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Effect of Cooling Rate and Pouring Temperature on the Hardness and Wear Resistance of Bronze SAE660

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Abstract

Metallic bearing alloys have different types, most of which are tin (Babbitt) or bronze based. Bronze bearings are used at heavy duty conditions. The goal of this research is an investigation on the effect of cooling rate and pouring temperature (two important factors in casting production) on the Brinell hardness and pin-on-disc wear resistance (two important properties in bearing applications) of bronze SAE660. The melt had prepared by induction furnace. Then, it had poured in sand mold in four different casting conditions, including pouring temperatures of 950 °C and 1200 °C, and cooling with water and air. Finally, the microstructure, hardness and wear resistance of the SAE660 had investigated. The results indicated that if the maximum hardness, along with the minimum weight loss due to wear (or maximum wear resistance) is required; the contents of intermetallic compounds, lead phase and the solid solution phase should be more. In this way, the samples which are cooled in air and poured at 950 °C have the high hardness and the lowest weight loss.

Keywords: Microstructure, Bearing, Pouring, Casting

1. Introduction

Casting is the most common method for producing bearings, which, by melting and pouring into molds, are converted into pieces of the desired shape, size, and type [1].

Bearing alloys have different types, most of which are tin-based (Babbitt) or bronze-based. Bronze bearings are used when the operating conditions of the bearings are difficult (heavy duty operation). According to Table 1, the chemical composition used in this study is bronze containing 13.6% lead, 6.5% tin, and 2.7% zinc, which is approximately equivalent to bronze SAE660, which is widely used to make bronze bearings [2].

Factors affecting the properties of the casting products (such as the content of elements, mold material, mold cooling rate, pouring temperature, pouring rate, etc.) are very diverse, affecting the microstructure and, finally, the properties of the pieces [3]. In this study, two important factors i.e. the effect of pouring temperature and cooling rate on the Brinell hardness and pin-on-disc wear resistance of bronze SAE660 are studied.

There is a lot of casting processes, in each of them, the rate of cooling; the method of melting, the shape of the mold, and the method of molding and so on is different [4]. For example, in gravity die casting or gravity casting in metal molds, permanent and semi-permanent molds are used which, due to the higher cooling rate and fine surface, have higher mechanical properties and higher dimensional accuracy, respectively [5].

One of the methods of producing bronze bearing is soldering. In this method, the melt is cast into steel pre-mold [6]. In other words, casting/melting takes place in metal molds.

Another approach is to use the centrifugal casting process. In this method, casting is done by pouring into the centrifugal steel mold [7]. In this research, casting is done in the sandy mold, because the goal is to study the pouring temperature and cooling rate on the hardness and wear resistance of the bearing metal.
The bearing facilitates the relative rotational or linear motion of the two pieces. On the other hand, the bearing reduces the friction of the involved surfaces. Therefore, two important tasks of bearing in the set of moving parts are [8]:

- to prevent excessive looseness of the axis by restricting radial/axial movement.
- to prevent moving parts contact by restricting lateral movement.

In this way, bearing plays a role as a wearing piece in the set of moving parts of the device. On the other hand, a variety of axial and radial forces are tolerated by the bearing [8]. Therefore, for a good bearing performance, two important characteristics, including hardness and wear resistance, are needed. For this reason, in this study, the Brinell hardness and pin-on-disc wear resistance properties of bronze SAE660 are studied.
So far, a little research has been done on the effect of the pouring temperature (or casting temperature) and cooling rate on the wear resistance and hardness of the SAE660 bearing in the sand mold. In this study, some of these shortcomings are resolved.

2. Materials and Experimental process

In this research, transistor induction furnace in Payvaran Company, including operator panel, electronics and control circuit, oscillator and LC circuit (including tank capacitor, coil, and trans-CT), are used for melting, as shown in Fig. 1a. The frequency (P) of 90Hz and 110Hz are used for a low and high pouring temperature, respectively. As shown in Fig. 1b, the mold is sandy with a steel holder and its shape is cylindrical to a height of 20cm and diameter of 11cm, for a charge of 65 kg. As shown in Fig. 1c, the pouring is carried out at two temperatures, one at a high pouring temperature of 1200C, and the other at a low pouring temperature of 950C and the cooling is done by air and water. Figure 2 shows the stages of research.
Chemical composition, the mold cooling method, and the pouring temperature are according to Table 1.
To ensure the accuracy of the results, the tests have conducted in labs approved by the Iranian Bureau of Standards or at prestigious Universities and to ensure the accuracy of the results, the tests have repeated at least twice. The wear test has carried out with a 3 mm diameter pin of AISI52100 tool steel with hardness of more than 2060 Vickers [9] at a speed of 0.26 m/s (or a rotational speed of 500 rpm) and a force of 10N and a distance of 440m at Tarbiat Modares University according to ASTM G99 [10]. In addition, Brinell hardness test has performed with a 2.5mm diameter ball at 62.5kg force in 10 to 15 seconds, and microstructure study has carried out using a TESCAN VEGA scanning electron microscope at the Razi Metallurgical Research Center (RMRC). The volume percentage of phases has obtained by calculating the occupied area ratio by each phase to the entire field surface by means of three images of an electron microscope at a scale of 200µm (at a magnification of 150).

