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DEVELOPMENT OF LOW COST BLOCK MOLD FOR COPPER ALLOY CASTING

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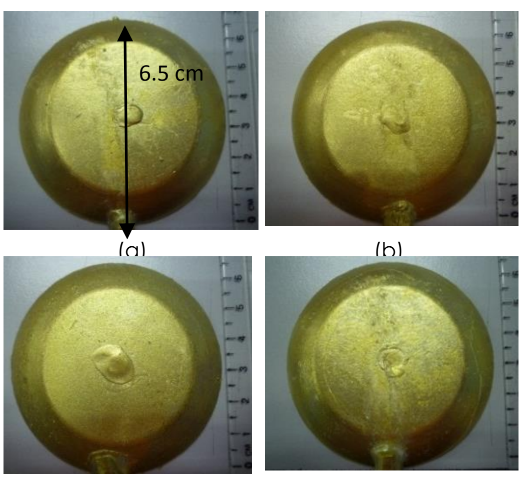
Graphical abstract



(a) (b) (c) (d)

Abstract

Suitable block mold formulations for copper alloy casting have been developed and the formulations used were 25% plaster of paris (POP), 75% silica sand and 31-37% water. Silica sand with a grain size of 106-212 μm was added into dilute suspension of POP and the mixing process was continued until a thick slurry (mixture) was obtained. It has been found that the mixing time of molding materials was highly depended on the type of plaster and optimum slurry viscosity around the diameter of 7.7 – 9.6 cm (slump test) was essential to ensure that the wax pattern could be fully invested. In the dewaxing process, the mold was subjected to the temperature of $170^{\circ}C$ for 3 hours and burnout process was effectively achieved by heating the molds at $750^{\circ}C$ for 5 hours. The pouring process was successfully carried out without any leakage and it was found that all molds can be easily broken under a force of a hammer. The developed mold also able to produce fully formed of casting without any major defects such as misrun, fin or flash and rat tail, which can be associated with inadequate mold temperature, mold cracks and the separation of mold's material respectively.

Keywords: Silica sand, block mold, wax pattern, copper alloy casting

1.0 INTRODUCTION

Investment casting method is regarded as precise fabrication processes for component having intricate shape, excellent surface finish and dimensional accuracy [1]. This method is currently selected for casting thin wall components from a very wide variety of alloys including super alloys, stainless steel, aluminum and copper based alloys. The processes which include ceramic shell molding and block mold process have been used for decades in jewelry, artworks and dental application. The block or solid investment casting process is still retained in some applications, as for dental and jewelry casting [2].

This method can also be used to produce implant alloy [3]. Commonly the block mold process uses gypsum bonded investments (GBI) consists of refractory material and a binder. The refractory material is silica and the binders include gypsum or phosphate and metallic oxides [4]. Currently, there is an interest in the use of block mold process to produce craft items, engineering parts and household products, but the high price of commercial GBI had caused the molding cost became expensive, hence the production cost. Therefore, it is anticipated that by introducing low cost block mold material, the cost of the molding can be significantly reduced without compromising the product quality.

Based on our previously reported work [5], two types of silica sand containing 97.9% silica (SiO_2) and 97.2% silica are highly potential to be developed as a mold material for copper alloy and aluminum alloy casting. According to Brown [6], as a foundry materials, the silica content should be more than 95%. Therefore, without restricting to certain types of silica, any silica with 95% silica content is likely to be used. Plaster of paris (POP) is usually selected as a binder due to its availability and its low price. When the dry plaster powder is mixed with water, it re-forms into gypsum crystals and these crystals create interlocking between gypsum crystals, hence, bond the refractory grain of the molding material [7].

Besides formulation, mixing time and slurry flowability are also the main factors that will determine the success of the molding process. Over-mixing will make the slurry thicken thus foil the process, meanwhile, insufficient mixing time will result in separation of molding materials. The wax patterns in the set molding material are usually removed using a dewaxing and preheating furnace. Slow initial heating is crucial to avoid the wax boiling inside the mold, hence erodes the inner surface of the mold.

