技術資料

# Permanent Mold Casting of Copper-Base Alloys for Plumbing Applications

M. Sahoo, M. Sadayappan and F. A. Fasoyinu

## Abstract

The lead content of drinking water has been restricted to less than 15 ppb by the Environmental Protection Agency (EPA) in USA. This has led to extensive research and development work at the Materials Technology Laboratory (MTL) of CANMET, a Canadian Government research laboratory, on the development of low-lead and lead-free copper alloys for plumbing applications. Attentionhas also been focused on the environmentally friendly and energy efficient permanent mold casting process to minimize the disposal of foundry sand contaminated by lead due to the use of leaded alloys in the non-ferrous foundries.

A new series of alloys called SeBiLOY contaning Bi and Se been introduced to replace lead in the leaded alloys. This paper addresses some important casting characteristics such as fluidity, hot tear resistance, mechanical properties and microstructureof lead-free alloys such as SeBiLOY III and low-lead alloys such as silicon brass, silicon bronze and yellow brass in gravity permanent mold casting.

## 1. Introduction

Plumbing fittings in North America have traditionally been produced by sand casting process using leaded copper-abse alloys, such as C83600 and C84400 with a nominal lead content of 5 and 7% respectively. This is contrary to the practice in Europe where permenent mold casting is more common to produce plumbing fittings in leaded copper-base alloys are also facing several environmental concerns. One of them is the sand contamination by lead, which can be declared a hazardous material depending on the lead content and the disposal of such foundry sand is expensive. There is also the concern of lead contamination in the drinking water supply. Over the years, the U. S. Environmental Protection Agency (EPA) has been limiting the lead content in potable water. Effective November 1992, the limit has been set at 15 part per billion (ppb0. As a result of such restrictions, lead content of plumbing fitting must be reduced substantially.

The problems associated with the lead contamination of foundry sand can be minimized significantly by changing the production technique of plumbing fittings from sand casting to permanent mold casting. Other advantages of the permenent mold casting process are better surface finish, improved mechanical properties, closer dimensional control and energy efficiency. Thus, a combination of low-lead (if possible lead-free) copper-base alloys and permenent mold casting would minimize both the sand disposal problem commonly encountered in sand-casting foundries, and the lead problem in drinking water.

Bismuth and selenium could be used to enhance the machinability of copper-base alloys and replace lead. Extensive research and development work has led to the introduction of three Bi and Se added alloys (BeBiLOY). Of these SeBiLOY I (C89510) and SeBiLOY II (C89520) have been developed to replace the sand cast leaded red brasses, C83600 and C84400. The third alloy, SeBiLOY III (C89550) is the substitute for leaded yellow brass and suitable for permanent mold cast condition.

Since 1991, research at the Materials Technology Laboratories (MTL) of the Canada Centre for Mineral and Energy Technology (CANMET) has been aimed at promoting the permanent mold casting technology kfor copper-base alloys and to develop low-lead and lead-free

Materials Technology Laboratory, 568 Booth Street, Ottawa, Ontario, Canada
"본 기술자료는 1999년도 춘계학술발표 및 기술강연대회에서 발표예정이었던 내용임"

alloys for plumbing fittings and the projects were cost-shared with various organizations, namely, International Copper Association (ICA), Copper Development Association (COA), American Foundrymen's Society (AFS), Brass and Bronze Ingot Manufacturers (BBIM) and Selenium and Tellurium Development Association (STDA). The effective casting fluidity, hot tear resistance and corrosion behaviour in hard and soft water of alloys such as silicon brasses (C87500 and C87800), silicon bronzes (C87600 and C87610), high-zinc yellow brass (C85800) and SeBiLOY III (C89550) have been evaluated. In addition, prototype plumbing fittings have been produced in these low-lead and lead-free alloys. This paper summarizes the important findings of this work since details have already been published elsewhere[1-34].

## 2. ALLOY CHEMISTRY

The nominal composition oranges and sim compositions of the alloys studied at MTL are presented in Table 1[1,2,6-9]. Although the lead content of the alloys have varied between 0.1 and 2%, some of the alloys werrfe cast without lead to evaluate the casting characteristics. These lead free alloys were also used to produce prototype plumbing fittings.

The solidification ranges of these alloys are shown in Table 2. As shown, the yellow brasses (C85800 and C89550) have narrow freezing range and other two are long freezing range alloys.

## 3. MICROSTRUCTURE

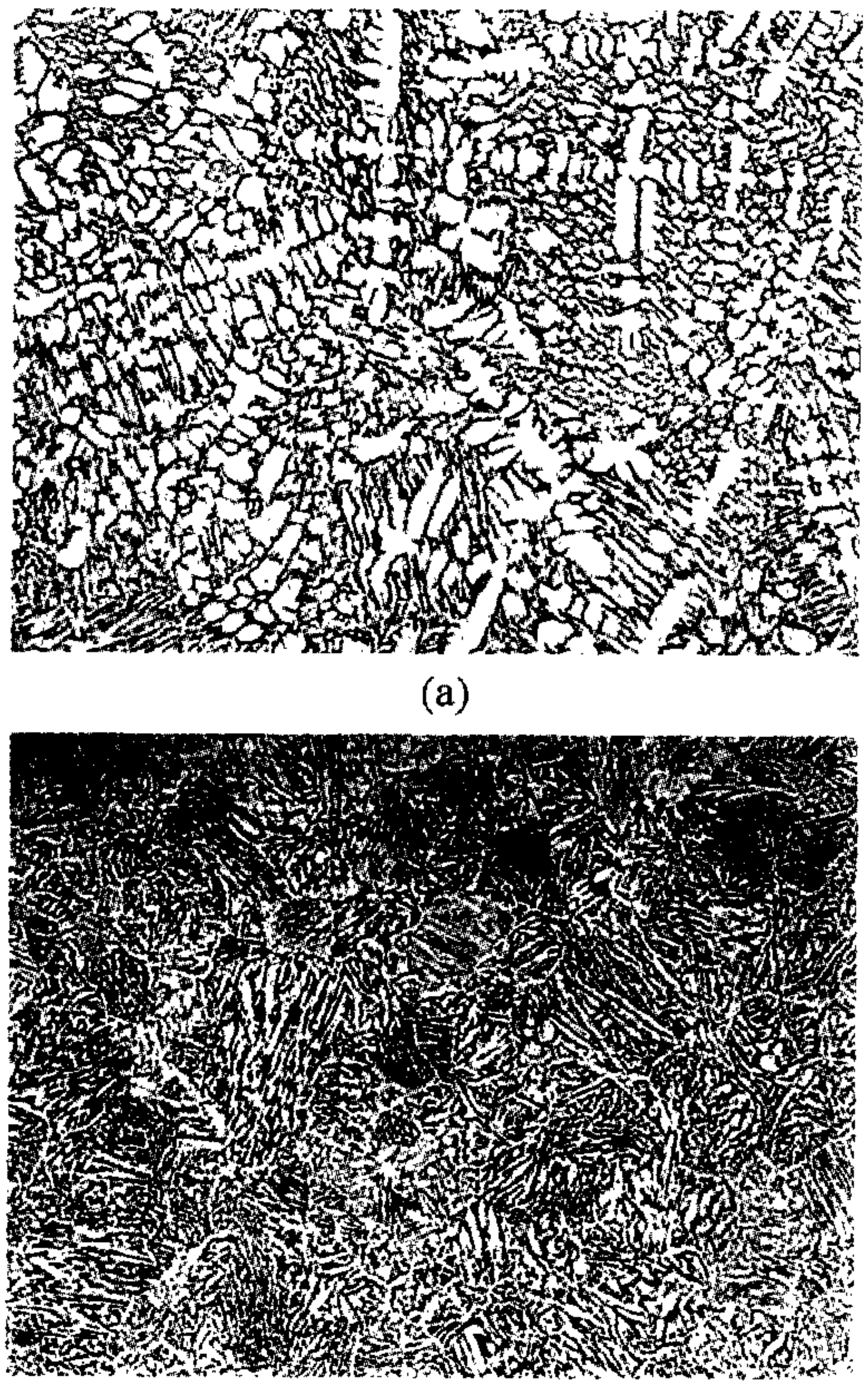
The typical microstructure of all the alloys consists of primary α dendrites and a eutectic mixture of α and β. The interlocking dendritic structure changes into a feathery non-dendritic structure upon the addition of aluminum. The general features of the micorstructure of all the

