Melting and Casting

SUCCESSFUL PRODUCTION of copper and copper alloy castings depends on three important factors:

- An understanding of casting and solidification characteristics of copper and its various alloys
- Adherence to proper foundry practices including melting practices (e.g., selection of melting furnace and molten metal treatments), pouring practices, and gating and risering techniques
- Proper selection of the casting process which, in turn, depends on the size, shape, and technical requirements of the product

This article addresses each of these factors. Additional information on the selection and application of copper castings can be found in the article "Cast Copper and Copper Alloys" in this Handbook.

Casting Characteristics

Copper is alloyed with other elements because pure copper is extremely difficult to cast as well as being prone to surface cracking, porosity problems, and to the formation of internal cavities. The casting characteristics of copper can be improved by the addition of small amounts of elements including beryllium, silicon, nickel, tin, zinc, chromium, and silver. Alloy coppers, for example, constituted to have improved strength properties over those of high-purity copper, while maintaining a minimum of 85% conductivity, are widely used for cast electrical conducting members.

In the liquid state, copper alloys behave much the same as ferrous alloys of similar density. Molten copper alloys are susceptible to contamination from refractories as well as from the atmosphere. Copper casting alloys are subject to fuming from the vaporization of zinc, which is a major alloying element in about three-fourths of the copper casting alloys. With a few exceptions, such as beryllium-coppers and 1% Cr copper, the copper casting alloys contain at least 10% alloying additions and sometimes these additions exceed 40%. Alloying additions have a marked effect on the temperature at which melting is completed (solidus and liquidus). Temperatures at the beginning and at the end of melting are discussed in this article in the section "Solidification Ranges."

When casting copper and its alloys, the lowest possible pouring temperature needed to suit the size and form of the solid metal should be adopted to encourage as small a grain size as possible as well as to create a minimum of turbulence of the metal during pouring.

Solidification Ranges

The copper-base casting alloy family can be subdivided into three groups according to solidification (freezing) range. Unlike pure metals, alloys solidify over a range of temperatures. Solidification begins when the temperature drops below the liquidus; it is completed when the temperature reaches the solidus. The liquidus is the temperature at which the metal begins to freeze, and solidus is the temperature at which the metal is completely frozen. The three groups are as follows.

Group I alloys are alloys that have a narrow freezing range, that is, a range of 50 °C (90 °F) between the liquidus and solidus. These are the yellow brasses, manganese and aluminum bronzes, nickel bronzes, (nickel silvers), manganese (white) brass alloys, chromium-copper, and copper. Nominal compositions and liquidus/solidus temperatures for these alloys are shown in Table 1.

Group II alloys are those that have an intermediate freezing range, that is, a freezing range

Table 1 Nominal chemical compositions and solidification ranges for group I alloys

		Composition, %										Liquidus temperature		Solidus temperature	
Alloy type	UNS No.	Cu	Sn	Pb	Zn	Ni	Fe	Al	Mn	Si	Other	°C	°F	°C	°F
Copper	C81100	100	…	…	…	…	…	…	…	…	…	1083	1981	1064	1948
Chrome copper	C81500	99	…	…	…	…	…	…	…	…	1.0 Cr	1085	1985	1075	1967
Yellow brass	C85200	72	1	3	24	…	…	…	…	…	…	941	1725	927	1700
	C85400	67	1	3	29	…	…	…	…	…	…	941	1725	927	1700
	C85700	61	1	1	37	…	…	…	…	…	…	941	1725	913	1675
	C85800	62	1	1	36	…	…	…	…	…	…	899	1650	871	1600
	C87900	65	…	…	34	…	…	…	…	1	…	926	1700	900	1650
Manganese bronze	C86200	63	…	…	27	…	3	4	3	…	…	941	1725	899	1650
	C86300	61	…	…	27	…	3	6	3	…	…	923	1693	885	1625
	C86400	58	1	1	38	…	1	5	5	…	…	880	1616	862	1583
	C86500	58	…	…	39	…	1	1	1	…	…	880	1616	862	1583
	C86700	58	1	1	34	…	2	2	2	…	…	880	1616	862	1583
	C86800	55	…	…	36	3	2	1	3	…	…	900	1652	880	1616
Aluminum bronze	C95200	88	…	…	…	…	3	9	…	…	…	1045	1913	1042	1907
	C95300	89	…	…	…	…	1	10	…	…	…	1045	1913	1040	1904
	C95400	86	…	…	…	…	4	10	…	…	…	1038	1900	1027	1880
	C95410	84	…	…	…	2	4	10	…	…	…	1038	1900	1027	1880
	C95500	81	…	…	…	4	4	11	…	…	…	1054	1930	1038	1900
	C95600	91	…	…	…	…	…	7	…	2	…	1004	1840	982	1800
	C95700	75	…	…	…	2	3	8	12	…	…	990	1814	950	1742
	C95800	81	…	…	…	4.5	4	9	1.5	…	…	1060	1940	1043	1910
Nickel bronze	C97300	57	2	9	20	12	…	…	…	…	…	1040	1904	1010	1850
	C97600	64	4	4	8	20	…	…	…	…	…	1143	2089	1108	2027
	C97800	66	5	2	2	25	…	…	…	…	…	1180	2156	1140	2084
White brass	C99700	58	…	2	22	5	…	1	12	…	…	902	1655	879	1615
	C99750	58	…	1	20	…	…	1	20	…	…	843	1550	818	1505

of 50 to 110 °C (90–200 °F) between the liquidus and solidus. These are the beryllium-coppers, silicon bronzes, silicon brass, and copper-nickel alloys. Nominal compositions and liquidus/solidus temperatures for these alloys are shown in Table 2.

Group III alloys have a wide freezing range, well over 110 °C (200 °F), even up to 170 °C (300 °F). These are the leaded red and semired brasses, tin and leaded tin bronzes, and high-leaded tin bronzes. Nominal compositions and liquidus/solidus temperatures for these alloys are shown in Table 3.

Melting Practice

Melting Furnaces

Furnaces for melting copper casting alloys are either fuel fired or electrically heated. They are broadly classified into three categories:

- Crucible furnaces (tilting or stationary)
- Open-flame (reverberatory) furnaces
- Induction furnaces (core or coreless)

Selection of a furnace depends on the quantity of metal to be melted, the degree of purity required, and the variety of alloys to be melted. Environmental restrictions also influence furnace selection.

Fuel-Fired Furnaces. Copper-base alloys are melted in oil- and gas-fired crucible and open-flame furnaces. Crucible furnaces, either tilting or stationary, incorporate a removable cover or lid for removal of the crucible, which is transported to the pouring area where the molds are poured. The contents of the tilting furnace are poured into a ladle, which is then used to pour the molds (Fig. 1 and 2).

These furnaces melt the raw materials by burning oil or gas with sufficient air to achieve complete combustion. The heat from the burner heats the crucible by conduction and convection; the charge melts and then is superheated to a particular temperature at which either the crucible is removed or the furnace is tilted to pour into a ladle. While the molten metal is in the crucible or ladle, it is skimmed, fluxed, and transferred to the pouring area, where the molds are poured.

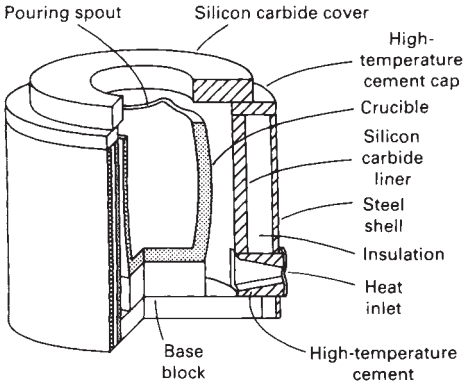

Fig. 1 Typical lift-out type of fuel-fired crucible furnace, especially well adapted to foundry melting of smaller quantities of copper alloys (usually less than 140 kg, or 300 lb)

Table 2 Nominal chemical compositions and solidification ranges for group II alloys

		Composition, %								Liquidus temperature		Solidus temperature	
Alloy type	UNS No.	Cu	Zn	Ni	Fe	Mn	Si	Nb	Other	°C	°F	°C	°F
Beryllium-copper	C81400	99.1	…	…	…	…	…	…	0.6 Be 0.8 Cr	1093	2000	1066	1950
	C82000	97	…	…	…	…	…	…	0.5 Be 2.5 Co	1088	1990	971	1780
	C82200	98	…	1.5	…	…	…	…	0.5 Be …	1116	2040	1038	1900
	C82400	97.8	…	…	…	…	…	…	1.7 Be 0.5 Co	996	1825	899	1650
	C82500	97.2	…	…	…	…	0.3	…	2.0 Be 0.5 Co	982	1800	857	1575
	C82600	96.8	…	…	…	…	0.3	…	2.4 Be 0.5 Co	954	1750	857	1575
	C82800	96.6	…	…	…	…	0.3	…	2.6 Be 0.5 Co	932	1710	885	1625
Silicon brass	C87500	82	14	…	…	…	4	…	…	916	1680	821	1510
Silicon bronze	C87300	9.5	…	…	…	1	4	…	…	916	1680	821	1510
	C87600	91	5	…	…	…	4	…	…	971	1780	860	1580
	C87610	92	4	…	…	…	4	…	…	971	1780	860	1580
	C87800	82	14	…	…	…	4	…	…	916	1680	821	1510
Copper-nickel	C96200	87	…	10	1.5	1	…	1	…	1149	2100	1099	2010
	C96400	66	…	30.5	0.5	1	…	1	…	1238	2260	1171	2140

Table 3 Nominal chemical compositions and solidification ranges for group III alloys

		Composition, %					Liquidus temperature		Solidus temperature	
Alloy type	UNS No.	Cu	Sn	Pb	Zn	Ni	°C	°F	°C	°F
Leaded red brass	C83450	88	2.5	2	6.5	1	1015	1860	860	1580
	C83600	85	5	5	5	…	1010	1850	854	1570
	C83800	83	4	6	7	…	1004	1840	843	1550
Leaded semired brass	C84400	81	3	7	9	…	1004	1840	843	1550
	C84800	76	2.5	6.5	15	…	954	1750	832	1530
Tin bronze	C90300	88	8	…	4	…	1000	1832	854	1570
	C90500	88	10	…	2	…	999	1830	854	1570
	C90700	89	11	…	…	…	999	1830	831	1528
	C91100	84	16	…	…	…	950	1742	818	1505
	C91300	81	19	…	…	…	889	1632	818	1505
Leaded tin bronze	C92200	86	6	1.5	4.5	…	988	1810	826	1518
	C92300	87	8	1	4	…	999	1830	854	1570
	C92600	87	10	1	2	…	982	1800	843	1550
	C92700	88	10	2	…	…	982	1800	843	1550
High-leaded tin bronze	C92900	84	10	2.5	…	3.5	1031	1887	857	1575
	C93200	83	7	7	3	…	977	1790	854	1570
	C93400	84	8	8	…	…	…	…	…	…
	C93500	85	5	9	1	…	999	1830	854	1570
	C93700	80	10	10	…	…	929	1705	762	1403
	C93800	78	7	15	…	…	943	1730	854	1570
	C94300	70	5	25	…	…	…	…	900	1650

The other type of fuel-fired furnace is the open-flame furnace, which is usually a large rotary-type furnace with a refractory-lined steel shell containing a burner at one end and a flue at the other. The furnace is rotated slowly around the horizontal axis, and the rotary movement helps to heat and melt the furnace charge. Melting is accomplished both by the action of the flame directly on the metal and by heat transfer from the hot lining as this shell rotates. These furnaces usually tilt so that they can be charged and poured from the flue opening. At the present time, these furnaces are not used often because of the requirement that a baghouse be installed to capture all the flue dust emitted during melting and superheating. While these furnaces are able to melt large amounts of metal quickly, there is a need for operator skill to control the melting atmosphere within the furnace. Also, the refractory walls become impregnated with the melting metal, causing a contamination problem when switching from one alloy family to another.

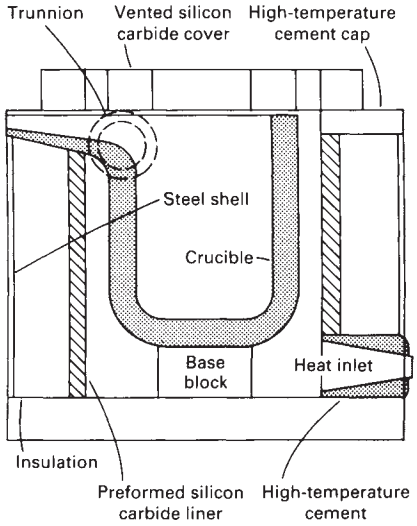

Fig. 2 Typical lip-axis tilting crucible furnace used for fuel-fired furnace melting of copper alloys. Similar furnaces are available that tilt on a central axis

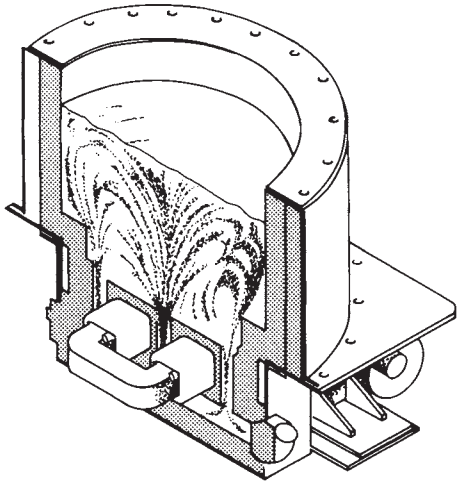

Fig. 3 Cutaway drawing of a twin-channel induction melting furnace

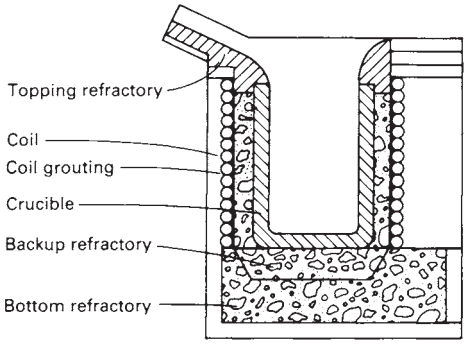

Fig. 4 Cross section of a tilt furnace for high-frequency induction melting of brass and bronze alloys. Crucible is of clay graphite composition.

Electric Induction Furnaces. In the past 30 years, there has been a marked changeover from fuel-fired melting to electric induction melting in the copper-base foundry industry. While this type of melting equipment has been available for more than 60 years, very few were actually used due to the large investment required for the capital equipment. Because of higher prices and the question of availability of fossil fuels and because of new regulations on health and safety imposed by the Occupational Safety and Health Administration (OSHA), many foundries have made the changeover to electric induction furnaces.

When melting alloys in group III, fumes of lead and zinc are given off during melting and superheating. The emission of these harmful oxides is much lower when the charge is melted in an induction furnace because the duration of the melting cycle is only about 25% as long when melting the same amount of metal in a fuel-fired furnace. By the use of electric induction melting, compliance with OSHA regulations can be met in many foundries without the need for expensive air pollution control equipment.

The two types of electric induction furnaces are the core type, better known as the channel furnace, and the coreless type.

Core Type. This furnace (Fig. 3) is a large furnace used in foundries for pouring large quantities of one alloy when a constant source of molten metal is required. This furnace has a primary coil, interfaced with a laminated iron core, surrounded by a secondary channel, which is embedded in a V- or U-shape refractory lining located at the bottom of a cylindrical hearth. Here the channel forms the secondary of a transformer circuit. This furnace stirs and circulates molten metal through the channel at all times, except when the furnace is emptied and shut down. When starting up, molten metal must be poured into the furnace to fill up the "heel" on the bottom of the bath. Because these furnaces are very efficient and simple to operate with lining life in the millions of pounds poured, they are best suited for continuous production runs in foundries making plumbing alloys of group III. They are not recommended for the dross-forming alloys of group I. The channel furnace is at its best when an inert, floating, cover flux is used and charges of ingot, clean remelt, and clean and dry turnings are added periodically.

Coreless Type. This furnace has become the most popular melting unit in the copper alloy foundry industry. In earlier years, the coreless furnace was powered by a motor generator unit, usually at 980 Hz. The present coreless induction furnaces draw 440V, 60 cycle power and, by means of solid-state electronic devices, convert the power to 440V and 1000 or 3000 Hz. These furnaces are either tilting furnaces (Fig. 4) or crucible lift-out units (Fig. 5, 6).

A coreless induction furnace comprises a water-cooled copper coil in a furnace box made

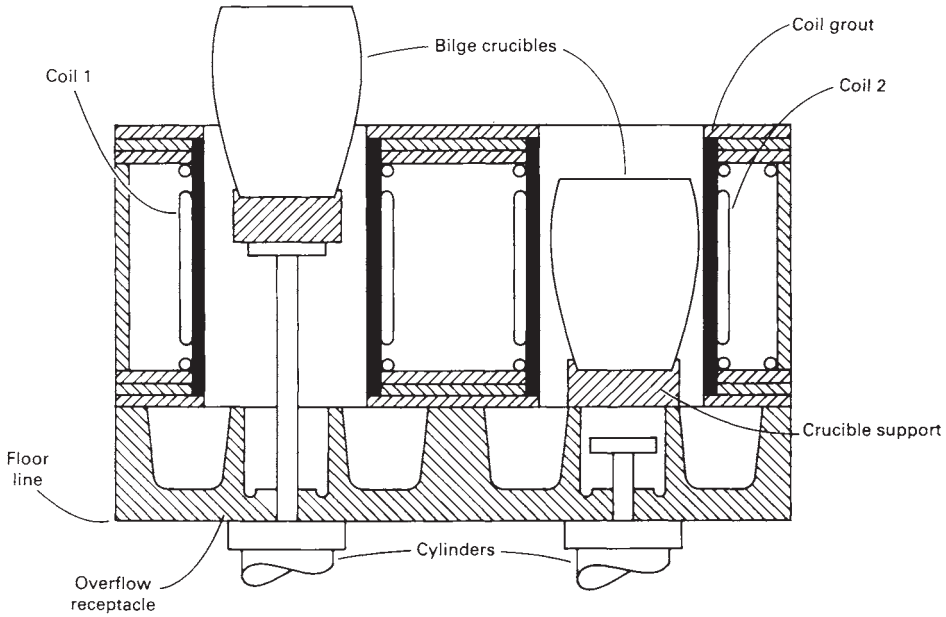

Fig. 5 Cross section of a double push-out furnace. Bilge crucibles are placed on refractory pedestals and raised and lowered into position within the coils by hydraulic cylinders.

of steel or Transite. The metal is contained in a crucible or in a refractory lining rammed up to the coil. Crucibles used in these furnaces are made of clay graphite; silicon carbide crucibles cannot be used because they become overheated when inserted in a magnetic field. Clay graphite crucibles do a good job of conducting the electromagnetic currents from the coil into the metal being melted.

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 optimal-size equipment for the specific operation. In general, the smaller the unit, the higher the frequency and the lower the power input.

Large tilting units are used in foundries requiring large amounts of metal at one time. These furnaces, if over 4.5 Mg (10,000 lb) capacity, operate at line frequency (60 Hz). They are very efficient and will melt large quantities of metal in a very short time if powered with the proper-size power unit.

Stationary lift-out furnaces are often designed as shown in Fig. 5. Here the crucible sits on a refractory pedestal, which can be raised or lowered by a hydraulic cylinder. This unit, also 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. While one crucible is melting, the other crucible can be charged and ready to melt when the knife switch is pulled as the completed heat is being pushed up for skimming and pouring.

The other common type of coreless induction melting is the lift swing furnace (Fig. 6). Here the coil (and box) is cantilevered from a center post to move up or down vertically and swing horizontally about the post in a 90° arc. Because there are two crucible positions, one crucible can be poured, recharged, and placed into position to melt, while the other is melting. When the metal is ready to pour, the furnace box is lifted (by hydraulic or air cylinder), pivoted to the side, and lowered over the second crucible. The ready crucible is then standing free and can be picked up and poured, while melting is taking place in the second furnace.

