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In situ surface composites of (Mg_2Si+Si)/ZA27 fabricated by centrifugal casting

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Abstract

In situ composites of Zn–27Al–6.3Mg–3.7Si alloy have been fabricated by centrifugal casting using the heated permanent mold. This kind of composites is consisted of three layers: inner layer segregates lots of blocky primary Mg_2Si and a little blocky primary Si, middle layer does not contain primary Mg_2Si and primary Si, outer layer contains a little primary Mg_2Si and primary Si. The position, quantity and distribution of primary Mg_2Si and primary Si are determined by solidification velocity under the effect of centrifugal force and their floating velocity inward. The inner and outer layer contained primary Mg_2Si and primary Si exhibit much higher hardness and wear resistance than the middle layer.

Keywords: Centrifugal casting; Zn–27Al–Mg–Si alloy; In situ composites; Surface composites

1. Introduction

In situ composites fabricated by centrifugal casting have been extensively studied because they overcome the interface problem in the artificial composites and have a lot of advantages such as clean interface between reinforced phase and matrix, excellent properties, simple fabrication technology, easiness to control technology parameters, small investment and adaptability to large-scale industry production [1]. In situ composites with outward precipitated primary reinforced phase have been obtained by centrifugal casting aluminum alloys with primary reinforced phase such as Al_3Fe, Al_7Cr and Al_3Ni [2–5]. However, it is mostly required that the inner layer has the special properties such as wear resistance or both the inner and outer layer have special properties for tube part. Therefore, there is a significant meaning to fabricate in situ composites with inward floated primary reinforced phase.

Because of the excellent friction and wear resistance, Zn–Al alloys have successfully substituted some copper alloys used to fabricate industry parts with high wear resistance, but their wear resistance under high velocity and heavy load need to be improved further [6]. Mg_2Si is very suitable as reinforced phase in metal matrix composites due to its low

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density, high melting point, high hardness, low thermal expanding coefficient and a suitable Young's modulus [7]. In recent years, in situ Mg and Al matrix composites reinforced by Mg_2Si particles have been obtained [8,9], and their microstructures were ameliorated and properties were improved through lots of methods such as the modification, hot extrusion, rapid solidification and mechanical alloying [10,11]. In the meantime, the composites of Al matrix reinforced by Mg_2Si were fabricated by centrifugally casting Al–Mg–Si alloy [12]. Through centrifugally casting Zn–Al–Si alloy, we have obtained in situ surface composites, whose inner layer contained lots of primary Si, outer layer contained a little primary Si and the middle layer consisted of fine eutectic structure [13]. Besides, we have fabricated in situ composites of hypereutectic Al–Si alloys by centrifugal casting at the advantage of excellent properties of Si [14,15]. Lately, Zhang et al. [16] fabricated in situ composites containing both Mg_2Si and Si in their structure.

This study investigated the Zn–27Al–6.3Mg–3.7Si alloy by centrifugal casting using the heated permanent mold, which make the primary Mg_2Si and Si segregated towards inside. The in situ composites in which the primary Mg_2Si and Si enriched in the inner layer and outer layer have been fabricated.

In situ composites with primary Mg_2Si and primary Si enriched in the inner layer and outer layer have been fabricated by centrifugal casting of Zn–27Al–6.3Mg–3.7Si alloy using heated permanent mold in this study.