Table 2. Solidification Range of Alloys

| Alloy No. | Temperature,°C | | |
|---|---|---|---|
| | Liquidus | Solidus | Range |
| C85800 | 899 | 871 | 28 |
| C89550 | 892 | 860 | 32 |
| C87500 | 916 | 821 | 95 |
| C87800 | 916 | 821 | 95 |
| C87600 | 971 | 860 | 111 |
| C87610 | 971 | 860 | 111 |

Table 1. Chemical Composition Range of Alloys

| Alloy | Alloy No. | Zn | Pb | Sn | Si | Al | Fe | Mn | Other |
|---|---|---|---|---|---|---|---|---|---|
| High-Zn yellow brass | C85800 | 31-41 | 1.5 | 1.5 | 0.25 | 0.5 | - | - | |
| | Aim 1 | 35 | 0.5 | 1.0 | - | 0.3 | - | - | |
| | Aim 1 | 35 | 1.0 | 1.0 | - | 0.3 | - | - | |
| SeBiLOY III | C89550 | 32-40 | 0.2 | 1.5 | - | 0.5 | 0.7 | 1.0 | Bi:0.7-2.0<br>Se:0.07-0.25 |
| | Aim 1 | 36 | - | 1.5 | - | 0.3 | 0.5 | 0.7 | |
| Si-brass | C87500 | 12-16 | 0.5 | - | 3.5-5.5 | - | - | - | |
| | Aim 1 | 14.0 | 0.5 | - | 4.0 | 0.1 | - | - | |
| | C87800 | 12-16 | 0.15 | 0.25 | 3.8-4.2 | 0.15 | 0.15 | 0.15 | |
| | Aim 1 | 14.0 | 0.1 | - | 4.0 | 0.1 | - | - | |
| Si-bronze | C87600 | 4-7 | 0.5 | - | 3.5-5.5 | - | - | - | |
| | Aim 1 | 5.5 | - | - | 4.5 | - | - | - | |
| | Aim 2 | 5.5 | 0.5 | - | 4.5 | - | - | - | |
| | Aim 3 | 5.5 | - | - | 4.5 | 0.3 | - | - | |
| | Aim 4 | 5.5 | 0.5 | - | 4.5 | 0.3 | - | - | |
| | C87610 | 3-5 | 0.2 | - | 3-5 | - | 0.20 | 0.25 | |
| | Aim 1 | 4.0 | 0.2 | - | 4.0 | - | - | 0.25 | |
| | Aim 2 | 4.0 | 0.2 | - | 4.0 | 0.3 | - | 0.25 | |



(a)

(b)

Fig. 1. Optical micrographs showing the effect of aluminum on the structure of SeBiLOY III (a) 0% Al and (b) 0.4% Al, 100X.

alloys are summarized as follows:[1,2,6,25]

· Aluminum appeared to promote the formation of feathery dendrites in all the four alloys.

· Increasing lead content in silicon brass, silicon bronze and yellow brass, even in the presence of aluminum, changes the feathery fine structure in to a coarser dendritic structure.

· In the case of SeBiLOY III, the newly introduced yellow brass with bismuth and selenium replacing lead, the micorstructure consists of the classical interlocking dendrites. Addition of aluminum changes the structure to a fine feathery structure. This is shown in Fig. 1.

· Bismuth in SeBiLOY III is found as discrete particles. Selenium is found as copper-selenide or bismuth-selenide and distributed evenly in the alloy matrix. The distribution of bismuth in SeBiLOY III is shown in Fig. 2.