Melt Treatments

In the melting of copper alloys, various auxiliary molten metal processing steps are necessary other than melting and alloying to improve melt quality through the control of impurities. Melt treatments for copper castings include:

- Fluxing and metal refining
- Degassing
- Deoxidation
- Grain refining
- Filtration

Each of these is described in the sections that follow. It should be noted that some of these process methodologies pertain not only to foundry melting and casting, but also to smelting, refining, and in certain cases mill product operations.

Fluxing of Copper Alloys

The term fluxing is used in this article to represent all additives to, and treatments of, molten metal in which chemical compounds or mixtures of such compounds are employed. These compounds are usually inorganic. In some cases, metallic salts are used in powder, granulated, or solid tablet form and may often melt to form a liquid when used. They can be added manually or can be automatically injected, and they can perform single or, in combination, various functions, including degassing, cleaning, alloying, oxidation, deoxidation, or refining. The term fluxing also includes the treatment of nonferrous melts by inert or reactive gases to remove solid or gaseous impurities.

Fluxing practice in copper alloy melting and casting encompasses a variety of different fluxing materials and functions. Fluxes are specifically used to remove gas or prevent its absorption into the melt, to reduce metal loss, to remove specific impurities and nonmetallic inclusions, to refine metallic constituents, or to lubricate and control surface structure in the semicontinuous casting of mill alloys. The last item is included because even these fluxes fall under the definition of inorganic chemical compounds used to treat molten metal.

Types of Fluxes

Fluxes for copper alloys fall into five basic categories: oxidizing fluxes, neutral cover fluxes, reducing fluxes (usually graphite or charcoal), refining fluxes, and semicontinuous casting mold fluxes.

Oxidizing fluxes are used in the oxidation-deoxidation process; the principal function here is control of hydrogen gas content. This technique is still practiced in melting copper alloys in fuel-fired crucible furnaces, where the products of combustion are usually incompletely reacted and thus lead to hydrogen absorption and potential steam reaction (see the section "Degassing of Copper Alloys" in this article). The oxidizing fluxes usually include cupric oxide or manganese dioxide (MnO_2), which decompose at copper alloy melting temperatures to generate the oxygen required. Figure 7 illustrates the effectiveness of oxidizing fluxes in reducing porosity due to hydrogen and in improving mechanical properties for a tin bronze alloy.

Neutral cover fluxes are used to reduce metal loss by providing a fluid cover. Fluxes of this type are usually based on borax, boric acid, or glass, which melts at copper alloy melting temperatures to provide a fluid slag cover. Borax melts at approximately 740 °C (1365 °F). Such glassy fluxes are especially effective when used with zinc-containing alloys, preventing zinc flaring and reducing subsequent zinc loss by 3 to 10%. The glassy fluid cover fluxes also agglomerate and absorb nonmetallic impurities from the charge (oxides, molding sand, machining lubricants, and so on). As with aluminum alloys, fluxes containing reactive fluoride salts (CaF_2 and NaF) can strip oxide films in copper-base alloys, thus permitting entrained metallic droplets to return to the melt phase. Table 4 indicates the effectiveness of this type of flux in reducing melt loss in yellow and high-tensile brass. For red brasses, however, it may not be proper to use a glassy flux cover, because such a cover will prevent or limit beneficial oxidation of the melt (see the section "Degassing of Copper Alloys" in this article). Use of a glassy cover flux can sometimes result in reduced alloy properties (Ref 1).

Oxide films in aluminum and silicon bronzes also reduce fluidity and mechanical properties.

Fig. 6 Foundry installation of high-frequency induction lift swing furnaces

Fluxes containing fluorides, chlorides, silica, and borax provide both covering and cleaning, along with the ability to dissolve and collect these objectionable oxide skins. Chromium and beryllium-copper alloys oxidize readily when molten; therefore, glassy cover fluxes and fluoride salt components are useful here in controlling melt loss and achieving good separation of oxides from the melt.

Reducing fluxes containing carbonaceous materials such as charcoal or graphite are used on higher-copper lower-zinc alloys. Their principal advantage lies in reducing oxygen absorption of the copper and reducing melt loss. Low-sulfur, dry, carbonaceous flux materials should always be used with copper alloys to avoid gaseous reactions with sulfur or with hydrogen from contained moisture. However, carbonaceous materials will not agglomerate nonmetallic residues or provide any cleaning action when melting fine or dirty scrap. For this reason, a glassy cover must also be used in the latter case. Table 4 indicates the beneficial effects of a glassy cover when melting brass turnings.

Melt Refining Fluxes. It is possible to remove many metallic impurity constituents from copper alloys through the judicious use of fire refining (oxidation). According to standard free energy of reaction (Fig. 8), elements such as iron, tin, aluminum, silicon, zinc, and lead are preferentially oxidized before copper during fire refining (Ref 2), and there is an order of preference for their removal (Fig. 9). These metallic impurities are thus rendered removable if the oxide product formed can be adequately separated from the melt phase itself. A wet cover flux such as borax is useful with fire refining because it will agglomerate the impurity metal oxides formed and minimize the metal content of the dross.

The need to refine specific metallic impurities is highly dependent on and variable with the specific alloy system being refined. An alloying element in one family of copper alloys may be an impurity in another, and vice versa. In red brass (Cu-5Zn-5Pb-5Sn; alloy C83600), the elements lead, tin, and zinc are used for alloying, while aluminum, iron, and silicon are impurities. In aluminum bronzes, on the other hand, lead, tin, and zinc become contaminants, while aluminum and iron are alloying elements.

Foundries typically do little melt refining, leaving this assignment to the secondary smelter supplier of their foundry ingot. However, there may be certain instances when additional refining capability is necessary within the foundry or mill. Table 5 gives the results of fire refining a melt of C83600 with aluminum, silicon, and iron contaminants under a variety of flux covers.

Fire refining (oxidation) can be used to remove impurities from copper-base melts roughly in the following order: aluminum, manganese, silicon, phosphorus, iron, zinc, tin, and lead. Nickel, a deliberate alloying element in certain alloys but an impurity in others, is not readily removed by fire refining, but nickel oxide can be reduced at such operating temperatures. Mechanical mixing or agitation during fire refining improves the removal capability by increasing the reaction kinetics. Removal is limited, however, and in dilute amounts (<0.05–0.10%) many impurities cannot be removed economically.

Oxygen-bearing fluxes can be effective in removing certain impurities, although they are less efficient than direct air or oxygen injection. Figure 10 demonstrates the effect of increasing the copper oxide content of a flux in removing iron and zinc from phosphor bronze.

Lead has been removed from copper alloy melts by the application of silicate fluxes or slags. The addition of phosphor copper or the use of a phosphate or borate slag flux cover and thorough stirring improves the rate of lead removal, as shown in Fig. 11 (Ref 4).

Sulfur, arsenic, selenium, antimony, bismuth, and tellurium can occur as impurities in copper alloy scrap, foundry ingot, and prime metal through incomplete refining of metal from the ore, electronic scrap, other scrap materials, or cutting lubricant. These impurities can largely be controlled by application and thorough contacting with fluxes containing sodium carbonate (Na_2CO_3) or other basic flux additives such as potassium carbonate (K_2CO_3). Figure 12 demonstrates the ability of Na_2CO_3 fluxes plus fire refining in eliminating arsenic, bismuth, and antimony from copper.

Sulfur is a harmful impurity in copper-nickel or nickel-silver alloys. It can be removed from these materials by an addition of manganese metal or magnesium.

Aluminum is often a contaminant in copper alloy systems, particularly the leaded tin bronzes and red brasses. Porosity and lack of pressure tightness result when the aluminum content is as little as 0.01%. Aluminum can be removed by a flux containing oxidizing agents to oxidize the aluminum, and fluoride salts to divert the Al_2O_3 from the melt and render it removable. Silicon can also be removed, but only after the aluminum has reacted. As much as 0.3% contaminant can be reduced to less than 0.01%, ensuring pressure tightness, by using a flux consisting of 30% NaF, 20% CaF_2, 20% Na_3AlF_6, 20% Na_2SO_4, and 10% Na_2CO_3 at an addition rate of 1 to 1.5% for 10 min at about 1100 °C (2010 °F) (Ref 6). As usual, the flux must be intimately mixed with the melt to ensure good reactivity. The melt should then be allowed to settle, and the flux residue or slag layer should be thoroughly skimmed.

Borax is useful as a flux constituent for refining to provide adequate fluidity and to agglomerate flux-reacted impurity oxides without excessive entrapment and loss of alloying elements. The borax mineral fluxes razorite and colemanite are commonly used in secondary smelting practice in converting copper alloy brass and bronze scrap to specified-composition foundry ingot.

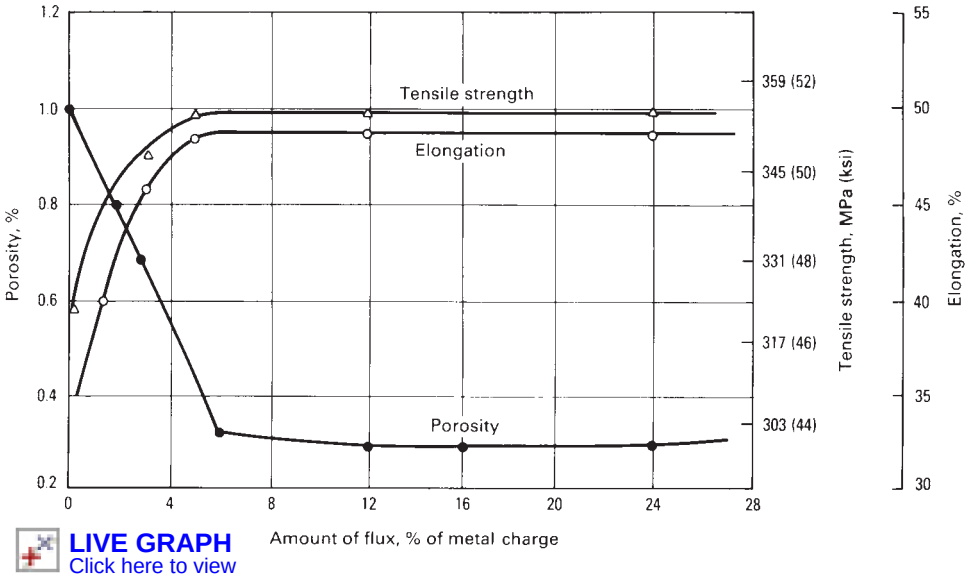

Fig. 7 Effect of amount of flux used on the porosity and mechanical properties of cast tin bronze alloy. Source: Ref 1

Table 4 Effect of various slags and covers on losses in the melting of high-tensile and yellow brass

Alloy	Melting conditions	Metal temperature, °C	Metal temperature, °F	Melting time, min	Gross loss, %	Net loss, %
Yellow brass	No lid or cover	1085	1985	50	2.8	1.8
	Charcoal	1087	1989	49	1.1	0.6
	Glassy cover flux	1100	2012	62	0.9	0.4
High-tensile brass	No lid or cover	1090	1994	65	2.5	1.2
	Charcoal	1095	2003	60	1.9	0.7
	Cleaning cover flux	1090	1994	54	0.6	0.3

Source: Ref 1

Chlorine fluxing also has potential for refining impurities from copper-base melts, particularly magnesium, aluminum, manganese, zinc, iron, lead, and silicon. However, very little chlorine refining is practiced commercially; the process may be cost effective only when removing aluminum.

Mold Fluxes. Certain mold-lubricating fluxes have been used in the direct chill semicontinuous casting of brass and copper alloys into semifinished wrought shapes. These fluxes serve to protect the metal from oxidation during casting. They also act as lubricants so that the solidifying skin separates easily from the mold wall as the solidifying billet or slab moves downward from the mold during casting. Especially in brass alloys, zinc flaring and zinc oxide (ZnO) formation on the melt surface reduce lubricity, causing tearing and other undesirable skin defects during solidification that are detrimental to subsequent forming operations. Fluxing compounds are used on the melt surface feeding the mold to alleviate these problems. Fluxes used to alleviate this problem usually contain borax, fluoride salts, soda ash, and eutectic salt mixtures to ensure that the flux is molten as the cast continues. In the direct chill casting of higher-copper alloys, graphite may also be present in such fluxes. Because solid flux particles can cause inclusions in the solidifying skin, the flux must be free of coarse particles and must melt quickly.

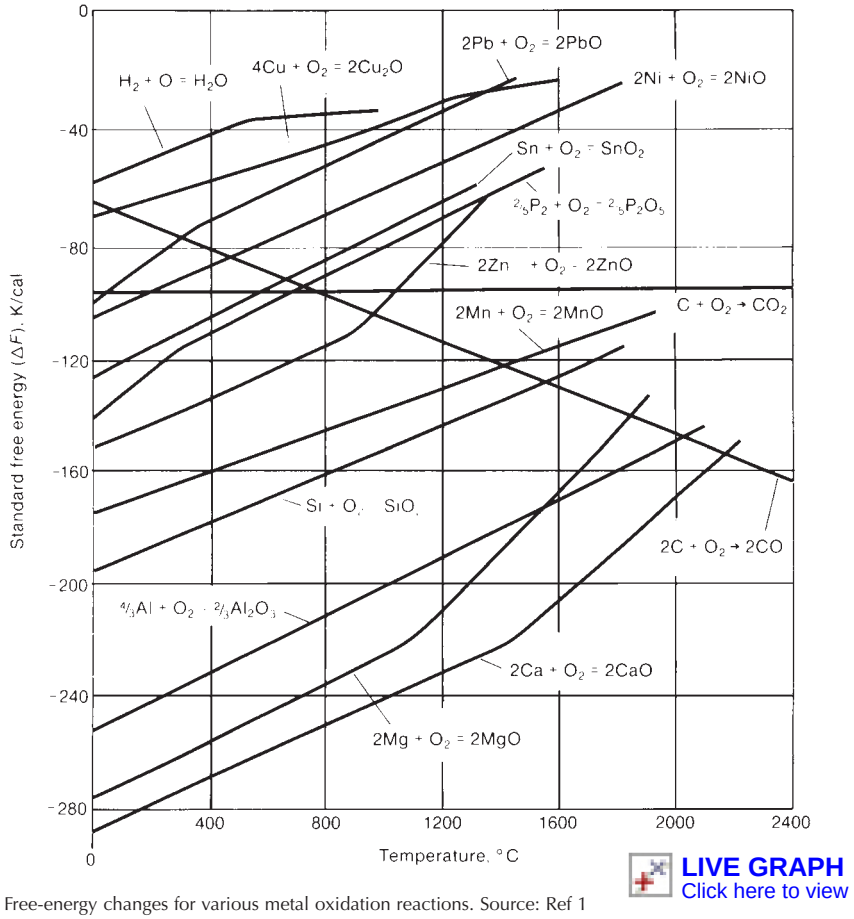

Fig. 8 Free-energy changes for various metal oxidation reactions. Source: Ref 1

Table 5 Effect of fire refining under various fluxes on impurity levels in leaded red brass

50 kg (110 lb) heats were melted under 1 kg (2.2 lb) of flux at 1150 °C (2100 °F).

Melt No.	Flux	Refining time, min	Oxygen used, liters per kilogram of metal	Amount of zinc in refined metal, %	Impurities in refined metal, %		
					Al	Si	Fe
1	Borax	0	0	5.49	0.05	0.08	0.38
		10	1.5	5.66	0.015	0.05	0.38
		20	2.9	5.00	0.011	0.02	0.29
2	Borax-25% sand	0	0	6.30	0.14	0.13	0.37
		10	1.5	6.24	0.017	0.12	0.42
		20	2.9	6.45	0.007	0.12	0.41
3	Borax-20MnO	0	0	7.40	0.21	0.26	0.47
		10	1.5	7.35	0.05	0.19	0.52
		20	3.1	7.33	0.017	0.12	0.51
4	$70CaF_2$-$20Na_2SO_4$-$10Na_2CO_3$	0	0	7.47	0.10	0.08	0.62
		10	1.5	7.07	<0.005	0.02	0.55
		20	3.1	6.69	<0.005	<0.005	0.45
5	30NaF-$20CaF_2$-20KF-$20Na_2SO_4$-$10Na_2CO_3$	0	0	7.35	0.23	0.38	0.70
		10	1.8	6.74	0.005	0.17	0.83
		20	3.5	7.20	<0.005	0.08	0.88

Source: Ref 3

Degassing of Copper Alloys

In the melting and casting of many copper alloys, hydrogen gas absorption can occur because of the generous solubility of hydrogen in the liquid state of these alloys. The solid solubility of hydrogen is much lower; therefore, the gas must be rejected appropriately before or during the casting and solidification process to avoid the formation of gas porosity and related defects (excessive shrink, pinholing, blowholes, and blistering). These defects are almost always detrimental to mechanical and physical properties, performance, and appearance. Different copper alloys and alloy systems have varying tendencies toward gas absorption and subsequent problems. Other gases, particularly oxygen, can cause similar problems (see the section "Deoxidation of Copper Alloys" in this article).

Sources of Hydrogen

There are many potential sources of hydrogen in copper, including the furnace atmosphere, charge materials, fluxes, external components, and reactions between the molten metal and the mold.

Furnace Atmosphere. The fuel-fired furnaces sometimes used in melting can generate free hydrogen because of the incomplete combustion of fuel oil or natural gas.

Charge Materials. Ingot, scrap, and foundry returns may contain oxides, corrosion products, sand or other molding debris, and metalworking lubricants. All these contaminants are potential sources of hydrogen through the reduction of organic compounds or through the decomposition of water vapor from contained moisture.

Fluxes. Most salt fluxes used in copper melt treatment are hygroscopic. Damp fluxes can therefore result in hydrogen pickup in the melt from the decomposition of water.

External Components. Furnace tools such as rakes, puddlers, skimmers, and shovels can deliver hydrogen to the melt if they are not kept clean. Oxides and flux residues on such tools are particularly insidious sources of contamination because they will absorb moisture directly from the atmosphere. Furnace refractories, troughs and launders, mortars and cements, sampling ladles, hand ladles, and pouring ladles also are potential sources of hydrogen, especially if refractories are not fully cured.

Metal/Mold Reactions. If metal flow is excessively turbulent during the pouring process, air can be aspirated into the mold. If the air cannot be expelled before the start of solidification, hydrogen pickup can result. Improper gating can also cause turbulence and suctioning. Excessive moisture in green sand molds can provide a source of hydrogen as water turns to steam.

Gas Solubility

Hydrogen is the most obvious gas to be considered in copper alloys. Figure 13 shows the solubility of hydrogen in molten copper. As in aluminum and magnesium alloys, solubility is reduced in the solid state; therefore, the hydrogen must be removed prior to casting or rejected in a controlled manner during solidification. Alloying elements have varying effects on hydrogen solubility (Fig. 14).

Oxygen also presents a potential problem in most copper alloys. In the absence of hydrogen, oxygen alone may not cause problems, because it has limited solubility in the melt. However, it forms a completely miscible liquid phase with the copper in the form of cuprous oxide (Fig. 15). During solidification, the combination of cuprous oxide and hydrogen can give rise to casting porosity resulting from the steam reaction (discussed later).

Sulfur gases have significance in primary copper through the smelting of sulfide ores and in the remelting of mill product scrap containing sulfur-bearing lubricants. Sulfur dioxide is the most probable gaseous product. Foundry alloys and foundry processing usually do not experience sulfur-related problems unless high-sulfur fossil fuels are used for melting.

Carbon can be a problem, especially with the nickel-bearing alloys. The nickel alloys have extensive solubility for both carbon and hydrogen. Carbon can be deliberately added to the melt, along with an oxygen-bearing material such as nickel oxide. The two components will react to produce a carbon boil, that is, the formation of CO bubbles, which collect hydrogen as they rise through the melt (Ref 9). If not fully removed, however, the residual CO can create gas porosity during solidification.

