International Journal of Engineering

Journal Homepage: www.ije.ir

Influence of Mould Thickness on Microstructure, Hardness and Wear of Al-Cu Cast Alloys

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PAPER INFO

Paper history:
Received 19 April 2021
Received in revised form 09 July 2021
Accepted 13 July 2021

Keywords:
Aluminium-Copper Alloys
Cooling Rate
Grain Size
Tribology

ABSTRACT

Aluminium-copper alloys have a wide range of industrial applications especially in military vehicles, rocket fins and aerospace. Solidification plays a vital role in controlling the mechanical and tribological properties, and influencing the microstructure of metallic alloys in general and aluminium alloys in particular. Therefore, the researchers have made many efforts to figure out the solidification behaviour of Al-Cu alloys. Despite all these endeavors, however, the behavior is not yet fully understood. This research aims to investigate the effect of cooling rate on the microstructure, mechanical and tribological properties of aluminium-copper cast alloys (Al-Cu alloys) under dry sliding conditions. Four cooling rates were achieved by using four various steel moulds made of different thicknesses and one of them was surrounded with green sand, to get a lower cooling rate, with the same respective mould hole geometries. The microstructure results showed that the grain size increases with decreasing the cooling rate. While the hardness increased largely due to the refinement of the microstructure. Finally, it was concluded that the wear rate increases with decreasing the cooling rate, and that is due to the reduction in hardness.

doi: *10.5829/ije.2021.34.08b.23*

NOMENCLATURE

V	Linear sliding speed (m/min)	t	Running time (min)
r	Distance between the center of sample to the centre of the disc (m)	W_r	Wear rate
n	Disc rotational speed (RPM)	**Greek Symbols**	
S	Total Sliding distance (cm)	ρ	Density (g/cm^3)

1. INTRODUCTION

Aluminium and copper alloys are characterized by high strength, lightweight, resistance to high temperature, and high ductility which made them very important alloys in many industries such as military and aircraft industries as well as in transport applications and lightweight construction. Where high strength and ductility are highly needed in such kinds of applications [1]. Therefore, the mechanism of precipitation hardening in wrought and cast binary Al-Cu alloys is well understood and extensively recorded in the literature. Copper element is considered as a great deposition-strengthening in aluminium. Adding copper improves machinability, toughness, tensile strength, and creep [2, 3]. Where, additions of about 0.05 *wt.%*. of copper to aluminium results in good toughness and high strength alloys after subjected to different aging including at elevated temperature (artificial aging) or at room temperature (natural aging) [4, 5]. Aryshenskii et al. [6] studied the recrystallisation process in aluminium alloys.

It is well known that the microstructure of the material has a significant effect on the mechanical properties, where decreasing the grain size leads to

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Please cite this article as: N. F. Soliman, D. O. Ramadan, J. A. Yagoob, Influence of Mould Thickness on Microstructure, Hardness and Wear of Al-Cu Cast Alloys, International Journal of Engineering, Transactions B: Applications, Vol. 34, No. 08, (2021) 2021-2027

improve mechanical properties, such as ductility and hardness [7] and resistance to corrosion [8]. In addition, decreasing in the size of the grains results in reducing the interface between the matrix and the phases and gives rise to a uniform distribution of solute components as well [9, 10]. The distribution of solute elements, supersaturated solid solution degree, morphologies of the secondary phases and the grain size are all affected by the rate of cooling [11]. The influence of cooling rate on the microstructure and properties of various alloys has been investigated previously using different experimental techniques for the design of high-efficiency materials [12]. Padmanabhan and Prabhub [13], studied the effect of cryogenic treatment on the mechanical and microstructure of different grades of aluminium. They found that the hardness increased with cryogenic coolant. Moulds of iron with different thicknesses, (5-50 *mm*), were made to get various cooling rates namely (2.3, 3.4, 9.8, and 24.1 *Kelvin per second*) [2]. The solidification rate has the greatest impact on the strength and the internal quality of the materials. Furthermore, it has an inverse relationship with the microstructure where increasing the solidification rate produces a refined microstructure [14,15]. Enhancing the mechanical properties of aluminium alloys that are susceptible to heat treatment is another advantage of refining the microstructure since the particles are smaller and need less time to dissolve during the heat-treating process [2, 5, 16]. Therefore, the aim of this study is to investigate the influence of cooling rate on the mechanical, microstructure, and the tribological properties of aluminium-copper cast alloys (Al-Cu alloys) under dry sliding conditions.