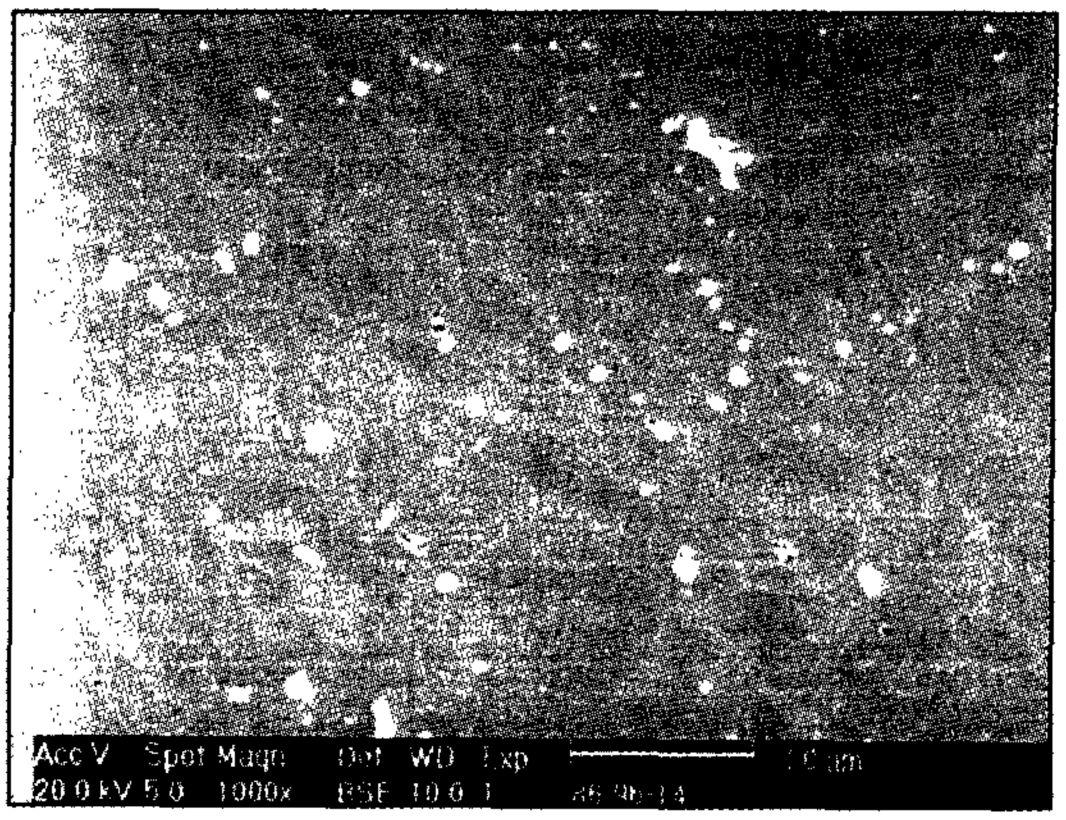
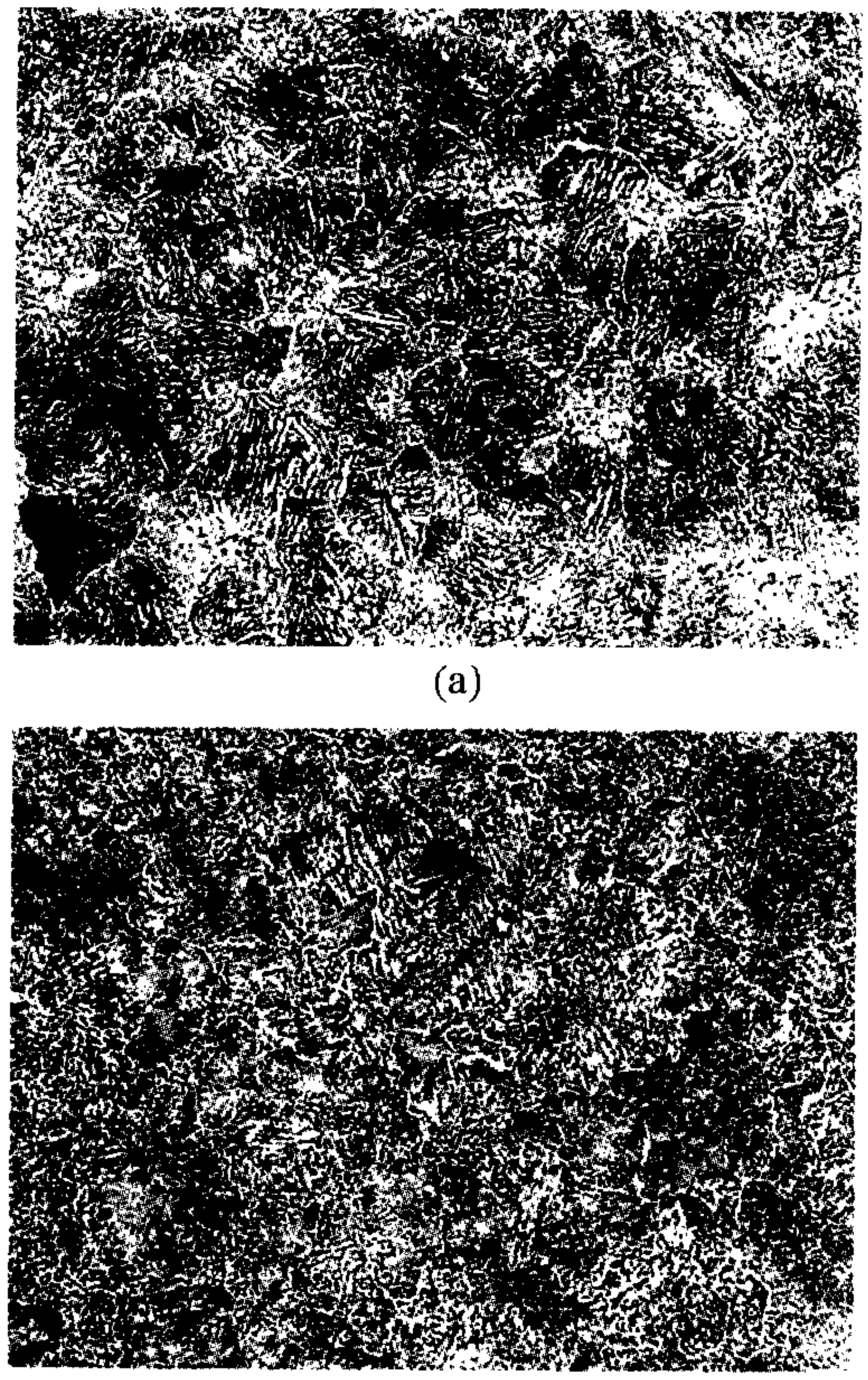



Fig. 2. SEM micorgraph showing bismuth distribution in BeBiLOY III, 1000X.



(a)

(b)

Fig. 3. Optical micrographs of SeBiLOY III with (a) 1.1% bismuth and (b) 1.7% bismuth, 100X.

· The microstructure of SeBiLOY III gets refined with increasing amount of bismuth. Theis is opposite to the trend observed for lead addition in other alloys. The typical microstructure showing the effect of increasing bismuth content are shown in Fig. 3.

## 4. CASTING FLUIDITY

The effective casting fluidity of permanent mold silicon brasses (C87500 and C87800), silicon bronzes (C87600 and C87610), yellow brasses (C85800) and SeBiLOY III (C89550) has been evaluated using a commercial casting machine with tilt pouring facility. One plate casting having a dimension of 5" long x 2" wide x0.125" thick was poured and the superheat to fill the casting was taken as the measure of fluidity. Another measure is the height of the plate filled at a selected superheat. The test mold, experimental procedure and variables involved are discussed in detail elsewhere[1,8,9]. The highlights of the fluidity work are the following.

· The fluidity increased with melt superheat for each alloy.

· The presence of aluminum and lead had a significant effect on the fluidity of the silicon brasses, silicon bronzes and high-zinc yellow brass. Aluminum always improved the fluidity. Addition of only 0.3%Al was found to be sufficient to produce maximum fluidity[28,32].

· By contrast, lead reduced the fluidity of the silicon brasses and silicon bronzes significantly. However, it had no adverse effect on the fluidity of the high-zinc yellow brass in the presence of aluminum[5,20].

· The effect of bismuth on the casting fludity in SeBiLOY III is similar to that of lead in yellow brass. The fluidity decreases with the bismuth level and at a bismuth content of 1.9% the plate casting could not be filled completely[6,25]

· The effects of base composition as well as lead and aluminum of fluidity could be explained in terms of the dendrite form in these alloys as discussed above.

· Alloys with feathery dendrites or small rounded dendrite arms had better fluidity than those with conventional interlocking dendrites.

· The mold temperature did not have a significant effect on the fluidity in the range 150 to 225°C.

· A mold rotation speed of 23 degrees per second was found to optimize mold filling.

Table 3. Casting fluidity

| Alloy type | Ranking (from best to least) |
|---|---|
| No Pb, Al, Bi | Silicon bronze (C87600 and C87610)<br>Silicon brass (C87500 and C87800)<br>High-zinc yellow brass (C85800)<br>SeBiLOY III (C89550) |
| No Pb, with Al | Silicon bronze (C87600 and C87610)<br>Silicon brass (C87500 and C87800)<br>High-zinc yellow brass (C85800) |
| With Pb and Al | Silicon bronze (C87600 and C87610)<br>Silicon brass (C87500 and C87800)<br>High-zinc yellow brass (C85800) |
| With Bi and Al | SeBiLOY III (C89550) |

