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Effect of some parameters of formation on surface graphite-bronze composite layer prepared by vacuum infiltration casting technique*

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Abstract: Surface composite up to 3.0 mm in thickness with compact microstructure was fabricated successfully via vacuum infiltration casting technique on the bronze substrate under the optimum experimental conditions: the vacuum degree of －0.08 MPa, pouring temperature of 1220℃, grain size of 0.20－0.24 mm, preheating temperature of 180℃. The preform was mainly composed of graphite particles and binder NJB (self-fabricated binder). The vacuum degree, pouring temperature, preheating temperature and grain size during infiltration casting play an important role on the process of forming the surface composite. The results show that three cases are obtained in the vacuum infiltration casting technique: no infiltration, partial infiltration and full infiltration. The main reason of no infiltration is that the vacuum degree is not enough so that the force acting on the liquid metal is lower than the resistance due to the surface tension and the pouring temperature is somewhat low. Partial infiltration is because of somewhat lower vacuum degree and pouring temperature. Full desired infiltration is on account of suitable infiltration casting conditions, such as vacuum degree, pouring temperature, grain size and preheating temperature. The influencing effect of vacuum degree is most obvious for the formation of surface composite, then pouring temperature and particle size. The infiltration mechanism is discussed on the bases of the different processing conditions.

Key words: graphite particle; vacuum infiltration casting; surface composite; preform

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1 Introduction

Composite coatings can provide various properties, such as wear resistance, oxidation resistance, corrosion resistance and self-lubrication. Self-lubricants are used for production of bearing materials and generally considered for use where grease and oil lubricants can't be used[1,2]. Several kinds of these materials, such as graphite, PTFE, MoS_2, and talc are used as self-lubricants with a metal matrix, such as Cu or Ni

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and its alloys[3-5]. A variety of methods for producing surface materials, such as spraying, plating, laser cladding, deposition and casting, have recently become available[6-15]. Amongst these methods, fabrication using liquid-state processing (casting technique) has a potential advantage to achieve a near-net shape product in a simple and cost effective manner. The wide selection of the matrix and good bonding between the particles and the matrix are also advantages.

In terms of both processing and properties, the main concern that should be addressed is that of obtaining surface composite layer with uniform particle distribution[16]. However, this is achieved in vacuum infiltration of preforms by liquid metal. Other casting techniques encountered several problems such as floation and agglomeration[16]. Another important problem is the poor wettability between the liquid metal and the reinforcement[17, 18]. In the vacuum infiltration casting technique, these problems have been solved.

In this study, the surface graphite-bronze composite layer was fabricated on bronze substrate by a vacuum infiltration casting process. The influence on formation of the parameters such as negative degree, pouring temperature, grain size and preheating temperature was investigated. Its infiltration mechanism is discussed.

2 Experimental

In this work, graphite particles with different grain sizes (110—400 μm) was chosen as the reinforcement, and bronze ZQAl9-4, with its composition listed in Table 1, as the matrix of the surface composites and the substrate material on which the surface composites formed.

Table 1 The chemical composition of tested aluminum bronze (%, mass fraction)

Cu	Al	Fe	Sb	Si	P	As	Sn	Pb	Mn	Zn	Total[1)]
Bal.	8.0—10.0	2.0—4.0	≤0.05	≤0.2	≤0.1	≤0.05	≤0.2	≤0.1	≤0.5	≤1.0	≤1.0

Note: 1) Total refer to all content of element As, Sn, Pb, Mn and Zn.

Before fabrication surface composite the graphite particles had been ultrasonically cleaned in water, and then rinsed in ethanol prior to drying in air. The surface layer was fabricated by a vacuum infiltration casting process. Firstly, the graphite powder with suitable grain size and self-fabricated binder NJB were mixed together according to desired proportion, paved on the inner surface of a casting mould or outer surface of mould cores, where the propertiy of wear resistance was needed to be improved, then heated to harden so as to form preform layers. Secondly, the liquid bronze was poured into the mould in condition of different

