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Compressive deformation of semi-solid SiC_p/ZA27 composites ①

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Abstract: The semi-solid compressive deformation behaviors of two kinds of SiC_p/ZA27 composites, one was modified by Zr and the other was not modified, were investigated. The results indicate that with increasing strain, the stress of the modified composite first increases to a peak value, then dramatically decreases to a plateau value, and again increases at the final stage of deformation; but for the unmodified composite, after being up to a peak value, the stress decreases slowly at all times. As the deformation temperature or the heating time decreases, or the strain rate increases, the stress level(the peak and the plateau values) and the degree of cracking of the modified specimens all increase, and the specimen with uniform deformation and without cracks is obtained after being held at 470 ℃ for 30 min and deformed at the strain rate of $9.33\times10^{-3}s^{-1}$. But the degree of cracking of the unmodified is just inverse to that of the modified. Under the same deformation conditions, the stress level and the degree of cracking of the unmodified composite are higher than those of the modified one, and the degree of cracking is very serious under any conditions. These phenomena were mainly discussed through analyzing the microstructures under different conditions and deformation mechanisms occurred at different deformation stages.

Key words: SiC_p/ZA27 composite; semi-solid; compressive deformation; microstructure; thixoforming

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1 INTRODUCTION

The application of casting SiC_p/ZA27 composites is greatly limited due to the inhomogeneous distribution of SiC_p and the porosity existed in the matrix[1]. However, semi-solid forming technology (SSF) emerged in the recent years can not only decrease or eliminate the porosity and enhance the compactness of the matrix, but also improve the uniform distribution of the reinforcement through the redistribution of the reinforcement from its unique characteristics of mould filling[2]. In addition, SSF is a near net-shape forming technology, which is particularly important to the metal-matrix composites that are difficult to machine[3]. Therefore, SSF may afford a new idea for driving this kind of composite towards commercial application.

Thixoforming is the most widely accepted method in SSF, including three procedures, production of non-dendritic billets, re-heating and semi-solid forming[2]. Among them, the semi-solid compressive deformation behavior is one of the interesting research subjects because it embodies the abilities of thixoforming and mould filling, which are very important for mould design and determining processing parameters, and directly affects the properties of the shaped components. However, the present studies emphasized on the relationship between stress and strain and macrostructure changes[4-9], and none of papers were concerned about the morphologies of the specimens after being deformed and the deformation behavior of composites. In this paper, the effects of semi-solid temperature, heating time and strain rate on the strain—stress curves and morphologies of the compressed specimens are studied during compression deformation of two kinds of SiC_p/ZA27 composites, that is, one is modified by Zr and has fine equiaxed grains, the other is not modified and has developed dendrites. Then the thixoformability of this kind of composite and other particle reinforced metal matrix composites was theoretically discussed.

2 EXPERIMENTAL

2.1 Materials

The ZA27 matrix composite reinforced with 20% (volume fraction) SiC_p (20 μm) was fabricated by compocasting[10]. The nominal compositions of

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ZA27 matrix alloy were Zn-(26 - 28)Al-(1.7-2.0)Cu-(0.02-0.04)Mg(mass fraction, %). The composite of about 1 kg was remelted in a crucible furnace at 550 ℃, then the same mass of ZA27 alloy(modified by 0.4% Zr(mass fraction)) was dissolved in it, followed by adjusting the temperature to 440 ℃. After being mechanically stirred for 30 min (stirring speed: 400 r/min), the temperature was rapidly raised to 550 ℃ and the composite slurry was poured into a permanent mould at ambient temperature. Thus, the ZA27 matrix composite billets reinforced with 10% (volume fraction) SiC_p(20 μm) and modified by 0.2% (mass fraction) Zr were obtained(billet dimension: d18 mm × 120 mm). In order to discuss the effect of the initial microstructure on the deformation, the slurry of 10% (volume fraction) SiC_p (20 μm) reinforced ZA27 composite was fabricated at 550 ℃ by compocasting and directly pouring into the permanent mould with ambient temperature, then the same constitutional composite with developed dendrites was obtained, which was compared with the Zr modified composite.

