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Constitutive behavior of C_{sf}/AZ91D composites compressed at elevated temperature and containing a small fraction of liquid

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ABSTRACT

Deformation behavior of 10 vol.% short carbon fiber reinforced AZ91D composite at the elevated temperature (596–696 K) and in the semi-solid state containing a small fraction of liquid (less than 10%) was investigated through compress test for the first time. The strain rate sensitivity and apparent activation energy in the semi-solid state are 0.2 and 392.3 kJ/mol respectively, which are higher than those in the elevated temperature. It is suggested that the presence of liquid phase causes the deformation behavior in the semi-solid state different from that at elevated temperature. The mechanical behavior of the composite can be characterized by the viscoplastic law in the elevated temperature. Considering the influence of liquid phase, a modified viscoplastic law was used to provide a unified description of the constitutive behaviors both at the elevated temperature and in the semi-solid state.

1. Introduction

Carbon fiber reinforced magnesium composite is an excellent candidate for high-performance and lightweight structural materials because of its low density, high specific strength, high damping capacity and dimensional stability [1,2]. Most of metal matrix composites (MMCs) have to be secondarily processed into structural parts. Processing MMCs above the solidus temperature of the matrix alloy have several merits in contrast to hot forming processes, including the feasible formability, low deforming force and low thermomechanical impact on moulds [3–8].

However the deformation behaviors of the composites above the solidus temperature of the matrix are quite different from those at elevated temperature. The resistance to deformation is lower than that in a solid state at elevated temperature for the reason that the stress concentration or pile-up of dislocations can be released by the liquid phase [9]. Liquid phase can also serve as a lubricant at the interface to improve the reinforcement redistribution which results in a lower work hardening rate [10,11]. The dominative deformation mechanism for the composite containing a small fraction of liquid phase may be grain boundary sliding rather than solute-drag controlled dislocation motion at elevated temperature [12,13]. But large fraction of liquid may lead to the liquid flow and low cohesion of interfaces, which results in a rapid decrease in formability [14]. In general, the mechanical behavior of composites containing liquid phase depends on the deformation conditions as well as the proportion and morphology of liquid phase, while the latter dependents on the metallurgical condition. For the magnesium matrix composites, the mechanical behavior of magnesium matrix composite containing liquid phase were less reported although many attempts have been devoted to understand their hot tensile [15,16], compressive [17–19] or superplastic [20,21] deformation behaviors in the solid state.

It is crucial to quantitatively characterize the mechanical behavior of the composites containing liquid phase for the selection of the process parameters and numerical simulation of the forming process operated above the solidus temperature. However, it is not easy to characterize the mechanical behavior in this condition because the deformation behavior and mechanism may be changed due to the appearance of liquid phase. Owing to the influence of reinforcement on the microstructure of matrix [22,23], the mechanical behavior of the composite containing liquid phase is also different from the corresponding matrix alloy in semi-solid state. Although there are various constitutive models for the semi-solid alloys [24–26], they cannot be utilized directly to characterize the mechanical response of the composites containing liquid phase.

In this paper, the compressive behaviors of 10 vol.% short carbon fibers reinforced AZ91D composite were tested both at the elevated temperature ranged from 596 K to 696 K and in the

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semi-solid state with less than 10 vol.% fraction of liquid. The constitutive behaviors of the composite at the elevated temperature and in the semi-solid state were analyzed and compared. On this basis, the influence of liquid phase on the deformation mechanism was discussed. Finally, a constitutive relationship was presented to describe the dependence of the peak flow stress on the temperature, liquid fraction and strain rate at the elevated temperature and in the semi-solid state.

2. Experimental

2.1. Material

The investigated material is 10 vol.% short carbon fibers reinforced AZ91D magnesium matrix composite, which is denoted as 10 vol.%C_{sf}/AZ91D composite. The composition of the AZ91D alloy is given in Table 1. The dimensions of the carbon fibers are 6 μm in diameter and 100–200 μm in length. The C_{sf}/AZ91D composite was fabricated by the squeeze casting, in which the preheat temperature of fiber preform and moulds was both 873 K, the pouring temperature 1073 K and the pressure 300 MPa.

2.2. Thermal analysis

The differential scanning calorimetry (DSC) analysis was conducted to test the remelting process of the composite using a STA449C DSC instrument. The sample for DSC analysis was machined from the composite ingot. The test temperature ranged from 303 K to 923 K and the heating rate was set as 30 K/min.

