Effect of centrifugal casting temperature on the microstructure and properties of ZTA<sub>P</sub>/HCCI matrix composites

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Keywords: centrifugal casting, ZTA, high chromium cast iron, casting temperature, three-body abrasive

Abstract

In the centrifugal casting process, the casting temperature parameters affected the microstructure characteristics, and the performance of the materials was greatly significant. ZTA (ZrO<sub>2</sub> reinforced Al<sub>2</sub>O<sub>3</sub>) particles reinforced HCCI (High chromium cast iron) matrix composites with honeycomb structure were obtained by centrifugal casting. With the increased casting temperature (1450 °C, 1500 °C, 1550 °C, and 1600 °C), the austenite equivalent diameter size was 43.5 μm, 34.8 μm, 33.1 μm, 22.3 μm respective in the compound area and 58.3 μm, 63.1 μm, 65.2 μm, 71.5 μm respective in substrate area. The average size of eutectic carbides in the compound area decreased from 5.7 μm to 2.5 μm with the casting temperature increased. Meanwhile, the lattice constants of austenite and carbide increased with the increased temperature. The hardness of the composites increased by 4 ~ 6HRC with a change in casting temperature. The results of three-body abrasive wear under high-stress static load conditions showed that the wear volume loss of the composites reduced with the temperature increased and the wear resistance was 1.4 times at 1600 °C than that at 1450 °C.

1. Introduction

Particle reinforced metal matrix composites (PRMMCs), especially zirconia toughened alumina (ZTA) particles reinforced iron matrix composites are widely used in cement, mining, and aerospace, particularly under adverse working conditions with good strength, fatigue resistance, and fracture resistance. The wear resistance, hardness, and specific modulus of metal matrix composites enhanced by particles are significantly improved [1–5]. B Qiu et al [6] prepared an iron matrix composite reinforced by ZTA particles and found that the composites had better impact wear resistance than traditional high chromium cast iron. Moreira AB et al [7] studied the centrifugal casting process to prepare WC<sub>P</sub>/ white cast iron composite material, the composite material with no defects and improved wear resistance about 7.23 times compared with high chromium cast iron. As far as roller is concerned, which is difficult to achieve under the traditional gravity casting, adding local reinforcement of ceramic particles on the outside surface [8, 9]. The centrifugal process parameters like casting temperature should be controlled to obtain the castings with the ideal performance [10, 11].

The change of casting temperature in centrifugal casting has a certain influence on the macrostructure and microstructure. Xiao Huang et al [12] studied the preparation of SiC reinforced Al alloy piston by centrifugal casting, through the study of the influence of different casting temperature, analyzing the higher casting temperature has a certain promoting effect to improve the quality of castings. Shrinkage cavity and porosity defects will exist because of the low casting temperature [13]. P Hidber et al found that by controlling the temperature, the densification of materials could also be enhanced [14]. At the same time, there is also a phenomenon that the casting temperature is too high, which leads to particle dissolution [15, 16]. However, very
few reports investigated the relationship between casting temperature and the microstructure, wear resistance in centrifugal casting ZTA particles reinforced high chromium cast iron matrix composites. In this paper, the effect of casting temperature on the matrix and carbides of the ZTA ceramic particle reinforced high chromium cast iron (ZTAP/HCCI) by the centrifugal casting process was investigated.

2. Experimental procedure

2.1. Materials processing

The ZTA ceramic particles (56% Al$_2$O$_3$, 40% ZrO$_2$, 3%TiO$_2$, and 1%Fe$_2$O$_3$) with the size of 2mm in equivalent diameter were selected for reinforcement and high chromium cast iron (table 1) was selected for matrix material in this work, respectively. The preform was mainly composed of particles and covered with ceramic powder. The particles were put into the mold cavity for curing and obtained the ZTA perform as shown in figure 1(a) and the schematic diagram of the centrifuge was shown in figure 1(b). The honeycomb hole/wall thickness ratio of the preform is 1.25 has the best compressive strength and wear resistance in our study [17]. An insulating layer of sodium silicate sand was covered on the inner surface of the mold and was preheated to 200 °C, the centrifuge
speed was set at 800r/min. The ceramic preform was divided into several pieces and put into the centrifuge cavity. The metal smelting was used by the medium frequency induction furnace and the casting temperature is 1450 °C, 1500 °C, 1550 °C, and 1600 °C, respectively.

