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Hot deformation behavior and processing maps of fine-grained SiCp/AZ91 composite

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ABSTRACT

Hot deformation behavior of fine-grained SiCp/AZ91 composite was investigated at the temperature of 543–693 K and strain rate of 0.001–1 s^{-1}. Processing maps based on dynamic material model (DMM) were developed at the strain of 0.1–0.5. Both the optimum process conditions and the dominant flow instability mechanism of fine-grained SiCp/AZ91 composite were given and analyzed. To describe the hot deformation behavior of fine-grained SiCp/AZ91 composite more exactly, the stress calculated by three typical constructive equations was compared with the measured value. The results show that the power law is deduced to be the most suitable constructive relationship for fine-grained SiCp/AZ91 composite, which is unlike previous reports. The calculated *Q* value increases with increasing temperature and strain rate. At 0.001 s^{-1}, the deformation mechanism of the composite is deduced to be grain boundary diffusion controlled dislocation climb; while, the deformation mechanism is deduced to be dislocation climb at 0.1–1 s^{-1}.

1. Introduction

Over the recent years, particle reinforced magnesium matrix composites (PMMCs) have attracted extensive attentions for their promising applications in automotive, defenses and aerospace field because of their low density, high specific strength, high specific stiffness and simple preparation process [1–3]. However, the hexagonal close-packed (HCP) crystal structure of magnesium matrix and the addition of brittle ceramic particles could limit their plastic forming ability at ambient temperatures. Thus, the PMMCs are usually deformed at high temperatures, where additional slip systems can be activated.

Based on the author's previous research [4], the fine-grained SiCp/AZ91 composite can be prepared by the combination of hot forging and subsequent extrusion process. This technology would help not only in refining microstructures but also in improving particle distributions. Previous researches have revealed that microstructural refinement was an effective way to improve the workability of magnesium alloys [5,6]. Presently, amounts of researches mainly focus on the hot deformation behavior of as-cast PMMCs [7–9], however, the deformation mechanism and workability of fine-grained SiCp/AZ91 composite is still unclear.

The constructive equations and processing maps are the main technology frequently employed by investigators to reveal the deformation mechanism and describe workability of PMMCs [2,10–13]. The constitutive equations, which describe the relationship between flow stress and strain rate during deformation process, are of vital important in conducting secondary processing. Up till present, three typical kinds of constitutive equations, i.e. the power, the exponential and the hyperbolic sine law, have been employed by investigators to describe the hot deformation behavior of metals and MMCs during hot working process. Such as nano-alumina reinforced AZ31 magnesium matrix composites (AZ31-NAL) [13], 10 μm 10 vol.% SiC particle reinforced AZ91 magnesium matrix composite (SiCp/AZ91) [7], $Mg_2B_2O_5$ whisker reinforced AZ31B magnesium composite [8] and AZ91 alloy [14].

Furthermore, the stress exponent *n* and the activation energy of deformation *Q*, which can be obtained by the constitutive equations, are the key parameters related to the deformation mechanism of the materials. It was reported that different *n* value corresponds to distinct deformation mechanism: $n = 2$ for slide of grain boundaries, $n = 3$ for viscous glide of dislocation, $n = 5$ for climb of dislocation and $n = 8$ for a constant substructure model (the microstructure remain constant during deformation) [15,16]. Wang et al. [7] have studied the hot deformation behavior of 10 vol.% SiCp reinforced AZ91 composite at the temperature range of 523–673 K and the calculated *n* and *Q* were 5 and 99 kJ/mol, respectively. The controlling mechanism during hot deformation

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was concluded to be the climb of dislocations. On Liu et al.'s [14] investigation of hot deformation behavior of commercial AZ91 alloy at the temperature range of 523–723 K, the calculated n and Q were 5.578 and 176 kJ/mol, respectively. The deformation mechanism was thought to be the cross-slip of screw dislocation from basal plane to prismatic plane and the deformation was controlled by dislocation climb.

Based on previous researches, the power law relationship is generally applied in the hot deformed alloys at low stress level [17]; the exponential law relationship is used at high stress level [18]; while, the hyperbolic sine law, in which both power and exponential law are involved, can be applied at a wider stress range [8,14]. In such circumstances, the selection of constructive equations seems important when investigating the deformation mechanism of certain materials. To describe the hot deformation behavior more accurately, comparison between above three constructive equations should be made to obtain the one with minimum deviation.

As a consequence, the aim of the present study is to investigate the hot deformation mechanism and characterize the workability of fine-grained SiCp/AZ91 composite utilizing processing maps and standard kinetic analysis.