a) b) c)
Fig. 1. Equipment used in the research, which are available in Payvaran Parsian Company, a) Induction Furnace, b) Sand Mold, c) Pouring

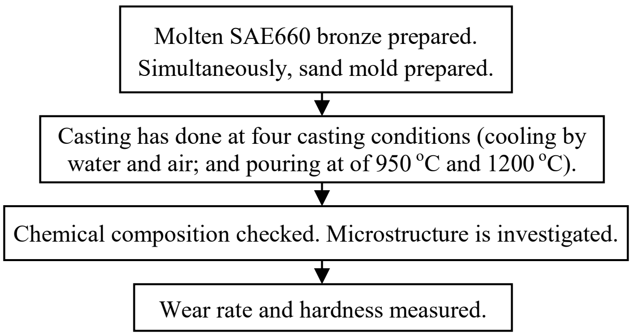


Fig. 2. The stages of the research

Table 1.
Chemical composition and pouring temperature of bronze bearing

Sample	Pouring temperature (°C)	Cooling	Element	Cu	Zn	Sn	Pb	P	S	Ni	Fe
1	1200	water	Wt%	balance	2.7	6.5	13.6	0.13	0.02	0.18	0.23
2	950										
3	1200	air									
4	950										

3. Results and discussion

The different production conditions, including the pouring temperatures and cooling environment of mold, with the results of the tests including weight loss, hardness, grain size, and phase value and size range for each of the four samples are given in Table 2.

Table 2.
Casting conditions, phase content and size range, hardness and weight loss for SAE660 bronze

Sample	Cooling	Pouring temperature °C	Weight loss (mg)	Hardness (HB)	Grain size (µm)	Phase content by vol.% ±%10			Phase size range (µm)		
						Solid solution	Pb	Intermetallic compound	Solid solution	Pb	Intermetallic compound
1	water	1200	6.1	63±3%	180±10%	1	3	0.5	Up to 60	Up to 100	Up to 20
2		950	6.5	75±3%	180±10%	0.9	3	0.3	Up to 80	Up to 140	Up to 60
3	air	1200	3.9	68±3%	200±10%	1.8	4	0.2	Up to 100	Up to 100	Up to 20
4		950	3.6	72±3%	200±10%	1.8	5	0.5	Up to 120	Up to 160	Up to 20

3.1. Microstructure evaluation

The microstructure of sample 1, that is, a pouring sample at 1200 °C,which immediately, by the steel holder of the sandy mold is cooled with water, and the microstructure of sample 2, that is, a pouring sample at 950 °C,which immediately, by the steel holder of the sandy mold is cooled with water, and the microstructure of sample 3, that is, a pouring sample at 1200 °C, which is cooled by air, and the microstructure of sample 4, that is, a pouring sample at 950C, which is cooled by air, are shown in Fig. 3, 4, 5, and 6, respectively. By the three similar images of the same electron microscope in each of Figures 3 to 6, the mean of the phase values and the phase size range are determined and listed in Table 2.
Comparing Figures 3 and 4 with Figures 5 and 6, it is qualitatively observed that in samples 1 and 2 (which are cooled with water), particles are more dispersed and smaller than that of samples 3 and 4 (which are cooled by air).

