binders (MDI) has not been known to cause the asthma-like attacks associated with TDI.

### SHELL SAND COATING OPERATIONS

Coating of sands with liquid or solid resins is generally performed in a pug-mill or muller-type mixer. One of three accepted procedures is normally used to accomplish coating, as follows:

**Cold Coating**—Phenol-formaldehyde novolac resin (either a powdered resin followed by a suitable volatile solvent such as alcohol, or a predissolved resin) is blended with ambient-temperature sand and subsequently mixed until it is made dry and free-flowing by the application of a blast of ambient-temperature air. A powdered hexamethylenetetramine (HEXA)/calcium stearate mixture is added with the resin or prior to its addition.

**Warm Coating**—Resin and ambient-temperature sand are blended and then dried by use of heated air (300 to 450F).

**Hot Coating**—Granular, flaked, or water-borne novolac resin is blended with preheated sand (275 to 350F), which causes the resin to melt and coat 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 aeration with ambient-temperature air.

Once coated, the sand is placed against a heated pattern to further melt and polymerize, thus bonding the sand grains to produce a core or mold.

The predominant hazard in shell sand coating is the danger of fire or explosion from the solvents used to dissolve the resins, particularly when heated air is used

in the process. This hazard is minimized when so-called water-borne resins are used in hot coating, because all these resins contain only small amounts of solvent. The hazard is eliminated with the use of granular or flaked resins in the hot coating procedure.

Exposure to the resins and/or additives may cause dermatitis; in addition, vapors can cause respiratory and eye irritation.

### **SODIUM SILICATE BINDER SYSTEMS**

Sodium silicate is usually made by fusing silica sand and sodium carbonate (soda). The binders used in foundries often contain ingredients such as sugar, as well as the hydrated sodium silicate, and are alkaline liquids.

Three to six percent of the sodium silicate binder is mixed with sand and with varying types and quantities of organic and inorganic additives to produce a variety of bonding characteristics.

The molds or cores are usually cured by passing carbon dioxide gas through the sand ( $\text{CO}_2$  process). They can also 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.

Sodium silicate solutions as encountered in foundry practices are strongly alkaline. They are irritating to the skin and highly irritating to the eyes. Carbon dioxide as used in the system is normally not a hazard. Carbon monoxide is the major thermal decomposition product of the organic additives and organic chemical activators during pouring. Very little information is available concerning the extent or consequences of exposure to the other decomposition products. One additional hazard is that, should the hose separate from the  $\text{CO}_2$  hand applicator, the operator's hand may freeze to the applicator due to the cooling effect of rapidly expanding compressed gas.

### **UREA-FORMALDEHYDE RESINS**

Urea-formaldehyde resins are liquid, synthetic, thermosetting resins used in combination with cereal, water, kerosene, and fatty acid release agents to bond sand. 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. Cores and molds are normally used in the casting of aluminum, magnesium, brass, and bronze. Ammonia and formaldehyde gases are liberated at core-making or pouring operations.

Exposure to ammonia and formaldehyde gases will irritate the eyes and respiratory tract. Exposed workers may develop a degree of tolerance to these irritant effects. Contact with the resins can cause skin irritation.

### **URETHANE RESINS**

Urethane resins are known in the foundry industry as alkyd or oil-isocyanates or oil urethanes, phenolic-

isocyanates or phenolic urethanes, or just as polymeric isocyanates or urethanes. In their liquid form, they are usually two- or three-component systems consisting of a polyol component, a polymeric isocyanate component, and a catalyst. When mixed, the components form tough, solid plastics. Urethane sand binders are used in the making of both cores and molds.

Sometimes the catalyst is combined with the polyol component to form a two-component system. Both the polyols and isocyanates are sometimes dissolved in solvents such as kerosene, mineral spirits, aromatic petroleum solvents, ketones, and esters. The isocyanates used as core binders are always of the polymeric MDI type. Other polymeric isocyanates may be used to make core box liners and pattern wear plates. Catalysts can be amines such as triethylamine (TEA) and dimethyl ethyl triethyl-enediamine, amine (DMEA) as well as metal salts such as cobalt and lead naphthenate, and dibutyltin dilaurate.