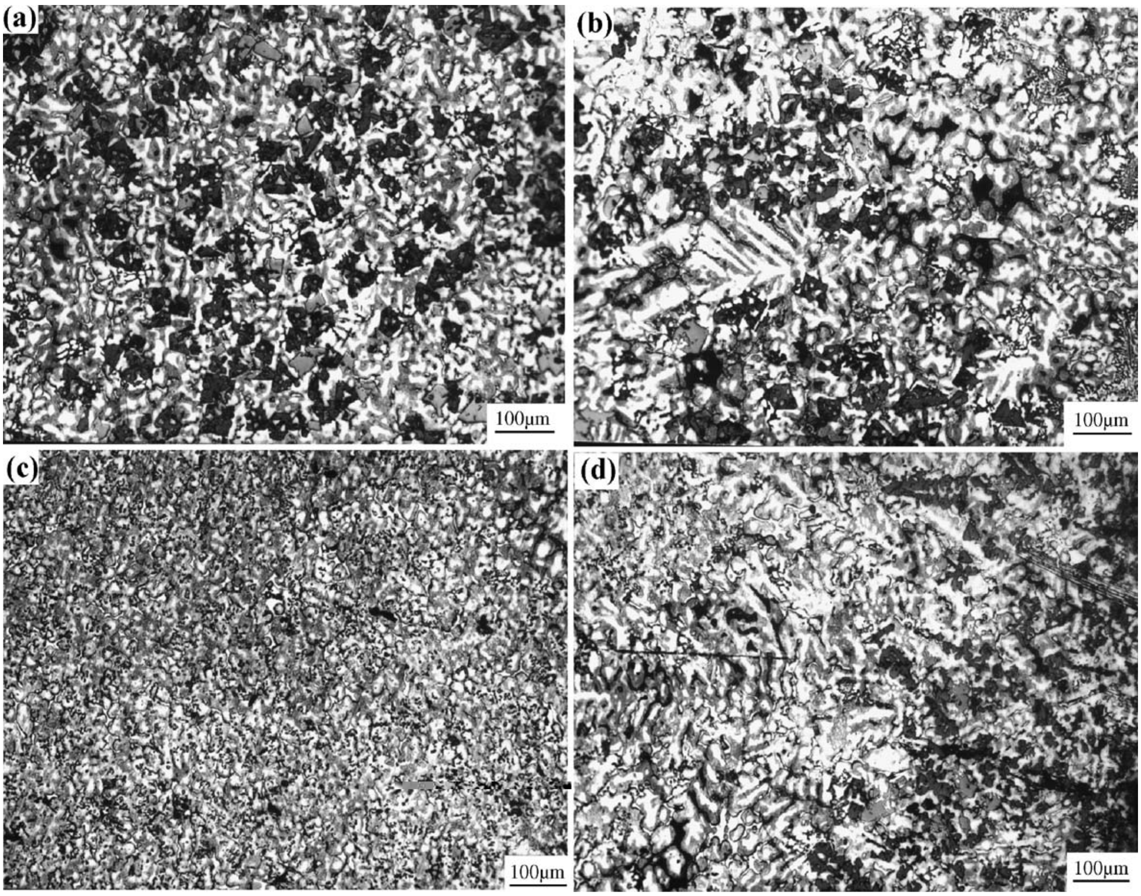

Fig. 1. Microstructure of (Mg_2Si + Si)/ZA27 composites (T_m = 200 °C, n = 1000 rpm). (a) Inner layer, (b) transitional layer, (c) middle layer, (d) outer layer.

2. Experimental procedure

The alloy was prepared with commercially pure Zn, Al, Mg and Si in an electronic-resistance furnace. The nominal alloy composition is Zn–27Al–6.3Mg–3.7Si. The specimens were produced in a vertical centrifugal casting apparatus as before [13]. The metal mold was preheated at 200 °C before pouring. The rotating rate of the mold was 1000 rpm. The pouring temperature was controlled at 700 °C. The heating furnace was shut immediately after pouring and the specimen was cooled in the furnace. A tube specimen with an outside diameter of 88 mm and thickness of 12 mm was obtained.

The microstructure of the composites was examined with an optical microscope. Vickers hardness was measured along the radial direction on the transverse cross section under the load of 5 kg. Thermal analyzer (Universal V2.4F) was used to record the temperature difference curve and temperature curve during heating and cooling for Zn–27Al–6.3Mg–3.7Si alloy, and the heating rate was 10 °C/min. Dry sliding wear tests were conducted on 60-mm diameter cylindrical samples against a 45 steel counterpart disc with hardness of HB177 by using an MPX-2000 pin-on-disc wear testing machine. Two kinds of samples were used in the wear test. One is perpendicular to the axis of the tube, which is used to test the wear behavior of the inner layer and outer layer; the other is parallel to the axis of the tube, which is used to test the wear behavior of the middle layer. The sliding speed was 0.3 m/s, the load applied was 50 N and the test period was 30 min. The weight loss was used to evaluate the wear properties of different radial position of the specimen.