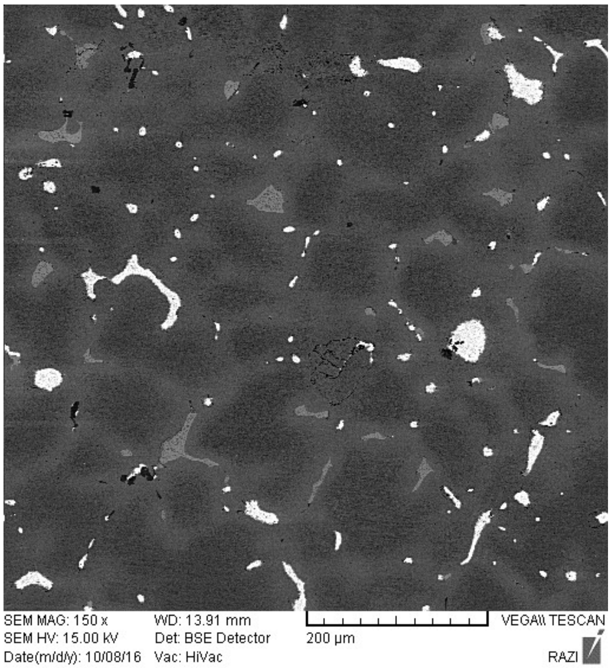


Fig. 3. Microstructure of sample 1, SAE660 bronze, pouring at 1200 °C and cooling the mold with water

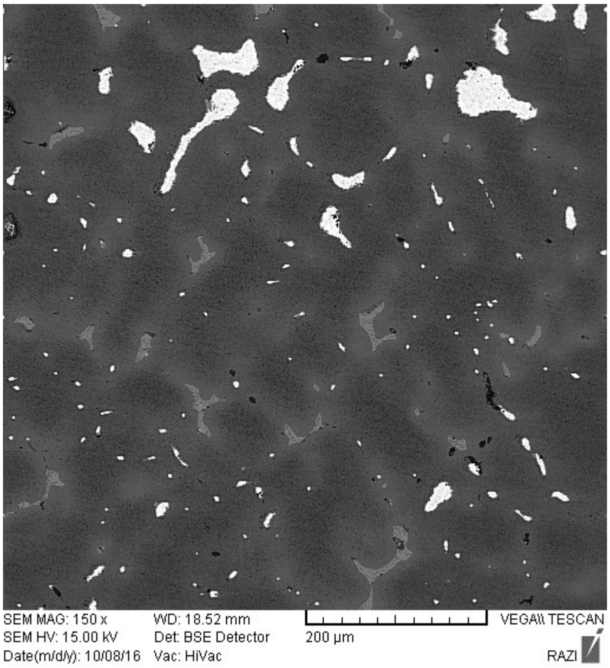


Fig. 4. Microstructure of sample 2, SAE660 bronze, pouring at 950 °C and cooling the mold with water

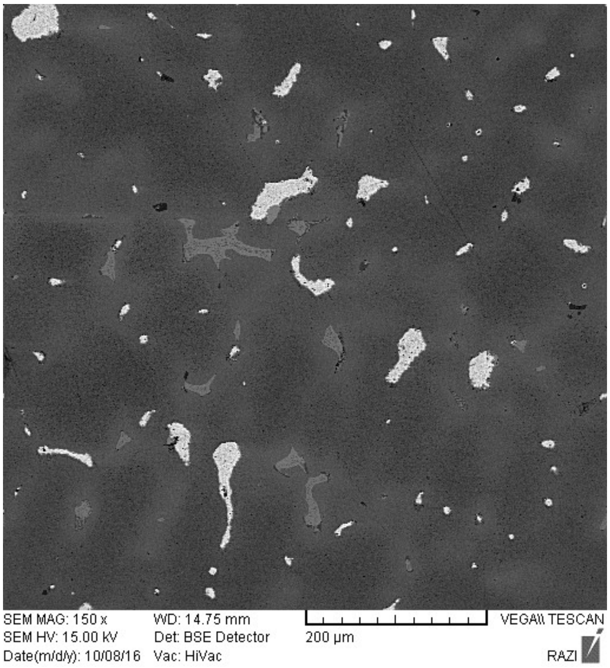


Fig. 5. Microstructure of sample 3, SAE660 bronze, pouring at 1200 °C and cooling the mold by air