Luk and Darvel [8] reported that the strength of the mold had been affected by various factors, e.g. binder, mixing and firing environment. According to Mohd Nor *et al*., [9] the compressive strength of the developed mold was between 600–1100 kN/m^2 which depended on the water content. The mold tended to form cracks during the firing process which could produce casting defects [10]. The temperature at which the calcium sulfate starts to decompose is debatable. O'Brien and Nielsen [11] found that the pure calcium sulfate would not decompose until 1200°C, while Jones [12] reported that the rapid decomposition occurred between 900°C and 1000°C. Meanwhile, Matsuya and Yamane [13] reported that the decomposition of GBI had begun at about 900°C. Experts of GBI agreed that the gypsum's decomposition does not start in the temperature of 650°C to 750°C, which are common maximum firing temperatures for GBI [14]. The GBI molds should not be heated above 750°C because the residual carbon from the wax patterns will then react with the gypsum from the molding material, thus results in sulfur dioxide, which decreases the surface quality of castings [13]. In the worst case scenario, the liquid metal does not remain within the cavity, but runs out of the mold through the cracks. In order to minimize the tendency for the block mold to crack, the molding material is generally optimized with respect to the water quantity, mixing duration and the addition of supplements [14]. Therefore, the quality of casting is determined by the molding materials' mixing and by the firing process. The casting surface quality is also depends on the gating system and molten metal. In this context, the composition and the purity of the melt is important [15].

Bonilla *et al*. [16] had studied the effect of wax pattern accuracy on the dimension of investment cast parts and they reported that computer aided modeling can be used to predict the wax pattern contraction. Idris and Sharif [17] had studied a rapid prototype of Acrylonitrile Butadiene Styrene (ABS) patterns that had been produced by Fused Deposition Modelling (FDM) machine. In conjunction with rapid prototyping and accurate patterns, the block mold casting process enables faster production of metal prototypes or small batches of castings. Using the ideal molding material, nearly all casting materials can be processed using this casting method, whereby the process time is much shorter compared to the more time-consuming shell mold process [18]. The objectives of this study are to develop low cost block mold for copper alloy casting and to determine the appropriate casting parameters in an effort to reduce the molding cost, thus, allowing it to be used in the casting process of copper alloy.

2.0 MATERIALS AND METHODS

2.1 Mold Formulations

Due to high silica content, Kuala Abang's (KA) silica sand and Jambu Bongkok's (JB) silica sand which have the average grain size of 220-250 µm was found suitable to be developed as the block mold material. Plaster of Paris (POP) was chosen as a binder and two types of POP from two different manufacturers were used. They are Eurochemo (EC) POP obtained from Euro Chemo Pharma Pvt. Ltd. and Cast-C POP which was purchased from the Concorde Chemical Corporation. Prior to the molding process, raw silica sand was sieved in advance to select the sand with the size of 106-212µm. Several mold formulations using 25% POP, 75% silica sand and 31-37% water had been developed and the samples of formulation and its abbreviation used is shown in Table 1. Then, several molds were made following the developed formulations and each of these formulations had been tested in the casting process of copper alloy.

2.2 Mixing Process and Mixing Time

Mixing is referred to the time taken to mix the mold materials that are silica sand, POP and water. In the study of mixing time, 200g of molding material was made following the ratio of materials in the Table 1. To facilitate the mixing process and to avoid lumpy mixture, POP was added into the water and waited for it to dihydrate before further mixing to obtain a homogenous mixture. After that, the silica sand was added and the mixing process was continued until a creamy and thick slurry (mixture) was obtained and optimum viscosity was achieved. The mixing time, which was closely related to slurry viscosity, was measured using a stopwatch and it began with the mixing process of POP and finished when the optimum viscosity was achieved.

Table 1 Samples formulations and its abbreviation used in this work

Sample	KA Silica (%)	JB Silica (%)	EC POP (%)	Cast-C POP (%)	Water (%)
KA1	75	0	25	0	31
KA2	75	0	25	0	33
KA3	75	0	25	0	35
KA4	75	0	25	0	37
KA5	75	0	0	25	31
KA6	75	0	0	25	33
KA7	75	0	0	25	35
KA8	75	0	0	25	37
JB1	0	75	25	0	31
JB2	0	75	25	0	33
JB3	0	75	25	0	35
JB4	0	75	25	0	37
JB5	0	75	0	25	31
JB6	0	75	0	25	33
JB7	0	75	0	25	35
JB8	0	75	0	25	37

Besides that, slurry flowability is also an important factor to be considered during the process of molding. To measure the flowability of slurry, a slump test was used. The slurry was poured into a cylinder, 5 cm tall and 3.5 cm diameter, standing on a glass plate. After the top was struck off level the cylinder was lifted off the glass and the slurry was dropped out and spread out equally in all directions. The diameter of the spread was measured and recorded. Figure 1 shows the molding process to make the block mold where the slurry with excellent flowability can be poured effortlessly into the metal flask.