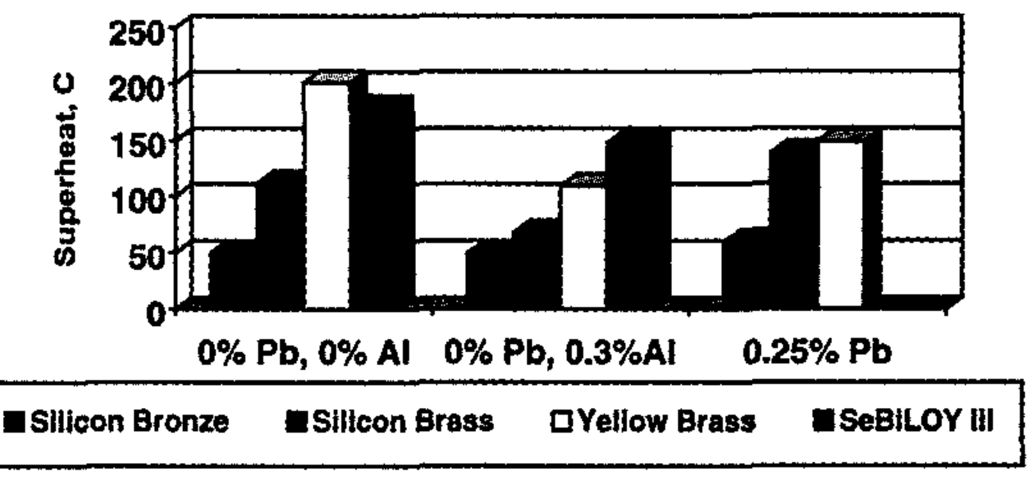



Fig. 4. Effect of Al and Pb on Casting fluidity

· The slloys studied could be ranked, in the order of decreasing fluidity, as shown in Table 3 and the effect of aluminum, lead and bismuth on the casting fluidity is illustrated in Fig. 4.

· In general, the silicon bronze has excellent fluidity. SeBiLOY III has lower fluidity than leaded yellow brass.

## 5. HOT TEARING

The hot tearing resistance of the alloys was evaluated by casting a hollow cylinder, 51 mm inside diameter, 6.4 mm thick and 57 mm in length. A metal core, with cooling channels for air circulation, was used to produce maximum stress at the base of the cylinder[1,9]. Hot tearing normally occurs when the casting is stressed at a stage where it is partially liquid. A typical cup casting and a cut section of the cup revealing the hot tear cracks are illustrated in Fig. 5.

The hot tearing characteristics of the alloys could be summarized as follows:[1,2,9,25]

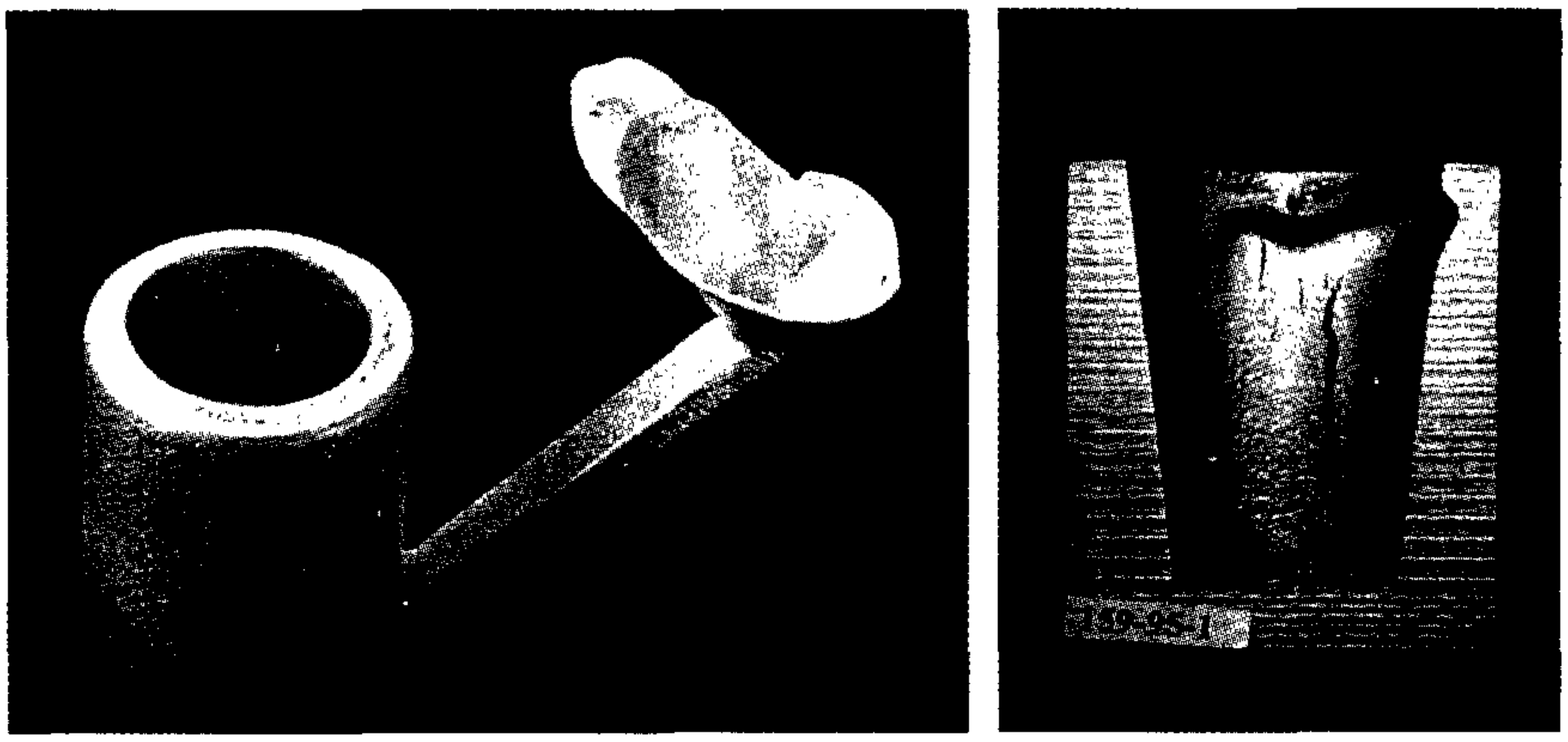


Fig. 5. Photographs of (a) cup casting and (b) section of the cup showing the hot tear cracks, used in hot tearing studies

· High-zinc yellow brass: no hot tearing at 0.5% Pb but extensive hot tearing at 1.0%Pb.

· SeBiLOY III: Bismuth affects the hot tearing. Alloy with less than 1% bismuth is free from hot tearing. Higher bismuth contents promote hot tearing. However, if the melt superheat temperature is maintained below 140C, hot tearing could be prevented even in alloys containing 1.9% bismuth.

· Silicon bronze: hot tearing over all the range of temperatures investigated at 0.5%Pb. Alloy C87610 (0.2%Pb, 0.25%Mn) did not exhibit any hot tearing at lower pouring temperatures.

· Silicon brass: no hot hearing at 0.10%Pb but extensive hot tearing at 0.26%Pb.

All these data show that none of the alloys tested exhibited hot tearing at low lead and bismuth contents. However, lead promotes hot tearing above 0.5% wt. In the case SeBiLOY III, the bismuth limit was found to be 1% above which hot tearing occurred. The freezing range of the alloys does not appear to be the controlling factor.