2.2 Experimental procedure

Fig. 1 shows a schematic diagram of the compression apparatus used in this paper. The above-mentioned billets were machined into small specimens with dimension of d15 mm × 7.5 mm. After the temperature of the furnace was up to the pre-determined deformation temperature and held for 30 min, the specimen was quickly put on the bottom compression plate. Adjustment of the bottom plate made the specimen's surfaces exactly touch these two plates(the bottom and top plates). When the specimen was heated for the pre-determined time, starting the load apparatus made the bottom plate move up until its displacement reached 3.5 mm(the specimen was compressed by 3.5 mm in height), after which the specimen was quenched in water. The displacement—load curves were automatically recorded during deformation. The liquidus and solidus temperatures of the matrix alloy ZA27 were 492 and 437 ℃, respectively[5]. Three deformation temperatures, 450, 460 and 470 ℃, which were monitored by a thermocouples close to the specimen, three heating times, 15, 20 and 30 min, three velocities of the bottom plate, 21, 42 and 70 mm/min were used in this experiment, by which the effects of semi-solid temperature, heating time and strain rate on the deformation behavior were investigated, respectively. In order to reduce the friction between the specimen and the plates during deformation, the touching surfaces of specimen/plates were ground by 5 μm SiC sand paper and a layer of graphite powder was smeared on the surfaces of the plates(a kind of machinery oil was acted as the cohesive agent) prior to testing.

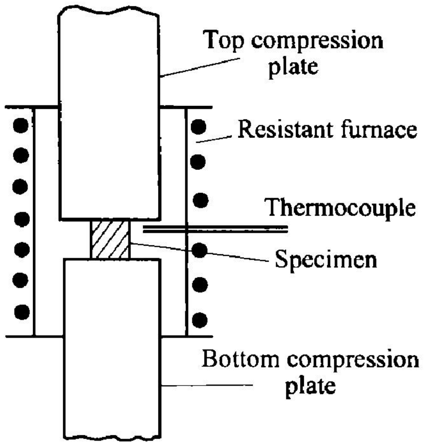

Fig. 1 Schematic diagram of compression apparatus

For the convenience of discussion, the bottom plate velocities were converted into strain rates. These three strain rates used in this experiment were 4.67×10^{-3}, 9.33×10^{-3} and $1.56\times10^{-2}\,s^{-1}$, respectively. The displacement—load curves were converted into strain—stress curves, the stress was calculated on the basis of overall volume conservation,

$$\sigma=(F/\pi R_0^2)(h/h_0) \quad (1)$$

where F is the load, h and h_0 are the instantaneous and initial heights of the specimen, respectively, and R_0 is the initial radius. The strain was calculated by

$$\varepsilon=|\ln(h/h_0)| \quad (2)$$

3 RESULTS

3.1 Effect of heating time

Fig. 2 shows the strain—stress curves of the compression deformation of Zr modified and unmodified SiC_p/ZA27 composites after being heated at 460 ℃ for different durations (strain rate = $9.33\times10^{-3}\,s^{-1}$). For the modified composite, with the deformation proceeded, the stress dramatically increases and exhibits a peak value at the strain of 0.04-0.07, then decreases sharply to a plateau value, which slightly decreases, and finally again increases at the strain of 0.7. It is also found that the strain at the peak stress shifts to lower values and the peak value decreases with increasing heating time(Fig. 2(a)). But for the unmodified material, after the peak values appears at the strain of 0.1-0.2, the stress does not decrease and directly reaches the plateau values; at the end of deformation, the stress does not increase and continuously decreases slightly; with increasing heating time, at least within the range of this experiment, there is no obvious change for the curves (Fig. 2(b)). Compared Fig. 2(a) with 2(b), it is found that the stress levels of the unmodified material are greatly higher than those of the modified. According to the characteristics of semi-solid alloys[11], it can be concluded that the thixoformability of the modified material is better than that of the unmodified.