The polyols, sometimes called B components of urethanes, represent varying degrees of hazard. Skin irritation from contact and respiratory irritation from vapor inhalation are potential hazards. Catalysts and isocyanates are also potential skin and respiratory irritants.

Vapors generated at metal pouring operations and shakeout are potential respiratory irritation hazards. These vapors may also be generated at baking ovens.

In the absence of sand, isocyanates can react with water, alcohols, and other active hydrogen compounds such as ammonia, to cause considerable heat. These should not be mixed with isocyanates in bulk containers as this may create excess foaming, increased pressure in a closed container, and increased evolution of flammable vapors. Indiscriminate mixing should be avoided.

### **CARBON MONOXIDE**

Carbon monoxide ( $\text{CO}$ ) 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.  $\text{CO}$  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 have been classified as *nuisance dusts*. These dusts have always had little

adverse effect on lungs, and they 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 ( $\text{Al}_2\text{O}_3$ )]

Calcium carbonate [albacar, aeromatt, limestone, precipitate chalk ( $\text{CaCO}_3$ )]

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— $\text{Fe}_2\text{O}_3$ )

Kaolin

Magnesite ( $\text{MgCO}_3$ )

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 ( $\text{TiO}_2$ )]

## SILICA

Free silica, or quartz ( $\text{SiO}_2$ ), 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. Cristobalite is also a crystalline form of silica which may be present in some bentonites. Quartz may be transformed into cristobalite at the mold-metal interface; however, in nonferrous operations, the temperature of the poured metal is generally not high enough to affect this transformation. It should be noted from Table 18-1 that the permissible exposure depends on the crystalline form of the silica.

Many foundry operations result in employee exposure to fine silica dust which is generated as a result of mechanical or thermal fracture of sand particles. The main sources of foundry exposure involve (1) the handling or mulling of new sand or dry sand from shakeout, (2) the use of silica-containing parting compounds or mold washes, (3) shakeout, and (4) casting cleaning. Other sources of silica dust exposure include general maintenance, cleaning, and furnace and ladle repair operations.

Silicosis is the occupational disease associated with excessive exposure. The degree of hazard depends on silica content, concentration, and the size of the airborne dust, as well as the length of exposure.

Overexposure to silica can cause nodular fibrosis in the lungs and is characterized by shortness of breath, dry cough, lessened capacity for work, and increased susceptibility to tuberculosis. There is much variation in individual susceptibility; certain workers show radiological evidence of the disease before their fellows who are similarly exposed.

Because of the potential long-term hazard of silica, there has been a trend to substitute materials such as olivine for silica sand.

## 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 (Z7.1-1979) drop-ball test 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. The wearing of torn, ragged, and oil- or 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. Snug-fitting gloves, over which the shirt sleeves are

Table 18-2. Potential Airborne Emissions from Self-Setting (No-Bake) Chemical Binder Systems at Various Work Stations in the Foundry