3. Results and discussion

3.1. Microstructure of the composites

Fig. 1 shows the microstructure of (Mg_2Si + Si)/AZ27 composites. It can be observed from Fig. 1a that a great deal of primary Mg_2Si with average size of 30–50 μm (blocky phases with deep grayness) segregated and enriched in the inner layer of composites; in the meantime, there exists a little primary Si with average size of 20–40 μm (blocky phases with light grayness); the thickness of the whole inner layer was about 5 mm. Fig. 1b shows the microstructure of transitional layer, where the microstructure transited from inner layer containing lots of bulk primary Mg_2Si and primary Si to middle layer containing fine Mg_2Si and Si. Mg_2Si and Si in middle layer (Fig. 1c) shows the shapes of thin stripes and dots, exhibiting the characteristics of eutectic microstructure. The outer layer (Fig. 1d), whose thickness is about 0.3 mm, contains a little small bulk primary Si and primary Mg_2Si, where the primary Mg_2Si connects with each other and distributes as long bunches. Compared with that in inner layer, the primary Mg_2Si and primary Si in the outer layer are finer and more fewer and they distributes unevenly.

3.2. Determination of phase and composition

Fig. 2 shows the X-ray diffractogram of inner layer (a) and outer layer (b) of (Mg_2Si + Si)/AZ27 composites. It is demonstrated from Fig. 2 that both inner

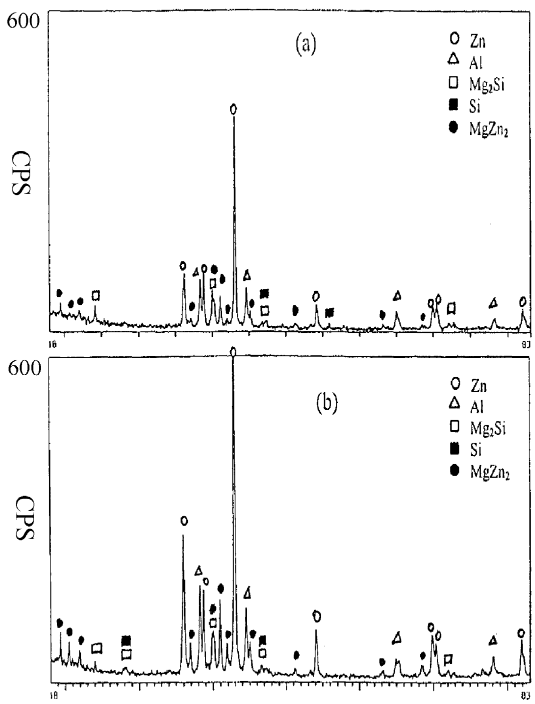

Fig. 2. X-ray diffractogram of (Mg_2Si + Si)/ZA27 composites.

and outer layer of the composites contain Zn, Al, Mg_2Si, Si, $MgZn_2$.

The composition of each phase in the composites was further determined through SEM (Fig. 3) and EDAX (Fig. 4). Fig. 4a shows the EDAX spectrum of deep gray blocky phase in Fig. 3a; it can be determined as Mg_2Si. Fig. 4b shows the EDAX spectrum of light gray bulk phase in Fig. 4a; it can be determined as Si. Fig. 4c shows the EDAX spectrum of the bright stripe phase in Fig. 3a; it can be determined as $MgZn_2$ phase by the result that the atom ratio of Zn to Mg is about 2. At the same time, other test results confirmed that the bright stripe phase at the outer layer in Fig. 3b is also $MgZn_2$; the deep gray stripe phase in Fig. 3b is Mg_2Si. The EDAX analysis (Fig. 4d) of the light gray stick phase around the outer layer in Fig. 3c demonstrates that it is Si.

3.3. Forming process of composites

Little research result about the solidification process of Zn–Al–Mg–Si alloys has been reported up to now. The forming process of composites is analyzed as follows. Firstly, the solidification process of Zn–27Al–6.3Mg–3.7Si alloy is analyzed, based on the phase analysis results and utilizing the DTA curves of Zn–27Al–6.3Mg–3.7Si alloy (Fig. 5) and the ternary phase diagrams [17] of Zn–Al–Si and Zn–Al–Mg, the binary phase diagrams of Zn–Al and Zn–Mg. Secondly, the forming process of (Mg_2Si+Si)/AZ27 composites during the centrifugal casting is further investigated.