Fig. 3 shows the morphologies of the two kinds of specimens (modified and unmodified) after being compressed. For the modified one, the degree of cracking of the specimen decreases with increasing heating time (Figs. 3(a) and (b)). After being heated for 30 min, there are cracks around of the edge where the strain is high, but they are filled with liquid phase and the specimen maintains its integrity (Fig. 3(c)). For the unmodified one, the degree of cracking of all of the specimens is very serious. This is consistent with the thixoformability discussed above: the better the thixoformability, the better the deforming ability. Because of the serious cracking, the unmodified specimens are difficult to show their configurations before quenched. But it can be found that although the areas of their central residual parts increase with the heating time (Figs. 3(d), 3(e) and 3(f)), their microstructures become loose and the small cracks increase, which indicates that the degree of cracking become serious with the heating time pro-

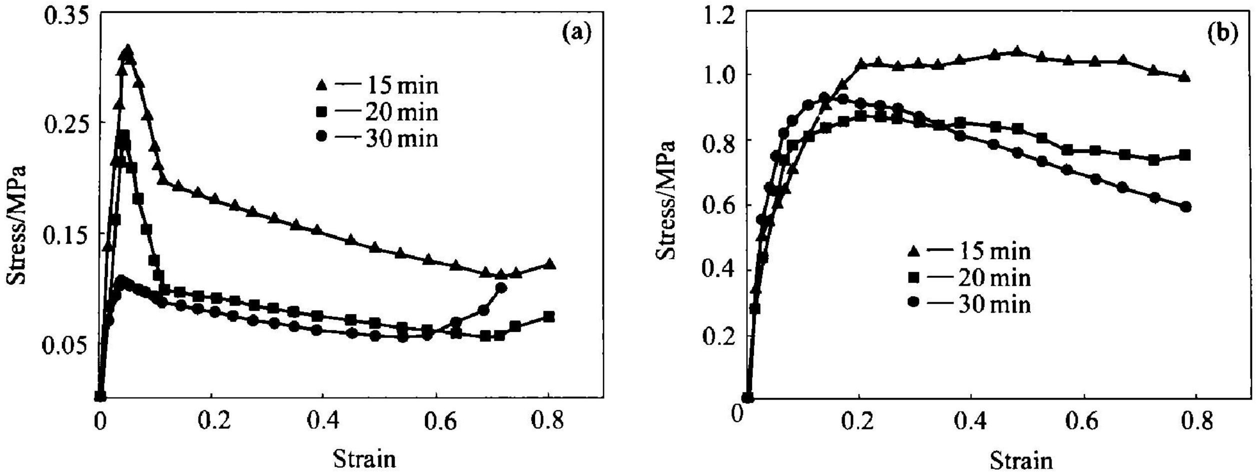

Fig. 2 Strain—stress curves of Zr modified (a) and unmodified (b) SiC_p/ZA27 composites during compression after being heated at 460 ℃ for different durations (strain rate = $9.33\times10^{-3}s^{-1}$)