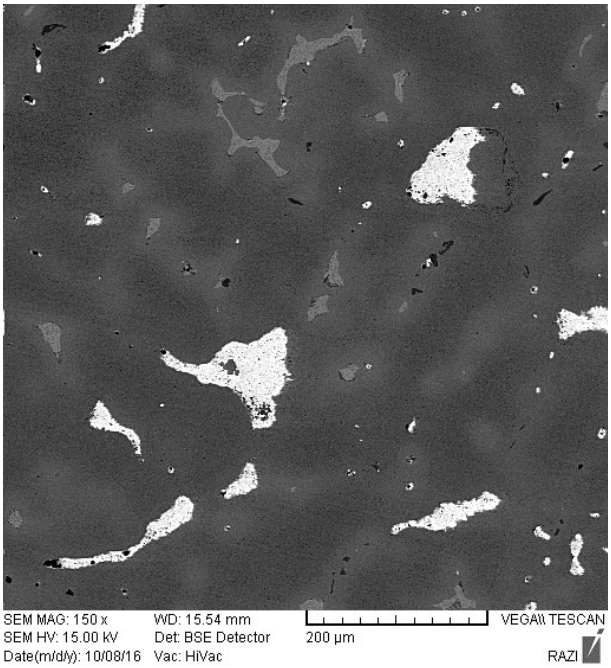


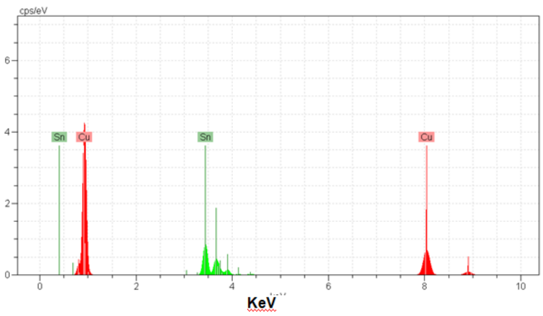
Fig. 6. Microstructure of sample 4, SAE660 bronze, pouring at 950 °C and cooling the mold by air

According to quantitative and qualitative results of the energy dispersive spectroscopy (EDS), in Figures 7 to 11, in all four production conditions, according to Fig. 5, the gray phase, the solid solution of 84 to 92 At% is copper and the rest (i.e. 8 to 16 At%) are tin and zinc. The amount of tin is more than zinc.

According to Fig. 8, the black phase, which is located next to the gray phase (solid solution of copper and tin), is an intermetallic compound of copper and phosphorus.

In addition, the black phases, which are usually single or near the lead, have sharp corners, and according to Fig. 9 and Fig. 10, are impurities such as the intermetallic compound of iron-nickel-phosphorus and zinc sulfide, respectively.

Also, according to Fig. 11, the white phase is pure lead. According to Fig. 12, in some lead particles (the white phase), impurities (black phase) are observed because the lead is the last phase that is solidified and therefore the impurities are immersed in it and eventually placed in the grain boundaries.



Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Copper	K series	73.88	76.86	86.12
Tin	L series	22.24	23.14	13.88

Total: 96.1 %

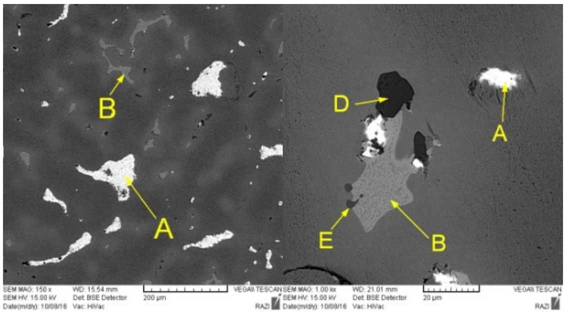
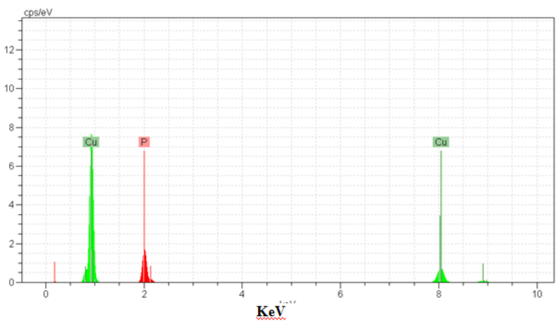


Fig. 7. EDS of the solid solution of copper-tin (particle B)



Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Phosphorus	K series	13.93	18.00	31.05
Copper	K series	63.47	82.00	68.95

Total: 77.4 %

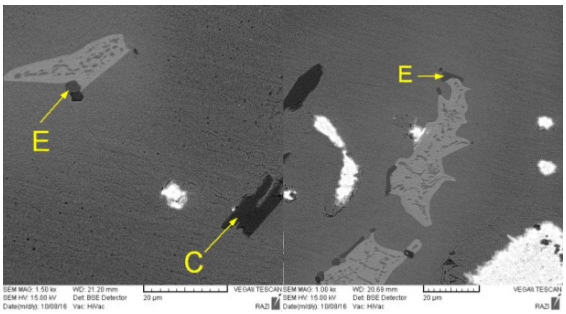
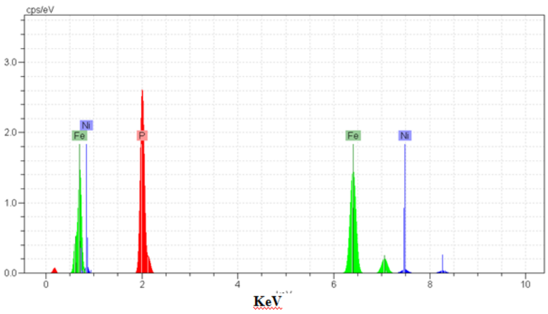


