EXECUTIVE SUMMARY

The lack of adequate data on permanent-mold design and mechanical properties is an impediment to the acceptance of the permanent-mold casting of copper alloys - especially in applications where their inherent corrosion resistance, and high thermal and electrical conductivities are superior to other engineering alloys.

This report summarizes the results of a three-year study on the mechanical, impact, and fatigue properties and fracture toughness of 13 copper alloys (aluminum bronzes [C95200, C95300, C95400, C95500, and C95800], yellow brass [C85800], high-strength yellow brass [C86300], silicon brass [C87500], manganese yellow brasses [C99700 and C99750] and the high-copper alloys [C80100, C81500, and C82500]). Some limited data on tensile properties are also presented for silicon bronze (alloy C87600). For the first time, comprehensive data on mechanical, impact, fatigue and fracture toughness properties, as well as wear and corrosion (selected alloys from the group) properties, are available for these alloys.

The results of this study show that the mechanical, impact properties and fracture toughness of these alloys are strongly dependent on the chemical composition. The nominal composition did not always provide the best combination of strength and ductility. The fatigue properties were dependent on both the stress level and the chemical composition. In order to achieve optimum properties for a given application, a narrower composition range than in the current specifications should be targeted, especially for those elements that have been shown to have the greatest effect on properties. Specifically, high UTS and YS (0.2% offset and 0.5% extension) were observed with significant reduction in ductility (% elongation) at higher aluminum levels for the aluminum bronzes. Significant improvements in the ductility were observed when the aluminum levels were close to the lower end specified in ASTM B806-93a.

A significant reduction in ductility (% elongation), similar to that observed for the aluminum bronzes, was observed at high zinc levels for the high-Zn yellow brass, high-strength yellow brass and high-manganese brasses. Adding chromium (alloy C81500) and beryllium (alloy C82500) to pure copper significantly improved the tensile properties. The fatigue properties of the alloys are sensitive to both applied stress and chemical composition.

The erosion resistance of the aluminum bronzes (C95400 and C95500) and high-strength yellow brass (C86300) was investigated using slurry jet tests at 90° and 20° impingement angles, and the Coriolis tests. The high-strength yellow brass (C86300) shows a slightly higher erosion resistance than the aluminum bronzes (C95400 and C95500) in both the 20° slurry jet impingement and Coriolis tests.

The corrosion resistance of high-copper alloys (C80100 and C81500), aluminum bronzes (C95400 and
C95800), yellow brass (C85800), high-strength yellow brass (C86300), high-manganese brass (C99700), silicon brass (C87500) and silicon bronze (C87600) cast in permanent and green-sand molds has been determined using the standard ASTM salt-spray test in CO$_2$- and SO$_2$-enriched test environments at 25°C and 50°C. A potentiodynamic polarization test in NaOH and KH$_2$PO$_4$ solution was also performed. The results show that copper-base alloys cast in permanent molds exhibit better corrosion resistance than those cast in green-sand molds. Long-term immersion tests in a salt spray chamber indicated that sand-cast alloys are more susceptible to pitting corrosion than permanent-mold cast samples. The SO$_2$ test environment was the most aggressive for all the alloys evaluated. Based on the results of the electrochemical polarization and salt fog tests, the high-manganese brass alloy (C99700) exhibited remarkable corrosion resistance compared with the other alloys.

The shrinkage and metal core taper allowances required during the permanent-mold casting of a plate and a cylinder in pure copper (C80100), aluminum bronze (C95400), high-Zn yellow brass (C85800), silicon brass (C87500) and silicon bronze (C87600) alloys have been evaluated. The average shrinkage allowance required ranged from 0.185 to 0.252 in./ft based on plate casting data for each of these alloys. The lowest and highest shrinkage allowances were required for alloys C87600 and C80100, respectively. The cylinder casting results show that a core taper greater than 1.5° is necessary to facilitate casting ejection as these alloys tend to shrink onto cores during solidification.