It can be observed from Fig. 1 that (Mg_2Si+Si)/AZ27 composites contain blocky Mg_2Si and blocky Si. We can infer from the DTA curves (Fig. 5) that the following reactions would take place during the initial solidification stage of Zn–27Al–6.3Mg–3.7Si alloy: $L \rightarrow L + Mg_2Si$ and $L \rightarrow L + Si$. The exothermal peaks at 922.02 and 841.66 K in Fig. 5 correspond to the precipitation of primary Mg_2Si and primary Si, respectively.

According to the ternary phase diagram of Zn–Al–Mg (Fig. 6) [17], for the studied Zn–27Al–6.3Mg–3.7Si alloy, the following reaction would happen during the temperature range from 673 to 773 K: $L \rightarrow L + \alpha(Al)$, and the exothermal peak at

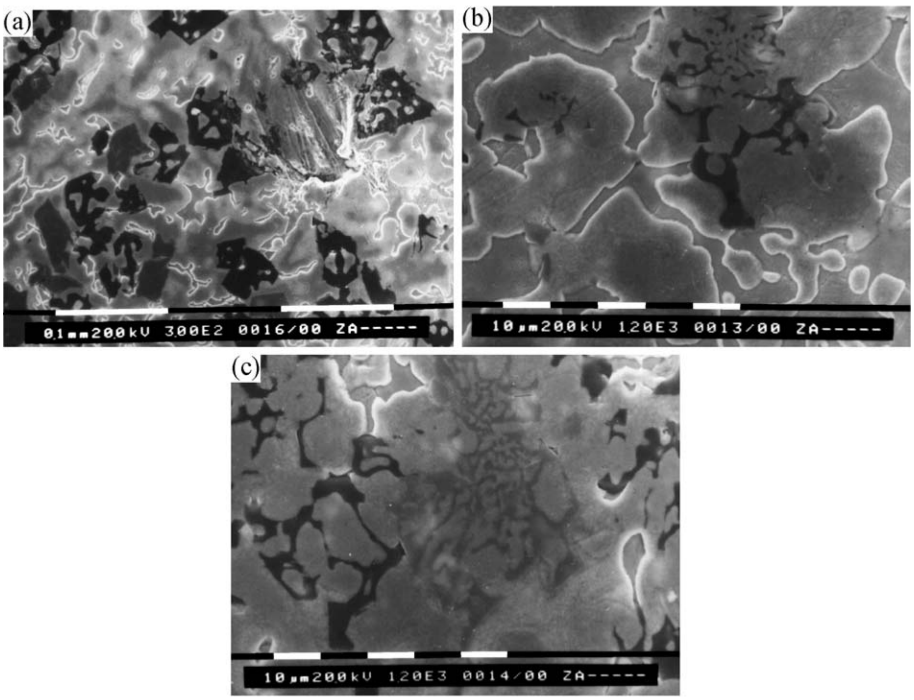

Fig. 3. SEMs of (Mg_2Si+Si)/ZA27 composite. (a) Inner layer, (b) and (c) outer layer.