2.3. Compression tests

The compression tests were carried out using a Gleeble1500 thermomechanical simulator, at the deformation temperature ranging from 596 K to 748 K, strain rate ranging from 0.005 s^{-1} to 0.5 s^{-1} and ultimate compression ratio 50%. Cylinder specimens with the dimensions Ø8 mm × 12 mm were also machined from the composite ingot. Graphite lubricant was used in the compression tests so as to reduce friction. Specimens were heated to the pre-set temperatures with a heating rate 30 K/min. Specimen temperatures during heating and compression were recorded by a thermocouple inserted in the middle section under the surface.

3. Remelting and flow stress behavior

3.1. Remelting behavior

The DSC curve of C_{sf}/AZ91D composite has two endothermic peaks during the whole melting process, as shown in Fig. 1. The microstructure of the C_{sf}/AZ91D composite is shown in Fig. 2. According to the phase diagram of alloy AZ91D, the main constituents of the matrix alloy are the primary solid solution (α-Mg) and lamellar eutectic (constituted by α-Mg and β-$Mg_{17}Al_{12}$). The interfacial region includes the precipitated phase (β-$Mg_{17}Al_{12}$) and reactive phase (Al_4C_3), which has been verified by SEM, EDS and TEM in literatures [27,28]. The endothermic peak at low temperature on the heat flow curve (in Fig. 1) corresponds to the heat consumed during the melting of lamellar eutectic (constituted by α-Mg and β-$Mg_{17}Al_{12}$) and interfacial precipitated phase

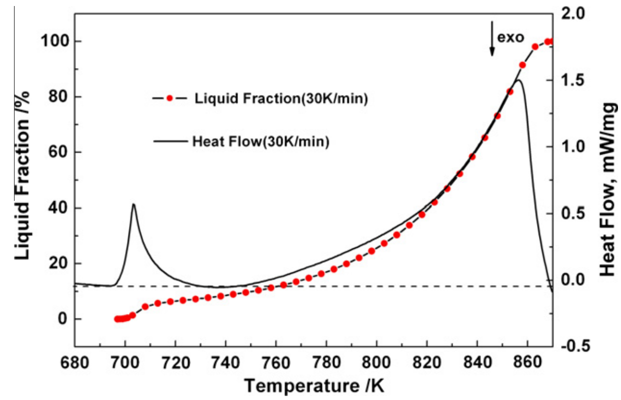

Fig. 1. DSC and liquid fraction curves of the as-cast C_{fiber}/AZ91D composite.

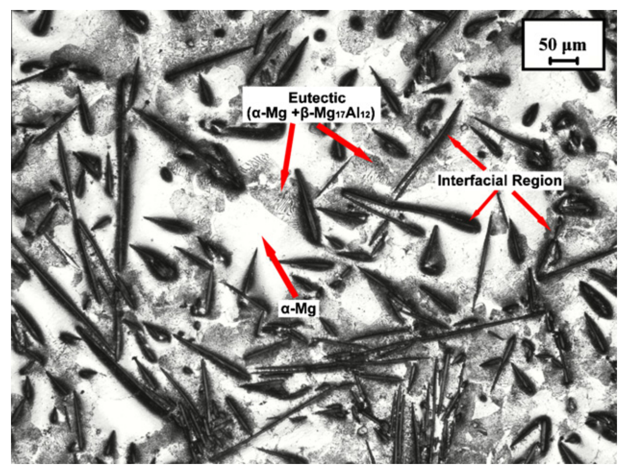

Fig. 2. Microstructure of the as-cast C_{fiber}/AZ91D composite.

β-$Mg_{17}Al_{12}$. While the endothermic peak at high temperature is related to the melting heat of the primary magnesium solid solution (α-Mg) in the matrix.

Melting the matrix alloy is first-order phase transition, in which the absorbed heat from phase transition is proportional to the fraction of transformation, as proposed in the non-isothermal DSC analysis [29]. The relationship between the volume fraction of liquid (fL) and the transition temperature (T) can be described by Eq. (1)

$$f_L(T) = \frac{\int_{T_S}^{T} W(T)dT}{\int_{T_S}^{T_L} W(T)dT} \quad (1)$$

where T_L and T_S is the liquidus and solidus temperature (K), *W(T)* is the rate of heat flow varying with temperature (mW/mg).

Based on the DSC data and Eq. (1), the relationship between the volume fraction of liquid and the transition temperature was calculated and then plotted in Fig. 1. The result shows the incipient melting temperature of the matrix is about 700 K, which can be regarded as the solidus temperature of the composite. As temperature ranging from 700 K to 750 K, it can be seen that the liquid fraction increase from 0% to 10% rapidly. This indicates that the

Table 1
Weight percentage of the main alloying elements (wt.%).

Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
8.3–9.7	0.35–1.0	0.15–0.50	<=0.10	<=0.030	<=0.002	<=0.005	Balanced