Figure 2(a) shows the schematic diagram and sample location. The black part is the compound area and the grey honeycomb hole is the high chrome cast iron matrix. The samples were divided into the substrate area, the compound area, and no obvious defects were found as shown in figure 2(b).

2.2. Characterization

The surfaces of the specimens were polished and etched in 4 vol.% alcohol nitrates. The microstructure and wear morphology of the composites were analyzed by Nikon M300 metallographic microscope, energy disperse spectroscopy (EDS), and ZEISS EVO18 scanning electron microscope (SEM). The composite’s phases were identified by the X-ray diffraction (XRD, D/max-2500) and were scanned in the 2θ range of 20°–80° at a scanning rate of 2° min⁻¹. The hardness of the composites was tested by Rockwell hardness tester HR-150. The average grain size and volume fraction were analyzed by Image-pro plus, which has analyzed 150 metallographic pictures with uniform microstructure and nearly 2000 grains in the same cross-section at each temperature.

The wear resistance of ZTAP/HCCI composites was determined by means of a reciprocating abrasive machine at room temperature. Using SiO₂ of 0.6mm as the abrasive particles, the reciprocating horizontal speed of the samples was 1500 mm/min and the applied load was 600 N. The wear samples were 30 mm × 20 mm × 20 mm with 45° angle and was fixed by clamps. To ensure the accuracy of the experiment, the abrasive particles were changed new every one hour. The samples were cleaned with ultrasonic and weighed the samples mass loss by the electronic balance (the accuracy is 0.0001g) after each grinding-process over. The volume loss of the composites was calculated according to the formula in reference [18]:

\[ V_{\text{loss}} = \frac{m_{\text{loss}}}{\rho} \]  

(1)

In this formula, \( V_{\text{loss}} \) and \( m_{\text{loss}} \) refer to the volume and mass loss of the worn samples. The average density formula of the composites is as follow [19]:

\[ \rho = \rho_p + \rho_m(1 - \alpha) \]  

(2)

Among them, \( \rho_p \) and \( \rho_m \) indicated the density of ZTA ceramic particles and the density of high chromium cast iron, respectively. The \( \alpha \) indicated the volume fraction of ZTA particles in the composites.

3. Results and discussion

3.1. The results of microstructure and performance

From the results of X-ray diffraction shown in figure 3 that the substrate phases mainly are austenitic and (Fe, Cr)₇C₃ carbides, while the composites phases are austenitic, (Fe, Cr)₇C₃ carbides, Al₂O₃, and ZrO₂. The composite materials did not generate a new phase with the change of temperature as shown in figure 3. In these composites, the growth of carbide is mainly along with three directions: [421], [402], and [440]. At 1600 °C, the
and [440] peaks of (Fe, Cr)\(_2\)C\(_3\) were enhanced, indicating that (Fe, Cr)\(_2\)C\(_3\) mainly grew along the [421] and [440]. The Lattice parameters of austenite and (Fe, Cr)\(_3\)M\(_7\) at different casting temperatures was shown in table 2.