Nitrogen does not appear to be detrimental or to have much solubility in most copper alloys. However, there is some evidence to suggest that nitrogen porosity can be a problem in cast copper-nickel alloys (Ref 10).

Water vapor can exist as a discrete gaseous entity in copper alloys (Ref 7, 11, 12). Water vapor is evolved from solidifying copper alloys, which always have some residual dissolved oxygen. When the oxygen becomes depleted, hydrogen is produced as a separate species.

The type and amount of gas absorbed by a copper alloy melt and retained in a casting depend on a number of conditions, such as melt temperature, raw materials, atmosphere, pouring conditions, and mold materials. Table 6 lists the gases that can be found in a number of copper alloy systems.

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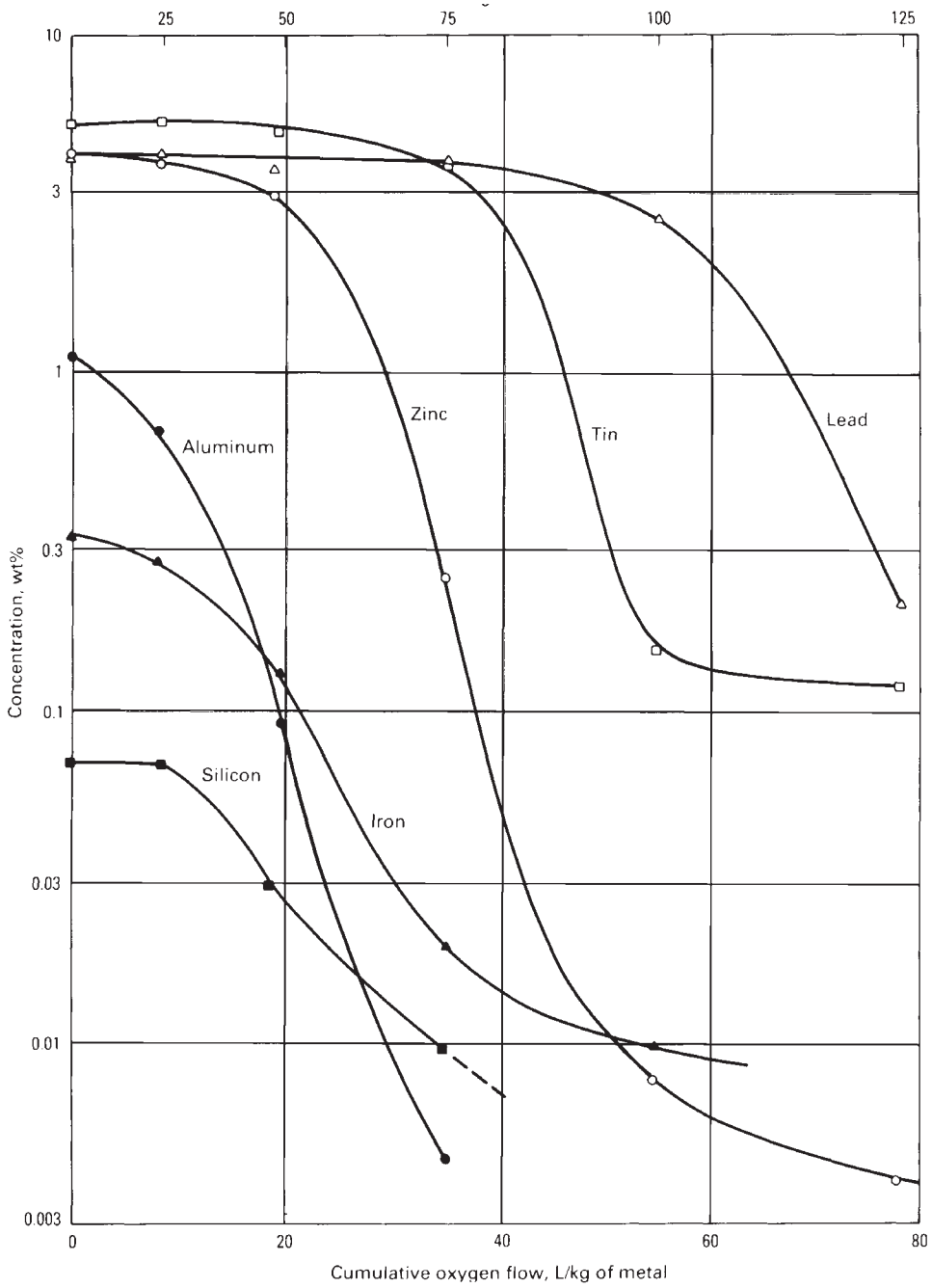

Fig. 9 Effect of fire refining (oxygen blowing) on the impurity content of molten copper. Source: Ref 3

Testing for Gases

There are essentially three ways to determine the presence of gas in a copper alloy melt. The easiest and simplest is a chill test on a fracture specimen. In this method, a standard test bar is poured and allowed to solidify. The appearance of the fractured test bar is then related to metal quality standards (Ref 13).

The second method is a reduced-pressure test similar to the Straube-Pfeiffer test used for aluminum alloys. In recent years, considerable development and definition have been given to this test as adapted for copper alloys, because the different classes of copper alloys have different solidification characteristics that affect the response to the test (Ref 7, 14–16). The objective of the test is to use a reduced pressure only slightly less than the dissolved gas pressure so that the surface of the sample mushrooms but does not fracture (Fig. 16). The test apparatus is shown schematically in Fig. 17. The key to establishing controllable results, that is, unfractured but mushroomed test sample surfaces, is to provide wave front freezing. This is accomplished by proper selection of vessel materials to

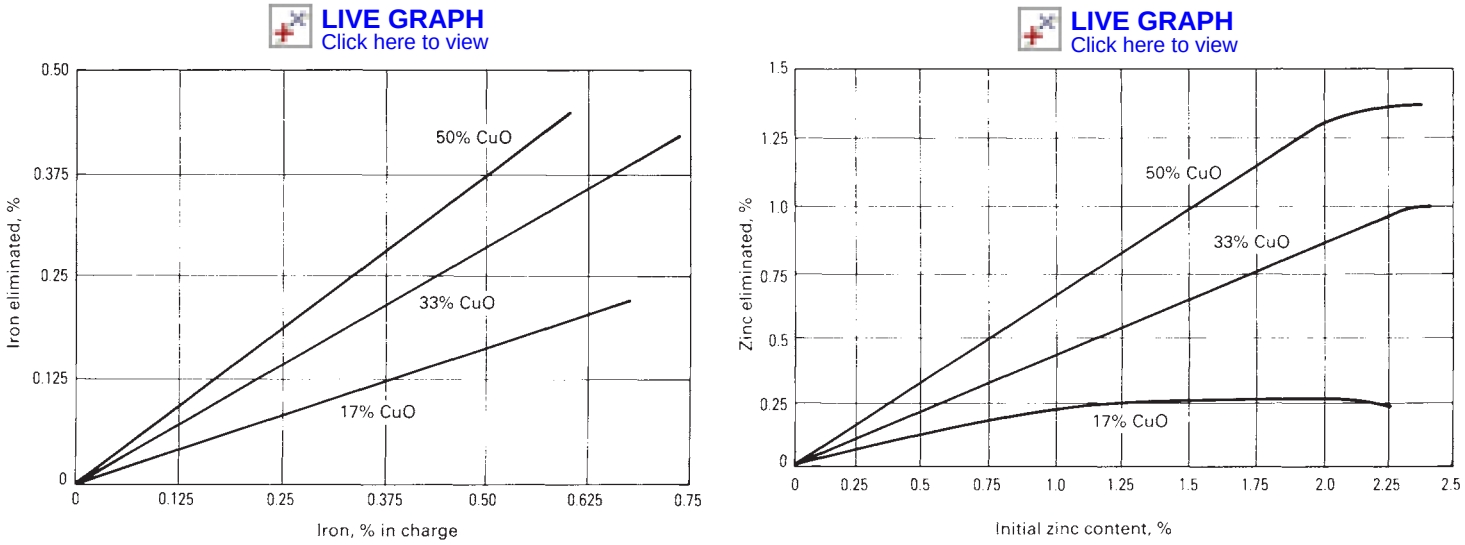

Fig. 10 Influence of oxygen content of flux in reducing iron (a) and zinc (b) impurities in phosphor bronze. Source: Ref 1

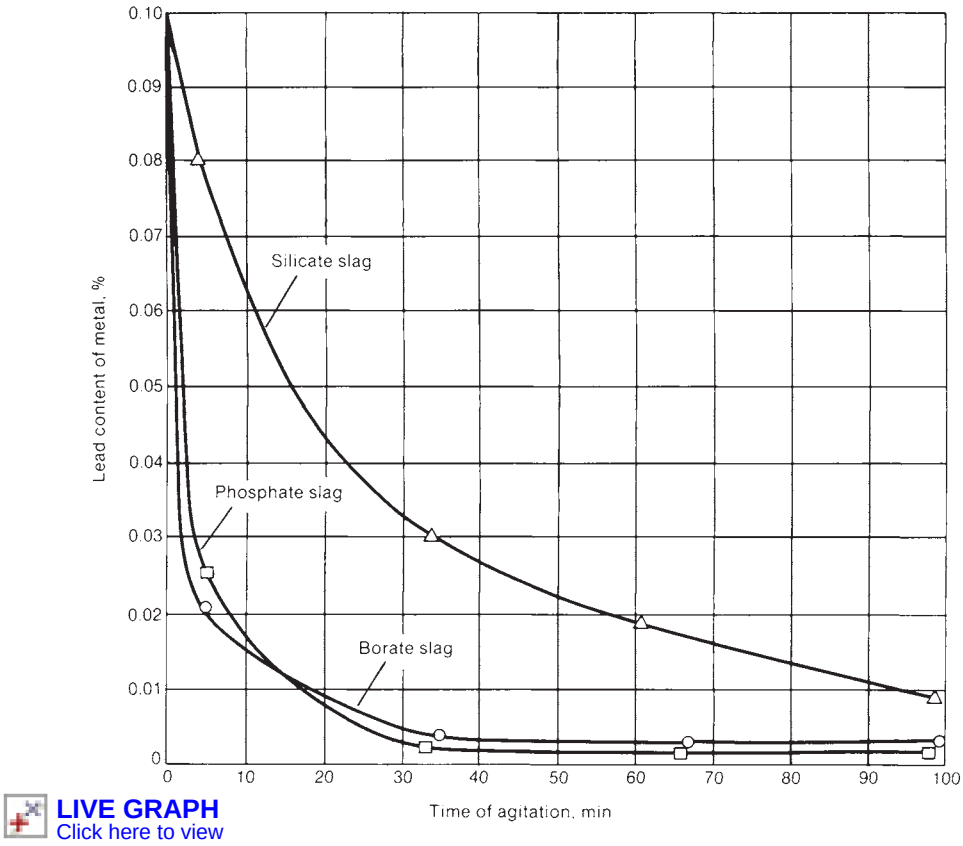

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Fig. 11 Removal of lead from oxidized Cu-0.1 Pb melts at 1150 °C (2100 °F) by different slags (fluxes) 2% of charge weight. Melt stirred with nitrogen at 2 L/min. Source: Ref 4

achieve the correct solidification characteristics. Because the freezing ranges of copper alloys vary from short to wide, different materials must be used. The various material combinations that have proved successful are described in Ref 7.

Degassing Methods

Oxidation-Deoxidation Practice. The steam reaction previously mentioned is a result of both hydrogen and cuprous oxide being present in the melt. These constituents react to form steam, resulting in blowholes during solidification as the copper cools:

$$2H + Cu_2O \rightarrow H_2O \text{ (steam)} + 2Cu$$

The proper deoxidation of a copper alloy melt will generally prevent this steam reaction, although excessive hydrogen alone can still cause gas porosity if it is not expelled from the casting before the skin is completely solidified. Fortunately, there is a mutual relationship between hydrogen and oxygen solubility in molten copper (Fig. 18). Steam is formed above the line denoting equilibrium concentration, but not below. Consequently, as the oxygen content is raised, the capacity for hydrogen absorption decreases. Therefore, it is useful to provide excess oxygen during melting to preclude hydrogen entry and then to remove the oxygen by a deoxidation process to prevent further steam reaction during solidification.

This relationship gave rise to the Pell-Walpole oxidation-deoxidation practice for limiting hydrogen, especially when fossil-fuel-fired furnaces were used for melting. The melt was deliberately oxidized using oxygen-bearing granular fluxes or briquetted tablets to preclude hydrogen absorption during melting. The melt was subsequently deoxidized to eliminate any steam reaction with additional hydrogen absorbed during pouring and casting.

Zinc Flaring. The term zinc flare applies to those alloys containing at least 20% Zn. At this level or above, the boiling or vaporization point of copper-zinc alloys is close to the usual pouring temperature, as shown in Fig. 19 (Ref 8). Zinc has a very high vapor pressure, which precludes hydrogen entry into the melt. Zinc may also act as a vapor purge, removing hydrogen already in solution. Furthermore, the oxide of zinc is less dense than that of copper, thus providing a more tenacious, cohesive, and protective oxide skin on the melt surface and increasing resistance to hydrogen diffusion. In zinc flaring, the melt temperature is deliberately raised to permit greater zinc vapor formation. Because some zinc loss may occur, zinc may have to be replenished to maintain the correct composition.

Inert Gas Fluxing. With gas fluxing, an inert collector or sparger gas such as argon or nitrogen is injected into the melt with a graphite fluxing tube. The bubbling action collects the hydrogen gas that diffuses to the bubble surface, and the hydrogen is removed as the inert gas bubbles rise to the melt surface. The reaction efficiency depends on the gas volume, the depth

to which the fluxing tube or lance is plunged, and the size of the collector gas bubble generated. Again, finer bubble sizes have higher surface-area-to-volume ratios and therefore provide better reaction efficiencies. Figure 20 depicts the amount of purge gas necessary to degas a 450 kg (1000 lb) copper melt. Figure 21 shows the response of an aluminum bronze alloy to nitrogen gas purging. The curve for oxygen purging is also shown.

Solid Degassing Fluxes. Other materials can be used to provide inert gas purging. A tabletted granular flux such as calcium carbonate ($CaCO_3$), which liberates CO_2 as the collector gas upon heating, has been successful in

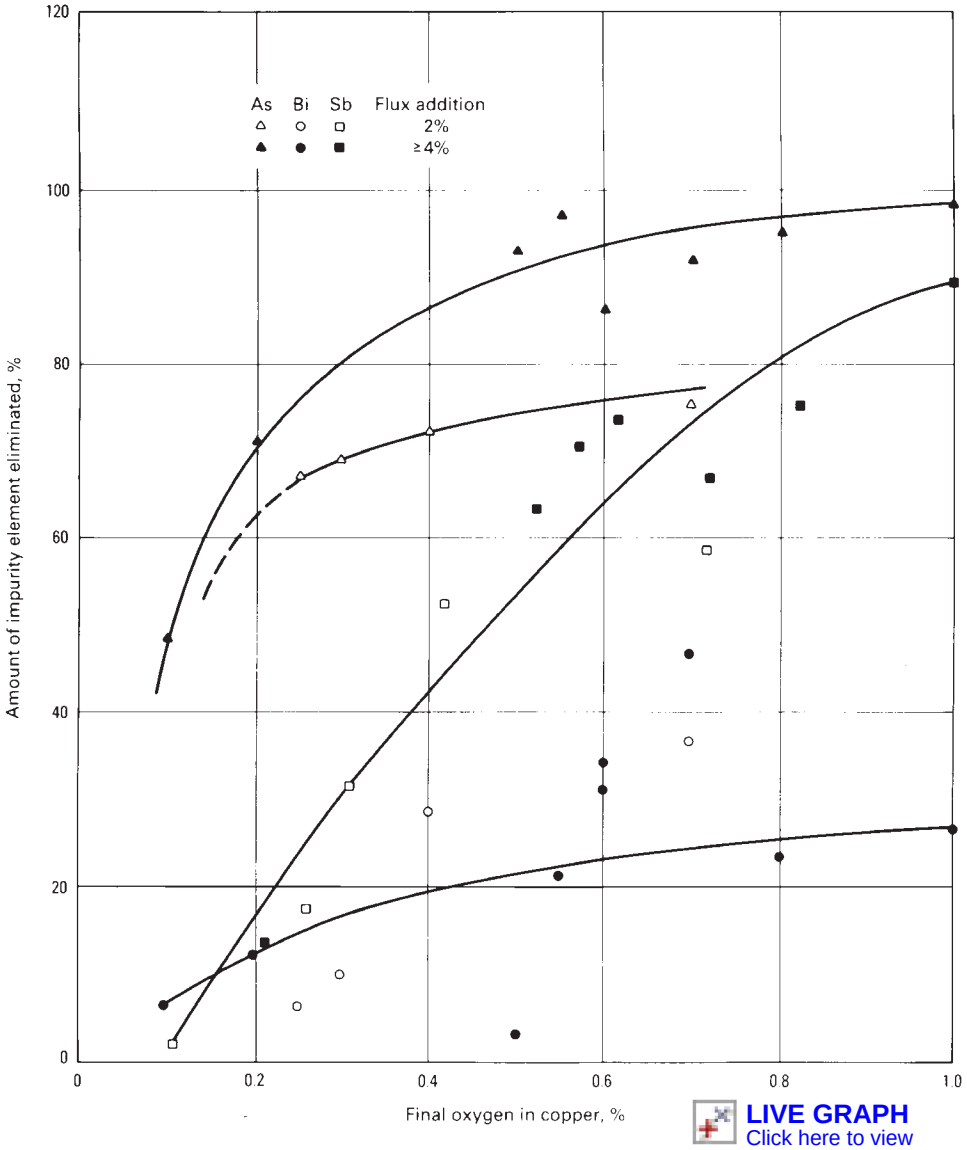

Fig. 12 Effect of fire refining and use of Na_2CO_3 flux on removal of arsenic, bismuth, and antimony impurities from copper. Source: Ref 5

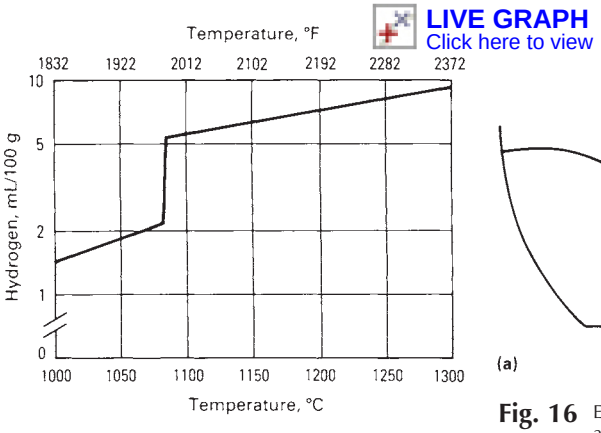

Fig. 13 Solubility of hydrogen in copper. Source: Ref 7

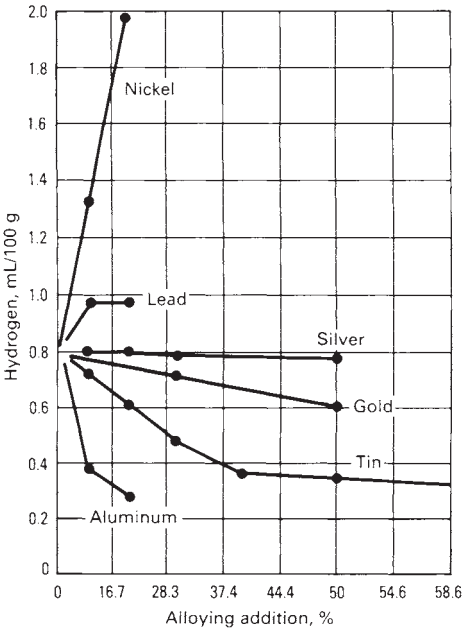

Fig. 14 Effect of alloying elements on the solubility of hydrogen in copper. Source: Ref 8

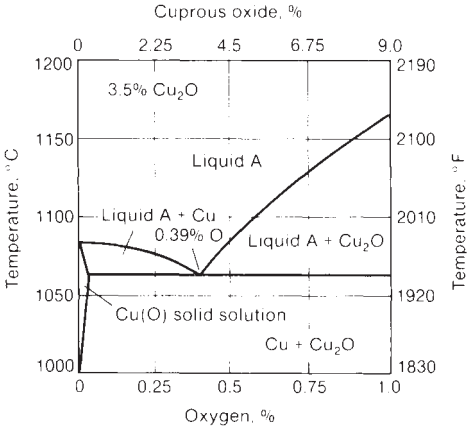

Fig. 15 Copper-oxygen phase diagram. Source: Ref 8

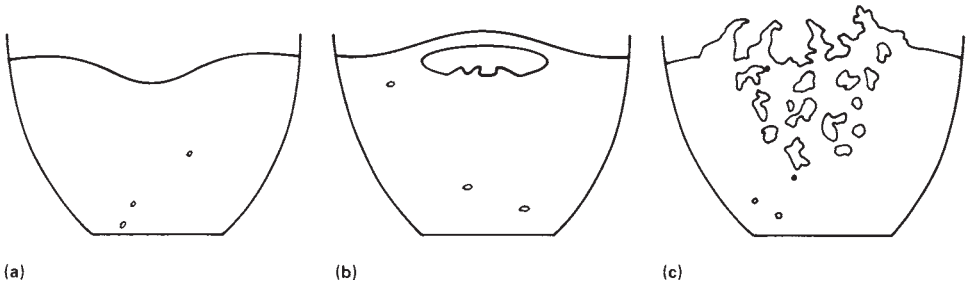

Fig. 16 Effect of pressure on the appearance of copper alloy reduced-pressure test samples containing the same amount of gas. (a) Pressure of 7 kPa (55 torr) results in surface shrinkage. (b) At 6.5 kPa (50 torr), a single bubble forms. (c) Boiling and porosity occur at 6 kPa (45 torr).