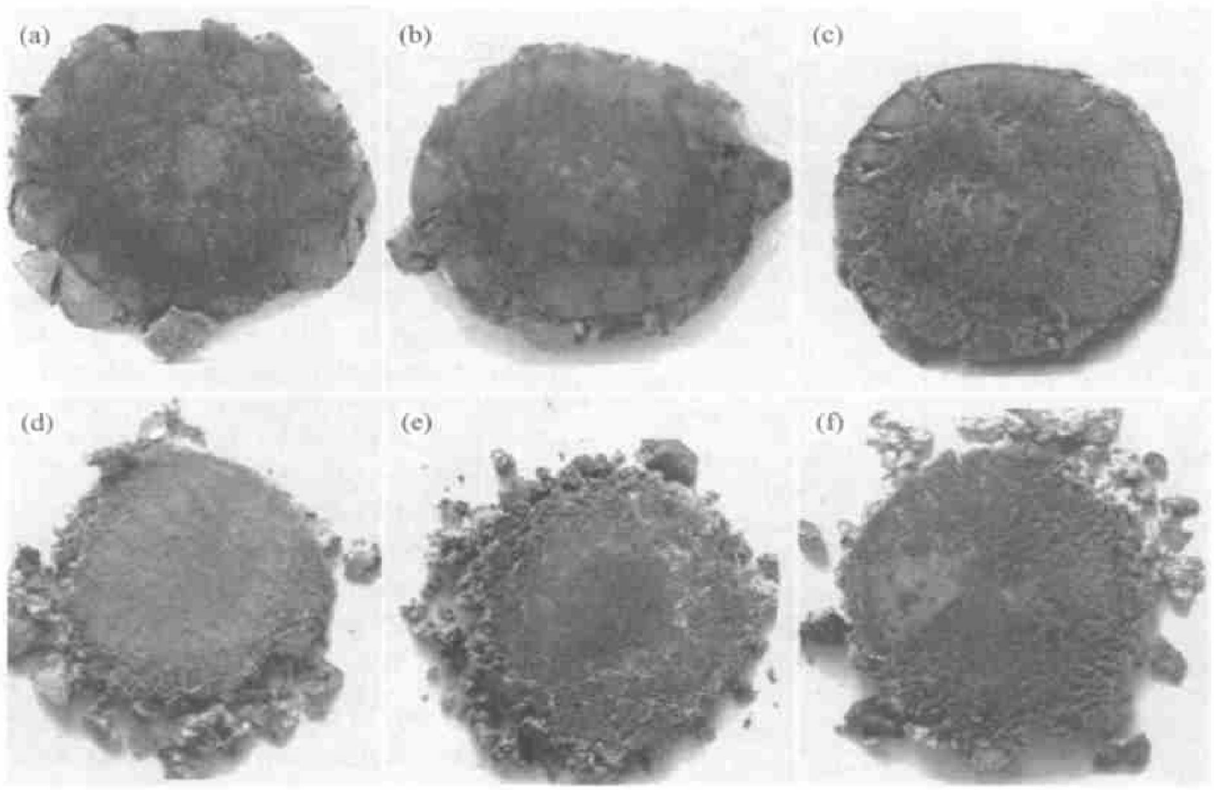

Fig. 3 Morphologies of specimens after compressive deformation when heated at 460 ℃ for different durations

(a), (b), (c) —Zr modified and heated for 15 min, 20 min and 30 min, respectively; (d), (e), (f) —Unmodified and heated for 15 min, 20 min and 30 min, respectively longing.

3.2 Effect of semi-solid temperature

Fig. 4 shows the strain—stress curves of the Zr modified and unmodified SiC_p/ZA27 composites after being heated at different temperatures for 30 min during deformation (strain rate= $9.33 \times 10^{-3} s^{-1}$). For the Zr modified, the stress is very high when the temperature is 450 ℃ and greatly decreases when temperature raises to 460 ℃, which indicates that its thixoformability enormously becomes better. When the temperature further increases, the peak value continuously decreases while the plateau value maintains constant. From the view of thixoformability and maneuverability in practice, the best forming temperature is 460–470 ℃, the small plateau value is suitable for mould filling and the moderate peak value is suitable for conveying of semi-solid material. For the unmodified composite, the curve at 450 ℃ is the same as that at 460 ℃, showing high stress level and bad thixoformability. But the stress dramatically decreases when the temperature rises to 470 ℃.

The morphologies of the specimens after being compressed show that, for the modified, the cracking around the edge is serious when deforming at 450 ℃(Fig. 5(a)), but decreases with increasing temperature (Fig. 3(a)), and no crack is found at 470 ℃(Fig. 5(b)); but for the unmodified composite, the tendency of cracking is just opposite to that of the modified(Figs. 5(a), 3(c) and 5(b)).