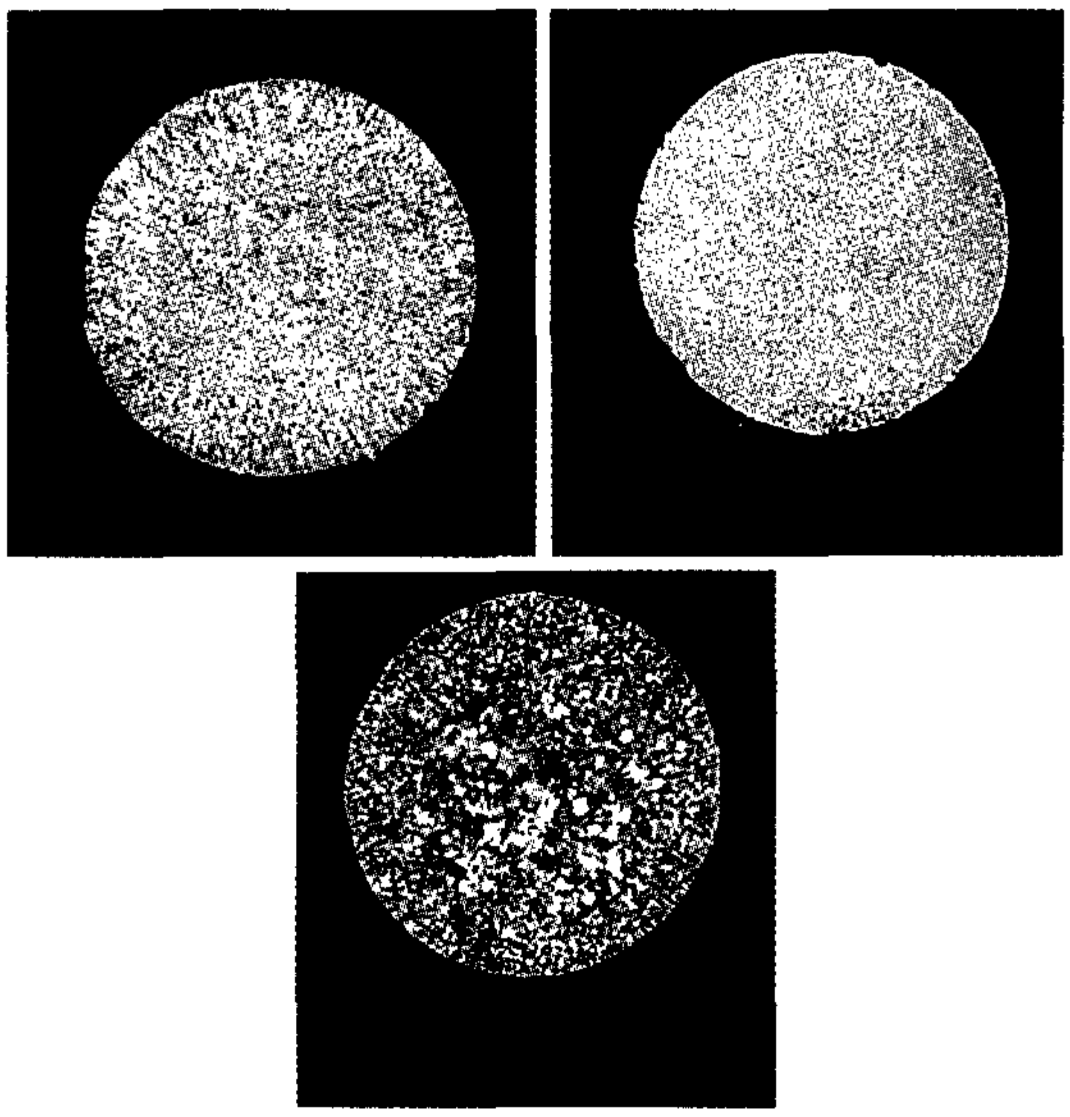


Fig. 6. Macrographs of yellow brass (C85800) in (a) unrefined, (b) 0.01% boron refined and (c) 0.025% boron refined conditions, 5X.

## 6. GRAIN REFINEMENT

The hot tearing resistance of many cast alloys could be improved by grain refinement. Grain refinement increases the number of grains which are very fine in size. The last liquid to solidify will then be spread over a wider area which could resist the stresses at the final stages of solidification. This was proven for many alloys and grain refinement is being used in aluminum and steel to prevent hot tearing and improve mechanical properties.

Copper alloys, as shwon earlier are prone to hot tearing and efforts were made to prevent these defects. Grain refinement behaviour of these four alloys was studied in detail. Three major refiners, boron, zirconium and FKM 2000, were tried. The effect of boron addition in yellow brass is shown in Fig. 6. The major findings are listed in

Table 4. Grain refinement of permanent mold cast copper alloys

| Alloy | Refiner | Addition, % | Structure |
|---|---|---|---|
| Yellow Brass | Boron | 0.01 | Fine |
| | | 0.025 | Coarse |
| | FKM 2000 | 0.01 | Coarse |
| | | 0.03 | Partial |
| | | 0.04 | Fine |
| | Zirconium | 0.02 | Partial |
| SeBiLOY III | Boron | 0.01 | Coarse |
| | | 0.02 | Coarse |
| | FKM 2000 | 0.01 | Coarse |
| | | 0.04 | Coarse |
| | Zirconium | 0.03 | Partial |
| | | 0.055 | Fine |
| Silicon Brass | Boron | 0.02 | Coarse |
| | | 0.03 | Coarse |
| | FKM 2000 | 0.1 | Coarse |
| | Zirconium | 0.01 | Partial |
| | | 0.05 | Fine |
| Silicon Bronze | Boron | 0.02 | Coarse |
| | FKM 2000 | 0.1 | Coarse |
| | Zirconium | 0.01 | Coarse |
| | | 0.04 | Fine |

Table 4 and highlights of the grain refinement work are given below[5-7,27,29,30,34].

1. Boron refined the structure of leaded yellow brass. Tin content was not a factor in deciding the grain refiner.

2. Iron, in excess of 0.05%, in boron refined yellow brass promotes the formation of hard spots.

3. SeBiLOY III with low tin contents was refined by boron. Zirconium refined the alloy with~1% tin content.

4. Silicon brass and silicon bronze were refined by zirconium.

5. The hot tearing resistance of all the four alloys was enhanced by grain refinement.

## 7. MECHANICAL PROPERTIES

The mechanical properties, UTS, 0.5% yield strength and % elongation, were measured using permanent mold cast ISO test bars. In all cases minimum six test bars were tested and the average properties are reported in Table 5 and highlights of the findings are discussed below [10,11,25,29,34].

Table 5. Mechanical properties of selected alloys

| Alloy | Alloy No* | UTS Mpa | 0.5%YS Mpa | Elongation % |
|---|---|---|---|---|
| C85800 | Aim 1 | 334 | 190 | 10 |
| | Aim 2 | 359 | 192 | 13 |
| C89550 | Aim 1 | 398 | 233 | 12 |
| C87500 | Aim 1 | 519 | 249 | 15 |
| C87800 | Aim 1 | 534 | 229 | 24 |
| C87600 | Aim 1 | 422 | 265 | 6 |
| | Aim 2 | 369 | 195 | 12 |
| | Aim 3 | 429 | 252 | 8 |
| | Aim 4 | 369 | 209 | 10 |
| C87610 | Aim 1 | 323 | 146 | 16 |
| | Aim 2 | 401 | 246 | 7 |

Note: *-See Table I for the chemical composition

- All the four alloys show good strength coupled with reasonable ductility.
- Silicon brass possesses high strength and ductility followed by silicon bronze, SeBiLOY III and yellow brass.
- The strength of lead containing silicon bronze (Aim 2 & 4 in C87600) is lower than that of lead-free silicon bronze but it has higher ductility.
- Aluminum improves the strength but reduces ductility in silicon bronzes.
- As mentioned before, grain refinement did not improve the mechanical properties.