2. EXPERIMENTAL WORK

In this study, aluminium with a weight ratio of 95.5% was cast with copper with a weight ratio of 4.5 %. The purity of both materials was 99.9%. A digital scale was used for determining the weight of the materilas. Tables 1 and 2 summarized the chemical compositions of pure aluminium and pure copper, respectively.

Aluminium without additives was put in a preheated crucible by using an electrical furnace of maximum temperature 1200^oC. The aluminium was heated to 750^oC and kept at this temperature for half an hour to ensure the homogeneity. Then, the copper was poured on the molting aluminium with fast continuous stirring by using a graphite rod, then poured into the four different permanent steel moulds with three different thickness range as shown in Figure 1.

The temperatures of inside the moulds were recorded using a thermocouple (K- type) with a range of (20-1400^oC). The four cast specimens have the same dimensions which is 10 *mm* in diameter and length of 110 *mm*. The samples were prepared according to the required test including hardness, wear and micrsotructure. The following sections describe in detail how the samples prepared for each of the tests. Figure 2 shows the pouring process of the Al-Cu alloy inside the four different moulds.

2. 1. Hardness Test

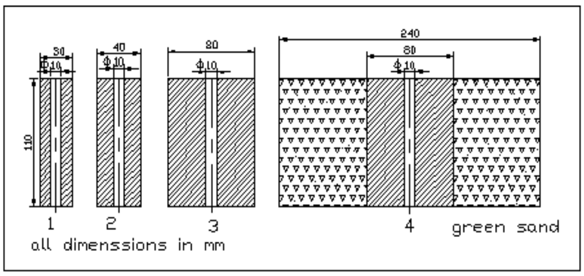
The preparation procedure included cutting each specimen into three parts using a handsaw, each with dimension (10 *mm* diameter and 10 *mm* length), for hardness and microstructure test. The

TABLE 1. Chemical composition of pure aluminum [17]

Elements	Fe	Si	Mn	Cu	Mg	Zn	Ti	Zn	Na	Al
Weight %	0.09	0.05	0.001	0.005	0.004	0.008	0.004	0.008	0.005	balance

TABLE 2. Chemical composition of pure copper [18]

Elements	Sn	P	Mg	Zn	Pb	Se	Cu
Weight %	0.001	0.02	0.002	0.002	0.001	0.001	balance



(a) A schematic of the moulds


(b) The first three moulds

(c) The fourth mould which surrounded with green sand

Figure 1. A schematic and photographs of the utilized different moulds

Figure 2. Pouring the alloy inside the moulds

hardness tests were carried out according to ASTM E10-18 standard. The cast alloys were tested using a Brinell hardness tester.

2. 2. Microstructure Test The microstructural features of Al - Cu cast alloys were investigated using an optical microscope. To reduce the influence of the externalities on the specimens, the microstructure samples were taken between the mould wall and the centre of the mould. The microstructure samples were applied to a mechanical grind using wet emery papers with different grades of grit including 600, 800, and 1200 grits. For further surface finishing the grinded specimens were polished with a light cloth. To reveal the boundary conditions, the samples were etched, using a solution which prepared according to the ASTM E407 standard with (3 *ml* of Hydrochloric acid (HCl) + 5 *ml* of Nitric acid (HNO_3) + 2 *ml* of Hydrofluoric acid (HF) + 190 *ml* of distilled water] for 10 seconds [19].