Table 6 Summary of gases found in copper alloys

Alloy family	Gases present	Remarks
Pure copper	Water vapor, hydrogen	Approximate hydrogen/water vapor ratio of 1. Higher purity increases the amount of water vapor and lowers hydrogen.
Cu-Sn-Pb-Zn alloys	Water vapor, hydrogen	Lead does not affect the gases present. Higher tin lowers total gas content. Increased zinc increases the amount of hydrogen, with a loss in water vapor.
Aluminum bronzes	Water vapor, hydrogen, CO	The presence of 5 wt% Ni in alloy C95800 causes CO to occur rather than water vapor. Lower aluminum leads to higher total gas contents.
Silicon brasses and bronzes	Water vapor, hydrogen	Approximate hydrogen/water vapor ratio of 0.5. Increased zinc decreases hydrogen and increases water vapor.
Copper-nickels	Water vapor, hydrogen, CO	All three gases are present up to 4 wt% Ni, after which only CO and hydrogen are present. Hydrogen increases with increasing nickel up to 10 wt% Ni, but is decreased at 30 wt% Ni.

Source: Ref 10

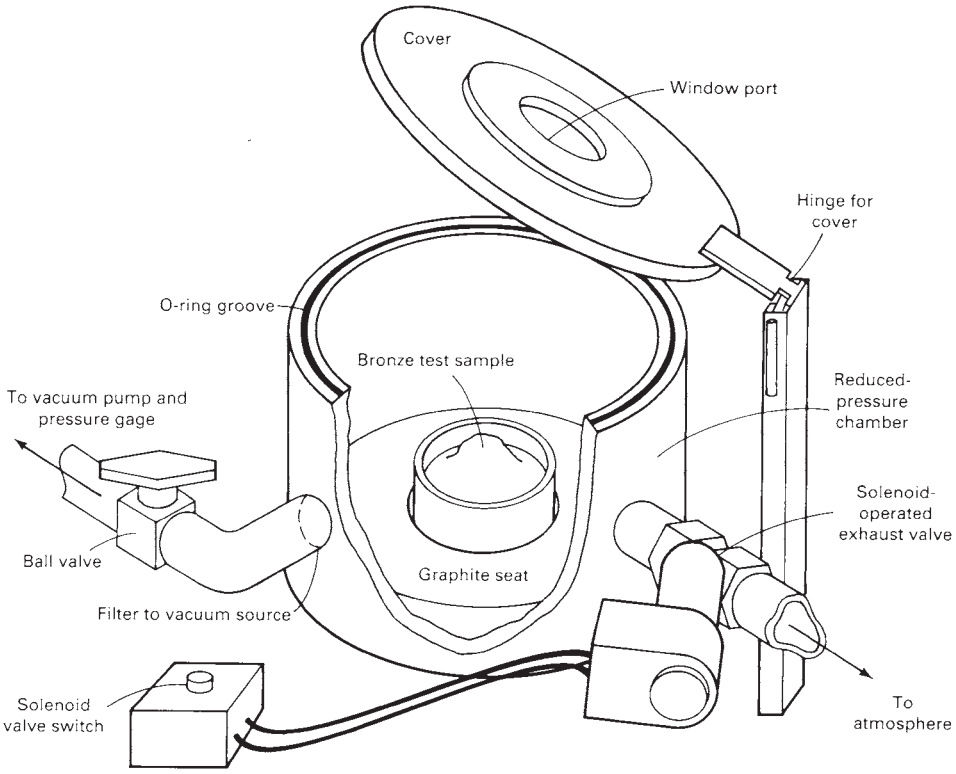

Fig. 17 Schematic of the reduced-pressure test apparatus used to assess amounts of dissolved gas in copper alloys

degassing a wide variety of copper alloys. This type of degassing is simpler than nitrogen, but must be kept dry and plunged as deep as possible into the melt with a clean, dry plunging rod, preferably made of graphite. This type of degasser may also have the advantage of forming the collector gas by chemical reaction in situ. This results in an inherently smaller initial bubble size than injected gas purging for better reaction efficiency. Such an advantage can be inferred from Fig. 22, although after 5 min of degassing the end results are the same.

Other solid degassers in the form of refractory metals or intermetallic compounds, such as Ca-Mn-Si, nickel-titanium, titanium, and lithium, are effective in eliminating porosity due to nitrogen or hydrogen by their ability to form stable nitrides and hydrides. Again, maintaining dry ingredients, deep plunging, and stirring or mixing will enhance their effectiveness. For best results and optimal reaction efficiency, such degassers should be wrapped or encapsulated in copper materials to provide controlled melting when plunged. Alternatively, copper master alloys containing these elements are available.

For both inert gas fluxing and solid degassing additions, the sparging gas reaction should not be so violent as to splash metal and create an opportunity for gas reabsorption. Furthermore, a melt can be overdegassed; an optimal amount of residual gas remaining in the melt helps to counter localized shrinkage in long freezing range alloys such as leaded tin bronzes.

Vacuum degassing is not generally applied to copper alloys, although it can be very effective. However, the cost of the equipment necessary is relatively high, and there may be a substantial loss of more volatile elements having a high vapor pressure such as zinc and lead. Furthermore, significant superheat (up to 150 °C, or 300 °F) may be required to accommodate the temperature drop during the degassing treatment, further aggravating the vapor losses.

Auxiliary Degassing Methods. There are other ways to degas a copper alloy melt than using a specific treatment. The technique of lowering the melt superheat temperature, if possible, and holding the melt (in a dry, minimal gas environment) provides outgassing simply by lower-

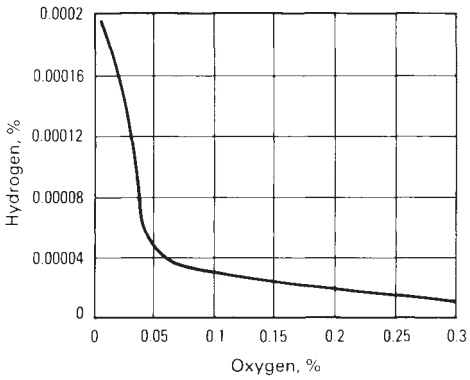

Fig. 18 Hydrogen/oxygen equilibrium in molten copper. Source: Ref 7

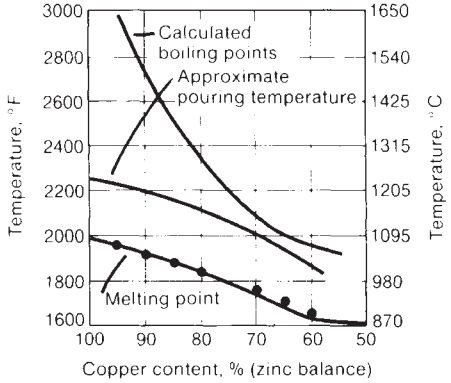

Fig. 19 Influence of zinc content on boiling point or vapor pressure in copper alloys. Source: Ref 8

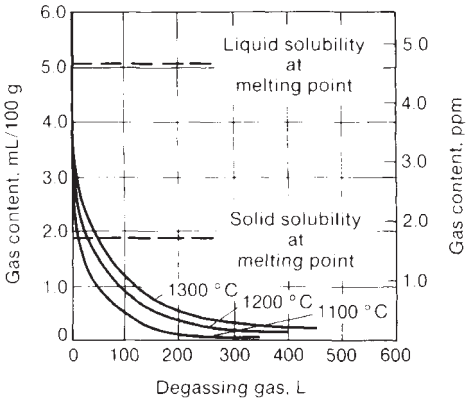

Fig. 20 Amount of purge gas required to degas a 450 kg (1000 lb) copper melt. Source: Ref 16

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ing the equilibrium liquid state solubility of the gas. During casting, the use of chills to provide directional solidification, particularly for the long freezing range group III alloys such as the red brasses and tin bronzes, results in less tendency for gas porosity.

In the mold-metal reaction, previously degassed and deoxidized metal containing excess phosphorus or lithium deoxidants can react with green sand containing moisture. Hydrogen is liberated and absorbed as the metal comes into contact with the sand. This can be minimized by correct deoxidant additions (discussed in the following section in this article). In addition, finer facing sands or mold coatings (inert or reactive such as sodium silicate or magnesia) can be used; these confine any reaction to the mold/metal interface area and retard hydrogen penetration into the solidifying skin of the cast metal.

Deoxidation of Copper Alloys

All copper alloys are subject to oxidation during most melting operations. Oxygen reacts with copper to form cuprous oxide, which is completely miscible with the molten metal. A eutectic is formed at 1065 °C (1950 °F) and 3.5% Cu_2O, or 0.39% O, as shown in the copper-oxygen phase diagram in Fig. 15.

Therefore, cuprous oxide exists within the melt as a liquid phase and is not generally separated by gravity alone. If not removed, this liquid phase will cause discontinuous solidification during casting, resulting in considerable porosity and low mechanical strength. Thus, some type of deoxidation process is required. In addition, proper deoxidation of all melts enhances fluidity and therefore castability.

Of course, deliberate oxidation treatments (the oxidation-deoxidation process previously described) are still employed. These are designed to preclude hydrogen pickup in copper alloy melts.

Phosphorus Deoxidation. Most copper alloys are deoxidized by a phosphorus reduction of the cuprous oxide. Although several other oxygen scavengers are possible according to the free energy of oxide formation, phosphorus is usually the easiest, most economical, and least problematic deoxidant. The phosphorus is usually added in the form of 15% phosphor copper master alloy, either in granular shot or briquetted waffle form. Care must be taken to ensure that the deoxidant is dry. The deoxidant is often added to the bottom of the ladle before pouring so that during pouring the deoxidant reacts with the cuprous oxide contained in the melt. The turbulence created during pouring is sufficient to ensure adequate mixing. The phosphorus copper deoxidant should not be simply thrown onto the surface of the ladle after pouring, because little mixing will result. When the deoxidant is added directly to the furnace, however, it should be completely stirred into the melt using clean, dry tools, and pouring should begin as soon as possible so that the effect is not lost.

Use of phosphorus deoxidation results in the formation of a liquid slag of cuprous phosphate:

$$2P + 4Cu + 7O \rightarrow 2Cu_2O \cdot P_2O_5$$

This product easily separates from the rest of the melt; therefore, the phosphorus effectively scavenges the oxygen, delivering the product to the surface dross phase, where it can be easily skimmed.

Phosphorus is usually added at a rate of 57 g (2 oz) of 15% master alloy per 45 kg (100 lb) of melt. In cases where oxidation of the melt is deliberately employed to reduce hydrogen absorption, double this amount can be required for full deoxidation. This is usually sufficient to deoxidize completely a melt saturated with 0.39 wt% O. However, the recovery of phosphorus is less than 100% and may be as little as 30 to 60% (Ref 18). It is desirable to maintain a residual level of at least 0.01 to 0.015% P in the melt, especially during pouring, so that reoxidation and potential steam reaction problems are alleviated.

Each foundry must determine the proper addition rate for a given set of conditions. Furthermore, with foundry returns, a certain residual amount of phosphorus is usually already present. A routine addition of phosphor copper for deoxidation could then actually result in excessive phosphorus. If the phosphorus content is too high during melting or pouring, the lack of oxygen may invite hydrogen entry and result in the steam reaction during casting. Adding more phosphorus to control the steam reaction can therefore actually aggravate the condition. In addition, when the phosphorus content is 0.03% and beyond, excessive metal fluidity can result in penetration of the molding sand or burn-in during casting.

Phosphorus copper is an effective deoxidant for the red brasses, tin bronzes, and leaded bronzes. However, phosphorus should not be used for deoxidizing high-conductivity copper alloys, because of its deleterious effect on electrical conductivity (as is discussed in the next section), and it should not be used for copper-nickel alloys. In these materials, the presence of phosphorus results in a low-melting constituent that embrittles the grain boundaries. A silicon addition of 0.3% and a magnesium addition of 0.10% serve to deoxidize and desulfurize copper-nickel melts. For nickel silver alloys (Cu-Ni-Zn), the use of 142 g (5 oz)

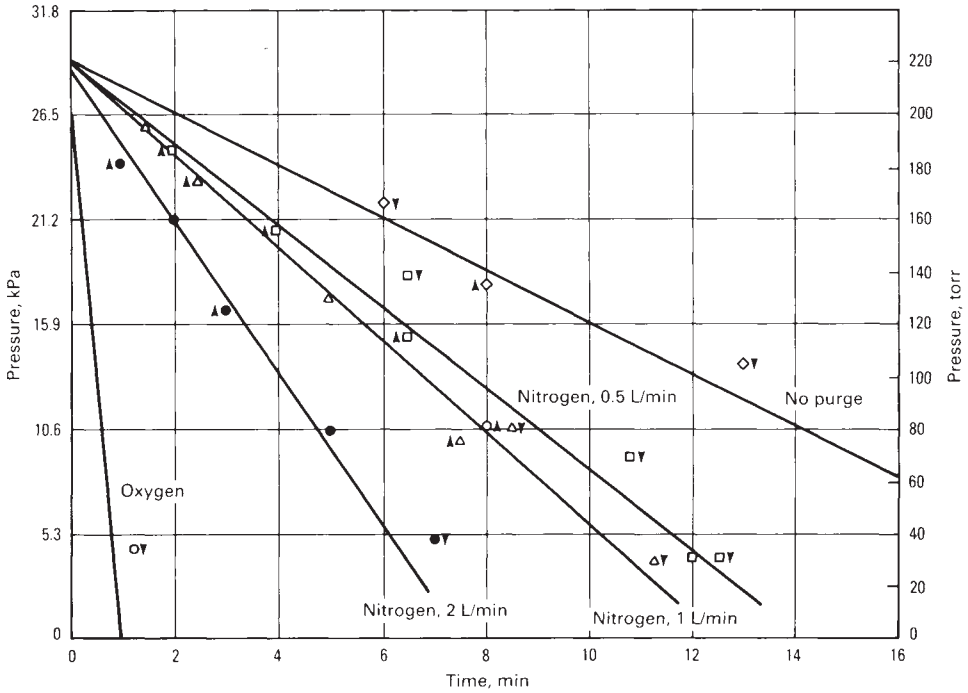

Fig. 21 Effect of nitrogen flow rate during purging on the residual gas pressure remaining in an aluminum bronze melt. The curve for oxygen purging is also shown. Source: Ref 15, 17

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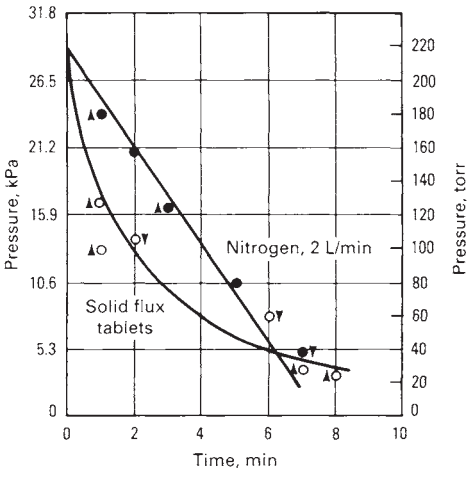

Fig. 22 Comparison of the effectiveness of solid degassing flux versus nitrogen purging. Source: Ref 17

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copper-manganese shot per 45 kg (100 lb) of melt, and 57 g (2 oz) manganese coupled with 85 g (3 oz) of 15% P-Cu, is a recommended deoxidation technique.

The yellow brasses, silicon bronzes, manganese bronzes, and aluminum bronzes usually do not require deoxidation per se, because of the oxygen-scavenging effects of their respective alloy constituents.

High-Conductivity Copper (Ref 18–21). Where the high-copper alloys (pure copper, silver-copper, cadmium-copper, tellurium-copper, beryllium-copper, chromium-copper) are employed and electrical conductivity is a desirable property, phosphorus-copper cannot be used as a deoxidant. Moreover, the strong oxide formers beryllium and chromium serve as their own deoxidants.

Figure 23 shows the effects of a variety of elements on the electrical conductivity of copper. Clearly, phosphorus even in small amounts significantly decreases conductivity; therefore, alternative deoxidants must be used. Fortunately, both boron and lithium are capable of deoxidizing high-conductivity copper without appreciably affecting electrical conductivity.

Boron Deoxidation. Boron is available either as a copper-boron master alloy or as calcium boride (CaB_6). The boron probably forms a copper-borate slag of the general form $2Cu_2O{\cdot}B_2O_3$ in much the same fashion as phosphorus produces a cuprous oxide phosphate slag (Ref 18). Theoretically, the boron combines with 60% more oxygen than the stoichiometric amount required to form B_2O_3 and therefore appears to be superefficient. However, practical experience has shown that this theoretical efficiency is not always achieved and that lithium is more effective, as shown in Fig. 24 (Ref 18). Therefore, lithium is often preferred, although there are greater precautions attendant upon its use.

Lithium Deoxidation (Ref 18, 19–22). Lithium has the advantage of serving as both a deoxidant and a degasser because it reacts readily with both oxygen and hydrogen. Lithium is soluble in molten copper but insoluble in the solid state. There is very little residual lithium contained in the casting or in scrap for remelt.

Because lithium metal is very reactive in air, bulk lithium metal must be stored in oil. For foundry applications, lithium is supplied in sealed copper cartridges. These cartridges must be stored in a safe, dry environment and must be preheated (to above 105 °C, or 225 °F) before use to drive off any surface moisture. These preheated cartridges should then be carefully yet firmly and quickly plunged to the bottom of the reacting vessel (furnace or ladle) to achieve full intimate contact and reactivity with the bulk of the melt. Only clean, dry, preheated plunging tools should be used for this task. Graphite rods are usually preferred.

Lithium-copper cartridges are generally available in various sizes ranging from 2.25 g (0.09 oz) for 23 kg (50 lb) melts to 108 g (4 oz). Thus, lithium additions can be made at maximum efficiency.