## 8. MACHINABILITY

For machinability testing, ingots of size 3.8 cm × 7.6 cm × 30.5 cm (1(1/2)" × 3" × 12") were cast. The cast iron molds used for these castings were coated with zircon wash and heated to 200C[18].

Two test blocks of size 3.8 cm × 7.6 cm × 5 cm(1(1/2)" × 3" × 2") were cut from the bottom of the machinability ingot. The cut surfaces were milled to produce parallel surfaces. The machinability was determined by measuring the time (s) and energy (J) consumed while drilling a 12.7 mm (0.5in.) diameter by 25.4 mm (1in) deep hole. Test parameters included using a newly sharpened drill bit for each hole drilled, drilling 6 holes per block and averaging results, maintaining a block tem-

Table 6. Mechinability rating of selected alloys

| Alloy | Condition | Time, S | Energy Consumed, J | Index | |
|---|---|---|---|---|---|
| | | | | Time | Energy |
| C36000 | 3% Pb | 20.6 | 2050 | 100 | 100 |
| | 0% Pb | 140 | 10948 | 15 | 19 |
| C89550 | 0% Bi | 83.6 | 6429 | 25 | 32 |
| | 0.57% Bi | 57.5 | 2466 | 36 | 83 |
| | 0.67% Bi | 51.2 | 2743 | 40 | 75 |
| | 1.13% Bi | 36.1 | 2115 | 57 | 97 |
| | 1.89% Bi | 29 | 3899 | 71 | 53 |
| C87500 | 0% Pb | 40 | 1954 | 52 | 105 |
| C87600 | 0% Pb | 39 | 2640 | 53 | 78 |
| | 0.2% Pb | 36 | 2435 | 57 | 84 |

Table 7. Some corrosion rates of selected alloys

| Alloy | Lead, % | Corrosion rate, $\mu A/Cm^2$ | | | Leached Zinc, ppb | | |
|---|---|---|---|---|---|---|---|
| | | pH 5 | pH 6 | pH 8 | Day 1 | Day 15 | Day 30 |
| C85800 | 1.5 | 12 | | 4 | 10 | 5 | 2.4 |
| C89550 | - | | 2.5 | 0.6 | | | |
| C87500 | 0.5 | 8 | | 2.5 | | | |
| C87800 | 0.1 | 8 | | 3 | 5.5 | 2.9 | 3.6 |
| C87600 | 0.5 | | | | 32 | 39 | 80 |
| C87610 | 0.2 | 3 | | 1.6 | 15 | 20 | 7 |

perature of <40C, and collecting a sample of the drilling for visual analysis. In order to obtain a machinability index, a test block of free-machining brass (alloy C36000) was tested and assigned a rating of 100%. All values obtained from the test castings were indexed against the free-machining brass. The machinabilit ratings are tabulated in Table 6.

The time and energy indices show a increasing trend for all the alloys investigated with increase in lead or bismuth contents. The energy rating increases at a higher rate as compared to the time index. The ratings indicate that lead improves the machinability of silicon bronze and free machining brass and for SeBiLOY III, bismuth increases the machinability[6, 7, 18, 25]. The enerby consumed to machine silicon brass is lower than that required for free machining brass indicating superior machinability. Also, the machinability of SeBiLOY III with ~1.2% bismuth is close to that of free machining brass. However, all thest alloys have lower rating in time index indicating the machining time will be longer as compared to free machining brass

## 9. CORROSION BEHAVIOUR

Potentiodynamic polarization technique was used for the experimental determination of corrosion currents of all the alloys in permanent mold-cast condition. Such corrosion studies were carried out in soft water at pH5 and 8 for silicon brass, silicon bronze and yellow brass [1, 2, 12, 14]. In case of SeBiLOY III the solutions were of pH 6 and 8[6]. Leaching of lead from selected alloys in the form of flat pieces instead of faucets was studied according to the proposed procedure given in NSF standard #61, Section 9. This was done only for leaded alloys and not for SeBiLOY III. Dezincification behaviour of the alloys was established in cupric chloride solution maintained at 75 ± °C (ISO Test) for 24 hours. Some of the results are presented in Table 7.

The highlights of the corrosion studies are as follows:

- The corrosion rates from polarization studies indicate that, SeBiLOY III (C89550) is more corrosion resistant than yellow brass (C85800), silicon brass and silicon bronzes.
- Addition of aluminum improved the corrosion resistance of silicon brass and silicon bronze alloys.
- Leaching of lead as per proposed NSF#61 method showed the leaded alloys studied gave a leach rate of lead content less than 5 ppb after 60 days of exposure. However, the lead leached from silicon bronzes were higher than 5 ppb.
- All the alloys were also tested in different water conditions. The data is available in earlier reports [2, 3, 6, 7, 12, 15].

## 10. PROTOTYPING

The gravity permanent mold casting machine (IMR C30) was used to produce prototype components. The die halves are mounted in the two hydraulically operated

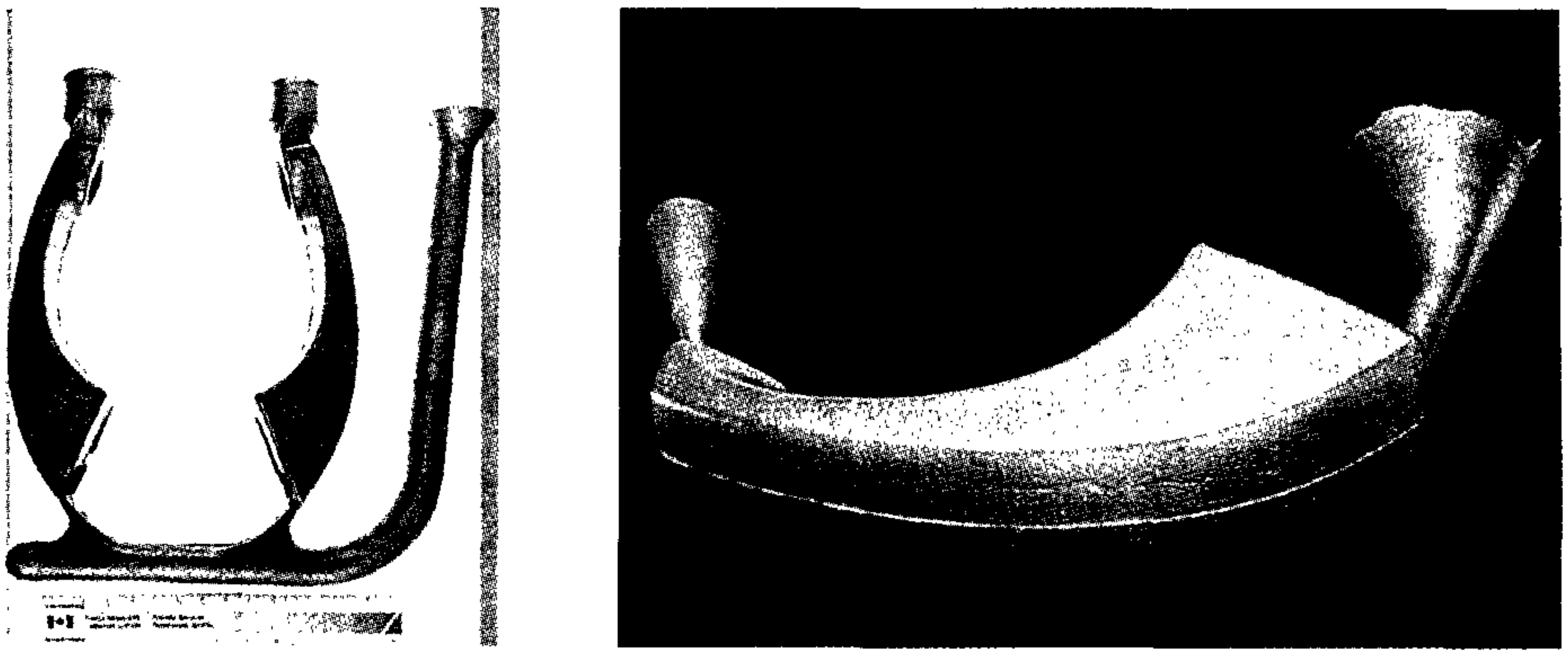


Fig. 7. Photographs of the faucet castings with gating and risers (a) double faucet and (b) single faucet