In order to examine the microstructure of the composite materials in detail, the substrate area and compound area were observed using a scanning electron microscope and obtained images were shown in figure 4. In figure 4(a), the carbides mainly are chrysanthemum-like eutectic carbides, while the carbides in the composites zone are finely hexagonal and lath-like as shown in figure 4(b). The results of energy disperse spectroscopy for four points in figure 4 was shown in table 3, it can be determined the chrysanthemum-like

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**Table 2.** Lattice parameters of austenite and (Fe, Cr)\(_3\)M\(_7\) at different casting temperatures.

| Casting temperature °C\(^{-1}\) | Lattice parameter /a(nm) |
|---------------------------------|--------------------------|
|                                 | Austenite                | (Fe,Cr)\(_3\)M\(_7\)    |
| 1450                            | 0.36004                  | 1.39591                  |
| 1500                            | 0.36012                  | 1.39648                  |
| 1550                            | 0.36021                  | 1.39767                  |
| 1600                            | 0.36101                  | 1.39878                  |

**Table 3.** Chemical Compositions of different point by the scanning electron microscope with electric mirror.

| Element (wt.%) | C   | Si   | Cr   | Fe   | Mo   | Mn   | Ni   |
|---------------|-----|------|------|------|------|------|------|
| Point1        | 2.10| 1.70 | 12.09| 81.40| 0.84 | 1.28 | 0.59 |
| Point2        | 9.82| 0.32 | 58.96| 29.75| 0.86 | 0    | 0.39 |
| Point3        | 1.74| 1.77 | 11.79| 84.3 | 0.51 | 0    | 0.28 |
| Point4        | 9.55| 0.23 | 54.88| 34.14| 0.44 | 0    | 0.37 |

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Figure 4. Scanning electron microscopy of substrate and compound at 1550 °C: (a), (c) Substrate (b), (d) Compound.
Eutectic carbides are Fe\(_2\)Cr\(_3\)C\(_3\) carbides. It can be seen that the elemental of Fe, Cr in the vicinity of the austenitic matrix in the compound area is different from the elemental of Fe, Cr in the vicinity of the austenitic matrix in the compound area.

**Figure 5.** Metallographic micrographs of the substrate area and compound area of the centrifugal casting composite materials at different casting temperatures (a) 1450 °C, (b, e) 1500 °C, (c, f) 1550 °C, (d, g) 1600 °C.
Figure 5 shows the microstructure of the substrate area and the compound area at four casting temperatures. From figure 5, it can be obviously seen that the appearance of isometric dendrites between the ceramic particles gradually transformed into fine and uniform cellular crystals with the increase of temperature.

Figure 6 (a) shows the equivalent grain size and volume fraction of austenite in the substrate area and compound area. The average size of austenite grains in the substrate area are 58.3 μm, 63.1 μm, 65.2 μm, and 71.5 μm, respectively. Compared to the substrate area, it can be learned that the equivalent diameter of the austenite grains in the compound area are 43.5 μm, 34.8 μm, 33.1 μm, and 22.3 μm with increasing casting temperature, respectively. The relationship between the casting temperature and the eutectic carbides size and volume fraction of the compound area was shown in figure 6(b). At the casting temperature of 1450 °C, 1500 °C, 1550 °C, and 1600 °C, the carbides volume fractions are 32.3%, 29.6%, 32.0%, and 31.3%, respectively. The

| Table 4. Microstructure changes at different casting temperatures. |
|-----------------|----------------|-----------------|-----------------|-----------------|
| Microstructure  | Austenitic physique | Austenite dimensions μm⁻¹ | Carbide size μm⁻¹ | Carbide content/% |
|                 | Substrate | Compound | Compound | Compound |
| 1450 °C        | Dendrite + Cellular crystal | 58.3 | 43.5 | 5.7 | 32.3 |
| 1500 °C        | Dendrite + Cellular crystal | 63.1 | 34.8 | 4.6 | 29.6 |
| 1550 °C        | Dendrite + Cellular crystal | 65.2 | 33.1 | 3.9 | 32.0 |
| 1600 °C        | Cellular crystal | 71.5 | 22.3 | 2.5 | 31.3 |

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The casting temperature has no obvious influence on the volume fraction of the carbides in the compound. The grain size of carbides changes from 5.7 μm to 2.5 μm as shown in table 4. With the increase in casting temperature, the hardness of the substrate area is 48HRC, 51HRC, 52HRC, and 51HRC, respectively. The hardness of the compound area increases from 50HRC to 55HRC with the casting temperature rise. Meanwhile, there is a phenomenon that the yield strength increased with the increasing casting temperature. The results of the three-abrasive wear tests with different casting temperatures were shown in figure 7(b). It can be seen that the composite material has the highest wear volume loss at the initial stage of the wear process (first 4 h). It can be seen from figure 7 that the hardness of the compound area is the highest and the wear volume loss is the lowest at the casting temperature of 1600 °C as shown in table 5.