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IMPURITY LIMITS IN ALUMINUM BRONZES

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EXECUTIVE SUMMARY

At present, there is no consensus on the maximum allowable limits for impurity elements in aluminum bronze castings which could adversely affect the ductility and promote cracking during welding and heat treatment. This work was carried out to evaluate the effect of some impurity elements on the mechanical properties and heat treatment of two most popular aluminum bronze alloys namely, C95800 and C95400. In addition, the cracking in the heat affected zone (HAZ) during welding of alloy C95800 was investigated.

Selected impurity elements (Pb, Zn, Sn, Bi, Se, Cr, Si and Be) were added as one, two or three element combinations in alloy C95800. Some of the samples were given the corrosion inhibition heat treatment of annealing at 700°C for six hours followed by air cooling. The mechanical properties were evaluated under as-cast and heat treated conditions. The as-cast strengths (UTS and YS) were always above the ASTM specified limits. However, the ductility (% elongation) was reduced to just above and in some cases below the minimum specified value. The heat treatment marginally increases strength but reduces the ductility. Only Pb, Sn, Si and Bi appear to be the elements to have any major impact on the ductility (% elongation). Of this Si should be controlled below 0.1% to have good ductility. In case of other three elements, namely Pb, Sn and Bi the effect is more significant when they elements are present in combination. The maximum content of lead (preferably 0.01%) and bismuth (maximum of 0.05%) should be less than 0.06% to achieve good ductility. Tin content should be controlled below 0.1% when present together with lead or bismuth.

The weldability of alloy C95800 was assessed by conducting full bend test. However, it was found out that this test could not be used to predict the cracking in heat affected zone (HAZ). The simulation of the HAZ, using a Gleeble 2000 weld simulator, was found to be more representative than the bend test. Of all the impurity elements tested only lead and bismuth were found to promote cracking in the HAZ. The other impurity elements (Zn, Sn, Se, Cr, Si and Be) did not have any significant effect on HAZ cracking. Based on the results for various combinations of the impurity elements and microstructural observations, the limits to prevent HAZ cracking in C95800 can be specified as follows: Lead - 0.05%, Zinc - 1.2%, Tin - 0.3%, Bismuth - 0.03%, Selenium - 0.035%, Silicon - 0.25%, Chromium - 0.1% and Beryllium - 0.1%. Combining the results from the mechanical properties and weldability the new limits for the impurity elements in alloy C95800 are as follows:

- Lead 0.01%
- Zinc 1.2%
- Tin 0.1%
- Bismuth 0.03%
- Selenium 0.035%
- Silicon 0.1%
- Chromium 0.1%
- Beryllium 0.1%

Only five elements, Pb, Sn, Zn, Bi and Se were added to alloy C95400. The heat treatment for this alloy
consists of solutionizing and annealing treatment. The solutionizing was carried out at 900°C for one hour followed by water quench. The castings were then annealed at 400°C for one hour. Alloy C95400 exhibited high yield strength but very poor ductility in the as-cast and heat treated conditions, probably because of the high aluminum and nickel contents used in the investigation. Aluminum was found to be more important than impurity elements when mechanical properties are concerned. Only when the aluminum content was below 10.6% the ductility specified by ASTM could be achieved. Further work to assess the effect of aluminum on mechanical properties is needed. The effect of impurity elements on the as-cast properties was minimum. However, after heat-treatment, an alloy with either lead or bismuth at very low levels (0.02%) failed in a complete brittle manner at very low stresses indicating the adverse effect of these elements. It is suggested that these two elements should be controlled below 0.02%.

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EXECUTIVE SUMMARY

Permanent mold casting, an environmentally friendly process is quite common for producing castings from alloys of aluminum and zinc. Copper-base alloys due to their higher process temperatures are not widely accepted as materials for permanent mold process. The advantages of the process include near-net shape components, better surface finish, improved mechanical properties and energy efficiency. Only recently permanent mold casting is gaining acceptance from North American copper casting industry despite the fact that this process is widely in use in Europe. The permanent mold process has one more advantage over sand casting in that the problem of disposal of lead contaminated sand is eliminated.