arms of the equipment. The casting sequence such as mold dipping, hold time and casting ejection could be programmed. However, the casting operation is semi automatic with manual pouring.

Considering the size of this IMR machine at MTL, it was decided to cast a 10.2 cm spout washroom faucet[2, 16]. To this end, a mold was designed and machined from a gray cast iron block. It was was designed to cast two faucets. Each mold half was 29.5 cm wide, 25.7 cm high and 6 cm thick. The sprue and runner were 1.6 cm in diameter. The ingate was 1.6 cm by 3.2 mm. The complete faucet casting is shown in figure 6(a). The silicon brass, alloy C87800, with and without lead but containing about 0.3.%Al appeared to be the preferred alloy to produce the washroom faucets with this double faucet mold design. The silicon bronze, alloy C87600, could also be used despite the hot tearing tendency. However, one has to be very careful about the coating thickness in the cavity, gates and risers and the pouring temperature. The recommended casting parameters such as coating thickness, mold temperature, mold rotation and pouring temperature are presented elsewhere[2,16].

Due to the build-up of zinc oxide in the gates of the double cavity faucet mold. sound faucets were produced only occasionally in the high-zinc yellow brass (C85800). A new single cavity mold was designed and machined from a gray cast iron block to produce a washroom faucet [4, 7, 33]. The riser had to be enlarged to eliminate shrinkage porosity. A typical faucet casting is shown in Fig. 6(b) with the gating and risering system. This mold was used to produce faucets from SeBiLOY III also.

The mold halves were heated to 300C before casting operation and coated with a insulating mold wash. The mold temperature was maintained between 220 and 240°C. The molds were mounted in the casting machines and could be dipped in to the water and graphite slurry between the casting cycle to cool the molds, remove the zinc oxide deposition and coat the mold wit lubricating graphite. In both gravity and low pressure processes shell cores were used.

The casting was removed after 30-45 seconds after ensuring that the solidification was complete. The mold temperature was measured and molds were dipped in the water and graphite slurry if required. The core was placed in the cavity and mold was closed to receive metal. The melt temperature was maintained between 1000-1020C. The faucet castings were cleaned after removing the cores. The inlet and outlets of the faucets were machined and threaded to secure the water pipes for pressure tightness evaluation at 100 psi.

The results from the pressure tightness testing indicate that all the alloys possess good pressure tightness. The faucets that failed the water pressure testing exhibited some casting defects such as hot tearing and shrinkage. These problems were related to the casting design as well as the shell sand core used in this investigation rather than the alloys themselves. The shell core sand with a high resin content (~2.7%) induced hot tearing and gas porosity and led to poor core collapsibility. The castings had to be soaked at 450C to remove the cores in this investigation. Low resin cores were easy to remove and hot tearing could be eliminated. These defects can be eliminated by proper mold design and choice of appropriate core formulation.

## 11. CONCLUDING REMARKS

The casting characteristics of yellow brass, SebiLOY III, silicon brass and silicon bronze were established for permanent mold casting process. The fluidity data indicate that silicon bronze is better than other alloys investigated. However, this slloy is much more prone for hot tearing. Both lead and bismuth at hihger levels promote hot tearing. Grain refinement of these alloys could eliminate hot tearing.

The silicon brass have higher strength and ductility followed by silicon bronze, SeBiLOY III and yellow brass. Lead reduces the strength of the alloys. The machinability of these alloys is also enhanced by lead or bismuth. However, lead-free silicon brass and SeBiLOY III could achieve high machinability ratings than any other alloys tested.

The corrosion testing indicates that SeBiLOY III is better than other alloys. The lead leach test indicated that except silicon bronze all other alloys would satisfy the new EPA regulations.

The work on the production of the washroom faucets shows that sound faucets can be produced by proper mold design, coating application and adjusting the casting parameters.

These observations show that the silicon brasses, silicon bronzes and high-zinc yellow brasses (C85800) are ideally suited for permanent mold casting to produce plumbing fittings. The SeBiLOY III is also suitable for permanent mold casting. However, additional work is needed to improve its casting fluidity.

## REFERENCES

[1] F. A. Fasoyinu, J. L. Dion, M. Elboujdaini, K. G. Davis and M. Sahoo "Permanent Mold Casting of Copper Base Alloys-Phase I", Final Report No: MTL 92-29 (TR-R), 1992, 86 pages.

[2] M. Sahoo, J. L. Dion, M. Elboujdaini and V. S. Sastri, "Permanent Mold Casting of Copper Base Alloys-Phase II", Final Report, No: MTL 93-8(TR-R), 1993, 63 pages.

[3] M. Sahoo, J. L. Dion, M. elboujdaini and V. S. Sastri, "Permanent Mold Casting of Copper Base Alloys-Phase III", Final Report No: MTL 94-3 (TR-R), 1994, 74 pages.

[4] F. A. Fasoyinu, J. L.Dion, D. Cousineau, C. Bibby and M. Sahoo, "Permanent Mold Casting of Copper Base Alloy-Phase IV", Final Report No: MTL 95-4 (TR-R), 1995, 35 pages.

[5] F. A. Fasoyinu, G. Morin, D. Cousineau, L. V. Whiting, P. Newcombe and M. Sahoo "Permanent Mold Casting of Copper Base Allokys-Phase V", Final Report No: MTL 96-7 (TR-R), 1996, 146 pages.

[6] M. Sadayappan, F. A. Fasoyinu, D. Cousineau, R. Zavadil, V. Scepanovic, R. J. Brigham and M. Sahoo "Permanent Mold Casting of Copper Base Alloys-Phase VI", Final Report No: MTL 97-1 (TR-R), 1997, 83 pages.

[7] M. Sadyappan, F. A. Fasoyinu, V. Scepanovic, R. J. Brigham, L. V. Whiting and M. Sahoo "Permanent Mold Casting of Copper Base Alloys-Phase Vil", Final Report No: MTL 98-6 (TR-R), 1998, 88 pages.

[8] F. A. Fasoyinu, J. L. Dion, D. Cousineau, R. A. Matte, K. G. Davis and M. Sahoo "Fluidity of Permanent Mold-Cast Copper-Base Alloys", Trans. Americal Foundrymen's Society, Vol. 100, pp. 547-559, 1992.