Figures 8(a)–(d) shows the wear morphology of the composite material under different casting temperature conditions, from which it can be seen that the casting temperature has a significant influence on the wear resistance of the composite material. When the casting temperature is low (1450 °C, and 1500 °C), distinct grooves were visible.

Table 5. Performance changes at different casting temperatures.

| Performances | Hardness/HRC | Yield strength/Mpa | Wear loss mm\(^{-3}\) |
|--------------|--------------|--------------------|------------------------|
| 1450 °C      | 48           | 50                 | 971                    | 98                     |
| 1500 °C      | 51           | 52                 | 1167                   | 86                     |
| 1550 °C      | 52           | 53                 | 1206                   | 83                     |
| 1600 °C      | 51           | 55                 | 1351                   | 74                     |

Figure 8. The wear morphology of the samples with different temperature of (a) 1450 °C, (b) 1500 °C, (c) 1550 °C, and (d) 1600 °C.
3.2. The discussion of microstructure and performance

In order to understand the formation reason of microstructure, we found that the stability of high-temperature austenite is poor, and the phase transformation occurs easily during cooling to room temperature. When the cooling rate reaches the critical transformation rate of austenite transform to martensite that the martensite phase can be obtained. In the process of cooling process in this study, the cooling rate of the composites much lower than the critical cooling rate of martensite formation [20]. So, it is difficult to detect the martensite phase in the matrix of the composites. And the existence of austenite at room temperature is universal of high chromium cast iron, because the change of rapid cooling causing austenite to be oversaturation with C, Cr, and Mn, causing austenite stability increased, which reduced the initial temperature of martensite to below room temperature and inhibited the formation of martensite [21]. In addition, the composition of the experimental is in the range of hypoeutectic alloys which causing the matrix phase is austenite. On the other hand, Cr, and C dissolve more in matrix, causing atomic substitution of elements with large atomic radius and lattice distortion of austenite matrix, leading to the rise of lattice constant with the increase of casting temperature [22]. The lattice parameter will expand because of the interstitial atom logged in, which include C, Mo etc. With the increase of the interstitial carbon atom and Mo atom, the lattice parameter of (Fe, Cr)C carbides enlargement [23].

As the solidification progresses, the elements of Fe and Cr in austenite are supersaturated and precipitated. The eutectic reaction takes place and eutectic carbides begins to grow. Therefore, the eutectic structure composed of austenite and eutectic carbides is formed. In figure 4, there is directionality in the (Fe, Cr)2C3 carbides of short bar and slate-shaped. This is due to the rapid cooling of the liquid metal that is first in contact with the particles during pouring, and the increased subcooling of the components, which destabilizes the interface of solid-liquid, and the solid-liquid interface becomes curved and causes a disturbance in the carbides growth direction [24]. As can be seen in figure 4, the carbides morphology of the substrate area and compound area is different. The compound area is dominated by rod (Fe, Cr)2C3 carbides, while the substrate area is dominated by slate-like (Fe, Cr)2C3 eutectic carbides. According to the above findings, the composition content of the substrate area and compound area is different. Due to the different content of solute, the area of high solute concentrations reduces the local solid-liquid equilibrium temperature and thus prevent the growth of the carbides phase. The enhanced accumulation of solutes helps the carbides phase to grow preferentially as rods and avoiding lamellar growth. The carbides in the compound area are therefore more inclined to grow as bar carbides [25].