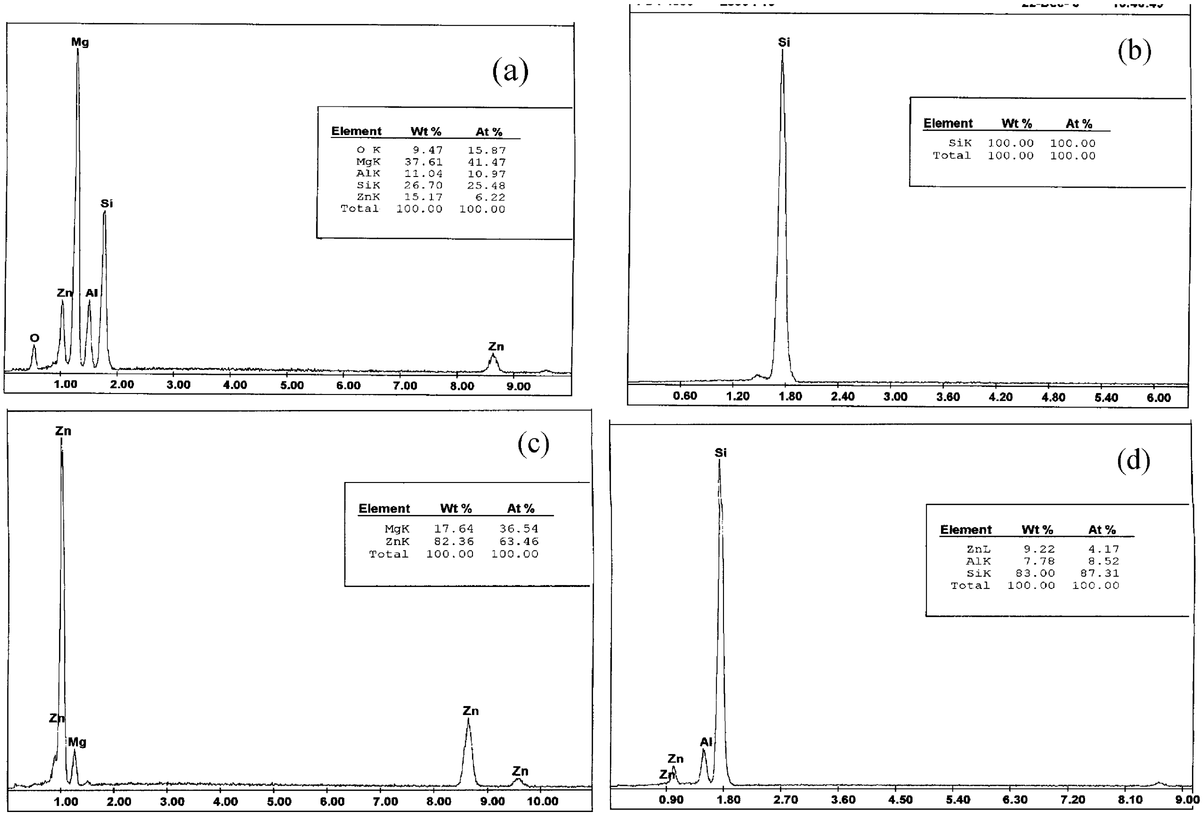

Fig. 4. EDAX spectrum of ($Mg_2Si + Si$)/ZA27 composites. (a), (b), (c) Inner layer, (d) outer layer.

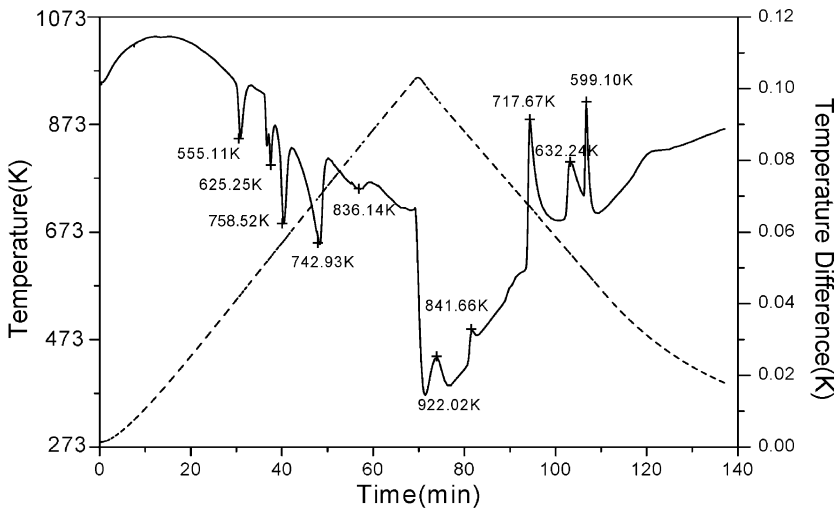

Fig. 5. DTA curve of Zn–27Al–6.3Mg–3.7Si alloy.