Fig. 8. EDS of the intermetallic compound of phosphorus and copper (particle E)



Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Phosphorus	K series	20.72	19.54	30.53
Iron	K series	79.06	74.58	64.62
Nickel	K series	6.23	5.88	4.85

Total: 106.0 %

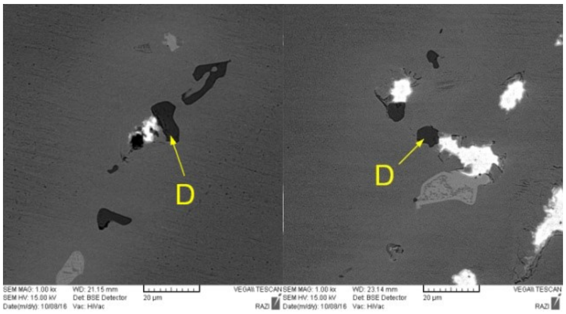
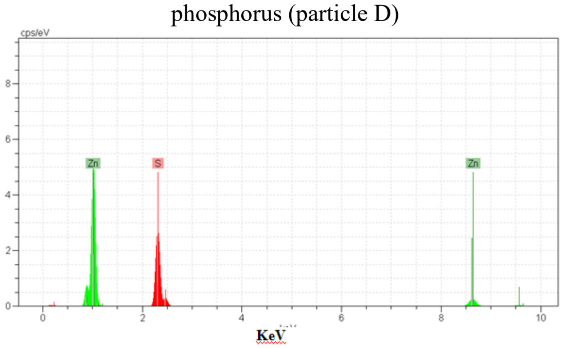


Fig. 9. EDS of the intermetallic compound of iron-nickel-phosphorus (particle D)



Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Sulfur	K series	25.38	39.54	57.14
Zinc	K series	38.81	60.46	42.86

Total: 64.2 %

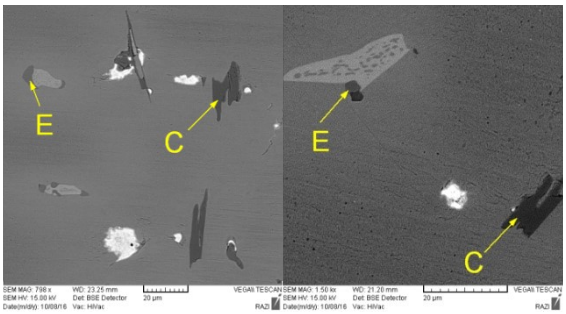
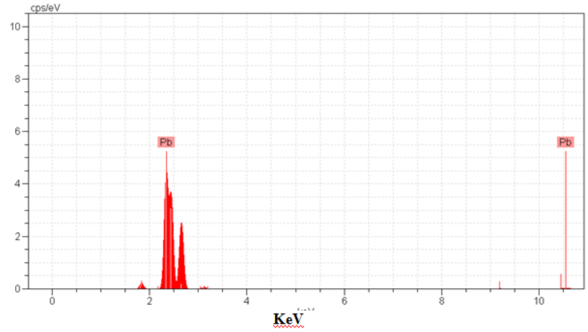


Fig. 10. EDS of zinc sulfide (particle C)



Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Lead	M series	129.68	100.00	100.00

Total: 129.7 %

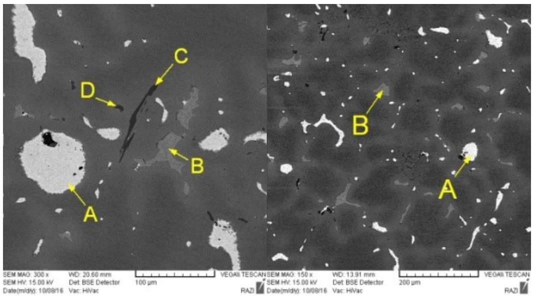


Fig. 11. EDS of pure lead phase (Particle A)