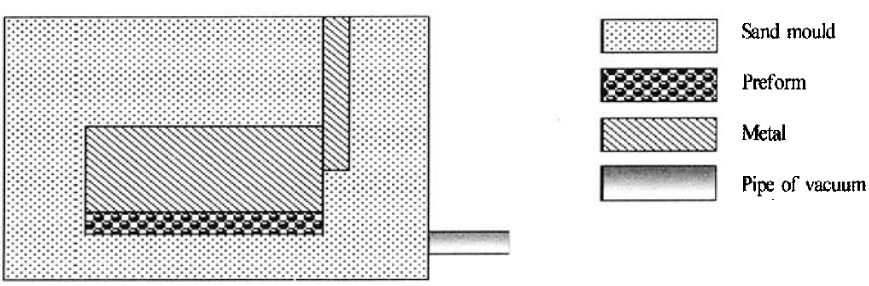

Fig. 1 Schematics of process to fabricate surface composite

vacuum degree, the melt was sucked into the preforms. Finally, the surface layer on bronze substrate was obtained after solidification of castings. The fabrication schematic of surface infiltrated layer is shown in Fig. 1.

The thickness of surface infiltrated layer (surface composite layer) with compact microstructure and good bonding with substrate was used to qualify the infiltrated layer. Average thickness of infiltrated layer was derived from measurements per sample using optical microscope. The microstructure of infiltrated layer was observed by scanning electron microscope (SEM). The specimens of surface composite layer for SEM observation were ground and polished using standard metallographic techniques.

3 Results and discussion

3.1 Infiltration cases

The extent of infiltration is characterized by infiltration thickness. The following three cases of infiltration are shown in Fig. 2 depending on the process conditions.

(1) No infiltration: no composite was formed because no liquid metal penetrate the interfaces in the preform. The main reason is that vacuum degree is not enough so that the infiltration force could not overcome the resistance resulting from the surface tension of metal liquid (refer to Fig. 2b).

(2) Partial infiltration: the composite was formed with limited thickness adjacent to the substrate metal or partial area having infiltrated layer. The main reason is that pouring temperature is somewhat low. The infiltration begins while vacuum being enough, but the temperature of the substrate metal is too low to pass through the whole prefrom.

(3) Full infiltration: the composite with desired thickness was formed because the liquid metal could infiltrate through the whole preform. This case happened when the infiltration conditions (vacuum degree, pouring temperature, etc.) were suitable. The suitable vacuum could make the infiltration start, and suitable pouring temperature could make the metal liquid pass through the whole perform.

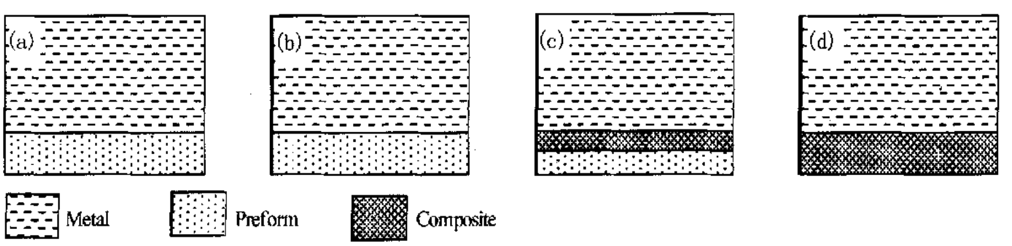

Fig. 2 A sketch showing the different infiltration cases in infiltration casting
(a) before the beginning of infiltration; (b) case 1: no infiltration;
(c) case 2: partial infiltration; (d) case 3: full infiltration

3.2 Effect of infiltration parameters on the surface composite

3.2.1 Vacuum degree

Fig. 3 shows the effect of the vacuum degree on thickness of the surface infiltrated layer, while the thickness of preform and grain size were kept constant as 3.0 mm and 0.20-0.24 mm, respectively. The preheating and pouring temperatures were also kept constant at 180℃ and 1220℃, respectively. The thickness of preform was 3 mm that was determined on the base of point of the engineering. The thickness of preform, 3 mm, is enough for needs of surface special properties, such as wear, corrosion and oxidation resistance[19, 20].