When the casting temperature increases from 1450 °C to 1600 °C, the solidification rate of the molten iron gradually decreases that the austenite grains have sufficient time to grow and the grain size becomes coarse in the substrate area [26]. The austenite in the compound area was refined due to the large temperature difference between the ceramic particles and the molten iron that accelerate the metal liquid solidification. Ren Shi et al. [27] found that the grain size decreased significantly with increasing cooling rate. As the casting temperature increases, the temperature gradient increases and the solidification rate decreases that the austenite change from dendrites to cellular crystals [28]. Due to the temperature rise and exist of the ZTA ceramic particles cause the degree of undercooling increases that the eutectic carbides are easier to form the nucleus. It is difficult to diffuse the elements Fe, C, and Cr that nucleus growth rate is slower and even stop growing, which leads to carbides grain size fine and uniform distribution[29, 30]. At the same time, Hoang et al found that with the decrease of the size of austenite crystallizer in high chromium cast iron, the size of carbides is gradually smaller [31]. Combined with the analysis results of figure 6, it can be seen that the organization of the degree of refinement and carbides size, distribution state is an important factor in determining the hardness of the casting [32]. The fine carbides and its uniform distribution around the austenite matrix increased the hardness and yield strength of the composite at 1600 °C.

The ceramic particles protrude during wear process, the main reason is that high-chromium cast iron has a lower hardness than ZTA ceramic particles and the high-chromium cast iron substrate was the first to be worn. As the wear time increased, the ceramic particles salient and the substrate was concave. The ceramic particles acted as a protection to the substrate, while the substrate acted as a support to the ceramic particles. With further increase in the wear process, the volume loss tends to be stable [33]. In the process of abrasion, the abrasive produces micro-cutting on the metal matrix between the particles, and the metal matrix between the particles under the repeated action of the abrasive. It produced micro-fatigue, pulled off of particles, and formed the abrasive ultimately [34, 35]. According to Richardson [36, 37] theory, the wear resistance of the material is directly proportional to its hardness, and the wear performance improvement because of the structure refinement [38]. At the casting temperature of 1450 °C, and 1500 °C, the hardness between metal and particles is low causing deep groove appears. At the casting temperature of 1600 °C, the hardness of the composite matrix was high, so it has good anti-wear properties and strong protection for the particles. On the other hand, coarse carbides usually have a lower fracture toughness than fine carbides and are more likely to fracture during wear process, thereby reducing the wear resistance of the material [39, 40]. The carbides at 1450 °C is thicker than that
at 1600 °C, which is prone to fracture and increases the wear volume. Therefore, as the casting temperature increases, the size of carbides and austenite decreases that causing the wear resistance increases.

4. Conclusions

In this study, the effect of temperature on the organization and properties of centrifugally cast ZTA<sub>4</sub>/HCCI with honeycomb structure composites was investigated, and the following conclusions were drawn:

1. Casting temperature is an important parameter to determine the microstructure of the casting. With increasing casting temperature, the grain size of austenite increased from 58.3 μm to 71.5 μm in substrate area. On the contrary, the grain size of austenite decreased from 43.5 μm to 22.3 μm with the increased casting temperature in compound area.

2. At four pouring temperatures of 1400 °C, 1500 °C, 1550 °C, and 1600 °C, the sizes of carbides were 5.7 μm, 4.6 μm, 3.9 μm and 2.5 μm respectively. The increase of casting temperature can refine the carbides of the compound area.

3. The increase in casting temperature significantly increased the hardness of the compound area. At 1400 °C, the rockwell hardness in substrate area is 50 HRC, while the rockwell hardness is 55 HRC in compound area at 1600 °C.

4. At the casting temperature of 1600 °C, the wear volume loss of the composite is minimal, and the wear resistance is the best under four casting temperatures.

Acknowledgments

This work was supported by talent Training Program of Kunming University of Science and Technology, China (KKSY201901004) and Yunnan Fundamental Research Projects (No.202001AU070084).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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