Many of the common copper base alloys such as red and yellow brasses used for plumbing applications have lead as a major alloying element. Lead improves the machinability and pressure tightness of these alloys. However, the recent restrictions on the leachable lead in the drinking water have led to the research and development of low-lead or lead-free copper base alloys for plumbing applications.

The design engineers should be aware of the advantages of the permanent mold cast copper alloys to increase their market share and there is a need for establishing the process and design parameters for permanent mold cast copper base alloys for their wider acceptance as engineering alloys in the place of steels, cast irons and aluminum alloys. The three-year project on process parameters for lead-free copper base alloys in permanent molds deals with different process parameters as elaborated below:

1. Evaluation of mold life of potential mold materials for permanent mold casting of copper alloys.
2. Effect of minor alloy additions on the effective casting fluidity of lead free tin bronzes/red brass.
3. Grain refinement of permanent mold cast brasses and bronzes, with emphasis on its effect on hot tearing resistance and casting fluidity.
4. Numerical modeling to describe the microstructural changes observed in Cu-Zn brass by the addition of aluminum and its effect on casting fluidity.
5. Water modeling of gating systems used in permanent mold castings to generate information on turbulence and jetting.
6. Development of a new lead-free low melting copper alloy for permanent mold casting.
7. Investigation of the zinc oxide deposit during permanent mold casting of yellow brass.

The salient findings of these investigations are summarized below:
Thermal shock resistance of various materials (e.g., cast iron, tool steel, Cu-Be, Ni-Be, Nickel Aluminide etc.) used to make the molds for copper alloy permanent mold casting process was evaluated and ranked as follows:

Ni-Be > Cu-Be > Nibryl > Ni\textsubscript{3}Al > H13 Steel > Cast Iron > Plain Carbon Steel

The grain refinement behaviour of permanent mold cast silicon brass, silicon bronze and lead-free red brass was studied. The grain refiners investigated were Cu-B, zirconium and a commercial grain refiner FKM 2000. Zirconium was effective for silicon brass and silicon bronze. Lead-free red brass was partially grain refined by boron.

The effect of minor alloy additions such as Al, Mg, and Pb on the fluidity of tin bronze, silicon brass and silicon bronze was investigated. Only aluminum improved the casting fluidity.

Water modeling studies were carried out to evaluate the fluid flow in selected permanent molds. The turbulent flow, jetting and air entrapment during the fluid flow could be visualized. These problems were shown to be reduced by altering the gating and pouring practices.

Aluminum is known to improve the fluidity of various alloys including leaded yellow brass, silicon brass and silicon bronze in permanent molds. Efforts were made to predict the microstructural changes and enhanced fluidity using mathematical modeling. The study shows that aluminum changes the surface tension of copper and this, in turn, modifies the nucleation and growth behaviour of dendrites during solidification. The dendrite morphology changes from interlocking to a fine feathery structure. These changes were shown to enhance the casting fluidity.

A new low melting copper alloy suitable for permanent mold casting was developed. This alloy contains zinc (20-25%), nickel (4-5%), phosphorous (3-5%) and aluminum (0.5%) as the major alloy additions. The low melting temperature of the alloy makes it attractive to permanent molds since it reduces thermal shock. The alloy posses good casting characteristics (fluidity and hot tearing resistance) as well as good tensile strength and corrosion resistance comparable to yellow brass and found to be pressure tight. However, this alloy has moderate ductility and poor machinability.

Zinc in yellow brass, produces zinc oxide which deposits on the permanent molds (due to the low vapor pressure). This deposit not only reduces casting fluidity but also produces poor surface quality. The deposit is usually removed by dipping the molds in a water/graphite slurry and in extreme cases has to be removed physically. In an attempt to minimize the oxide deposition, the effect of aluminum and magnesium additions on the zinc oxide formation and deposition was studied. It was found that a combination of 0.4% Al and 0.1% Mg reduced the zinc oxide deposition significantly.

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