2.3 Casting Processes

Prior to the molding process, the wax pattern which resembles a small plate with the diameter of 6.5 cm was prepared as desribed in our previous study [9]. In order to create the path for molten metal to fill the mold, gating system need to be prepared and it can be made in top and bottom configuration with one or two runners [19]. In this study the wax patterns were attached to the top gating system which consists of pouring cup, runner and ingate, known as a wax tree. The schematic diagrams of the gating system are shown in Figure 2.

Prior to the molding process, every material was weighed using an electronic balance following the formulation in the Table 1. In this study, 6 kg of block mold was made using a metal flask with a dimension of 16.5 cm diameter and 23.0 cm height. An Optimum slurry viscosity that is around the diameter of 6.2–9.6 cm (from slump test) was essential to ensure the wax pattern can be fully invested. The wax tree was placed on a wooden plate and encircled with a metal flask. Then the POP, silica sand and water were mixed until a creamy and thick slurry (mixture) was obtained. The slurry was quickly poured into the flask and permitted to solidify by chemical reaction forming a block mold. After six hours, the mold was placed in the furnace for dewaxing and preheating process. At the initial stage, it was heated at 170°C at a rate of 1.6C/min and was held at this temperature for 3 hours. Then, the temperature was increased to 750°C at a rate of 1.9C/min and held at this temperature for another 5 hours. At this stage, burn-out process was occurring to ensure all the wax in the mold can be completely eliminated. The preheating and dewaxing as well as the casting processes was following the processes as reported in our earlier study [9]. To remove the casting from the mold, it need to be broken, then the castings produced were inspected for the defects such as misrun, fin or flash and rat tail. The schematic diagram of the casting process is shown in the Figure 3.

(a) (b)

Figure 1 (a) slurry with optimum viscosity of 9.0 cm (slump test) easily filled the metal flask and (b) slurry harden forming a block mold

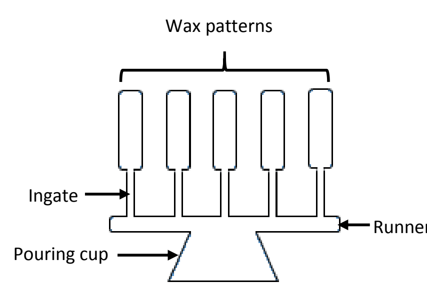


Figure 2 The schematic diagram of gating system

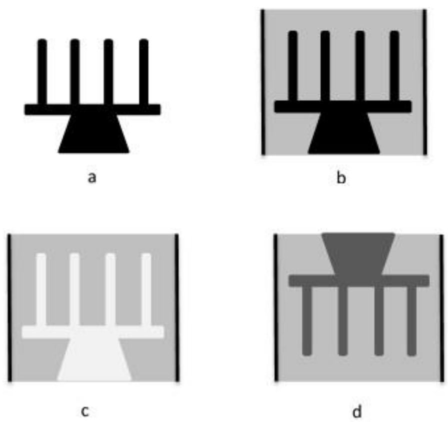


Figure 3 Casting processes where (a) assembling of wax patterns to gating system to make a wax tree, (b) slurry was poured into the flask to form a block mold (c) dewaxing and burn-out process to create mold cavities and (d) the pouring of molten metal

3.0 RESULTS AND DISCUSSION

3.1 Mixing times and Slurry Flowability

The results of mixing time and slurry flowability are shown in Table 2 and Table 3 and they depicted that the developed formulations required a certain mixing time before a thick mixture of slurry can be achieved. It was found that Cast-C formulations needed around 6-9 minutes to achieve an optimum viscosity compared to Eurochemo formulations which only took about 2-3 minutes. Based on the product specification of Eurochemo POP, it contains a small amount of accelerators which had accelerated the process of gypsum crystal formation, hence had resulted in a shorter mixing time and faster setting process. Contrary to Eurochemo POP, Cast-C POP is almost pure POP that did not contain any accelerators. The function of the accelerator and retarder in POP was described by Koslowski and Ludwig [20], where they had stated that the setting time of plaster can be regulated by accelerators or retarders. It was also found that, by exceeding the optimum mixing time, it had resulted in too thick mixture, thus had foiled the investment process of wax patterns. The developed formulations also had an excellent slurry flowability with slurry viscosity between 7.8–9.6 cm (slump test). Therefore, it was confirmed that the optimum water content of 31-37% was required to facilitate the mixing process and molding process.

Figure 4 shows the dewaxing and preheating temperature employed in this study. At the initial stage of de-waxing process, the molds was slowly heated from room temperature to the temperature of 170°C and was held at this temperature for 3 hours, indicated as point A to B in Figure 4. During these stage, the water which was existing as a moisture in the mold turned into steam at 100°C and it escaped through the pores of the mold.