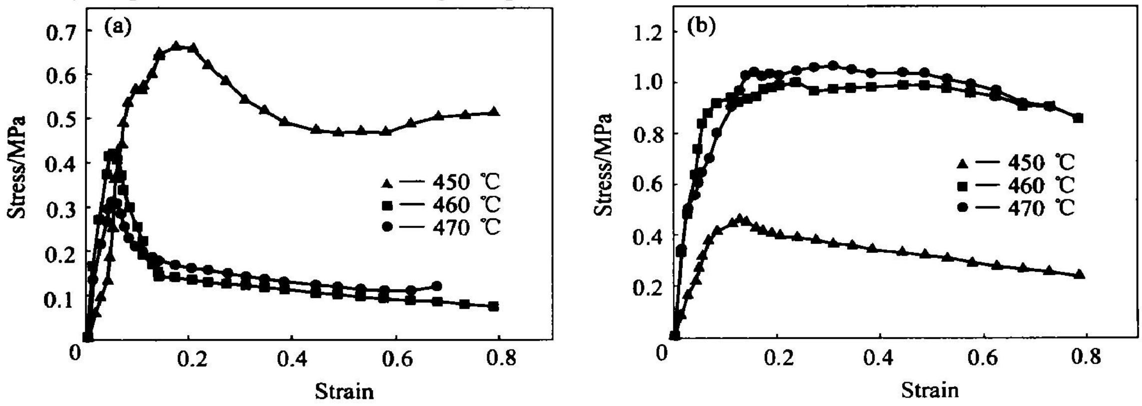

Fig. 4 Strain—stress curves of Zr modified(a) and unmodified(b) SiC_p/ZA27 composites during compression after being heated for 30 min at different temperatures (strain rate = $9.33 \times 10^{-3} s^{-1}$)

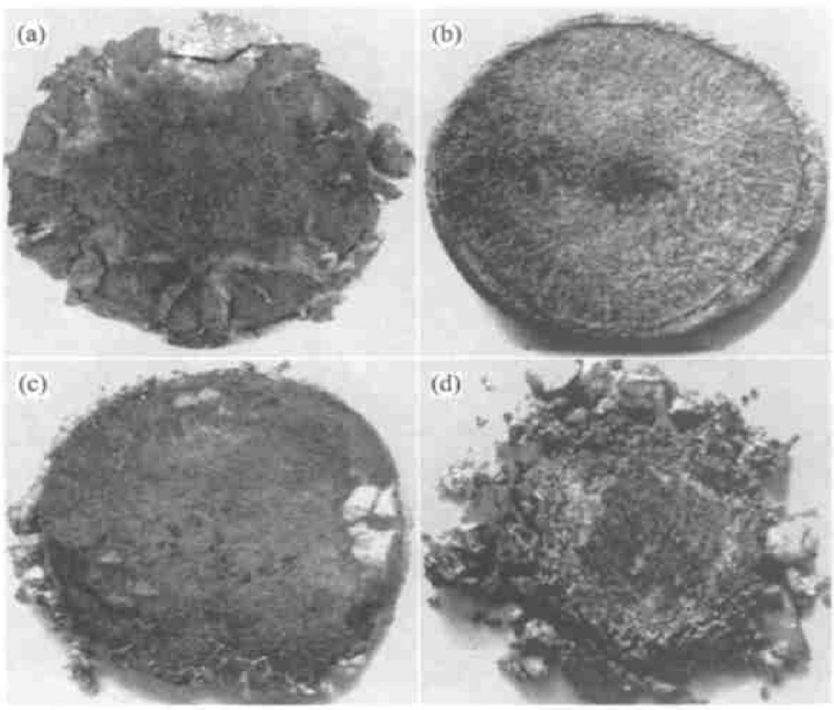

Fig. 5 Morphologies of specimens after compressive deformation when heated at different temperatures for 30 min

(a) —Zr modified, 450 ℃; (b) —Zr modified, 470 ℃; (c) —Unmodified, 450 ℃; (d) —Unmodified, 470 ℃

3.3 Effect of strain rate

Fig. 6 shows the strain—stress curves of the modified and unmodified SiC_p/ZA27 composites during compressing at different strain rates after being heated at 460 ℃ for 30 min. All of the modified composites show good thixoformability and the stress level decreases with increasing the strain rate. For the unmodified composites, the peak value is minimum at the strain rate of $4.67\times10^{-3}s^{-1}$, the stress is maximum at $9.33\times10^{-3}s^{-1}$, and the peak value is moderate, after which sharply decreases to the minimum plateau value when the strain rate is up to the maximum of $1.56\times10^{-2}s^{-1}$.