2. 3. Wear Test In this study, a pin-on-disc tribometer was used to evaluate the wear behavior of Al – Cu alloys at dry conditions. The casting specimens were prepared, for wear test, according to the ASTM G99-05 standard. The specimens' weight were measured before conducting the wear test using a digital scale having the least count of 0.1 *mg*. The wear tests were conducted at dry conditions under the dead weights of 10 *N* and a constant time of 5 *min*, and linear velocity of 626.74 *m/min* on the counter-face. The wear losses were calculated by measuring the difference between the weight of the specimens before and after the wear tests. An emery paper with a grit size of 1200 was used before the test to polish the contact surfaces of the test specimens.

The linear sliding speed (V) was calculated using Equation (1):

$$V = 2\pi rn \quad (1)$$

where *r* is the distance between the centre of the sample to centre of the disc which is equal to 0.07 *m*, and *n* is the rotational speed which is equal to 1425 *RPM*.

Equation (2) shows how the total sliding distance is calculated.

$$S = V \times t \quad (2)$$

where S is the total sliding distance in *cm*, and *t* is running time in minute. The wear rate was calculated using Equation (3).

$$W_r = \Delta W / \rho \times S \times 1000 \quad (3)$$

where ρ is the aluminium density ($\rho_{Al} = 2.7\ g/cm^3$), ΔW is difference in weight of the sample before and after testing (See Equation (4)).

$$\Delta W = W_\circ - W_1 \quad (4)$$

3. RESULTS AND DISCUSSION

3. 1. Cooling Rates for Mould Castings Figure shows the relation between the temperature and time for the various moulds utilized in this study. The rapid drop in the temperature of the castings from (750-400)°*C* with an approximate duration of (60 *seconds*) is due to the very low temperature of the moulds inner wall surfaces, which were equal to room temperature. Hence the heat transfer from the poured Al-Cu castings toward the wall of the moulds will be with the rapid manner and because the moulds were made of steel, therefore, the heat transfer from the wall of the mould outward to the surrounding environment will also become rapidly, by continuity of the heat transfer process the moulds wall temperature will increases while the temperature of the castings will decreases, accordingly the differences between the two temperatures will be lower. From this point of view, the cooling rate will become slower with time. This action will affect the relation between temperature drop and required time. Thereafter in order to reach the moulds wall temperature to room or near room temperature, this

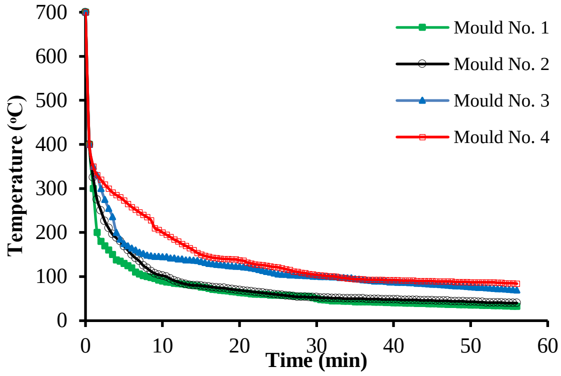


Figure 3. The relation between casting temperature and time for different wall thicknesses

will actually take place after prolonged time as explained at the lower portion of the cooling curves shown in Figure 2; particularly when the temperatures of moulds wall become less than 400°*C*. A digital camera and a thermocouple (K-type) were used to record the data of temperature changes during the solidification of the castings. It was then noticed that after (400°*C*), the temperature drop became gradually and data of the temperature detection and record can be performed by naked eye until it reaches room temperature. and the cause of rapid drop in temperature degree is due to using a mould casting material carbon steel in the experiment, and this what was proved by the researcher [20].