The specific chemical reactions that can occur with lithium include:

$$2Li + Cu_2O \rightarrow 2Cu + Li_2O \text{ (deoxidation)}$$

$$Li + H \rightarrow LiH \text{ (degassing)}$$

$$LiH + Cu_2O \rightarrow 2Cu + LiOH \text{ (recombination)}$$

$$2Li + H_2O \rightarrow Li_2O + H_2 \text{ (reaction during pouring)}$$

The lithium oxide (Li_2O) and lithium hydroxide (LiOH) products separate cleanly as a low-density fluid slag suitable for skimming (Ref 19). The lithium hydride that forms initially if hydrogen is present is unstable at normal copper melting temperatures and recombines with cuprous oxide (recombination).

When lithium is added in excess of the amount of cuprous oxide present, it will react with moisture in the air during pouring and can therefore generate sufficient hydrogen to regas the melt. This can result in unanticipated additional gas porosity and unsoundness during solidification.

Because lithium is such an effective deoxidant, it can also reduce residual impurity oxides (FeO, P_2O_5, and so on) in high-conductivity copper melts. This allows these elements to redissolve in the molten metal to the extent of their solubility limit and thus reduce electrical conductivity according to Fig 23. Furthermore, lithium can form intermetallic compounds with silver, lead, tin, and zinc when the residual lithium exceeds that required for deoxidation. These intermetallic compounds, while reducing solid solubility, may improve mechanical properties and electrical conductivity.

Occasionally, it may be desirable to practice a duplex deoxidation treatment using the less expensive phosphorus, followed by a lithium treatment (Ref 19, 21, 22). Care must be taken to do this quickly and not allow phosphorus reversion to occur by letting the copper phosphate deoxidation slag remain on the melt for an extended period of time.

Magnesium Deoxidation. Magnesium behaves similarly to lithium, but may be stored in air rather than oil. It is actually a stronger deoxidant in terms of its free energy of oxide formation (Ref 23), and it is used to deoxidize (and desulfurize) copper-nickel alloys. The

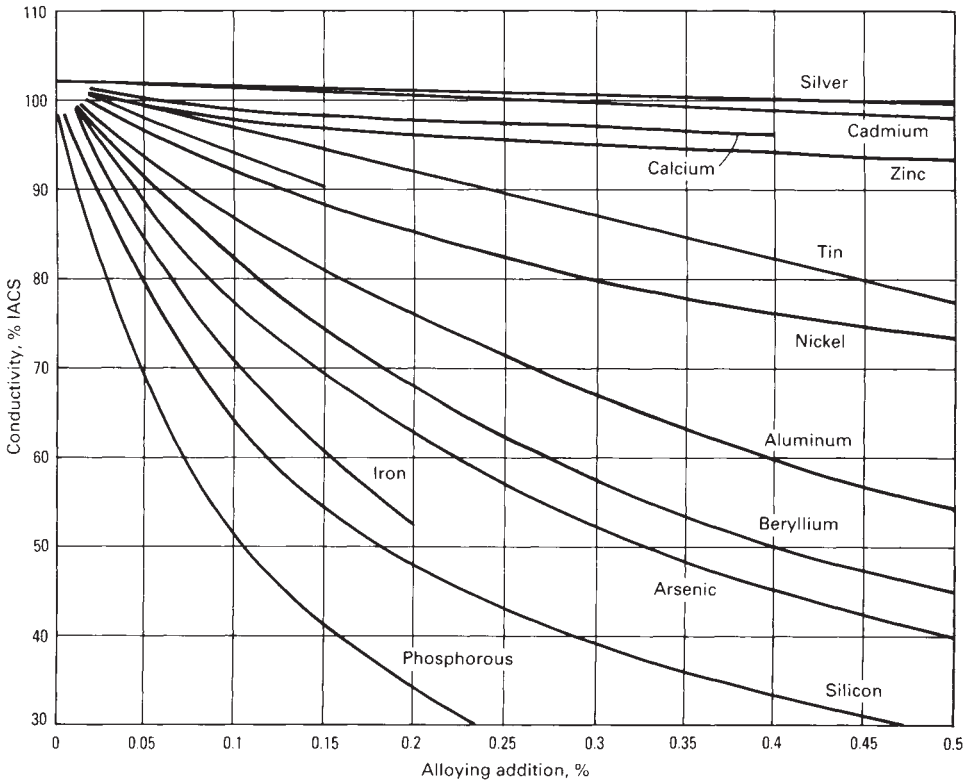

Fig. 23 Effect of alloying elements on the electrical conductivity of copper. Source: Ref 19

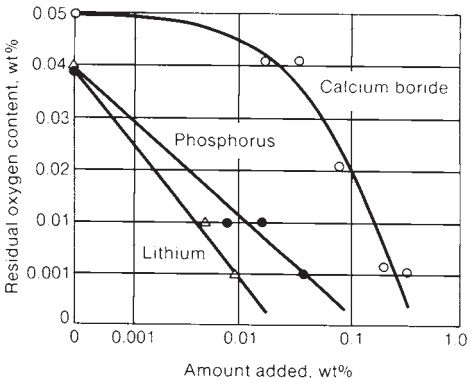

Fig. 24 Deoxidant efficiency in copper alloy melts. Source: Ref 18

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deoxidation product (magnesia) is a stable refractory, unlike lithium compounds, but it forms a tenacious oxide skin and can result in inclusions in copper casting alloys.

Testing for Proper Deoxidizer Addition. As stated previously, each foundry should assess its own casting practice for a given alloy and set of melting conditions and should determine the optimal addition of deoxidizer. However, there are two tests that can be used to determine whether a given amount of deoxidizer is adequate.

In the first test, a test plug or shrink bar of metal approximately 75 mm (3 in.) in diameter by 75 mm (3 in.) deep is poured. If a shrinkage cavity results, the metal is deoxidized and ready for pouring, which should then be done immediately. Shrinkage will not occur until about 0.01% residual phosphorus is present (Ref 23). A puffed-out or mushroomed cap on the test plug indicates that deoxidation is incomplete and that more should be added.

The second test involves a carbon or graphite rod immersed in the melt. When the rod surface reaches the molten metal temperature, if there is oxygen present, the rod will vibrate because of the reaction ($2C + O_2 \rightarrow 2CO$) occurring on the bar surface. The intensity of the vibration is a function of the oxygen content, and an experienced foundryman can readily determine the point at which the reaction becomes negligible, that is, when the melt is sufficiently deoxidized. The vibration decreases near the level of 0.01% residual phosphorus, as expected for a deoxidized melt (Ref 23).

Relative Effectiveness of Copper Deoxidizers. Various elements capable of scavenging oxygen from copper alloy melts have been described. The theoretical relative capabilities of several deoxidizers are:

Deoxidizer	Reaction products	Amount of deoxidizer required to remove 0.01% oxygen	
		g/100 kg	oz/100 lb
Carbon	CO	7.5	0.12
	CO_2	3.8	0.06
Phosphorus	P_2O_5	7.5	0.12
	$2Cu_2P_2O_5$	5.6	0.09
Cu-15P	P_2O_5	49.3	0.79
	$2Cu_2P_2O_5$	36.8	0.59
Boron	B_2O_3	4.4	0.07
Cu-2B	B_2O_3	224.5	3.60
Lithium	Li_2O	8.7	0.14
Magnesium	MgO	15.0	0.24

In practice, selection of the deoxidizer must be based on actual efficiency, economics, ease of use, and the specific metallurgical requirements of the alloy in question.

Grain Refining of Copper Alloys

In general, the grain refinement of copper alloys is not practiced as a specific molten metal processing step per se, because a certain degree of refinement can be achieved through normal casting processes. As with aluminum alloys, grain refinement in copper alloys can be achieved by rapid cooling, mechanical vibration, or the addition of nucleating or grain-growth-restricting agents. Further, many commercial copper alloys have sufficient solute (zinc, aluminum, iron, tin) to achieve constitutional supercooling during solidification. In this case, grain nucleation and growth are naturally retarded. Commercially pure copper can be grain refined by small additions (as little as 0.10%) of lithium, bismuth, lead, or iron, which provide constitutional supercooling effects (Ref 24, 25).

Copper-zinc single-phase alloys can be grain refined by additions of iron or by zirconium and boron (Ref 26). In the latter case, the probable mechanism is the formation of zirconium boride particle nuclei for grain formation. In one case, the vibration of a Cu-32Zn-2Pb-1Sn alloy improved yield and tensile strengths by about 15%, with a 10% reduction in grain size from the unvibrated state. In general, the α copper-zinc alloys (<35% Zn) exhibit grain size reduction and greater improvement in properties, while the α-β alloys do not.

Copper-aluminum alloys have been effectively grain refined with additions of 0.02 to 0.05% B; the effective nucleating agent is boron carbide (B_4C). Figure 25 illustrates the improvement in mechanical properties achieved by grain refining a Cu-10Al alloy.

Tin bronze alloys have been successfully grain refined by the addition of zirconium (0.02%) and boron master alloys (Ref 27). However, pressure tightness is reduced because in these long freezing range alloys, finer grain size concentrates porosity because of gas entrapment.

Filtration of Copper Alloys

The filtration process consists of passing the molten metal through a porous device (a filter) in which the inclusions contained in the flowing metal are trapped or captured. The filter material itself must have sufficient integrity (strength, refractoriness, thermal shock resistance, and corrosion resistance) so that it is not destroyed by the molten metal before its task is accomplished. Consequently, most filter media are ceramic materials in a variety of configurations. Although the bulk of filter technology has been directed toward aluminum alloys, the use of filtration is increasing for copper alloy melts.

Inclusions in Copper Alloys. In addition to the usual inclusions arising from oxides, fluxing salts, and intermetallics, copper oxide inclusions and phosphorus pentoxide (from deoxidation) may be present in copper alloys if the melt is not allowed to settle or if it is inadequately skimmed before pouring and casting.

Filter Applications. The filtration of copper casting alloys primarily involves the use of ceramic foam sections in the gating system. Oxide inclusions have been successfully removed from aluminum bronze alloys using such a filter deployment system (Ref 28). Investment castings can be successfully filtered using a filter section in the pouring cup or, in the case of larger castings, molded directly into the wax runner bars. Ceramic filters for copper alloys are usually alumina, mullite, or zirconia.

Melt Treatments for Group I to III Alloys

For group I to III alloys, the melting procedure, flux treatment, and pouring temperature (Table 7) vary considerably from one alloy family to another. It should also be noted that for any copper alloy, the temperature at which the metal is poured into the mold is higher than the liquidus temperature. Compare the liquidus temperatures in Tables 1 to 3 with those of the pouring temperatures in Table 7 for group I to III alloys. More detailed information on fluxing and

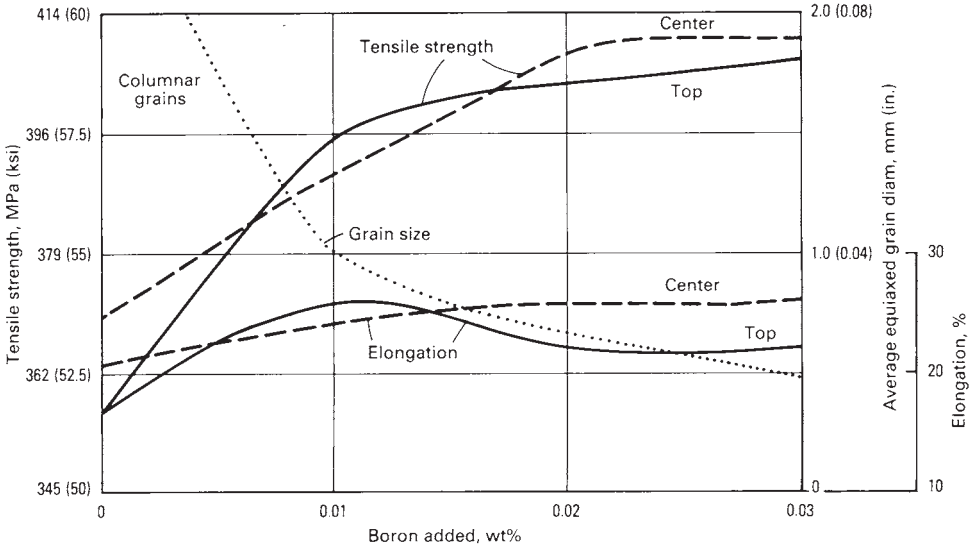

Fig. 25 Effect of boron-refined grain size on the mechanical properties of Cu-10Al alloy. Test specimens were removed from the center or the top of the ingot as indicated. Source: Ref 27

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other melt practices can be found in earlier sections of this article.

Group I Alloys

Pure Copper and Chromium-Copper. Commercially pure copper and high copper alloys are very difficult to melt and are very susceptible to gassing. In the case of chromium-copper, oxidation loss of chromium during melting is a problem. Copper and chromium-copper should be melted under a floating flux cover to prevent both oxidation and the pickup of hydrogen from moisture in the atmosphere. In the case of copper, crushed graphite should cover the melt. With chromium copper, the cover should be a proprietary flux made for this alloy. When the molten metal reaches 1260 °C (2300 °F), either calcium boride or lithium should be plunged into the molten bath to deoxidize the melt. The metal should then be poured without removing the floating cover.

Yellow Brasses. These alloys flare, or lose zinc, due to vaporization at temperatures relatively close to the melting point. For this reason, aluminum is added to increase fluidity and keep zinc vaporization to a minimum. The proper amount of aluminum to be retained in the brass is 0.15 to 0.35%. Above this amount, shrinkage takes place during freezing, and the use of risers becomes necessary. Other than the addition of aluminum, the melting of yellow brass is very simple, and no fluxing is necessary. Zinc should be added before pouring to compensate for the zinc lost in melting.

Manganese Bronzes. These alloys are carefully compounded yellow brasses with measured quantities of iron, manganese, and aluminum. The metal should be melted and heated to the flare temperature or to the point at which zinc oxide vapor can be detected. At this point, the metal should be removed from the furnace and poured. No fluxing is required with these alloys. The only addition required with these alloys is zinc. The amount required is that which is needed to bring the zinc content back to the original analysis. This varies from very little, if any, when an all-ingot heat is being poured, to several percent if the heat contains a high percentage of remelt.

Aluminum Bronzes. These alloys must be melted carefully under an oxidizing atmosphere and heated to the proper furnace temperature. If needed, degasifiers can be stirred into the melt as the furnace is being tapped. By pouring a blind sprue before tapping and examining the metal after freezing, it is possible to tell whether it shrank or exuded gas. If the sample purged or overflowed the blind sprue during solidification, degassing is necessary. As discussed earlier in this article, degasifiers remove hydrogen and oxygen. Also available are fluxes that convert the molten bath. These are in powder form and are usually fluorides. They aid in the elimination of oxides, which normally form on top of the melt during melting and superheating.

Nickel silvers, also known as nickel bronzes, are difficult alloys to melt. They gas readily if not melted properly because the presence of nickel increases the hydrogen solubility. Then, too, the higher pouring temperatures shown in Table 7 aggravate hydrogen pickup. These alloys must be melted under an oxidizing atmosphere and quickly superheated to the proper furnace temperature to allow for temperature losses during fluxing and handling. Proprietary fluxes are available and should be stirred into the melt after tapping the furnace. These fluxes contain manganese, calcium, silicon, magnesium, and phosphorus and do an excellent job in removing hydrogen and oxygen.

White Manganese Brass. There are two alloys in this family, both of which are copper-zinc alloys containing a large amount of manganese and, in one case, nickel. They are manganese bronze type alloys, are simple to melt, and can be poured at low temperatures because they are very fluid (Table 7). They should not be overheated, as this serves no purpose. If the alloys are unduly superheated, zinc is vaporized and the chemistry of the alloy is changed. Normally, no fluxes are used with these alloys.

Group II Alloys

Beryllium-Coppers. These alloys are very toxic and dangerous if beryllium fumes are not captured and exhausted by proper ventilating equipment. They should be melted quickly under a slightly oxidizing atmosphere to minimize beryllium losses. They can be melted and poured successfully at relatively low temperatures (Table 7). They are very fluid and pour well.

Silicon Bronzes and Brasses. The alloys known as silicon bronzes, UNS alloys C87300, C87600, and C87610, are relatively easy to melt and should be poured at the proper pouring temperatures (Table 7). If overheated, they can pick up hydrogen. While degassing is seldom required, if necessary, one of the proprietary degasifiers used with aluminum bronze can be successfully used. Normally no cover fluxes are used here. The silicon brasses (UNS alloys C87500 and C87800) have excellent fluidity and can be poured slightly above their freezing range. Nothing is gained by excessive heating, and in some cases, heats can be gassed if this occurs. Here again, no cover fluxes are required.

Copper-Nickel Alloys. These alloys—90Cu-10Ni (C96200) and 70Cu-30Ni (C96400)—must be melted carefully because the presence of nickel in high percentages raises not only the melting point but also the susceptibility to hydrogen pickup. In virtually all foundries, these alloys are melted in coreless electric induction furnaces, because the melting rate is much faster than it is with a fuel-fired furnace. When ingot is melted in this manner, the metal should be quickly heated to a temperature slightly above the pouring temperature (Table 7) and deoxidized either by the use of one of the proprietary degasifiers used with nickel bronzes or, better yet, by plunging 0.1% Mg stick to the bottom of the ladle. The purpose of this is to remove all the oxygen to prevent any possibility of steam-reaction porosity from occurring. Normally there is little need to use cover fluxes if the gates and risers are cleaned by shot blasting prior to melting.

Group III Alloys

These alloys, namely leaded red and semi-red brasses, tin and leaded tin bronzes, and high-leaded tin bronzes, are treated the same in regard to melting and fluxing and thus can be discussed together. Because of the long freezing ranges involved, it has been found that chilling, or the creation of a steep thermal gradient, is far better than using only feeders or risers. Chills and risers should be used in conjunction with each other for these alloys. For this reason, the best pouring temperature is the lowest one that will pour the molds without having misruns or cold shuts. In a well-operated foundry, each pattern should have a pouring temperature that is maintained by use of an immersion pyrometer.

Fluxing. In regard to fluxing, these alloys should be melted from charges comprising ingot and clean, sand-free gates and risers. The melting should be done quickly in a slightly oxidizing atmosphere. When at the proper furnace temperature to allow for handling and cooling to the proper pouring temperature, the crucible is removed or the metal is tapped into a ladle. At this point, a deoxidizer (15% phosphor copper) is added. The phosphorus is a reducing agent (deoxidizer). This product must be carefully measured so that enough oxygen is removed, yet a small amount remains to improve fluidity. This residual level of phosphorus must be closely controlled by chemical analysis to a range between 0.010 and 0.020% P. If more is present, internal porosity may occur and cause leakage if castings are machined and pressure tested.

In addition to phosphor copper, pure zinc should be added at the point at which skimming and temperature testing take place prior to pouring. This replaces the zinc lost by vaporization during melting and superheating. With these alloys, cover fluxes are seldom used. In some foundries in which combustion cannot be properly controlled, oxidizing fluxes are added during melting, followed by final deoxidation by phosphor copper.

Production of Copper Alloy Castings

Copper alloy castings are produced by sand, shell, plaster, investment, permanent mold, die, centrifugal, and continuous casting. Each of these casting/molding methods is briefly reviewed below in the section "Casting Process Selection." Additional information can be found in Volume 15 of the *ASM Handbook* and the *Metals Handbook Desk Edition,* second edition.

Pouring Temperature and Practice

Pouring Temperature. Temperature ranges for pouring the principal copper casting alloys are given in Table 7. It should not be inferred from the breadth of most of these ranges that pouring temperature is not critical; as noted in Table 7, the ranges are intended for pouring various section thicknesses. For castings with minimum section thickness, the metal should be poured at a temperature near the high side of the range. Conversely, for castings that have all heavy sections, pouring temperatures should be near the low side of the range. Under any conditions, identical castings should be poured at the same temperature, insofar as possible. It is generally advisable to allow a variation of no more than 55 °C (100 °F) during the pouring of a specific mold, or when pouring several molds from the same ladle. The casting process used also influences the pouring temperature for a specific alloy. In die casting, for instance, a temperature near the low side of a given range is used, in the interest of longer die life.