For the modified composite, no obvious cracks are observed except for some small cracks around the edge when the strain rate is $4.67\times10^{-3}s^{-1}$, and the tendency of cracking increases with increasing the strain rate(Fig. 7(a)), the depth of the cracks and the amount of liquid being squeezed out along the cracks also increase(Fig. 3(c)), and the specimen shows the morphology of gear wheel when the strain rate is $1.56\times10^{-2}s^{-1}$(Fig. 7(b)). For the unmodified, the cracking is also very serious, and the compactness of the specimens decreases and the small cracks increase with increasing

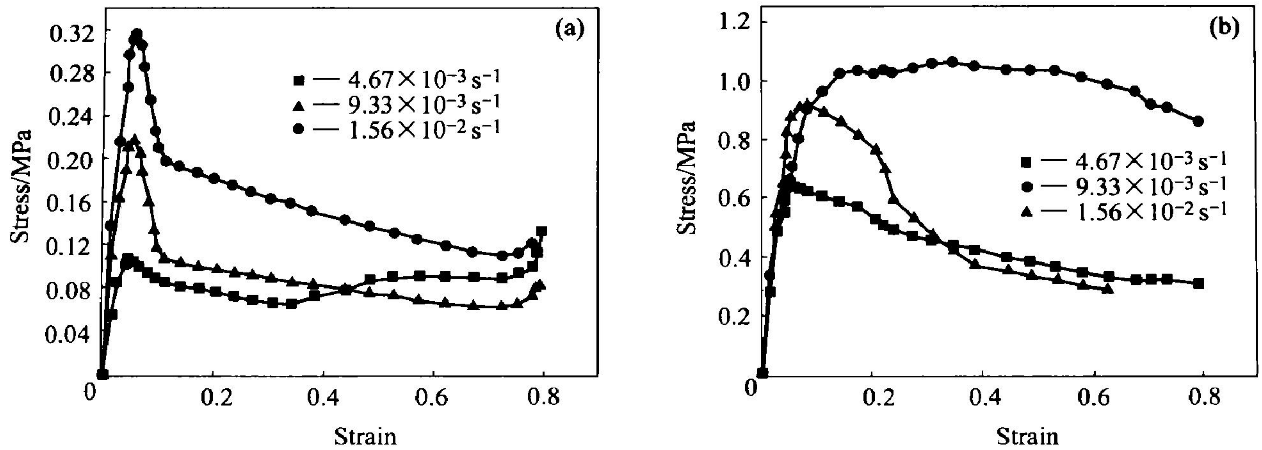

Fig. 6 Stress—strain curves of Zr modified(a) and unmodified(b) SiC_p/ZA27 composites during compression at different strain rates after being heated at 460 ℃ for 30 min