With the increasing vacuum degree, the force acted on the liquid metal increase, then thickness of the surface uniform infiltrated layer increases until the thickness almost keeps constant ranging from -0.08MPa to -0.10 MPa. The surface composite layer could not been obtained until the vacuum degree exceed-0.03 MPa. A linear relationship between vacuum degree and the thickness of infiltrated layer is obtained, as shown in Fig. 3. The different circumstance is that the thickness of surface composite is sensitive to the vacuum degree while ranging from -0.03MPa to -0.08 MPa. This is similar to the non-reactive system Al-Al_2O_3[21]. As indicated in Fig. 3, a minimum vacuum degree of −0.08 MPa is necessary for desired full infiltration. Higher vacuum degree is unnecessary. This value depends on pouring temperature, the type and surface condition of the particles, the preheating temperature of preform and the grain size of the particle[18,22]. The final thickness of infiltrated layer is no longer bigger than the thickness of the preform. That is because graphite powder could not melt, so there was no diffusion layer formed.

3.2.2 Effect of pouring temperature

Fig. 4 shows the effect of the pouring temperature on the thickness of surface infiltrated layer, whilst the vacuum degree, the thickness of preform, grain size of graphite particles, and preheating temperature are kept constant at −0.08 MPa, 3 mm, 0.20-0.24 mm and 180℃, respectively. With the rising of the pouring temperature, the thickness of surface composite layer increase quickly before the temperature reached to 1220℃. When the temperature was higher than 1220℃, the thickness of infiltrated layer kept nearly constant when the pouring temperature was exceeding 1220℃. For casting process, it is impossible to measure the pouring temperature accurately, therefore a pouring temperature range rather than precise temperature is necessary. The pouring temperature should not be higher than 1220℃ to avoid the oxidation of the liquid metal. As a consequence, the negative effect of the oxide layer, which often exists at the interface of reinforcement particle and matrix, on the microstructure could be reduced.

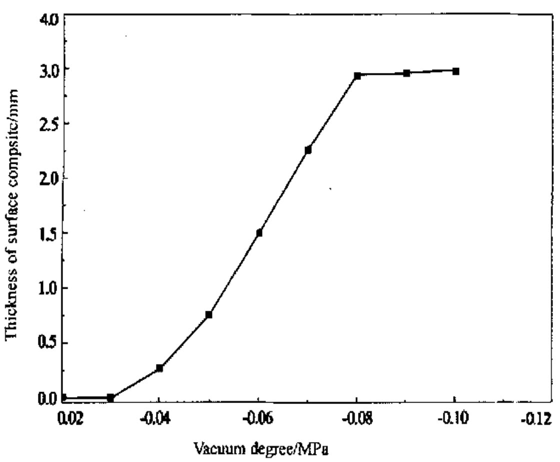

Fig. 3 Effect of vacuum degree on the thickness of surface composite

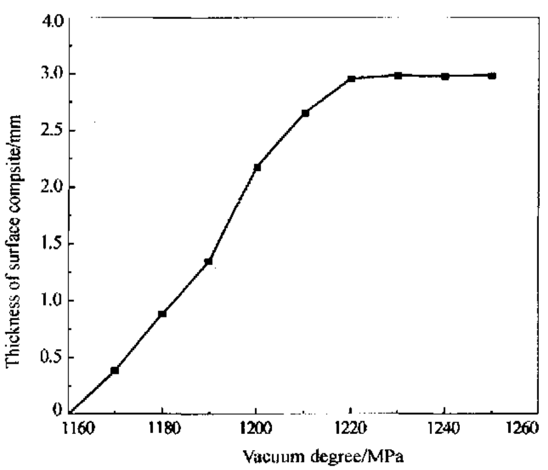

Fig. 4 Effect of pouring temperature on the thickness of surface composite

3.2.3 Effect of grain size

In this case, the vacuum degree is not constant during infiltration. It is controlled through the pressure valve. In order to study the effect of grain size on infiltration, the preform was prepared with constant thickness of 3 mm for all experiments conducted. The preheating temperature, pouring temperature are constant as 180℃ and 1220℃, respectively. Different graphite powder grain size and different vacuum degree were applied.