2. Experimental procedure

2.1. Materials and preparation

AZ91 magnesium alloy was selected as the matrix alloy. Two size of SiC particles with average diameter of ~0.2 μm and ~10 μm were used as reinforcement. The bimodal size (0.2 μm 1 vol.% + 10 μm 9 vol.%) SiCp/AZ91 composite (denoted as "S-1+10-9") were fabricated by stir-casting technology. After solution treated at 688 K for 24 h, the composite ingots were processed by forging and subsequent extrusion. The detailed fabrication process had been described in Refs. [4,19].

2.2. Hot compression test

Specimens of Φ8 mm × 12 mm for compression test were machined from the as-extruded rods along the extrusion direction. The hot compression test was carried out using a Gleeble 3500 thermomechanical simulator. The specimens were lubricated with graphite to reduce the friction at the punch–specimen interface. Prior to compression, the specimens were conductively heated to the designed temperature at a heating rate of 5 K/s and held at the temperature for 5 min to ensure that the temperature was homogeneous throughout the specimen. The final strain of all specimens was set as 0.5. The temperature was designed from 543 to 693 K with an interval of 50 K. For each temperature, the strain rate was varied from 0.001 s^{-1} to 1 s^{-1}. When the specimen reached the designed strain, it was water-quenched quickly.

2.3. Microstructure characterization

The microstructure characterization was carried out by 4XC optical microscope (OM) and MIRA 3XMU scanning electron microscope (SEM). The compressed samples were cut into two parts from the center plane of the samples along compression direction. Then they were ground, polished and etched in acetic picral [5 ml acetic acid + 6 g picric acid + 10 ml H_2O + 100 ml ethanol (95%)] to investigate the morphological characteristics of grains. The observation position of the compressed sample is depicted in Fig. 1.

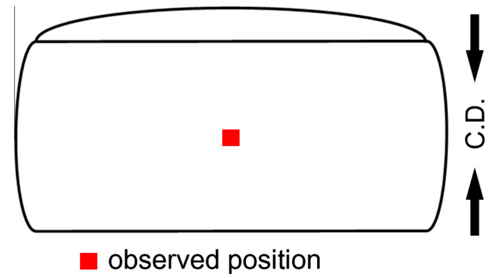

Fig. 1. The schematic diagram illustrating the observed position.

3. Results

3.1. Microstructures

The SEM micrographs of fine-grained S-1+10-9 composite before hot compression are depicted in Fig. 2. Fig. 2(a) shows that the SiC particles distribute uniformly in the matrix. The higher magnified SEM micrograph is depicted in Fig. 2(b). It illustrates that the composite matrix is composed of fine equiaxed grains. All the micron SiC particles locate at grain boundaries while the submicron SiC particles locate both at grain boundaries and within grains.

The optical microstructures of fine-grained S-1+10-9 composite compressed at different temperatures and strain rates are shown in Fig. 3. It shows that the grain size of matrix is fine and uniform at 543 K and 593 K. As the temperature increases to 643 K, bimodal size grains appear. The grains around micron SiCp are very fine while those away from micron SiCp grow up significantly, which indicates that micron SiCp can stimulate DRX nucleation. On Wang et al.'s investigation in Ref. [20], it has been proved that the micron SiCp had the promoting effect on DRX nucleation. As the deformation temperature increases to 693 K, the grain size of composite matrix keeps a bimodal distribution, while the fine grains around micron SiCp grow up slightly as compared with that at 643 K.

Fig. 3 also demonstrates that the microstructure varies with strain rates at a given deformation temperature. The matrix grains are refined with increasing strain rate at 543 and 593 K. The bimodal size grain distribution appears as the temperature increase to 643 and 693 K, and the distinctions of grain size between fine grains and coarse ones become much more evident with increasing strain rate.

Table 1 shows the average grain size of S-1+10-9 composite compressed under various conditions. It can be found that the average grain size decreases with increasing strain rate or decreasing temperature at 543 and 593 K. However, as temperature increases to 643 and 693 K, the changing trend of average grain size with strain rate or temperature becomes inconspicuous. This should be attributed to the appearance of bimodal size grain distribution. The standard deviation of average grain size increases with increasing strain rate, which can also indicate the distinct between fine grains and coarse ones becomes more evident.

3.2. Flow stress–strain curves

The true strain–stress curves of fine-grained S-1+10-9 composite compressed at the strain rate of 0.01 s^{-1} and at the temperature of 593 K are depicted in Fig. 4(a) and (b), respectively. It shows that the stress increases with increasing strain rate and decreasing temperature.

For a given strain rate (0.01 s^{-1}), the stress increases with strain during the whole deformation process at the temperate range of 543–593 K, which indicates that the work hardening is in the dominant position at lower temperatures, as demonstrated in Fig. 4(a).