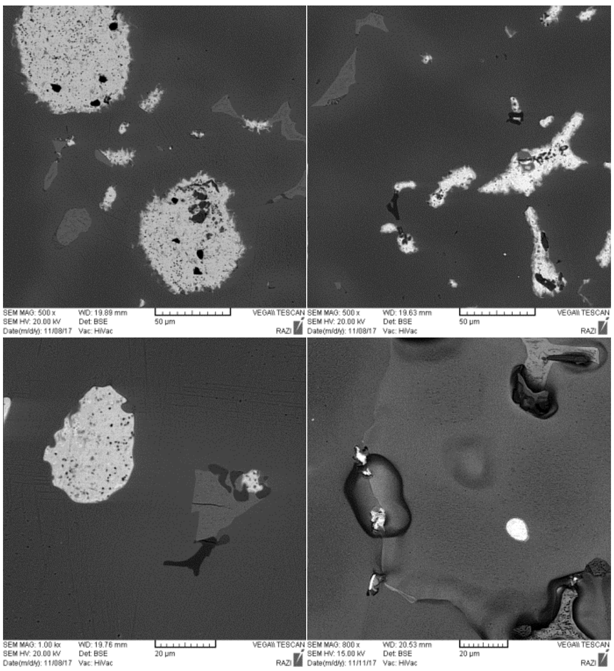


Fig. 12. The grain boundaries contain large amounts of lead (white phase) and the impurities (black-phase)

As shown in Fig. 12 and Table 2, the grain size in samples 1 and 2 is 200µm and in samples 3 and 4 is 180µm which are relatively large. Because of the melt volume was 65 kg (relatively high) and in the form of a cylinder in the sandy mold. In samples 3 and 4, where the mold holder was cooled with water, it did not have much effect on fine grains, because the relatively thick sandy molds made it act as an insulator and prevented the heat transfer to the outside of the sandy mold.

In order to verify the items in Figures 8 to 11, in Fig. 13, the layout of the elements of lead, zinc, copper, and tin is displayed in samples 1 to 4. It is observed that the white particles of lead are almost pure and the black particles inside it are zinc-rich (and other remaining elements such as iron, sulfur, and phosphorus are in accordance with Table 1,) and, moreover, some zinc metal is dissolved in lead.

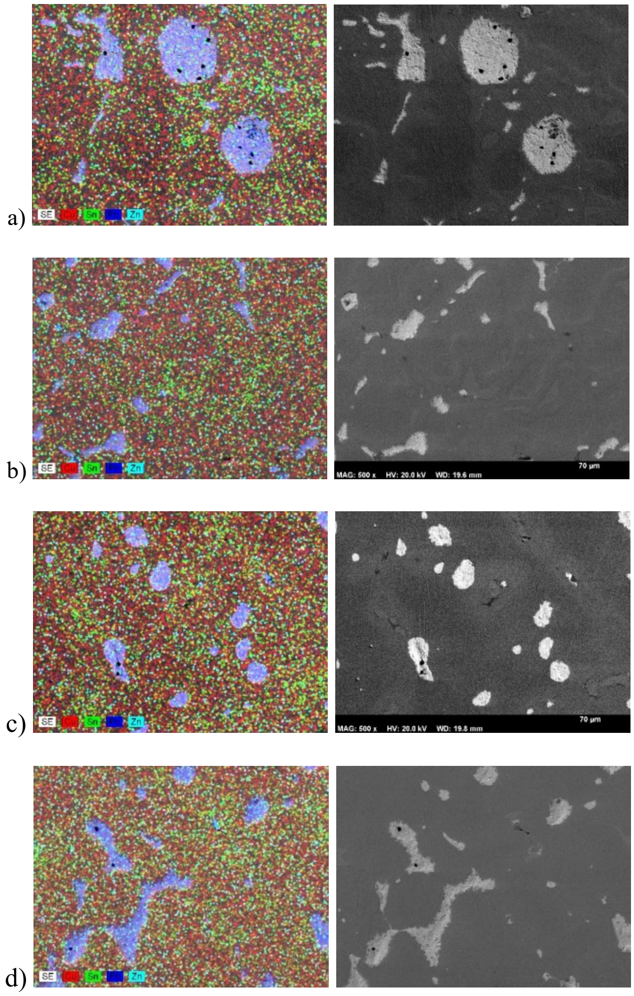


Fig. 13. Map of elements in samples 1 to 4
a) Map elements in sample 1, b) Map of elements in sample 2, c) Map of elements in sample 3, d) Map of elements in sample 4

According to the quantitative and qualitative results of the energy dispersive spectrum in Figures 14-17, which shows the chemical composition of the matrix of samples 1 to 4, in samples in which the mold was water-cooled (i.e., samples 1 and 2) the total amount of alloy elements in the matrix (mainly tin) is less than 6% by weight, while in air-cooled samples (i.e., samples 3 and

4), the total amount of alloy elements in the matrix (mostly tin) is more than 10% by weight. In this way, more cooling rates facilitate particle formation.