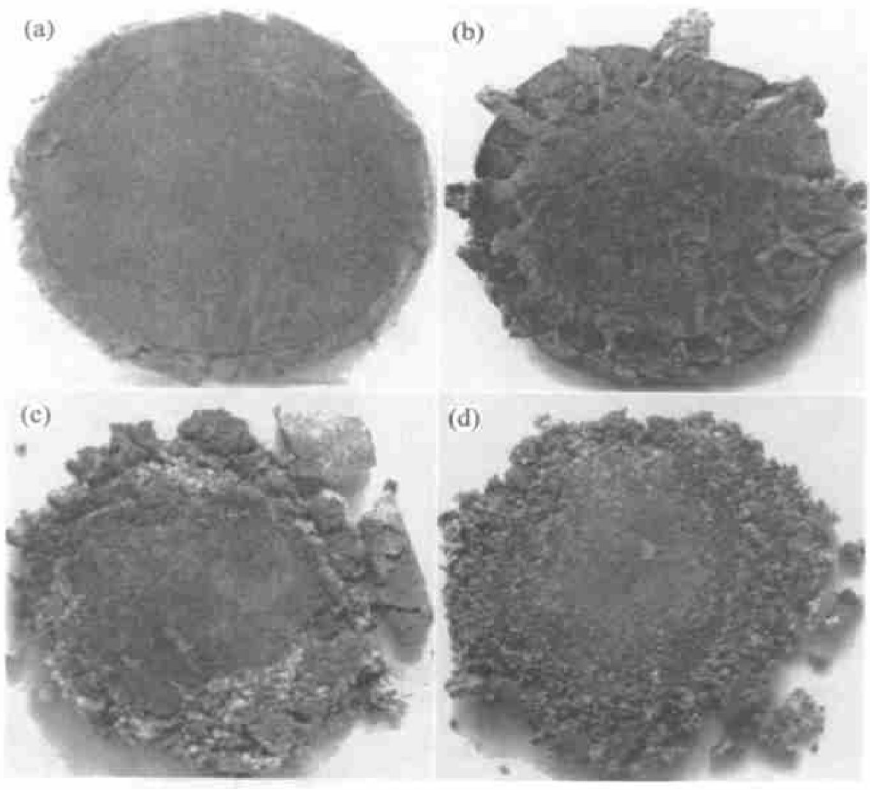

Fig. 7 Morphologies of specimens after compressive deformation at different strain rates when heated at 460 ℃ for 30 min

(a) —Zr modified, $4.67\times10^{-3}s^{-1}$; (b) —Zr modified, $1.56\times10^{-2}s^{-1}$; (c) —Unmodified, $4.67\times10^{-3}s^{-1}$; (d) —Unmodified, $1.56\times10^{-2}s^{-1}$

the strain rate, being similar to the effects of the heating time and temperature(Figs. 7(c), 3(f) and 7(d)).

4 DISCUSSION

Chen et al[12] proposed four deformation mechanisms of semi-solid non-dendritic materials: liquid flow(LF), flow of liquid incorporating solid particles (FLS), sliding between solid particles (SS) and plastic deformation of solid particles(PDS). The former two are dominant when the solid particles are surrounded by liquid phase and the later two are dominant when the solid particles are in contact with each other. During the initial stage of deformation, LF is dominant because the solid grains are always surrounded by liquid phase and it requires smaller force than the other three mechanisms. Subsequently, the liquid incorporating solid grains flow towards the edge of the specimen in order to meet the increasing of diameter, and FLS starts to dominate, which requires greater force than LF. Because a longer response time is required for liquid flow[4, 12], a peak value appears at very small strain(Figs. 2(a), 4(a) and 6(a)). As soon as the LF and LFS are active, the stress dramatically decreases. The liquid phase flows towards the edge of the specimen due to the compression deformation, resulting in the solid grains segregating in the center portion, and the liquid segregating around the edge. As the deformation proceeds, SS begins to dominate from the center of the specimen because it requires overcoming the friction force between solid grains and larger force than LFS. Therefore, the decreasing tendency of the stress decreases. The liquid phase in center further decreases with increasing area led by SS. As soon as the solid grains contact with each other, PDS starts to be active from the center, which requires larger force than SS. So the decreasing tendency of stress further decreases and then reaches the plateau value. At the end of the deformation, SS and PDS dominate and make the stress increase.