Pouring Practice. On the basis of the degree of care required when they are poured into molds, copper alloys can be classified into two groups:

- Alloys that form tight, adherent, nonfluid slags or oxides. Typical are group I aluminum bronze and manganese bronze alloys.
- Alloys that form fluid slags or oxides. These include most of the alloys in general use—those containing various combinations of copper, tin, lead, and zinc.

Copper alloys in the first group (those that form tight, adherent, nonfluid slags) require great care in pouring. Their general behavior can be compared to that of aluminum casting alloys, and similar pouring techniques are recommended.

Good pouring practice for this first group of alloys includes attention to:

- Molten alloys with tight oxide films should never be stirred. After the ladle is filled or the crucible is removed from the furnace, and before pouring, the metal should be carefully skimmed but not stirred or mixed—thus minimizing oxide entrapment.
- In addition to avoiding stirring of molten aluminum bronze and manganese bronze, other forms of agitation should also be avoided. If the metal is melted in a tilting furnace and must be transferred to a ladle for pouring, the distance the metal must drop should be minimized by holding the ladle close to the furnace lip.
- Pouring should be smooth and even to avoid splashing and separated metal streams. With careful pouring of aluminum bronze and manganese bronze, it is possible to form an aluminum oxide "glove" around the metal stream, which will protect the molten metal from further oxidation.

Alloys in this first group have a very narrow freezing range (see Table 1), so that they solidify in much the same way as does a pure metal. The total shrinkage is concentrated in the region of the casting that solidifies last. These alloys are thus prone to piping and gross shrinkage cavities. Risering is commonly used to prevent shrinkage from occurring in the casting. The metal is poured well above the liquidus so that the entire mold cavity is filled and so that solidification occurs from the bottom to the top, with feeding from a riser.

Copper alloys in the second group (those that form fluid slags) are generally less affected by turbulence in pouring than are those in the first group. Although turbulence in pouring can cause casting defects in any alloy, the fact that the oxides that are formed with this group of alloys separate readily from the molten metal means less likelihood of oxide entrapment in the casting and greater likelihood of the escape of entrained air bubbles.

Table 7 Pouring temperatures of copper alloys

		Light castings		Heavy castings	
Alloy type	UNS No.	°C	°F	°C	°F
Group I alloys					
Copper	C81100	1230–1290	2250–2350	1150–1230	2100–2250
Chromium-copper	C81500	1230–1260	2250–2300	1205–1230	2200–2250
Yellow brass	C85200	1095–1150	2000–2100	1010–1095	1850–2000
	C85400	1065–1150	1950–2100	1010–1065	1850–1950
	C85800	1150–1175	1950–2150	1010–1095	1850–2000
	C87900	1150–1175	1950–2150	1010–1095	1850–2000
Manganese bronze	C86200	1150–1175	1950–2150	980–1065	1800–1950
	C86300	1150–1175	1950–2150	980–1065	1800–1950
	C86400	1040–1120	1900–2050	950–1040	1750–1900
	C86500	1040–1120	1900–2050	950–1040	1750–1900
	C86700	1040–1095	1900–2000	950–1040	1750–1900
	C86800	1150–1175	1950–2150	980–1065	1800–1950
Aluminum bronze	C95200	1120–1205	2050–2200	1095–1150	2000–2100
	C95300	1120–1205	2050–2200	1095–1150	2000–2100
	C95400	1150–1230	2100–2250	1095–1175	2000–2150
	C95410	1150–1230	2100–2250	1095–1175	2000–2150
	C95500	1230–1290	2250–2350	1175–1230	2150–2250
	C95600	1120–1205	2050–2200	1095–1205	2000–2200
	C95700	1065–1150	1950–2100	1010–1205	1850–2200
	C95800	1230–1290	2250–2350	1175–1230	2150–2250
Nickel bronze	C97300	1205–1225	2200–2240	1095–1205	2000–2200
	C97600	1260–1425	2300–2600	1205–1315	2250–2400
	C97800	1315–1425	2400–2600	1260–1315	2300–2400
White brass	C99700	1040–1095	1900–2000	980–1040	1800–1900
	C99750	1040–1095	1900–2000	980–1040	1800–1900
Group II alloys					
Beryllium-copper	C81400	1175–1220	2150–2225	1220–1260	2225–2300
	C82000	1175–1230	2150–2250	1120–1175	2050–2150
	C82400	1080–1120	1975–2050	1040–1080	1900–1975
	C82500	1065–1120	1950–2050	1010–1065	1850–1950
	C82600	1050–1095	1925–2000	1010–1050	1850–1925
	C82800	995–1025	1825–1875	1025–1050	1875–1925
Silicon brass	C87500	1040–1095	1900–2000	980–1040	1800–1900
	C87800	1040–1095	1900–2000	980–1040	1800–1900
Silicon bronze	C87300	1095–1175	2000–2150	1010–1095	1850–2000
	C87600	1095–1175	2000–2150	1010–1095	1850–2000
	C87610	1095–1175	2000–2150	1010–1095	1850–2000
Copper nickel	C96200	1315–1370	2400–2500	1230–1315	2250–2400
	C96400	1370–1480	2500–2700	1290–1370	2350–2500
Group III alloys					
Leaded red brass	C83450	1175–1290	2150–2350	1095–1175	2000–2150
	C83600	1150–1290	2100–2350	1065–1175	1950–2150
	C83800	1150–1260	2100–2300	1065–1175	1950–2150
Leaded semired brass	C84400	1150–1260	2100–2300	1065–1175	1950–2150
	C84800	1150–1260	2100–2300	1065–1175	1950–2150
Tin bronze	C90300	1150–1260	2100–2300	1040–1150	1900–2100
	C90500	1150–1260	2100–2300	1040–1150	1900–2100
	C90700	1040–1095	1900–2000	980–1040	1800–1900
	C91100	1040–1095	1900–2000	980–1040	1800–1900
	C91300	1040–1095	1900–2000	980–1040	1800–1900
Leaded tin bronze	C92200	1150–1260	2100–2300	1040–1175	1900–2150
	C92300	1150–1260	2100–2300	1040–1150	1900–2100
	C92600	1150–1260	2100–2300	1050–1150	1920–2100
	C92700	1175–1260	2150–2300	1065–1175	1950–2150
High-leaded tin bronze	C92900	1095–1205	2000–2200	1040–1095	1900–2000
	C93200	1095–1230	2000–2250	1040–1121	1900–2050
	C93400	1095–1230	2000–2250	1010–1150	1850–2100
	C93500	1095–1205	2000–2200	1040–1150	1900–2100
	C93700	1095–1230	2000–2250	1010–1150	1850–2100
	C93800	1095–1230	2000–2250	1040–1150	1900–2100
	C94300	1095–1205	2000–2200	1010–1095	1850–2000

Casting Process Selection

Among the more important factors that influence the selection of a casting method are (Ref 29):

- The number of castings to be processed
- The size and/or weight of the casting
- The shape and intricacy of the product
- The amount and quality of finish machining needed
- The required surface finish
- The prescribed level of internal soundness (pressure tightness) and/or the type and level of inspection to be performed
- The permissible variation in dimensional accuracy for a single part and part-to-part consistency through the production run
- The casting characteristics of the copper alloy specified

Table 8 summarizes some of the technical factors that go into the choice of casting method for casting alloys. Additional information can be found in the descriptions of individual casting processes that follow.

Sand casting accounts for about 75% of U.S. copper alloy foundry production (Ref 29). The process is relatively inexpensive, reasonably precise, and highly versatile. It can be used for castings ranging in size from a few ounces to many tons. Further, it can be applied to simple shapes as well as castings of considerable complexity, and it can be used with all of the copper casting alloys.

There are a number of variations of the sand casting process. In green sand casting—the most widely used process—molds are formed in unbaked (green) sand, which is most often silica bonded with water and a small amount of clay to develop the required strength. The clay minerals absorb water and form a natural bonding system. Various sands and clays may be blended to suit particular casting situations. Other variations of sand casting include dry sand, cement-bonded sand, sodium silicate-bonded sand (the CO_2 process), and resin-bonded sand molding.

Sand casting imposes few restrictions on product shape. The only significant exceptions are the draft angles that are always needed on flat surfaces oriented perpendicular to the parting line. Dimensional control and consistency in sand castings ranges from about ±0.8 to 3.2 mm (±0.030–0.125 in.). Within this range, the more generous tolerances apply across the parting line. Surface finish ranges between approximately 7.7 and 12.9 μm (300 and 500 μin.) root mean square (rms).

Shell Molding. Resin-bonded sand systems are also used in the shell molding process, in which prepared sand is contacted with a heated metal pattern to form a thin, rigid shell. The shell molding process is capable of producing quite precise castings and nearly rivals metal-mold and investment casting in its ability to reproduce fine details and maintain dimensional consistency. Surface finish, at about 3.2 μm (125 μin.) rms, is considerably better than that from green sand casting.

Shell molding is best suited to small-to-intermediate size castings. Relatively high pattern costs (pattern halves must be made from metal) favor long production runs. On the other hand, the fine surface finishes and good dimensional reproducibility can, in many instances, reduce the need for costly machining. While still practiced extensively, shell molding has declined somewhat in popularity, mostly because of its high energy costs compared with no-bake resin-bonded sand methods; however, shell-molded cores are still very widely used.

Plaster Molding. Copper alloys can also be cast in plaster molds to produce precision products of near-net shape. Plaster-molded castings are characterized by surface finishes as smooth as 0.8 μm (32 μin.) rms and dimensional tolerances as close as ±0.13 mm (±0.005 in.) and typically require only minimal finish machining. Compared to other casting methods, plaster molding accounts for a very small fraction of the copper castings market.

Investment casting, also known as precision casting or the lost wax process, is capable of maintaining very high dimensional accuracy in small castings, although tolerances increase somewhat with casting size. Dimensional consistency ranks about average among the casting

Table 8 Technical factors in the choice of casting method for copper alloys

Casting method	Copper alloys	Size range	General tolerances	Surface finish	Minimum section thickness	Ordering quantities	Relative cost, (1 low, 5 high)
Sand	All	All sizes, depends on foundry capability	± 1/32 in up to 3 in.; ± 3/64 in. 3-6 in.; add ± 0.003 in./in. above 6 in.; add ± 0.020 to ± 0.060 in. across parting line	150-500 μin. rms	1/8 – 1/4 in.	All	1–3
No-bake	All	All sizes, but usually > 10 lb	Same as sand casting	Same as sand casting	Same as sand casting	All	1–3
Shell	All	Typical maximum mold area = 550 $in.^2$, typical maximum thickness = 6 in.	± 0.005–0.010 in. up to 3 in.; add ± 0.002 in./in. above 3 in.; add ± 0.005 – 0.010 in. across parting line.	125–200 μin. rms	3/32 in.	≥100	2–3
Permanent mold	Coppers, high-copper alloys, yellow brasses, high-strength brasses, silicon bronze, high-zinc silicon brass, most tin bronzes, aluminum bronzes, some nickel silvers	Depends on foundry capability; best, ~ 50 lb Best max thickness, ~ 2 in.	Usually ±0.010 in.; optimum ± 0.005 in., ±0.002 in. part-to-part	150–200 μin. rms. best ~ 70 μin. rms	1/8 – 1/4 in.	100–1,000, depending on size.	2–3
Die	Limited to C85800, C86200, C86500, C87800, C87900, C99700, C99750, and some proprietary alloys	Best for small, thin parts; max area ≤3 ft^2	±0.002 in./in.; no less than 0.002 in. on any one dimension; add ±0.010 in. on dimensions affected by parting line	32–90 μin. rms	0.05–0.125 in.	>1,000	1
Plaster	Coppers, high-copper alloys, silicon bronze, manganese bronze, aluminum bronze, yellow brass	Up to 800 $in.^2$, but can be larger	One side of parting line, ±0.015 in. up to 3 in.; add ±0.002 in./in. above 3 in.; add 0.010 in. across parting line, and allow for parting line shift of 0.015 in.	63–125 μin. rms, best ~ 32 μin. rms	0.060 in.	All	4
Investment	Almost all	Fraction of an ounce to 150 lb, up to 48 in.	±0.003 in. less than 1/4 ; ±0.004 in. between 1/4 to 1/2 in.; ±0.005 in./in. between 1/2 –3 in.; add ±0.003 in./in. above 3 in.	63–125 μin. rms	0.030 in.	>100	5
Centrifugal	Almost all	Ounce to 25,000 lb. Depends on foundry capacity	Castings are usually rough machined by foundry.	Not applicable	1/4 in.	All	1–3

Source: Ref 29

methods; however, surface finishes can be as fine as 1.5 μm (60 μin.) rms, and the process is unsurpassed in its ability to reproduce intricate detail.

Investment casting is better suited to castings under 45 kg (100 lb) in weight. Because of its relatively high tooling costs and higher-than-average total costs, the process is normally reserved for relatively large production runs of precision products and is not often applied to copper alloys.

Permanent Mold Casting. As the name implies, permanent mold casting makes use of reusable metal molds, or dies, in place of the sand-base molds used in conventional foundries. The molds are "permanent" in the sense that they can be used thousands of times.

Permanent mold castings are characterized by good part-to-part dimensional consistency and very good surface finishes (about 1.8 μm, or 70 μin.). Any traces of metal flow lines on the casting surface are cosmetic rather than functional defects. Permanent mold castings exhibit good soundness. There may be some microshrinkage, but mechanical properties are favorably influenced by the characteristically fine grain size of the casting. The ability to reproduce intricate detail is only moderate, however, and for products in which very high dimensional accuracy is required, plaster mold or investment processes should be considered instead.

Permanent mold casting is more suitable for simple shapes in midsize castings than it is for very small or very large products. Die costs are relatively high, but the absence of molding costs make the overall cost of the process quite favorable for medium to large production volumes.

Die casting involves the injection of liquid metal into a multipart die under high pressure. Pneumatically actuated dies make the process almost completely automated. Die casting is best known for its ability to produce high-quality products at very low unit costs. Very high production rates offset the cost of the complex heat-resisting tooling required, and with low labor costs, overall casting costs are quite attractive.

The process can be used with several copper alloys, including yellow brass, C85800, manganese bronzes, C86200 and C86500, silicon brass, C87800, the special die-casting alloys C99700 and C99750, plus a few proprietary compositions. These alloys can be die cast because they exhibit narrow freezing ranges and high β phase contents. Rapid freezing is needed to complement the fast cycle times of the process. Rapid freezing also avoids the hot shortness associated with prolonged mushy solidification. Beta phase contributes the hot ductility needed to avoid hot cracking as the casting shrinks in the unyielding metal mold.

Highly intricate copper alloy products can be made by die casting (investment casting is even better in this regard). Dimensional accuracy and part-to-part consistency are unsurpassed in both small (<25 mm, or 1 in.) and large castings. The attainable surface finish, often as good as 0.76 mm (30 μin.) rms, is better than with any other casting process. Die casting is ideally suited to the mass production of small parts.

Extremely rapid cooling rates (dies are normally water cooled) results in very fine grain sizes and good mechanical properties. Leaded alloys C85800 and C99750 can yield castings that are pressure tight, although lead is incorporated in these alloys more for its favorable effect on machinability than for its ability to seal porosity.

Centrifugal castings are produced by pouring molten metal into a mold that is being rotated or revolved. Both centrifugal and semicentrifugal castings can be described as castings that are spun on their own axes during the castings operation.

The axis of rotation may be horizontal or inclined at any angle up to the vertical position. Molten metal is poured into the spinning mold cavity, and the metal is held against the wall of the mold by centrifugal force. The speed of rotation and metal pouring rate vary with the alloy and size and shape being cast.

The castings with larger diameter than the axial length are cast vertically, while pieces with smaller lengths are cast horizontally. A wide range of castings such as bearings, bushings, and gears of all types for applications in general machine production, road building equipment, farm machinery, and steel mill and marine applications are produced.

Centrifugal castings are made in sizes ranging from approximately 50 mm to 3.7 m (2 in. to 12 ft) in diameter and from a few inches to many yards in length. Size limitations, if any, are likely as not based on the melt shop capacity of the foundry. Simply shaped centrifugal castings are used for items such as pipe flanges and valve components, while complex shapes can be cast by using cores and shaped molds. Pressure-retaining centrifugal castings have been found to be mechanically equivalent to more costly forgings and extrusions.

Continuous casting is a process whereby molten copper alloy is fed through an open-ended graphite mold yielding a bar, tube, or shape of the required cross section. This process, which is performed on a continuous basis, can be accomplished either vertically or horizontally, with the molten metal drawn from the molten metal reservoir or "tundish" at a point below the surface of the bath. The solidified form is cooled and withdrawn at a controlled rate from the water-cooled mold by rollers, and the material is cut to length with a traveling saw.

Continuous casting is used to produce bearing blanks and other long castings with uniform cross sections. It is the principal method used for the large-tonnage production of semifinished products such as cast rods, tube rounds, gear and bearing blanks, slabs, and custom shapes.

The extremely high cooling and solidification rates attending continuous casting can, depending on the alloy, produce columnar grains. The continuous supply of molten metal at the solidification interface effectively eliminates microshrinkage and produces high quality, sound products with very good mechanical properties. With its simple die construction, relatively low equipment cost, high production rate, and low labor requirements, continuous casting is a very economical production method.

Gating (Ref 30)

The major function of a gating system is to deliver clean metal from the ladle into the mold cavity without adversely affecting the quality of the metal. Secondary considerations are the ease of molding, removal of gates, and high casting yield. However, these factors should not dictate a design that contributes to the production of castings of unacceptable quality.

The Pouring Basin. The production of high-quality castings requires not only proper melting and molding operations and properly designed pattern equipment, but also an understanding of the principles of gating so that clean metal can be delivered to the mold cavity with a minimum amount of turbulence. A pouring basin allows a sprue to be filled quickly and maintains a constant head throughout the pour (Fig. 26).

When the weight of poured metal in a mold exceeds 14 kg (30 lb), use of a pouring basin offers many advantages. The pourer can better direct the flow of metal from the ladle into the basin, with less chance of spillages; also, the sprue need not be located near the edge of the mold. The pouring ladle can be brought within 25 to 50 mm (1–2 in.) of the basin, and a continued 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 the pouring basin is that the yield is lowered, thereby requiring more metal to be recycled.

Sprue. The correct sprue size is the single most important part of the gating system. If a wrong size is selected, or an improper taper is used, the damage done to the metal in the mold cavity is extensive and cannot be corrected regardless of the quality of the runner and gating systems.

Because most molds under about 14 kg (30 lb) of poured weight are made on a high production scale in flasks of 102 to 152 mm (4–6 in.) in cope height, a fairly standard sprue size may be used for all copper-base alloys. The top third of the sprue should be the pouring part, with about a 50 mm (2 in.) diam opening. The remaining portion of the sprue should taper down to 13 to 22 mm ($\frac{1}{2}$ to $\frac{7}{8}$ in.) in final diameter depending on the pouring rate to be used.

Figure 27 shows a sketch of a sprue that will do an excellent job of conveying brass or bronze into the gating system. There are many charts and formulas available to determine the entry diameter of a tapered sprue, but for the most part this diameter should be just sufficient to provide about a 10 to 20° slope on the side of the sprue. When the sprue height is over 305 mm (12 in.), the top diameter of the sprue is much more important and should be about 50% larger than the diameter at the base of the sprue. When designing a pouring system for sprues of 102 to 152 mm (4–6 in.) in height, it is best to select the desired pouring rate first in order to determine the proper sprue base to be used.