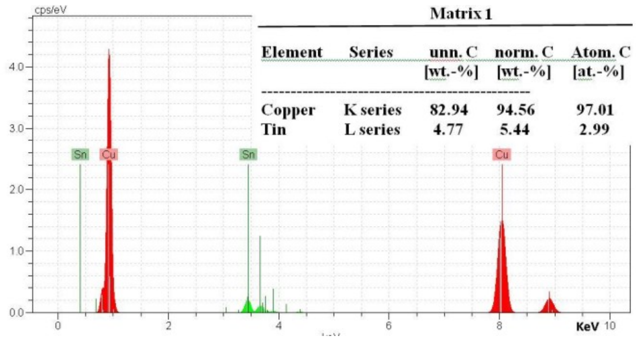


Fig. 14. EDS of matrix of sample 1

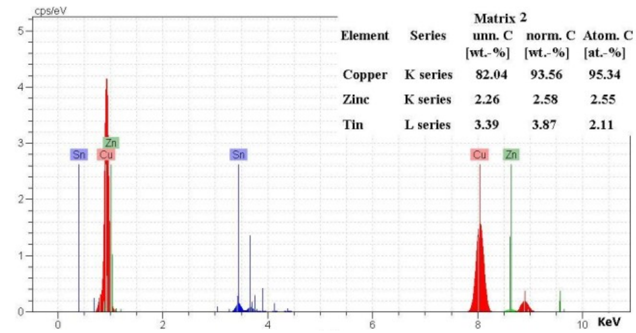


Fig. 15. EDS of matrix of sample 2

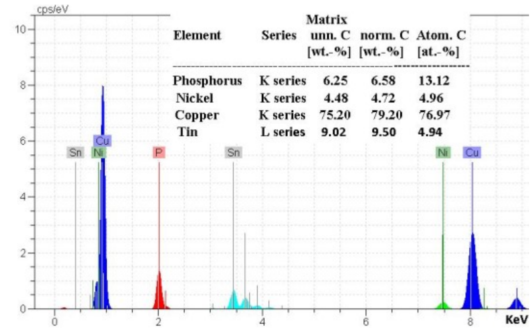


Fig. 16. EDS of matrix of sample 3

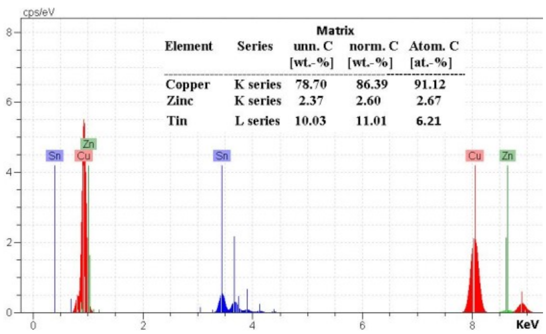


Fig. 17. EDS of matrix of sample 4

3.2. Evaluation of hardness and wear resistance

As shown in Figure 18 or Table 2, the weight loss of samples 3 and 4 (air-cooled samples) respectively, was 36% and 45% less than samples 1 and 2 (water-cooled samples). Because, according to Figures 14 to 17, the matrix of samples 3 and 4 is much richer than that of samples 1 and 2 in alloy elements (mainly tin and zinc, more than 10 wt% and less than 6 wt%, respectively), which increases the strength in the matrix of bronze, therefore, increases the wear resistance (or reduces weight loss due to wear). In addition, samples 3 and 4 have a higher (1.8% vol) and larger (up to 120 μm) amount of solid solution phase, which further increases the wear resistance.

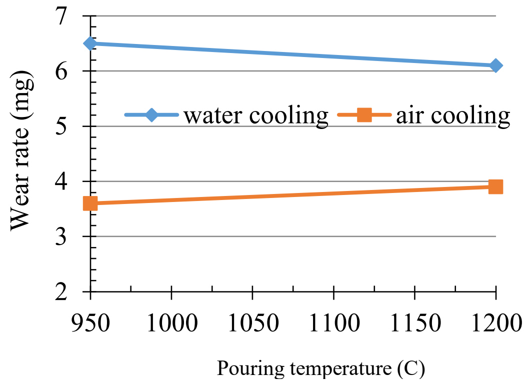


Fig. 18. The relationship between the pouring temperature and the wear resistance