[9] J. L. Dion, F. A. Fasoyinu, K. G. Davis, and M. Sahoo "Fluidity and Hot Tearing Resistance of Permanent Mold Cast Copper-Base Alloys", Proceedings of the International Conference on "Copper in the 90's", published by the Indian Copper Development Centre, 1992.

[10] F. A. Fasoyinu, J. L. Dion, M. Sahoo and K. Dave, "Comparison of Mechanical Properties of Cu-Base alloys in ASTM and ISO Permanent Test Bar Molds", Trans. American Foundrymen's Society, Vol. 100, pp. 73-91, 1992.

[11] F. A. Fasoyinu, M. Sahoo C. Bibby and j. L. Dion, "Mechanical Properties of Some Copper-Base Alloys Cast in the ISO Permanent Test Bar Mold", Trans. Americal Foundrymen's Society, Vol. 101, pp.211-224, 1993.

[12] M. Elboujdaini, M. Sahoo C, Bibby and J. L. Dion, "Corrosion Behaviour of Some Permanent Mold Cast Copper-Base Alloys in Aqueous Solution", Trans. American Foundrymen's Society, Vol. 101, pp. 29-36, 1993.

[13] M. Sahoo J.L. Dion, S. Kuyucak and M. Shehata, "A Feasibility Study of the Production of Free-Machinin Brass Without Lead", ICA Project No.471, MTL 93-6(TR-R), 1993, 37 pages.

[14] M. Sahoo J.L. Dion, S. Kuyucak and M. Shehata, "A Feasibility Study of the Production of Free-Machining Brass Without Lead", ICA Project No. 471, MTL 93-6(TR-R), 1993, 37 pages.

[15] M. Elboujdaini, V. S. Sastri and M. Sahoo "Corrosion Studies on Some Permanent Mold Cast Low Leaded Copper-Base Alloys in Aqueous Solutions", Trans. American Foundrymen's Society, Vol. 102, pp. 409-415, 1994.

[16] J. L. Dion, M. Sahoo D. Cousineau and C. Bibby, "Production of Faucet In Low-Lead Copper Base Alloys in Permanent Mold Casting", Trans. American Foundrymen's Society, Vol. 102, pp. 559-566, 1994.

[17] J. L. Dion, M. Sahoo D. Cousineau and C. Bibby, "Defect Analysis and Evaluation of a Copper Alloy Permanent Mold Casting", Trans. American Foundrymen's Society, Vol. 102, pp. 263-268, 1994.

[18] J. L. Dion, M. Sahoo M. Shehata and F. A. Fasoyinu, "A Feasibility Study of the Production of Free-Machining Brass Without Lead-Phase II", ICA Profect No. 471-93, MTL 94-4 (TR-R), 1994, 59 pages.

[19] M. Sahoo J. L. Dion, F. A. Fasoyinu, M. Shehata an ds. Kuyucak, "A Feasibility Study of the Production of Free-Machining Brass Without Lead", Proceedings of the International Symposium on " Globalization-Its Impact on the Indian copper Industry", Bombay, India, Dec. 13-15. 1994.

[20] J. L. Dion, F. A. Fasoyinu, D. Cousineau, C. Bibby and M. Sahoo "Gravity Permanent Mold Casting of Yellow Brass', Trans. American Foundrymen's Society, Vol. 103, pp. 409-415, 1995.

[21] J. L. Dion, F. A. Fasoyinu, D. Cousineau, C. Bibby and M. Sahoo "Permanent Mold Casting of High-conductivity Copper", Trans. American Foundrymen's Society, Vol. 104, pp. 405-414, 1996.

[22] F. A. Fasoyinu, J. L. Dion, D. Cousineau, C. Bibby and M. Sahoo "Gravity Permanent mold Casting of Graphite Dispersed Copper-Base Alloys", Trans. American Foundrymen's Society, Vol. 104, pp. 415-424, 1996.

[23] V. M. Scepanovic, R. Brigham and M. Sahoo "Corrosion Behaviour of Sand Cast Red Brass Containing Bismuth and Selenium", Trans. American Foundrymen's Society, Vol. 104, pp. 467-474, 1996.

[24] F. A. Fasoyinu, G. Morin, D. Cousineau, M. Sadayappan and M. Sahoo "Low Pressure Permanent Mold Casting of Copper-Base Alloys", Trans. American Foundrymen's Society, Vol. 105, pp. 333-342, 1997.

[25] M. Sadayappan, F. A. Fasoyinu, D. Cousineau, R. Zavadil, M. Sahoo and Dale T. Peters "Casting Characteristics and Mechanical Properties of Bi/Se Modified Yellow Brass (SeBiLOY III) in Permanent Molds", Trans. American Foundrymen's Society, Vol. 105, pp. 127-136, 1997.

[26] L. V. Whiting, P. D. Newcombe and D. Cousineau, "A Progress Report on Core Collapsibility for Permanent Mold Casign of Copper-Based Alloys", Trans. American Foundrymen's Society, Vol. 105, pp. 137-146, 1997.

[27] F. A. Fasoyinu, M. Sadayappan, R. Zavadil and M. Sahoo "Grain Refinement of Permanent Mold Cast Yellow Brass", Proc.Conf., 4th Decennial International Conference on "Solidification Processing-97", 7-10July, 1997, Sheffield. UK.

[28] M. Sahoo M. Sadayappan, F. A. Fasoyinu and D. Cousineau, "Structural modification to Enhance Mold Filling During Permanent Mold Casting of Copper Base alloys" Proc. Conf., 4th Decennial International Conference on "Solidification Processing-97", 7-10 July, 1997, Sheffield, UK.

[29] M. Sadayappan, F. A. Fasoyinu, D. Cousineau, R. Zavadil, M. Sahoo and Dale T. Peters "Grain Refinement Studies on Permanent mold Cast SeBiLOY III," Trans. American Foundrymen's Society, Vol. 106, pp. 305-311, 1998.

[30] F. A. Fasoyinu, M. Sadayappan, D. Cousineau, R. Zavadil and M. Sahoo, "Effect of Grain Refinement on the Hot Tear Resistance and Shrinkage Characteristics of Permanent Mold Cast Yellow Brass (C85800)," Trans. American Foundrymen's Society, Vol. 106, pp.327-337, 1998.

[31] F. A. Fasoyinu, M. Sadayappan, D. Cousineau and M. Sahoo, "Design Parameters for Lead-Free Copper-Base Engineering Alloys in Permanent Molds: A Progress Report on Mechanical Properties," Trans. American Foundrymen's Society, Vol. 106, pp. 721-734, 1998.

[32] M. Sadayappan, F. A. Fasoyinu, D. Cousineau and M. Sahoo, "Effect of Minor Alloy Additions on Fluidity of Permanent Mold Cast Cu-Base Alloys," Trans. American Foundrymen's Society, Vol. 106, pp. 735-742, 1998.

[33] F. A. Fasoyinu, M. k Sadayappan, D. Cousineau, G. Morin and M. Sahoo, "Prototyping of some Copper Alloy Plumbing Components by Gravity and Low Pressure Permanent Mold Casting Processes", Presented at 103rd AFS Casting Congress, St. Louis, 1999.

[34] M. Sadayappan, F. A. Fasoyinu, J. Thomson and M. Sahoo, "Grain Refinement of Permanent Mold Cast Silicon Brass, silicon Bronze and Red Brass," Presented at 103rd AFS casting Congress, St. Louis, 1999.