Figure 4 presents the cooling rates for Al-Cu castings poured in different used moulds at different temperature ranges including (640 to 200)°C, (640 to 150)°C, (640 to 100)°C and (640 to 50)°C. It is clearly shown that the cooling rates of the thinnest steel mould were greater at all temperature ranges listed above. While the cooling rates of the composite mould were the lowest at all temperature ranges listed above as shown in Figure 3. The cooling rates of the other steel moulds were decreased continually with an increase in the moulds wall thickness. It is important to note that the trend of the cooling rate decrease occurred with the highest manner

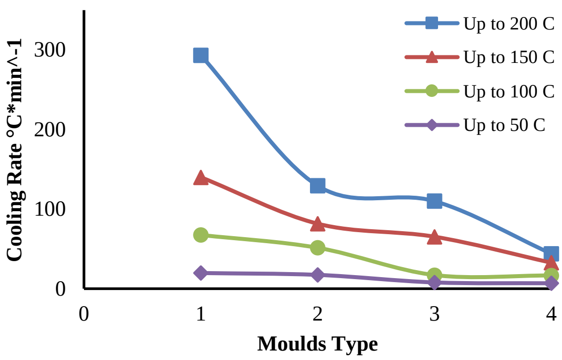


Figure 4. The relation between cooling rate and moulds type

for all used moulds at the temperature range (640 to 200)°C when compared with the three other temperature ranges. This result indicates that two cooling rate temperature ranges (640 to 200)°C and (640 to 150)°C have the most important effect on the microstructure, hardness, and wear resistance of the Al –Cu alloy because of their minimum temperatures (200 and 150) °C are near to the recrystallization temperature of the alloy which is approximately 122°C.

3. 2. Metallographic Examinations The nucleation rate and the growth rate are the two most significant parameters that affect grain size. The rate of nucleation relies on the melting undercooling below the liquids and on the amount of energy required for the creation of a new phase structure. In this study, four moulds, made of steel with different wall thicknesses, were used to get different cooling rates. The results reveal that the cooling rate increases with decreasing the wall thicknesses of the steel moulds, as shown in **Error! Reference source not found.**. This phenomenon is due to refining the grain size α- phase of (Al) and dark grains of (Cu Al_2) [10], and also can observe the grain size increase with decreasing the cooling rate as shown in Figure -8. This finding was also reported by the other researcher [19].

3. 3. Hardnees Results Figure 9 shows the variation of hardness with the steel mould types. The results showed that the hardness decreased as cooling rates decreased. It is likely that this is attributed to the grains size which is significantly affected by the cooling rate, where the size of the grains increases, thus decreasing the hardness, with decreasing the cooling rate. These results are in agreement with data reported in

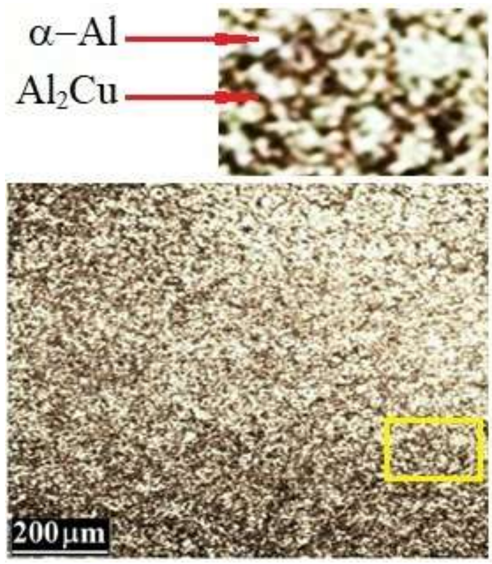


Figure 5. Microstructure of aluminium-copper alloys casted in steel moulds with wall thicknesses (10 *mm*)

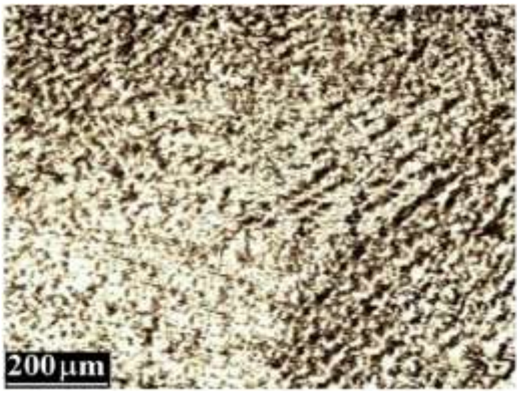


Figure 1: Microstructure of aluminium-copper alloys cast in steel mould with wall thicknesses (15mm)