Such difference in thickness increase with increase in either the vacuum degree applied and/or the graphite powder particle size as indicated in Fig. 5. The results indicate that surface composite layer formed as the grain size is shown from the Fig. 5 and whatever the degree of vacuum is. But the thickness of infiltrated layer was different for different grain size. The bigger the grain size was, the thicker the composite layer was under the same condition of vacuum degree. The difference of thickness of composite layer under the same vacuum degree decreases with the increasing of vacuum degree, especially for grain size larger than 0.20 mm. Under the higher vacuum degree, the surface composite layer easily formed, and thickness of compact infiltrated layer increased. In addition, it is somewhat difficult to form the surface infiltrated layer for the powder of grain size smaller than 0.20 mm.

3.2.4 Effect of preheating temperature

In this case, the vacuum degree, preform thickness, pouring temperature and grain size were kept constant at −0.08MPa, 3.0 mm, 1220℃ and 0.20-0.24 mm, respectively. Only preheating temperature changed. The thickness of infiltrated layer formed at preheating temperature being higher than 180℃ was always slightly thicker than that of infiltrated layer formed at preheating temperature being 180℃, as shown in Fig. 6. The excellent surface infiltrated layer could hardly form without preheating.

However, the value of changing thickness did not exceed 0.5 mm even for the highest preheating temperature when the preheating temperature exceed 180℃. The preheating temperature should not exceed 300℃ because the preform would lose the necessary strength due to the failure of the binder for pouring and infiltrating. In short, the preheating temperature is not the main factor for vacuum infiltration casting among these all parameters because the enough high pouring temperature could compensate partly the low temperature of preheating, as we know that the pouring temperature cold not be improved illimitably. The suitable preheating temperature could impose positive effect on the forming of surface composite layer. But the negative effect of lower pouring temperature could not be compensated through the preheating.

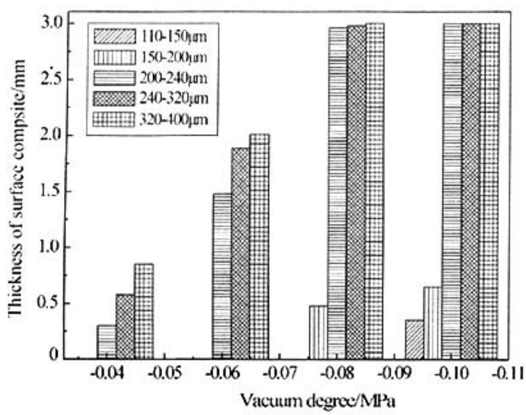

Fig. 5 Effect of grain size on the thickness of surface composite

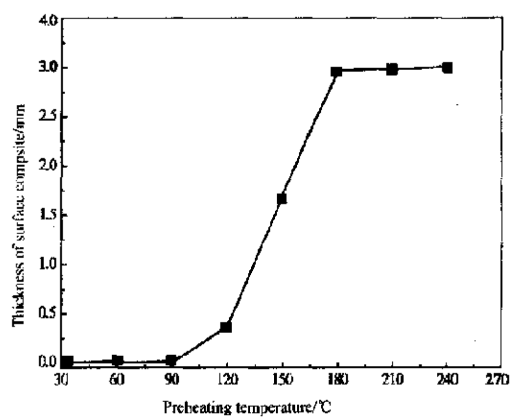

Fig. 6 Effect of preheating temperature on the thickness of surface composite

3.3 Infiltration mechanism

As we known, the pure copper melt is non wetting on carbon. The alloy element addition of Mo, Cr, V, Fe, Co, Ti to copper has positive effect for the wettability to carbon[23]. The substrate is bronze which contains somewhat Fe element. Though the bronze can wet the graphite particle to some extent, spontaneous infiltration of the metal into the preform is impossible without reactive systems under carefully controlled conditions, such as the PRIMEX process and related efforts[14, 15]. Fig. 7 presents a schematic illustration of the infiltration mechanism. Two opposite forces act on the molten bronze: (a) the P force which