| MOLD and CORE BINDER SYSTEM                              | WORKING AREA† | CHEMICAL SPECIES *       |                      |                           |                  |                             |                        |                           |                |                  |                   |                           |                          |
|----------------------------------------------------------|---------------|--------------------------|----------------------|---------------------------|------------------|-----------------------------|------------------------|---------------------------|----------------|------------------|-------------------|---------------------------|--------------------------|
|                                                          |               | Carbon Monoxide (50 ppm) | Formaldehyde (3 ppm) | Hydrogen Cyanide (10 ppm) | Ammonia (50 ppm) | Isocyanates - MDI (200 ppm) | Sulfur Dioxide (5 ppm) | Hydrogen Sulfide (20 ppm) | Phenol (5 ppm) | Benzene (10 ppm) | Toluene (200 ppm) | Furfuryl Alcohol (50 ppm) | Methyl Alcohol (200 ppm) |
| FURAN NO-BAKE<br>Phosphoric Acid Catalyst                | M/M/C         | 0                        | √(1)                 | 0                         | 0                | 0                           | 0                      | 0                         | 0              | 0                | 0                 | √                         | 0                        |
|                                                          | P/S           | x                        | 0                    | √(2)                      | √(2)             | 0                           | 0                      | 0                         | 0              | 0                | 0                 | 0                         | 0                        |
| FURAN NO-BAKE<br>Sulfonic Acid Catalyst                  | M/M/C         | 0                        | √(1)                 | 0                         | 0                | 0                           | 0                      | (3)                       | 0              | (5)              | (4)               |                           | (6)                      |
|                                                          | P/S           | x                        | 0                    | √(2)                      | √(2)             | 0                           | x                      | √                         | 0              | √(5)             | √(4)              | 0                         | 0                        |
| PHENOLIC NO-BAKE<br>Sulfonic Acid Catalyst               | M/M/C         | 0                        | x                    | 0                         | 0                | 0                           | 0                      | (3)                       | x              | (5)              | (4)               | 0                         | (6)                      |
|                                                          | P/S           | x                        | 0                    | 0                         | 0                | 0                           | x                      | √                         | √              | √(5)             | √(4)              | 0                         | 0                        |
| ALKYD URETHANE                                           | M/M/C         | 0                        | 0                    | 0                         | 0                | √                           | 0                      | 0                         | 0              | 0                | 0                 | 0                         | 0                        |
|                                                          | P/S           | x                        | 0                    | √                         | 0                | √                           | 0                      | 0                         | 0              | √                | √(7)              | 0                         | 0                        |
| PHENOLIC URETHANE                                        | M/M/C         | 0                        | √                    | 0                         | 0                | √                           | 0                      | 0                         | √              | 0                | 0 (7)             | 0                         | 0                        |
|                                                          | P/S           | x                        | 0                    | √                         | √                | √                           | 0                      | 0                         | √              | √                | √(7)              | 0                         | 0                        |
| SODIUM SILICATE<br>(CO <sub>2</sub> /Ester) or<br>CEMENT | M/M/C         | 0                        | 0                    | 0                         | 0                | 0                           | 0                      | 0                         | 0              | 0                | 0                 | 0                         | 0                        |
|                                                          | P/S           | x                        | (8)                  | 0                         | 0                | 0                           | 0                      | 0                         | (9)            | (9)              | (9)               | 0                         | 0                        |
| PHOSPHATE                                                | M/M/C (10)    | 0                        | 0                    | 0                         | 0                | 0                           | 0                      | 0                         | 0              | 0                | 0                 | 0                         | 0                        |
|                                                          | P/S           | √                        | 0                    | 0                         | 0                | 0                           | 0                      | 0                         | 0              | 0                | 0                 | 0                         | 0                        |

**CONSULT BINDER MANUFACTURERS FOR  
SPECIFIC INSTRUCTIONS AND PRECAUTIONS  
PERTAINING TO THE PROPER USAGE OF  
EACH BINDER SYSTEM**

\* OSHA Permissible Exposure Limits (PEL) for Volatiles are listed in parts per million (ppm)

0 absent (not normally expected to be present)

√ normally present in trace concentrations

x present in sufficient quantities to be considered a possible health hazard

Assumes normal ventilation, optimized binder usage and proper handling of the binder system

† M/M/C - Mixing, Molding & Coremaking

P/S - Pouring & Shakeout

**NOTES:**

1. Volatiles at M/M/C refer to sand at 80°F.

2. For phenolic modified furans, consult the entries for each individual system, that is Furan No-bake and Phenolic No-bake.

3. Control of CO to 50 ppm or lower should result in all other volatiles being below their respective PEL's or below their detectable limits.

(1) 0 if binder is formaldehyde-free

(2) 0 if binder is nitrogen (urea)-free

(3) Possibly present if reclaimed sand is used that originally was catalyzed with sulfonic acid

(4) Probably present if toluenesulfonic acid (TSA) is used as a catalyst

(5) Probably present if benzenesulfonic acid (BSA) is used as a catalyst

(6) Possibly present if methyl alcohol is used as a solvent for the sulfonic acid

(7) Plus other aromatic hydrocarbons

(8) Formaldehyde and other aldehydes may possibly be present depending on the ester hardener and other sand additives used with the system

(9) Possibly present depending upon specific sand additives used with system

(10) Powdered hardener may produce nuisance dust

worn, protect the hands while preventing 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.

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.

### 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. Use of local exhaust systems have the following advantages.

- 1) The contaminant is removed before it can reach the employees' breathing zone.
- 2) 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 air-flow patterns, with a subsequent reduction in overall effectiveness.

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