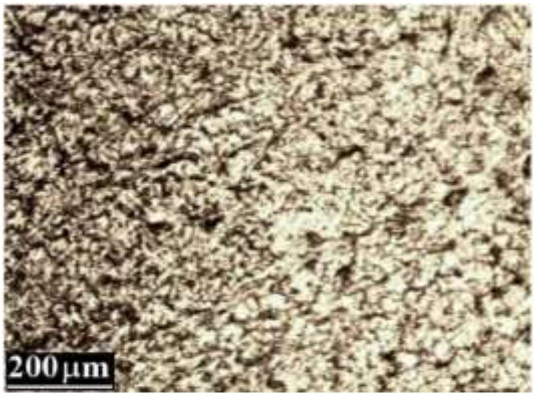


Figure 7. Microstructure of aluminium-copper alloys cast in steel mould with wall thicknesses (35mm)

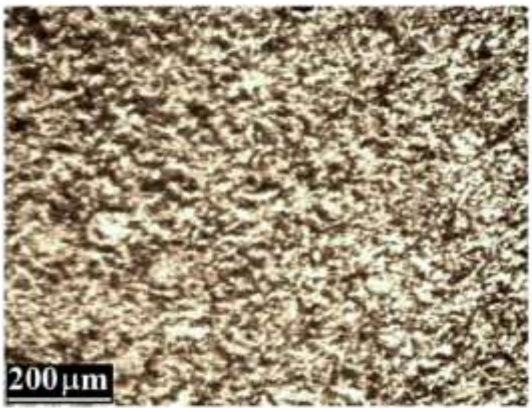


Figure 8. Microstructure of aluminium-copper alloys casted in steel mould with wall thicknesses (35mm). surrounded with green sand grains

literature [8, 10, 12]. The amount of heat dissipated from the first mould (Mould No. 1) is more than that dissipated from the other moulds (i.e. Moulds No. 2, 3 and 4). The grains size in the moulds which are relatively fast heat dissipated are more smaller than the other moulds and this caused increasing in hardness as shown in Figure 9. The results also reveal that the hardness of the first mould, which is the thinner, is about (83 Brinell hardness (*BHN*)) and that it relatively decreases with cooling rate. While the hardness in the thicker mould (Mould No. 4), which was surrounded with green sand grains, is about (73 *BHN*), and this what was proved by the other researcher [8], all these hardness numbers are in the range as reported in the literature [21].

3. 4. Wear Results The wear results reveal that the cooling rates are reversible in proportion with the wear rates, where the wear rate of the specimen number (1) (see Figure 10) was minimum (about $2.36*10^{-8}$ cm^3*cm^{-1}) while the wear rate of the specimen number (2) which cast in the medium mould increased (about $3.5*10^{-8}$ cm^3*cm^{-1}) and specimens (3 and 4) have the maximum

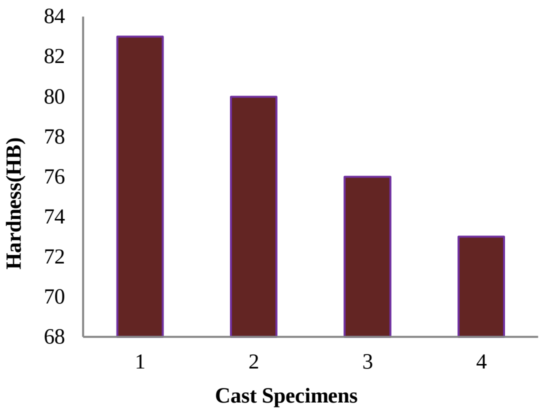


Figure 9. Brinell hardness (BHN) of the different specimens in different steel moulds.(1: Wall thickness=10 mm, 2: Wall thickness=15 mm, 3: Wall thickness=35 mm and 4: Wall thickness=35 mm surrounded with green sand grains)