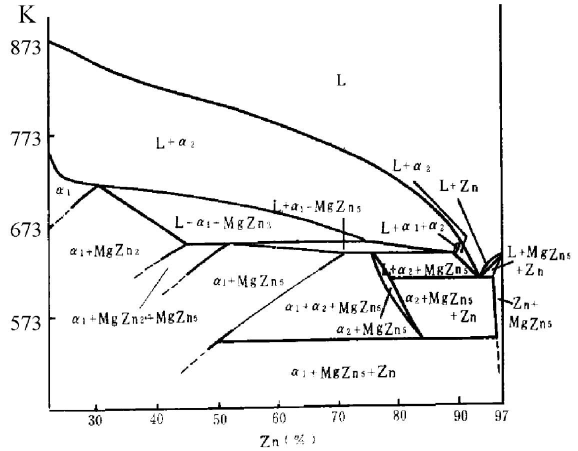

Fig. 6. The vertical projection of Zn–Al–3%Mg alloy.

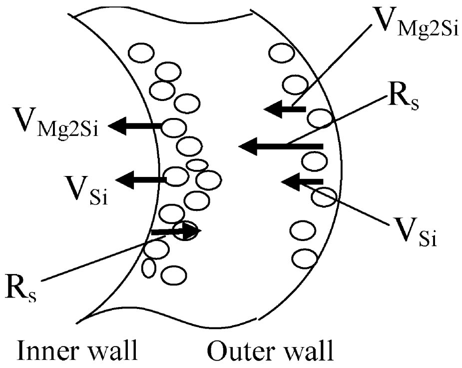

Fig. 7. Forming process of composites.

717.82 K in Fig. 5 reflects this reaction. With the temperature decreasing, Mg–Zn compounds will precipitate (Figs. 2–4), which corresponds to the exothermal peak at 632.24 K in the DTA curve (Fig. 5).

Then, the Mg content in solidifying molten alloy decreases rapidly, and based on the ternary phase diagram of Zn–Al–Si [18], it can be deduced that the ternary eutectic reaction: L → α(Al) + Zn + Si will occur at 656 K when the contents of Si and Zn are 0.06% and 87%, respectively. Therefore, the ternary or quaternary eutectic reaction: L → α-Al + Zn+(Si)+ (Mg_2Si) would take place during the final solidification stage of the quaternary alloy Zn–27Al–6.3Mg–3.7Si, which corresponds to the exothermal peak at 598.95 K in DTA curves.

Based on the above analysis to the solidification process of Zn–27Al–6.3Mg–3.7Si alloy, the forming process of the in situ composites of (Mg_2Si + Si)/AZ27 under the action of centrifugal force is further analyzed as follows (Fig. 7).

When molten alloy was poured into the tube mold, the outer layer of composites firstly solidified fast due to the rapid cooling effect of the mold wall, and a little primary Mg_2Si and primary Si precipitated. The density of each of these primary phases is much lower than that of the molten alloy (ρ_{Si} = 2330 kg/m^3, ρ_{Mg2Si} = 1990 kg/m^3 [9], $\rho_{ZA27(melt)} \approx$ 4900 kg/m^3 [19]), and the floating velocity of Mg_2Si and Si inward (V_{Mg2Si}, V_{Si}) was, respectively, slower than the solidification velocity (R_s). As a result, some primary Mg_2Si and primary Si were captured and stayed in outer layer. Because the solidification velocity in outer layer is very quick, the primary Mg_2Si and primary Si have no time to grow and are very small.

With the temperature of molten alloy decreasing, Mg_2Si and Si precipitated continually and moved to the inner layer under centrifugal force. On the other hand, due to the cooling effect of the air in the tube mold, the inner layer of composites also began solidifying at a lower velocity. And the floating direction of blocky primary Mg_2Si and primary Si in the inner layer is opposite with the solidification direction, therefore lots of primary Mg_2Si and primary Si stayed and solidified in inner layer.