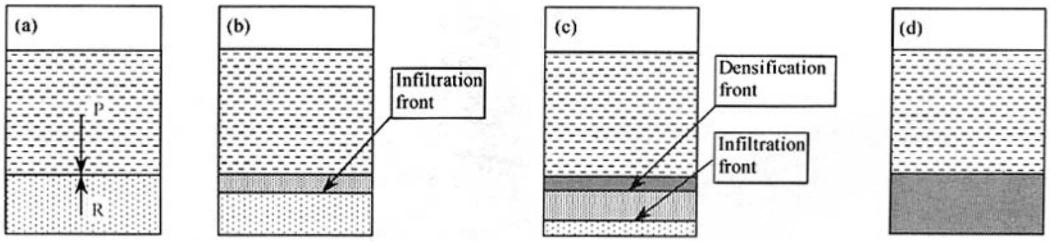

Fig. 7 A sketch of the infiltration in vacuum infiltration casting
(a)—No infiltration ($P \leqslant R$); (b)—Infiltration starts($P > R$); (c)—Infiltration continues; (d)—Surface composite obtained finally(P— infiltration pressure acting on the molten metal; R— resistance force)

include the suction force of vacuum and the gravity of the molten metal; (b) the resistance (R) of the graphite particles show that a cumulative force acts on the surface of the particles. As the pressure applied on the liquid metal exceeds the resistance force due to the surface tension of the molten metal, the liquid penetrates the interface of particles and starts to flow into the capillaries of the preform. The vacuum degree needed to form the surface composite is higher as the preform was composed of graphite than that as the preform is composed of other enforcement grain due to the structure of graphite is lamination[24]. It is noted that the velocity of front decreases with time, as the front reaches the mould such velocity approaches zero. During the propagation of the front a densification process occurs simultaneously on the same side and a moving densification front occur. This result is obtained from density measurements on partially infiltrated samples with different thickness. It can be deduced that the densification front velocity is almost constant whilst the infiltration front velocity decreases. The constant velocity of densification front is deduced from both fronts meeting at the mould, leading to uniform density along the whole section of the surface composite.

3.4 Microstructure of surface composite

An almost uniform distribution of graphite particulates is achieved according to Fig. 8. As seen from Fig. 8, there is almost no inclusion at the interface of the substrate and the graphite particle due to the following reasons. One is that the particles were ultrasonically cleaned in water, and then rinsed in ethanol prior to drying in air before mixing with the binder. The other is that no reaction happened at the interface between the substrate and the graphite particles. The inter-spacing of particles was found to have an almost constant value in the specimen.

4 Conclusion

(1) Surface composite was fabricated successfully using vacuum infiltration casting technique as the preform was composed of graphite particles on the suitable conditions of infiltration parameter. The vacuum degree, the pouring temperature and the grain size are the main factors for the formation of surface composite. And the thickness of surface composite increases with the increasing of the three main factors within certain range of respective parameter, then keeps nearly constant as these parameters reach some

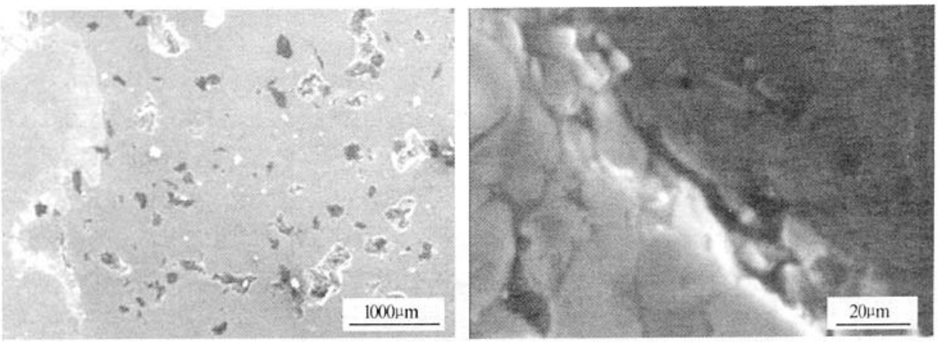

Fig. 8 SEM view of the surface composite

values. The preheating temperature is not the main factor, while it could operate a positive effect on the formation of surface composite.

(2) The infiltration mechanism for vacuum infiltration casting suggests that the composite formation starts from the metal-particle interface and the infiltration front progress towards the inner surface of the mould. A densification front simultaneously follows the infiltration front until meeting at the inner surface of the mould.

(3) Almost uniform particle distribution is achieved by vacuum infiltration casting. There is no inclusion at the interface of the bronze and graphite particles.

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