The Sprue Base. Because the velocity of the stream is at its maximum at the bottom of the sprue and is proportional to the square root of

the height of the fall of the metal, it is mandatory that a sprue base or well be used as a cushion for the stream flowing down the sprue. The base also helps change the vertical flow of metal into a horizontal flow with the least amount of turbulence. Recommended sprue basin sizes are about twice as deep as the drag runner and two to three times as wide as the base of the sprue. In most cases a well 25 to 38 mm (1–1½in.) deep with a width of 38 to 50 mm (1½–2 in.) on each side is usually adequate for the majority of sprues being used for most normal pouring rates. Little damage is done if the sprue base is larger than necessary except that the overall casting yield will be lowered slightly.

Chokes should be used only when the proper pouring rate cannot be controlled by the correct sprue size. If clean metal is delivered into the sprue, a strainer core serves the sole function of retarding the metal flow rate. Conventional strainer cores, whether of tinned steel, mica, glass fiber, or ceramic, usually reduce the flow of metal by about 70%, depending on the size and number of holes that are open to the sprue area. The best strainer is one that has only one hole with a diameter of the correct sprue size. This avoids the turbulence caused by the metal being divided into many streams as it enters the runner. In no instance should a strainer be placed into the top of the sprue; if one must be used, the only suitable place is just above the sprue base at the parting line. Tinned steel strainers are the least acceptable because the remelted runners can introduce iron and hard spots to the copper-base alloys if they are not properly skimmed during melting. The mica and glass fiber strainers are popular because they can be laid on the parting line just above the sprue base before the mold is closed, thereby requiring no "prints" or recesses, as do the thicker ceramic or sand strainer cores, which are usually about 3.2 mm (⅛ in.) thick.

A choke in the runner pattern is often the only consistent way to achieve a proper pouring rate. In no instance should the choke be put in the gate area. When necessary, it should be placed in the drag runner as close to the sprue as possible (Fig. 27). The chokes should have a smooth rediused contour and be located at the bottom of the drag runner. Choke depth may vary from ¼ to ¾ of the total runner depth with a cross-sectional area not exceeding ¾ of the area of the sprue base. The chokes should be located within an inch of the sprue base to ensure rapid filling of the sprue and maintenance of full capacity throughout the pour. This also permits dissipation of the turbulence before the stream reaches the gates.

Pouring rate depends on many factors, such as weight of the casting, section size, height of the sprue, and alloy system. Most alloys in group III for small work weighing 14 kg (30 lb) or less are poured with a hand ladle at about 1.8 kg/s (4 lb/s). Light memorial plaque castings are being successfully poured at 4.5 kg/s (10 lb/s), while many automatic pouring units operate at mold pouring rates of 3.6 to 4.5 kg/s (8–10 lb/s). Alloys in group I, if the poured weight is under 14 kg (30 lb), should be poured at 0.9 to 1.8 kg/s (2–4 lb/s) in order to obtain a clean, nonturbulent metal flow in the mold. Sprue exit diameters required for specific flow rates and various sprue heights are shown in Fig. 28. Table 9 shows flow rates from the bottom of the sprue for a number of commonly used sprue heights and diameters. As an example, for a gross casting weight of 14 kg (30 lb) or less and a sprue height of 102 to 152 mm (4–6 in.), a sprue diameter of 13 to 19 mm (½ – ¾ in.) is adequate to obtain a flow rate of 0.9 to 1.8 kg/s (2–4 lb/s). It should not be necessary to use a 22 to 29 mm (⅞ – 1⅛ in.) diam sprue base unless pouring plaque work or using automatic pouring. A quite popular sprue for most production work is the 16 to 19 mm (⅝ – ¾ in.) diam size, which will deliver enough hot metal to fill most molds up to 14 kg (30 lb) weight in 8 to 10 s. The total pouring time in seconds may be calculated by dividing the total weight of the mold poured (castings plus gates and risers) by the flow rate at the base of the sprue, or:

$$\frac{\text{Total weight of castings including gates and risers (lb)}}{\text{Flow rate at base of sprue (lb/s)}} = \text{Calculated pouring time in seconds}$$

Runners and Gates. For alloys in groups I and II, it is mandatory that all runners be placed in the drag and as much of the casting as possible be placed in the cope. In this way, all runners will be completely filled before any metal enters the gates, and the metal will drop the least amount or will rise to enter the mold cavity from the gates. Although this practice is also excellent for alloys in group III, experience has shown that quality castings may be obtained by using more traditional casting techniques because the alloys in group III are

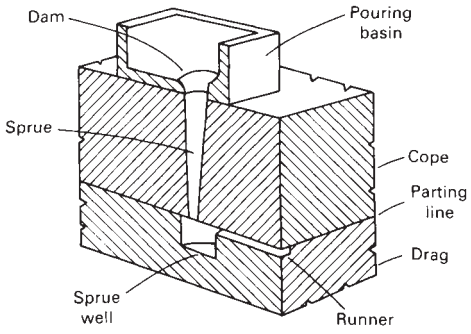

Fig. 26 Section of a typical sand mold with pouring basin

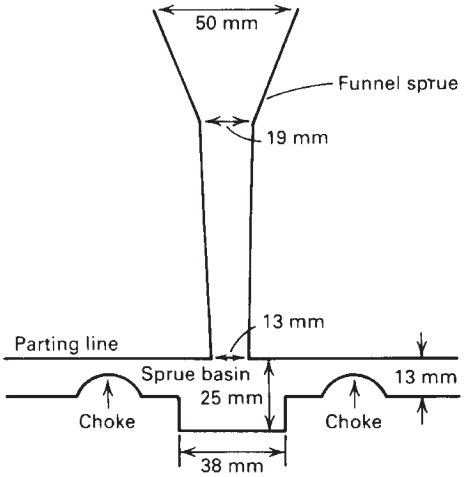

Fig. 27 Funnel sprue, sprue basin, and chokes (in drag runner) for reducing turbulence

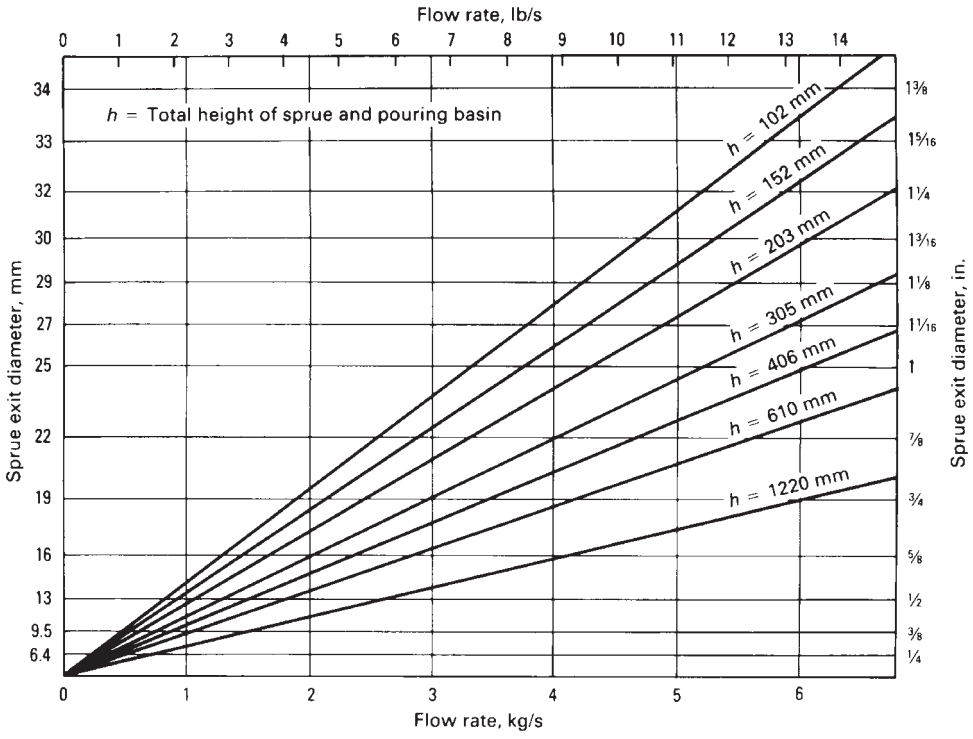

Fig. 28 Flow rates of copper-base alloys through tapered sprues of varying diameter and height

less sensitive to drossing and have a tendency to self-heal when dross is formed in the gating system. Runners should be as rectangular in shape as possible, and their total maximum cross-sectional area should be two to four times that of the tapered sprue or the choke, if chokes are used in the runner system. Care must be taken to ensure that the cross section of the runners is adequate in order to prevent premature chilling. Experience has shown that a rectangular runner with the wide side laying horizontal works best. The next best is a square runner, and the least desirable is a rectangular runner with the wide side being vertical, although sometimes space limitations necessitate use of this type of runner in order to obtain the proper ratios. The rectangular runner should be about twice as wide as it is deep.

The cross-sectional area of the runner must be reduced by that of each gate as it is passed, so that metal enters the mold cavity simultaneously from each gate (Fig. 29). Because back filling is seldom desired from the runner system, a well at the end of the runner can be used (Fig. 30), particularly if the runner does not have any taper. A good example of multiple-cavity gating may be seen in Fig. 30. X-ray movies of metal flow in sand molds show that relatively uniform gate discharge rates are achieved only when stepped or tapered runners are used.

Multiple gates are shown in Fig. 29 to 31. The preferred location is in the cope just above the runner at the parting line. A rectangular flat gate is more desirable than a square gate, and a gate that has its wide dimension in the vertical plane is the least desirable, just as is the case for runners. In order to avoid a pressurized gating system, it is important that the total gate area be at least as large as the total runner area. If a pattern has an excessive amount of small castings, it might be necessary to have the total gate area many times the runner area in order to obtain a sufficient gate to each casting. This deviation is acceptable because the gating system remains unpressurized. Figure 29 shows a good gating system that produces the minimum amount of turbulence. Gates should enter the casting cavity at the lowest possible level in order to avoid the erosion and turbulence associated with a falling stream of molten metal. To ensure nonturbulent filling of the casting nearest to the sprue, its gate should be at least 50 mm (2 in.) away from the base of the sprue.

Regardless of the excellence of a gating system design, castings of acceptable quality will not be produced if the ladle is not positioned as close as is practical to the pouring basin or sprue, and if the sprue is not filled quickly and kept at full capacity throughout the pour.

Knife and Kiss Gating Systems. Special applications of gating systems work in many cases for specific castings. Knife and kiss gating are popular when group III alloys are used but not recommended for groups I and II because these alloys form too much dross with this system and cannot be fed adequately to eliminate surface shrinkage. Advantages are a high casting yield, easy removal of runner systems, and minimum grinding of gates. The major disadvantage is that many small castings become detached during shakeout, necessitating their manual retrieval from mechanized systems. Figure 32 shows a graphic representation of the arrangement of knife and kiss gating. In kiss gating, the casting must be completely in the cope or the drag with the runner overlapping the casting by 0.8 to 2.4 mm ($^1/_{32}$ – $^3/_{32}$ in.). Actually there is no gate in this system because the metal goes directly from the runner into the casting.

Knife gating is used when the casting is in both the cope and the drag and there is a contact at the parting line of 0.8 to 2.4 mm ($^1/_{32}$ – $^3/_{32}$ in.) thickness just at the casting surface. Knife gating systems work well when the runner is in just the cope or just the drag or in both the cope and the drag.

Maximizing Casting Quality. Excellent, clean, high-quality castings may be obtained for the copper-base alloy groups of narrow, intermediate, and wide freezing range alloys if the basic principles discussed for the pouring basin, sprue, sprue base, chokes, pouring rates, runners, and gates are applied. By following these recommendations, the maximum ease in molding, casting yield, and ease of removal of gates and runners may be obtained.

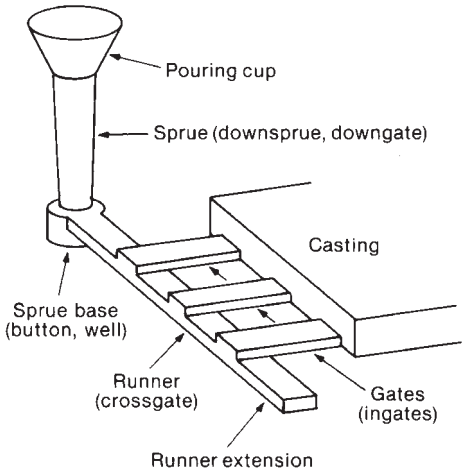

Fig. 29 Typical single-cavity gating system with tapered runner

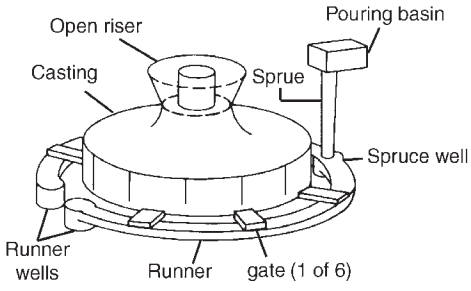

Fig. 30 Method of running a pump impeller with a well at the end of the runner

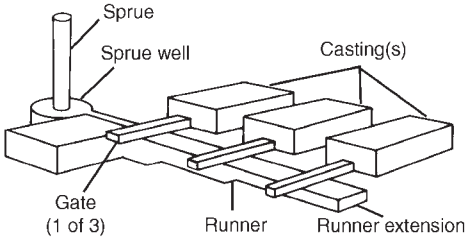

Fig. 31 Recommended multiple-cavity gating system with stepped runner

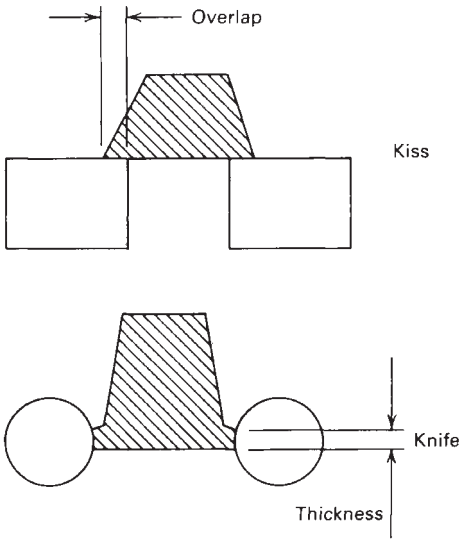

Fig. 32 Basic kiss and knife gates

Table 9 Flow rates of copper-base alloys through tapered sprues of varying diameter and height

Sprue				Flow rate for sprue height, mm (in.)									
Area		Diameter		102 (4)		152 (6)		305 (12)		610 (24)		1220 (48)	
mm^2	$in.^2$	mm	in.	kg/s	lb/s	kg/s	lb/s	kg/s	lb/s	kg/s	lb/s	kg/s	lb/s
129	0.2	13	1/2	0.82	1.8	0.91	2.0	1.36	3.0	1.81	4.0	2.72	6.0
194	0.3	16	5/8	1.27	2.8	1.50	3.3	2.04	4.5	2.72	6.0	4.08	9.0
284	0.44	19	3/4	1.81	4.0	2.04	4.5	2.95	6.5	4.08	9.0	6.12	13.5
387	0.60	22	7/8	2.49	5.5	2.95	6.5	4.08	9.0	5.67	12.5	8.16	18.0
506	0.785	25	1	3.40	7.5	3.86	8.5	5.22	11.5	7.48	16.5	11.11	24.5
645	1.0	29	1 1/8	4.30	9.5	4.76	10.5	7.71	17.0	9.30	20.5	13.61	30.0

Feeding

The objectives of feeding or risering are to eliminate surface sinks or draws and to reduce internal shrinkage porosity to acceptable levels (less than 1%).

To minimize porosity, the feeding system must establish:

- Directional solidification, as shown in Fig. 33, in which the solidification front is substantially V-shaped in a longitudinal cross section with the large end of the V directed toward the riser
- Steep temperature gradients along the casting toward the riser

The feeding techniques for group I (short freezing range) alloys and group II (medium freezing range) alloys can be discussed together. The basic principles of risering of group III (long freezing range) alloys will be described separately.

Group I and II Alloys

The feeding technique for these alloys is similar to that used in the manufacture of steel castings. Gates and risers are positioned such that directional solidification is ensured, 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, and to other sections having sudden changes in thickness.

Solidification Contours. The first step in determining riser placement is to draw the solidification contours. This is illustrated by the hypothetical casting shown in Fig. 34, which consists essentially of a plate to which is attached a thinner section, C, and a boss, B. The thin end of the casting, C, would normally undergo rapid cooling after pouring as the result of edge-cooling effects. Thus, it is possible to place the riser at the heavy section, A, and gate through the riser to provide favorable temperature gradients. The dotted lines in Fig. 35 show successive positions of the solidification front. As shown, porosity will develop in the boss unless a chill is placed on the boss or the riser is relocated there. A chill is a block of metal or other material with a higher heat conductivity and heat capacity than sand.

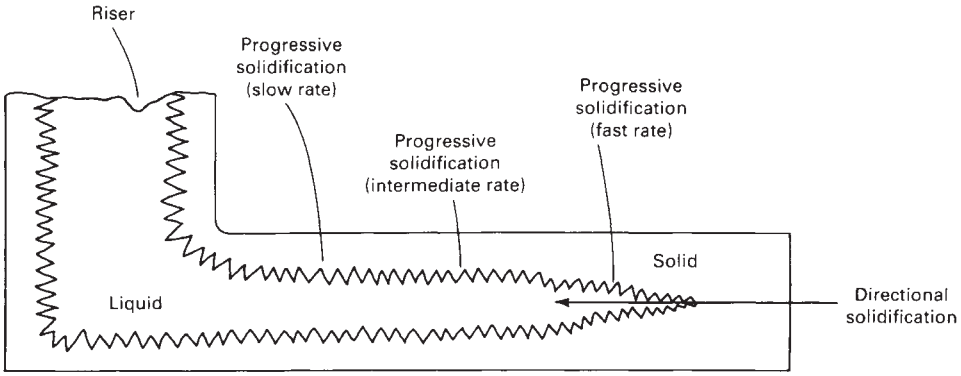

Fig. 33 Features of progressive and directional solidification. Source: Ref 31

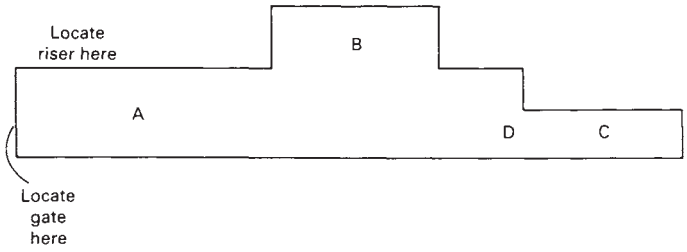

Fig. 34 Hypothetical casting used to illustrate the principles of feeding technique. Source: Ref 32

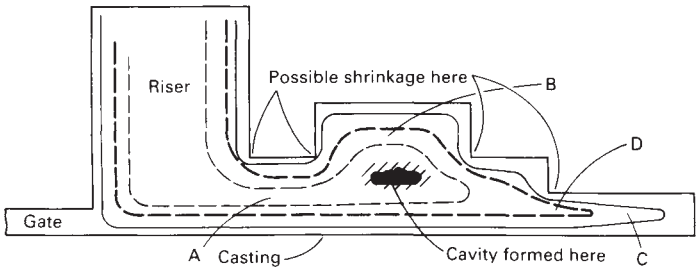

Fig. 35 Mode of freezing the casting in Fig. 34 without special precaution to avoid shrinkage. Source: Ref 32

Feeding Ranges. The number and location of the feeders to be used must be consistent with the feeding range of the alloy. The feeding range is the distance that can be fed by a feeder on a bar or plate. It is generally desirable to divide the casting into a number of sections to determine the number of risers to be used. Because 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 and II copper-base alloys have not been well documented. In the absence of specific data for particular alloys, satisfactory results can often be attained by applying values that have been developed for carbon steels. The following approximate values for feeding ranges have been quoted in the literature, but should be used with caution:

Alloy	Shape	Feeding distance, T
Manganese bronze	Square bars	4 T to 10 $\sqrt{T}$, depending on thickness
	Plates	5.5 to 8 T, depending on thickness
Aluminum bronze	Square bars	8 $\sqrt{T}$
Nickel-aluminum bronze	Square bars	$<8\sqrt{T}$
Copper-nickel	Square bars	5.5 $\sqrt{T}$

Use of chills can further increase feeding range. Consequently, the spacing between risers may be increased to about ten times the section thickness if chills are located midway between each pair of risers (Fig. 36).