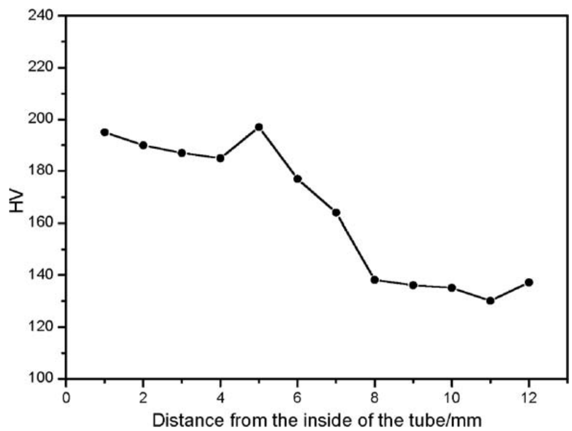

Fig. 8. Hardness distribution of composites.

With solidification going on, the Mg and Si content in solidifying molten alloy decreased. Finally, the solidifying molten alloy in the middle layer reached to eutectic composition, therefore eutectic structure was obtained.

It is demonstrated from the above analysis that the solidification velocity under the effect of centrifugal force and the floating velocity inward of primary Mg_2Si and primary Si determine together their position, quantity and distribution.

3.4. Hardness and wearability

Fig. 8 shows the results of radial Vickers hardness test of the studied composites. The distribution of hardness along the radial direction indicates that the hardness in inner layer is the highest, and then begins to decrease at some position toward outer layer; the hardness in middle layer is lowest, but in outer layer the hardness increases again slightly compared to middle layer.

Compared with the microstructure of the in situ composites, it is inferred that lots of blocky Mg_2Si and blocky Si, whose hardness are much higher than that of the matrix, segregated in inner layer, result in the higher hardness in inner layer. The hardness in middle layer without primary Mg_2Si and primary Si is the lowest. However, the hardness in outer layer is a little higher than that in middle layer due to a small amount of ununiformly distributed primary Mg_2Si and primary Si. Therefore, it is deduced that the hardness of the in situ composites increases with the increase of the amount of primary Mg_2Si and primary Si.

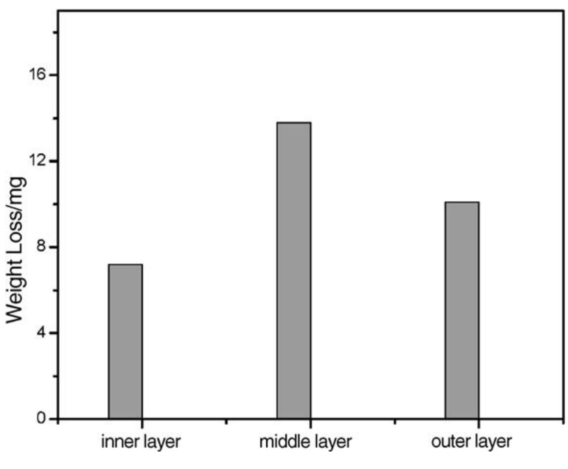

Fig. 9. Weight loss of the composites.

Fig. 9 shows the results of sliding wear test for studied composites. The results demonstrate that the wear resistance of middle layer without primary Mg_2Si and primary Si is the worst, and inner layer containing lots of blocky primary Mg_2Si and primary Si has the best wear resistance; the wear resistance of outer layer is higher than the middle layer and lower than inner layer. It is obvious that the wear resistance of the composites is determined by the quantity, shape and distribution of primary Mg_2Si and primary Si.

4. Conclusions

(1) In situ composites of Zn–27Al–6.3Mg–3.7Si alloy have been fabricated by centrifugal casting using the heated permanent mold. This kind of composites is consisted of three layers: inner layer segregates lots of blocky primary Mg_2Si and a little blocky primary Si, middle layer does not contain primary Mg_2Si and primary Si, outer layer contains a little primary Mg_2Si and primary Si.

(2) Zn–27Al–6.3Mg–3.7Si alloy solidifies according to following steps: firstly, the precipitation of primary Si and primary Mg_2Si, secondly, the precipitation of Zn-phase enriched with Al, thirdly, the precipitation of Mg–Zn compound, and lastly, the occurrence of ternary or quaternary eutectic reaction.

(3) The position, quantity and distribution of primary Mg_2Si and primary Si are determined by solidification velocity under the effect of centrifugal force and their floating velocity inward.

(4) The inner and outer layer contained primary Mg_2Si and primary Si exhibit much higher hardness and wear resistance.

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