4.1 Effect of heating time

The authors' research indicates that the matrix of the SiC_p/ZA27 composite modified by 0.2% Zr has fine equiaxed grains and it becomes interconnected piece structure with little liquid phase when it is heated at 460 ℃ for 15 min, then into independent polygon grains due to increasing of liquid phase after heating for 20 min, and finally into small, uniform and spherical particles through spheroidizing with further increasing liquid phase after heating for 30 min[13], which is similar to the microstructural evolution of Zr modified ZA27 alloy[11]. According to the deformation mechanisms discussed above, SS and PDS are active at the initial stage of deformation, so the peak and plateau values are large after heating for 15 min(Fig. 2(a)). Although the grains are independent and surrounded by liquid phase when heated for 20 min, their morphology is polygon, thus the deformation harmonization is worse compared with the spherical structure when heated for 30 min. Therefore, SS and PDS also operate earlier and the stress level is higher. That is to say, the longer the heating time, the better the deformation harmonization and the easier the deformation, which also can be further demonstrated by Figs. 3(a), 3(b) and 3(c).

The matrix of the unmodified composite has developed dendrites, and the separation of its structure also takes place with increasing liquid phase during heating at 460 ℃, but its structure is still coarsely irregular grains even heated for 30 min and the grains size and shape factor are still larger than those of the modified composite when heated for 15 min[13, 14]. Therefore, SS and PDS operate earlier during deformation, thus the stress does not obviously decrease after it is up to the peak value, and there is also no obvious change for the strain—stress curves because their structures are all irregular grains with increasing the heating time (Fig. 2(b)). Accordingly, the degree of cracking of the specimens after being compressed is very serious because of the bad deformation harmonization. The strength between grains is weakened due to the increasing of liquid phase with increasing heating time, thus the small cracks in the center of the specimens increase and the structure becomes loose(Figs. 3(d), 3(e) and 3(f)). It is just because of the small cracks, the macro-strength of specimens is low and the stress does not increase at the end of deformation(Fig. 2(b)).

4.2 Effect of semi-solid temperature

The higher the semi-solid temperature is, the smaller the solid fraction, then the smaller the coarsening degree of grains due to the Oswald ripening and coalescence is, so the smaller and more spherical the grains are, contrarily, the higher the solid fraction, then the larger and more irregular the grains are[15]. The microstructure of the Zr modified composite is similar to that of the unmodified when the deformation temperature is 450 ℃, so its strain—stress curve is also similar to that of the unmodified, i.e. the stress is high and the decreasing is slow after the stress is up to the peak value (Fig. 4(a)). The solid fraction and grain size decrease with increasing temperature, and the grain becomes more spherical, then the proportion of LF and FLS increase during deformation, the thixoformability is enhanced and the stress level decreased(Fig. 4(a)), correspondingly, the degree of cracking of the specimens also decreases (Figs. 5(a), 3(c) and 5(b)).

For the unmodified composite, the peak value does not obviously decrease until the temperature rises to 470 ℃ and the liquid phase is sufficient enough. Compared with the modified composite, the grain shape is more irregular, so SS and PDS run earlier relatively, and the decreasing is smaller after the stress is up to the peak value (Fig. 4(b)) and the thixoformability is worse. Because the strength between grains is weakened due to the increasing of liquid phase with increasing temperature and the deformation harmonization is bad due to the irregularity of grains, the cracking tendency of the specimens is just opposite to that of the modified specimens (Figs. 5(c), 3(f) and 5(d)).

4.3 Effect of strain rate

Because the response time required by the deformation mechanisms decreases in the sequence of LF, FLS, SS and PDS, the deformation mechanisms will dominate in the same sequence during deformation[4, 12]. It is just for that LF and FLS require long response time, the peak value increases with increasing strain rate (Fig. 6(a)), and it is just because SS and PDS will dominate with the strain rate, the plateau value also increase, and the cracking tendency of the specimens increase due to the short time for harmonizing deformation (Figs. 7(a), 3(c) and 7(b)). The liquid phase is rapidly squeezed out and the specimen appears as the morphology of gear wheel at the strain rate of $1.56 \times 10^{-2} s^{-1}$. For the unmodified, the specimens easily generate cracks, similar to the discussion above. The tendency of the cracks not filled in time by liquid phase increases with increasing strain rate (Figs. 7(c), 3(f)). The specimen breaks down at the strain rate of $1.56 \times 10^{-2} s^{-1}$ (Fig. 7(d)) and then the plateau value dramatically decreases (Fig. 6(b)).

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