Table 2 Mixing time and viscosity of KA formulations as a function of water content

Sample	Mixing time (Min)	Viscosity (Slump test, cm)
KA1	2.0	7.7
KA2	2.0	7.9
KA3	2.5	8.9
KA4	3.0	9.6
KA5	6.0	7.9
KA6	7.0	9.1
KA7	8.0	9.3
KA8	9.0	9.6

Table 3 Mixing time and viscosity of JB formulations as a function of water content

Sample	Mixing time (Min)	Viscosity (Slump test, cm)
JB1	2.0	7.9
JB2	2.0	8.3
JB3	2.5	8.6
JB4	3.0	9.5
JB5	6.0	7.7
JB6	7.0	8.2
JB7	8.0	8.8
JB8	9.0	9.4

3.2 Dewaxing and Preheating Temperature

The embedded wax patterns started to melt at the temperature of 75°C and from 75°C to 170°C, most of the wax melted and flowed out of mold through the runner and mold opening (pouring cup). The steam from the water helped to push wax off the walls of the cavities inside the mold. From point C to D, as the furnace temperature increased to 750°C, the wax residue turned to carbon at the temperature of 538°C. From 700–750°C, the carbon had combined with oxygen, forming carbon monoxide (CO) and carbon dioxide (CO_2) gases. These gases can escape through the runner and pouring cup as well as through the pores of the mold. Then, as depicted by point D to E. The mold was further heated at 750°C for 5 hours (burn out temperature) to eliminate any traces of carbon in the mold cavities. Complete burn out process was crucial to create clean mold cavities without the traces of carbon. Some stains could remain, but in general the pouring cup will turn from grey to chalky white [21]. The ramp of point E to H indicates the dropping of temperature to the desired mold pouring temperature which had been set at 500°C. In the case of the burnout process was not effectively achieved, traces of grey coating carbonized wax could be clearly seen on the mold surface.

3.3 Mold Temperature

Figure 5 (a)–(d) shows the fabricated molds by dint of various formulations developed (KA1, KA2, KA3 and KA4) after dewaxing and preheating process at 500ᵒC. From the Figure 5, it can be observed that the molds with the formulations of 31-35% water did not show any severe crack, but a very fine crack can be seen on the outer surface. When they were removed from the furnace, they had experienced rapid temperature changes and this had created thermal stress due to different temperature gradient. The temperature difference caused the cooler portion of mold to contract more than the warmer portion, which had restrained the contraction, hence induced cracks. Larger cracks were observed on the mold surface of 37% water content, but it was found that these cracks were only occurred on the external surface of the mold and it did not cause molten metal leakage during pouring process.

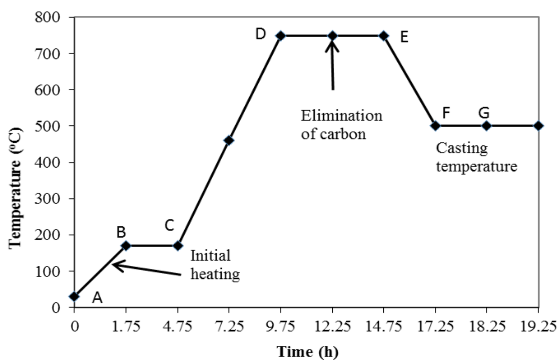


Figure 4 Dewaxing and preheating temperature setting in the dewaxing furnace

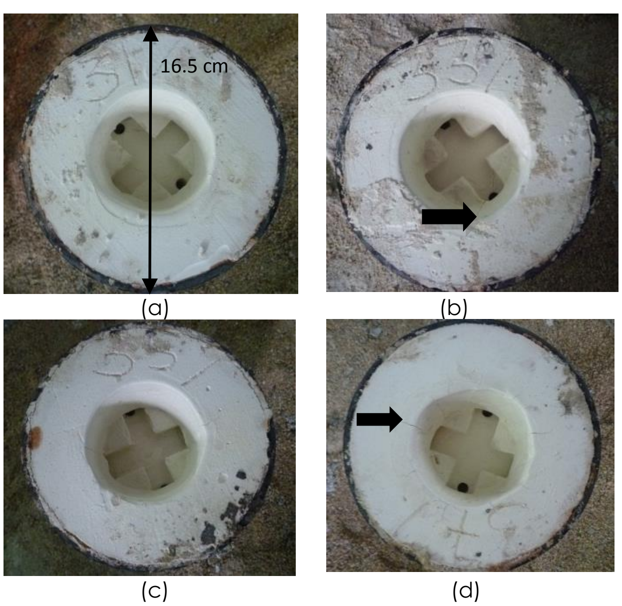


Figure 5 Molds formulated with 75% KA silica and 25% Eurochemo POP with (a) 31% water (b) 33% water (c) 37% water and (d) 37% water after dewaxing and preheating process at 500ᵒC. Arrow shows a fine crack