According to Table 2 or Figure 18, the sample 2 (with pouring temperature of 950 °C) has a larger insoluble lead than the sample 1 (with pouring temperature of 1200 °C) (up to 140μm and 100μm, respectively) but an equal content of 3 vol%. It makes easier lubrication in bronze and increases weight loss (or reduced wear resistance). The contrast between these two factors causes the weight loss of the sample 1 to be less than that of sample 2 by 6.1 and 6.5 mg, respectively. Moreover, the sample 4 (with pouring temperature of 950 °C) has a higher content of insoluble lead than the sample 3 (with pouring temperature of 1200 °C) 5 vol.% and 4 vol.%, respectively and it has a larger insoluble lead up to 160μm and up to 100μm, respectively; which makes easier lubrication in bronze and increases weight loss (or reduced wear resistance). The contrast between these two factors causes the weight loss of the sample 4 to be less than that of sample 3 by 3.6 and 3.9 mg, respectively. Although the above analysis exists for the relationship between weight loss due to wear and pouring temperature, but because the difference in weight loss is not very high (less than 10%), so for the above alloy in the range of 950 °C to 1200 °C, in engineering applications, one can ignore the effect of the pouring temperature on weight loss due to wear.

As shown in Figure 19 or Table 2, specimens 2 and 4 (pouring at 950 °C) are harder than samples 1 and 3 (samples pouring at 1200 °C), by 19% and 6%, respectively. Therefore, to achieve more hardness, the alloy should be cast at a lower pouring temperature of 950 °C.

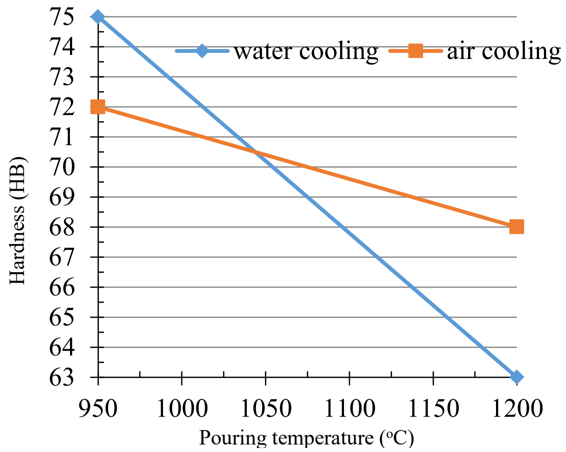


Fig. 19. Relationship between hardness and pouring temperature

It seems that the weight loss is inversely proportional to hardness. In Figure 20, the hardness and weight loss due to wear of samples are compared. In samples 3 and 4, hardness is inversely proportional to weight loss, but contrary to the above rule, in samples 1 and 2, hardness is directly related to weight loss. Although the above analysis exists for the relationship between weight loss due to wear and pouring temperature, but because the difference in weight loss is not very high (less than 10%), so for the above alloy in air cooling or water cooling condition, in engineering applications, one can ignore the effect of the hardness on weight loss due to wear.

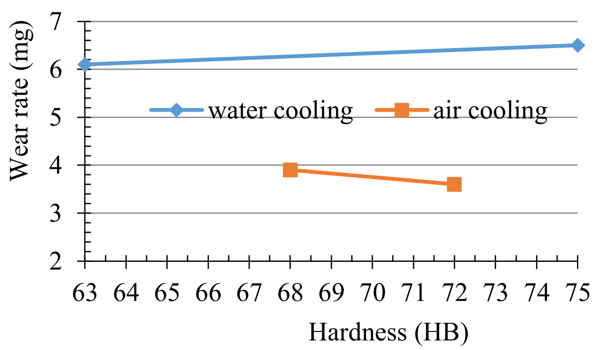


Fig. 20. Relationship between hardness and weight loss due to wear

4. Conclusions

In this study, the melt had prepared by induction furnace. Then, it had poured in sand mold at four different casting conditions, including pouring temperatures of 950 °C and 1200 °C, and cooling with water and air. Finally, the microstructure, Brinell hardness and pin-on-disc wear resistance of the SAE660 had investigated. The results indicated that:

1. The maximum hardness, along with the minimum weight loss due to wear (or maximum wear resistance) have achieved by increasing of the contents of intermetallic compounds, lead phase and the solid solution phase.
2. The samples which are cooled in air and poured at 950 °C have the high hardness (72 Brinell) and the lowest weight loss (3.6 mg).
3. Air-cooled samples compared with water-cooled have an average 40% reduction in weight loss due to wear, so, their wear resistance have increased about 40%.

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