Riser Size. From time to time, various methods have been proposed for the calculation of the optimal riser size to be used to feed a particular casting or casting section. One of the earlier methods was developed for steel castings at the Naval Research Laboratories (NRL). In this technique, an empirical "shape factor" defined as the length (L) plus the width (W) of the casting divided by the thickness (T), that is, $(L + W)/T$, is first determined. The correct riser size is obtained from a plot of V_R/V_C versus $(L + W)/T$, where V_R and V_C are the riser and casting volume, respectively.

Work sponsored by the American Foundry men's Society has lead to the development of a series of curves for aluminum bronzes, copper-nickel, and manganese bronzes (Fig. 37–40).

Figures 37 to 40 indicate that the riser volumes necessary for sound castings can be reduced and the effectiveness of feeding improved by the use of exothermic sleeves. Insulating sleeves also can be used to increase the effectiveness of the risers. Exothermic sleeves, which were once popular, have now largely been discontinued in favor of insulating sleeves, which are more economical to use and cause fewer problems.

In recent years, greater attention has been given to what has become known as the modulus method for calculating riser size, which includes the development of pertinent data and computer programs to check that riser volume

is adequate. This method is now, and no doubt will continue to be, the most widely used technique in the industry.

Chvorinov's rule states that the freezing time, *t*, of a cast shape is given by the relationship:

$$t = k \cdot (V/A)^2 \quad \text{(Eq 1)}$$

where *V* and *A* are the volume and surface area, respectively, of the cast shape, and *k* is a constant 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 by the symbol *M*, a value referred to as the modulus of the shape. Equation 1, above, can be rewritten more simply to read:

$$t = k \cdot M^2 \quad \text{(Eq 2)}$$

Because Chvorinov's equation can be applied to any cast shape, it applies equally to that which is intended to be the casting itself and to the attached riser. With connected shapes, such as a riser and a casting, the surface area of each shape to be considered includes only those portions that contribute to the loss of heat during freezing.

For the riser to be effective in feeding, its solidification time, t_R, must be greater than the solidifiation time t_C, for the casting. This can be written:

$$\frac{t_R}{t_C} = \frac{k \cdot M_R^2}{k \cdot M_C^2} = F^2, \text{ or } M_R^2 = F^2 \cdot M_C^2 \quad \text{(Eq 3)}$$

Further simplified, this becomes:

$$M_R = F \cdot M_C \quad \text{(Eq 4)}$$

This means that the modulus for the riser, M_R, must be greater than the modulus for the casting, M_C, by some factor, *F*. Experience has shown that the proper value of *F* depends on the metal being cast. A value of about 1.3 is preferred for the short freezing range copper-base alloys.

As a practical working equation, therefore, one may say that with these alloys the modulus of the riser should be about 1.3 times that of casting (or casting section) to be fed, or:

$$M_R = 1.3\, M_C \quad \text{(Eq 5)}$$

Equation 5 merely shows an empirical way of proportioning a riser so that it freezes 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. These values can be calculated if necessary; however, it is much easier (though less precise) to use data of the type shown in Table 10. The numbers listed in the table indicate the minimum values for the ratio between riser volume and casting volume (as percentages) to ensure 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 ratio (*H*/*D*) of 1 to 1 are more efficient than when the *H*/*D* is 2 to 1. More important, it can be seen that insulated risers are far more efficient than those formed directly in the sand mold.

Feeder Shape. One of the requirements of the riser is to remain liquid longer than the casting; that is, from Chvorinov's rule:

$$(V/A)_R > (V/A)_C \quad \text{(Eq 6)}$$

The shape with the highest possible *V*/*A* ratio is the sphere. However, spherical risers are rarely used in industry because of molding considerations.

The next best shape for a riser is the cylinder. The *H*/*D* for cylindrical risers is in the range of 0.5 to 1.0.

Riser Neck Dimensions. The ideal riser neck should be dimensioned such that it solidifies after the casting but slightly before the riser. With this arrangement, the shrinkage cavity is entirely within the riser, this being the last part of the casting-riser combination to solidify.

Specific recommendations for the dimensions of riser necks are contained in the literature for

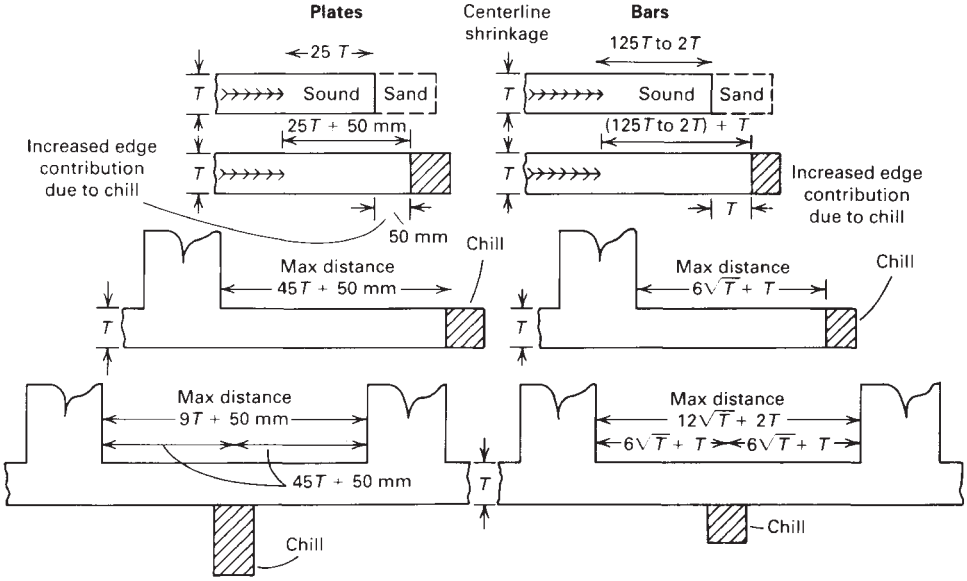

Fig. 36 Effect of chills in increasing feeding range of risers. Source: Ref 31

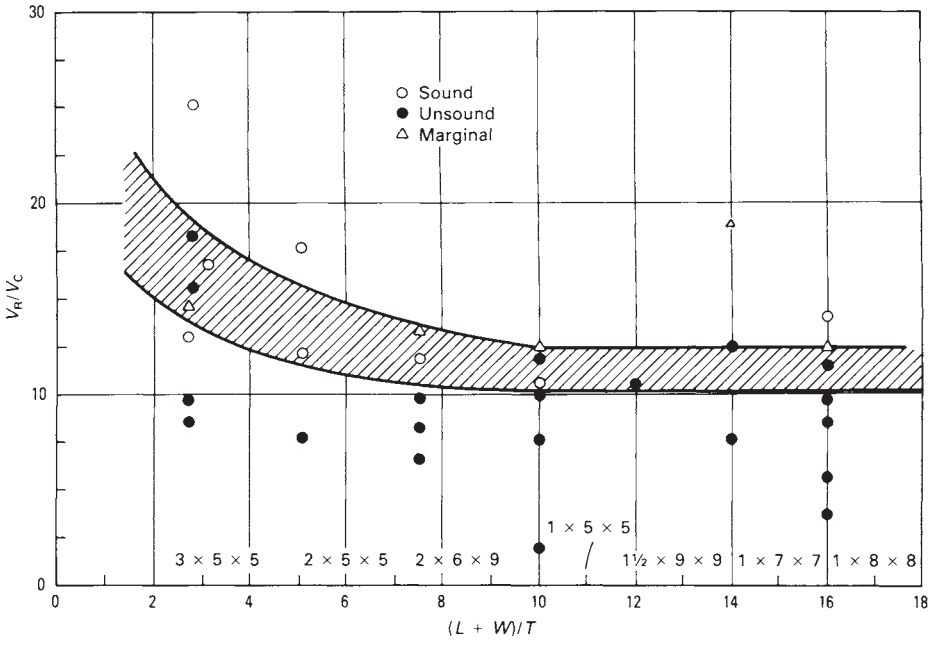

Fig. 37 Naval Research Laboratories (NRL)-type riser size curve for manganese bronze (alloy C86500). Source: Ref 33

ferrous alloys. These should apply to short freezing range copper alloys and are given in Table 11.

Hot Topping. About 25 to 50% of the total heat from a copper-base alloy riser is lost from the exposed surface by radiation. In order to minimize this radiation loss and thereby increase the efficiency of the riser, some sort of cover should be used on the top surface. Any cover, even dry sand, is better than nothing at all. A reliable exothermic hot topping is one form of usable cover.

Chills. The heat abstraction of the mold walls can be increased locally by the use of chills. Though expensive, metal chills are particularly effective because they reduce the solidification time by a factor of more than 55. As mentioned earlier, chills can be used to increase feeding distances and thereby reduce the number of feeders required. When it is impractical to attach feeders at certain locations, chills are particularly useful for initiating directional solidification, for example, at junctions, and so on, which would otherwise be porous.

Padding. The process of solidification can also be controlled by means of padding. Padding is the added section thickness (usually tapered) to promote directional solidification, and the bulk of it should be as close to the riser as possible.

Interaction of Gates and Risers. The effectiveness of side risers can be increased considerably by using a gating system that enters the mold cavity through the riser. The advantages of this arrangement are:

- Cleaner molten metal enters the mold cavity.
- Because the metal in the riser remains liquid for a longer time, steep thermal gradients are established to improve the soundness of the casting.

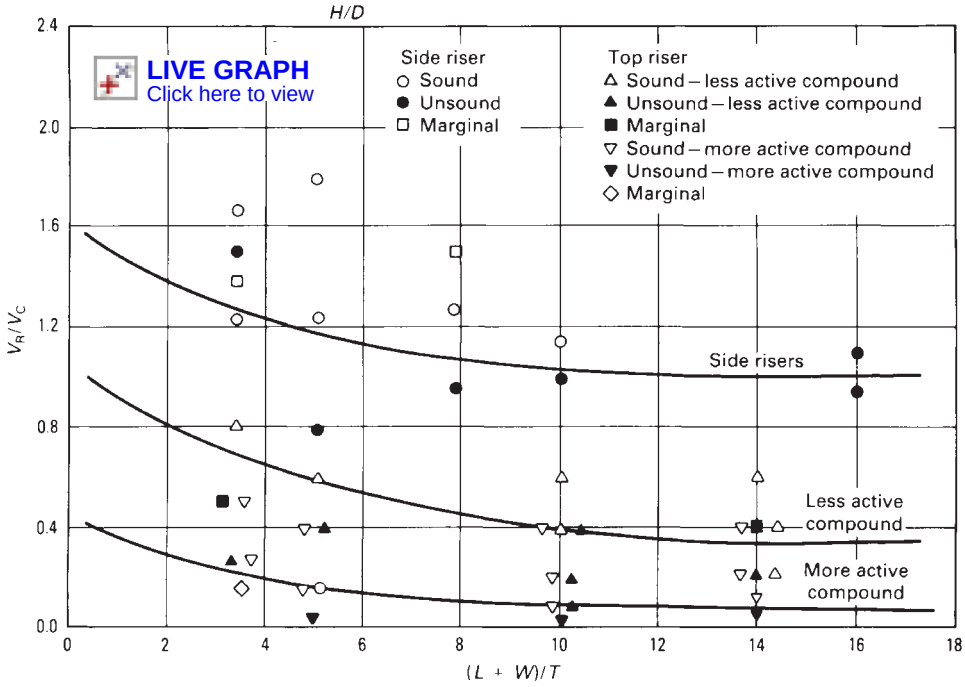

Fig. 38 NRL-type riser curve for manganese bronze (alloy C86500) using different types of exothermic hot topping and top risers. Source: Ref 34

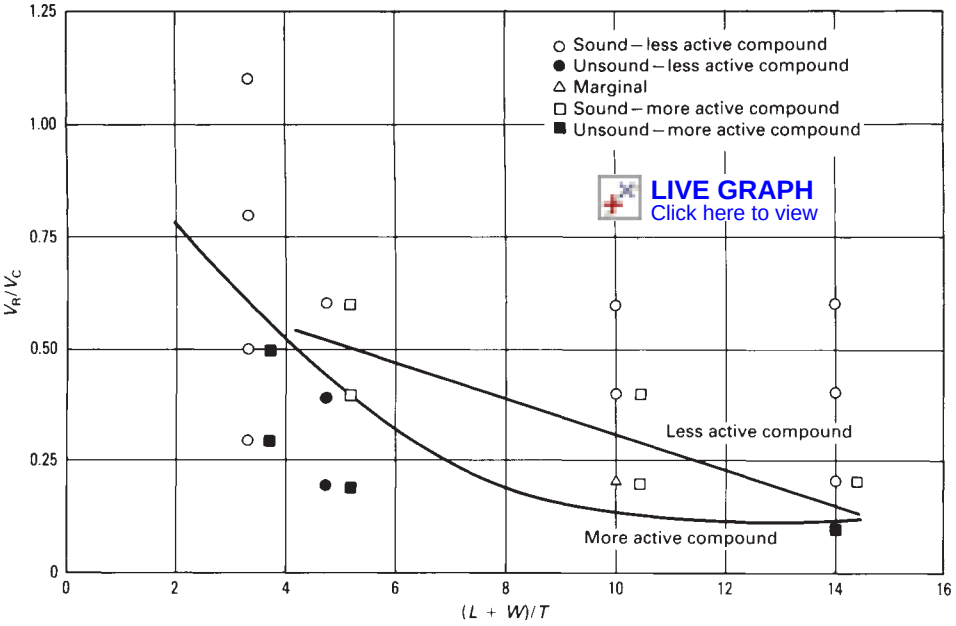

Fig. 39 NRL-type riser curve for aluminum bronze (alloy C95300) using different types of exothermic hot topping and top risers. Source: Ref 34

Group III Wide Freezing Range Alloys

The "workhorse" alloys of the copper-base group are the leaded red brasses and tin bronzes, virtually all of which have wide freezing ranges. These alloys have practically no feeding range, and it is extremely difficult to get fully sound castings. The average run of castings in these alloys contains 1 to 2% porosity. Only small castings may exhibit porosity below 1%. Attempts to reduce it more by increasing the size of the risers are often disastrous and actually decrease the soundness of the casting rather than increase it.

Experience has shown that success in achieving internal soundness depends on avoiding slow cooling rates. The foundryman has three possible means for doing this, within the limitations of casting design and available molding processes:

- Minimize casting section thickness.
- Reduce and/or evenly distribute the heat of the metal entering the mold cavity.
- Use chills and mold materials of high chilling power.

In order to produce relatively sound castings, the following points should be considered.

Directional solidification, best used for relatively large, thick castings, can be promoted in various ways:

- Gate into hot spot.
- Riser into hot spot.
- Ensure that riser freezes last (consider riser size, insulation, and chills).
- Promote high thermal gradients by the use of chills, preferably tapered chills unless casting section is light (less than 12.5 mm, or $\frac{1}{2}$ in. thick).
- Make sure risers are not so large that they unduly extend the solidification time of the casting, which would generate porosity beneath or behind the riser.

Uniform solidification, best used for smaller, thin-wall castings, can be promoted in various ways:

- Gate into cold spots, using several gates for uniform temperature distribution.
- Use no risers, except perhaps on gate areas.
- Use chills on hot spots to ensure that they cool at the same rate as the rest of the casting.

LIVE GRAPH
Click here to view

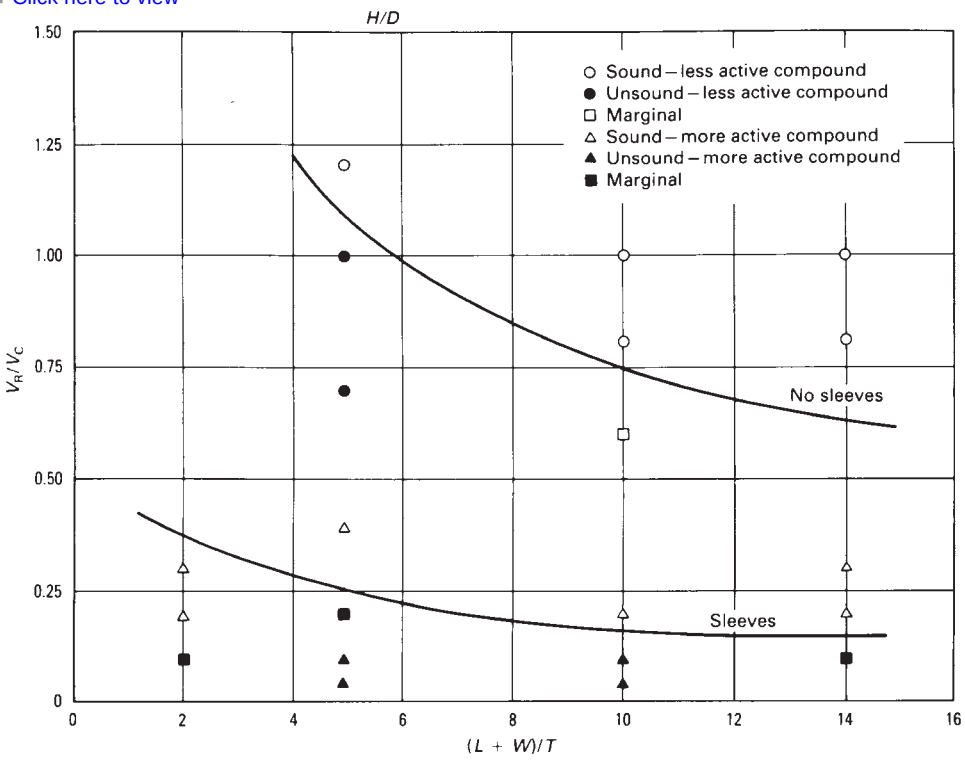

Fig. 40 NRL-type riser curve for Cu-30Ni (alloy C96400) using exothermic sleeves and hot topping versus hot topping alone. Source: Ref 34

Table 10 Minimum volume requirements of risers

	Minimum V_R/V_C, %			
	Insulated risers		Sand risers	
Type of casting	*H/D* = 1:1	*H/D* = 2:1	*H/D* = 1.1	*H/D* = 2.1
Very chunky; cubes, and so on; dimensions in ratio 1:1.33:2(a)	32	40	140	198
Chunky; dimensions in ratio 1:2:4(a)	26	32	106	140
Average; dimensions in ratio 1:3:9(a)	19	22	58	75
Fairly rangy; dimensions in ratio 1:10:10(a)	13	15	30	38
Rangy; dimensions in ratio 1:15:30 or larger(a)	8	9	12	14

(a) Ratio of thickness:width:length. Source: Ref 31

Table 11 Riser neck dimensions

Type of riser	Length, L_N	Cross section
General side	Short as feasible, not over *D*/2	Round, $D_N = 1.2\ L_N + 0.1D$
Plate side	Short as feasible, not over *D*/3	Rectangular, $H_N = 0.6$ to $0.8T$ as neck length increases. $W_N = 2.5\ L_N + 0.18D$
Top	Short as feasible, not over *D*/2	Round, $D_N = L_N + 0.2D$

L_N, D_N, H_N, W_N: length, diameter, height, and width of riser neck, respectively. *D*, diameter of riser. *T*, thickness of plate casting. Source: Ref 35

- Use chills on areas that must be machined, thereby moving porosity to areas where the cat skin will be left unmachined; that is, maintain pressure tightness.
- Gate into areas away from machined sections to maintain pressure tightness.
- Use low pouring temperature (care should be taken to avoid misruns).
- See whether increased gas content (no de gassing, reduced deoxidation) or induced metal mold reaction increases pressure tightness.
- Make castings as thin as possible to increase cooling rate and reduce machining.

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