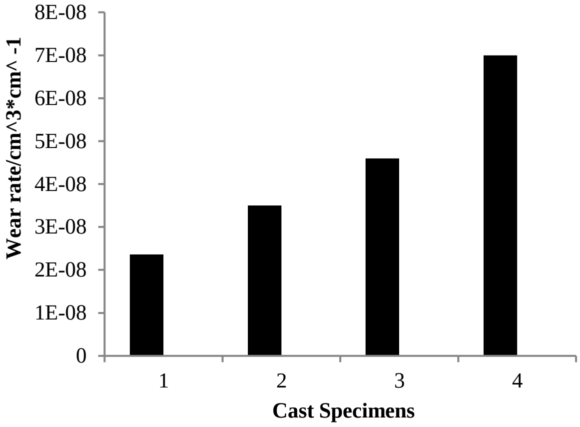


Figure 10. The relation between Wear rate with the cast specimens in different moulds (1: Wall thickness=10 mm, 2: Wall thickness=15 mm, 3: Wall thickness=35 mm and 4: Wall thickness=35 mm surrounded with green sand grains)

wear rate (about $4.6*10^{-8}$ cm^3*cm^{-1}) and ($7*10^{-8}$ cm^3*cm^{-1}), respectively. These results are due to the using low cooling rates, and the weight loss is due to mechanical wear at linear speeds of 626.74 *m/min*. The wear resistance increase for specimen cast in thin thickness wall mould (10 *mm*) this is the expected trend as it is supposed to increase wear resistance of specimen cast in steel mould with increasing of hardness, as shown in Figure 9. The wear resistance of cast alloys decreased gradually with increasing the wall thickness of the steel mould (2 and 3), especially steel mould which surrounded with sand grains (4) which means decreasing of the cooling rate due to increasing the wear, and these results are in agreement with the other researchers findings [21, 22].

4. CONCLUSION

The aim of the present research was to examine the effect of cooling rates on the tribological behaviour of Al-Cu alloys, namely the wear resistance. In addition, its effect on the hardness and microstructure have been examined as well. Four moulds of steel with the same length and diameter but varying thicknesses were made to attain four different cooling rates. The following conclusions can be drawn from the present study:

1. The cooling rate of the mould, particularly the composite mould, reduced as the wall thickness of the mould increased.
2. The grain size increased with decreasing the cooling rate.
3. The wear rate increased with an increase in the wall thickness of the mould, while the hardness decreased.

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Persian Abstract

چکیده

آلیاژهای آلومینیوم – مس کاربرد وسیع در صنعت به ویژه در وسایل نقلیه نظامی، باله موشکی و هوافضا دارند. انجماد نقش مهمی در کنترل، خواص مکانیکی و تریبولوژیکی و تأثیر بر ریزساختار آلیاژهای فلزی (به طور کلی) و آلیاژهای آلومینیوم (به طور خاص) دارد. از این رو، تحقیقات بسیاری جهت کشف رفتار انجماد آلیاژهای Al-Cu صورت گرفته است. با وجود همه این تلاش ها، این رفتار همچنان درک نشده است. هدف از این مقاله، بررسی تأثیر میزان خنک سازی بر ریزساختار، خواص مکانیکی و تریبولوژیکی آلیاژهای آلومینیوم مس) آلیاژهای (Al-Cu در شرایط خشک متغیر است. چهار میزان خنک سازی با استفاده از چهار قالب فولادی مختلف با ضخامت¬های متفاوت به دست آمد و یکی از آنها با ماسه سبز احاطه شده بود تا سرعت خنک سازی پایین¬تری با سوراخ یکسان داشته باشد. نتایج ریزساختار نشان داد که با کاهش سرعت خنک سازی، اندازه ذره افزایش می یابد؛ در حالی که سختی بیشتر به دلیل تصفیه ریزساختار زیاد میشود. در آخر نتیجه گیری شد که با کاهش سرعت خنک کننده، میزان سایش افزایش یافته که علت آن، کاهش سختی است.