A similar observation was also attained for JB formulations. Figure 6(a) shows the pouring process of brass molten metal and Figure 6(b) show the mold formulated with 33% water (KA2) after the pouring process of brass molten metal. After the molten metal was poured and allowed to cool down and solidified, the castings must be removed from the mold (shakeout) for further processing. It was observed that all the molds' formulations were shattered easily under knocking force of a hammer.

(a) (b)

Figure 6 Pouring process of copper alloy and the mold of 75% KA silica, 25% Eurochemo POP with 33% water (formulation of KA2) after the pouring process

3.4 Quality of Casting

The defect of misrun defect is the imperfection where a portion of the casting is missing and it can be associated with inadequate mold temperature. Figure 7(a)–(d) depicts the copper alloy castings produced using the KA molds (KA1, KA2, KA3 and KA4). As clearly shown, all the castings were fully formed without misrun defect and there was no sign of other major defect such as fin or flash which related to severe mold cracks. This revealed that the cavities in the mold were fully developed during the dewaxing process. The clean and bright surface of casting also indicated that the burnout process was effectively achieved. Fully formed of casting also showed the suitable mold temperature had been employed and the right pouring temperature was used, thus confirmed that the temperature of 500ᵒC was an appropriate mold pouring temperature. There was also no sign of rat tail defect, thus validated that the appropriate mixing time had been used. The same result was obtained for JB formulations where all castings displayed no sign of major defect.

3.5 Cost of Molding

The average market price of the commercial GBI in Malaysia is about Malaysian Ringgit (MYR) 4.20/kg, which required MYR 25.20 to make 6 kg of block mold. Table 4 shows the cost of the materials to make 6 kg of low cost block mold for a different mold formulation. It was found that the cost of molding was only between MYR 3.20 to 3.50 depended on the type of POP used. The application of low cost block mold has reduced the cost of molding between 86-87%. Therefore, with a significant reduction in cost, it is expected that this development can contribute in driving the growth of small and medium-sized copper-based casting industry.

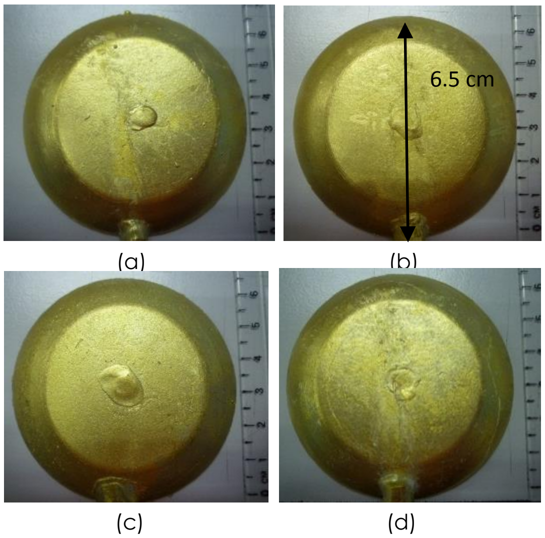


Figure 7 As-cast surface of casting produced by KA molds (a) KA1, (b) KA2, (c) KA3 and (d) KA4

Table 4 Cost of materials for 6 kg of mold

Sample	Materials cost (MYR)				Total cost (MYR)
	KA silica	JB Silica	EC POP	Cast-C POP	
KA1-KA4	0.50	0	2.70	0	3.20
KA5-KA8	0.50	0	0	3.00	3.50
JB1-JB4	0	0.50	2.70	0	3.20
JB5-JB8	0	0.50	0	3.00	3.50

4.0 CONCLUSIONS

The developed molds were proven suitable to be used in copper alloy casting where in the molding process, optimum slurry viscosity, around the diameter of 6.2-9.6 cm (slump test) was essential. By using an appropriate dewaxing and preheating process, as well as sufficient mold and pouring temperature, good quality of copper alloy casting can be manufactured. Smooth surface of casting also confirmed that the cavities were fully formed during mold dewaxing and preheating process. The application of low cost block mold can significantly reduce the cost of molding by 86-87% and this can contribute in driving the growth of small and medium-sized copper-based casting industry.

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