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Flow stress behavior and processing map of extruded 7075Al/SiC particle reinforced composite prepared by spray deposition during hot compression

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Abstract: Hot compression tests of the extruded 7075Al/15%SiC (volume fraction) particle reinforced composite prepared by spray deposition were performed on Gleeble−1500 system in the temperature range of 300−450 °C and strain rate range of 0.001−1 s^{-1}. The results indicate that the true stress−true strain curve almost exhibits rapid flow softening phenomenon without an obvious work hardening, and the stress decreases with increasing temperature and decreasing strain rate. Moreover, the stress levels are higher at temperature below 400 °C but lower at 450 °C compared with the spray deposited 7075Al alloy. Superplastic deformation characteristics are found at temperature of 450 °C and strain rate range of 0.001−0.1 s^{-1} with corresponding strain rate sensitivity of 0.72. The optimum parameters of hot working are determined to be temperature of 430−450 °C and strain rate of 0.001−0.05 s^{-1} based on processing map and optical microstructural observation.

Key words: 7075 Al; SiC; particle-reinforced composite; hot compression deformation; flow stress; processing map; superplastic deformation

1 Introduction

SiC particle reinforced aluminum matrix composites are widely used in structural applications, especially in the aerospace and automobile industries, due to their high specific stiffness and strength, high wear resistance, high dimensional stability, good erosion resistance and low thermal expansion coefficient [1−3]. Nowadays, many processes have been used to fabricate particle reinforced aluminum matrix composites [4], such as powder metallurgy [5], spray deposition [6], stir casting [7], rheo-casting technique [8]. Compared to the unreinforced matrix alloys, the composite materials are more sensitive to process variables, i.e., temperature, strain and strain rate, since the hard particles embedded in the soft matrix will lead to localized deformation [9]. Owing to the presence of hard ceramic reinforcements, these composites have worse hot workability than that of matrix alloy, hence it is of practical importance to explore hot deformation behavior of aluminum matrix composites.

The hot workability of SiC particle reinforced aluminum matrix composites has been extensively studied [10−14]. SU et al [10] compared the workability of spray-formed 7075/SiC_p aluminum matrix composites with conventional continuously-cast 7075Al alloy by employing the upset forming technique, and found that the yield strength of the spray-formed 7075/SiC_p aluminum matrix composites is larger than that of the continuously-cast 7075Al alloy for all initial strain rates. RAJAMUTHAMILSELVAN et al [11] studied the hot deformation behavior of 7075Al alloy reinforced by 10% of SiC particles fabricated by stir casting technique, and discovered that the flow stress is significantly low at lower strain rates whereas the work hardening rate is relatively high.

The processing maps, based on the dynamic materials model (DMM), considering the workpiece as a dissipator of the power supplied by a particular source, are frequently used to evaluate material workability as a function of process parameters such as temperature, strain rate, and strain [11−18]. ZHANG et al [12] obtained the optimum working regions of extruded

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Al−1.1Mn−0.3Mg−0.25RE alloy using processing maps. The processing map of 35%SiC_p/2024 aluminum alloy composites was established to evaluate the efficiency of the forging process in the ranges of temperature and strain rate investigated and the optimal hot deformation conditions were obtained by HAO et al [13]. The domains of dynamic recrystallization and wedge cracking were observed in the processing maps of 6061 Al/SiC_p composites by GANESAN et al [14], and the optimum working regions were identified. These studies suggest that the use of processing maps is currently a promising method to predict the deformation mechanisms under different deformation conditions, and it has been used to analyse the response of several aluminum matrix composites. It is also possible to optimize deformation process parameters and obtain products with improved properties.

According to DMM, the total provided power dissipated P can be obtained by the following relationships [15,16]:

$$P = \sigma\dot{\varepsilon} = G + J = \int_0^{\dot{\varepsilon}} \sigma \mathrm{d}\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon} \mathrm{d}\sigma \tag{1}$$

where the first integral (G) represents the temperature rise during deformation and the second integral (J) represents the power dissipated through metallurgical transformations (recovery, recrystallization, phase transformation) and material damage (void and fractured particle).

$$\sigma = K\dot{\varepsilon}^m \tag{2}$$

$$m = \frac{\partial(\lg\sigma)}{\partial(\lg\dot{\varepsilon})} \tag{3}$$

where K is a constant and m is the strain rate sensitivity.

According to PRASAD et al [17], the power dissipation capacity of the material can be evaluated by the efficiency of power dissipation η which is defined as

$$\eta = \left.\frac{2m}{m+1}\right|_{\varepsilon,T} \tag{4}$$

The variation of η with deformation temperature and strain rate was used to construct power-dissipation maps which are viewed as an equivalent efficient contour map. The power-dissipation maps describe the internal microstructure deformation mechanism of the work piece in a given range of processing temperature and strain rate. And the best hot working region is defined as a region with high power dissipation. However, a series of damage mechanisms, such as void formation, wedge cracking, inter-crystalline cracking, and other types of cracking processes, could happen in high power dissipation regions [18]. Hence, the instability criterion formulated on this basis is developed on the basis of the extremum principles of irreversible thermodynamics applied for large plastic flow. The instability map is developed on the basis of an instability criterion and given by the parameter ξ [13]:

$$\xi(\dot{\varepsilon}) = \frac{\partial \ln[m/(m+1)]}{\partial \ln\dot{\varepsilon}} + m < 0 \tag{5}$$

In the present work, the hot compression tests of the extruded 7075Al/15%SiC particle reinforced composite prepared by spray deposition were performed on Gleeble−1500 system in the temperature range of 300−450 °C and strain rate range of 0.001−1 s^{-1}. The hot deformation mechanism and optimum processing parameters were investigated by processing maps and microstructural observations.

2 Experimental

The 7075Al/SiC_p alloy metal-matrix composites, nominally containing 15% SiC particles (volume fraction), were produced by spray deposition [6]. The chemical compositions of matrix 7075Al alloy were 5.5% Zn, 2.2% Mg, 1.7% Cu, 2.2% Cr, 0.1% Mn, 0.4% Fe, 0.3% Si and balanced Al (mass fraction, %). The average diameter of SiC particles is 15 μm. The spray deposition billets were preheated at temperature of 400 °C and extruded on 1250T extruding machine with extrusion ratio of 64. The cylindrical specimens for hot compression test with diameter of 10 mm and height of 15 mm were machined from the extruded rods in respect to the extrusion direction. Hot compression tests were carried out on Gleeble−1500 system in the temperature range of 300−450 °C and strain rate range of 0.001−1 s^{-1}. The specimens were resistance heated to deformation temperature at a heating rate of 5 °C/s and maintained at that temperature for 3 min before deformation. The graphite mixed with machine oil lubricant was used on the interface of specimens and crossheads to minimize friction effect. After being compressed to a total true strain of 0.5, the specimens were quenched with cold water immediately to preserve the deformed microstructure.

The compressed specimens were sectioned parallel to the compression axis along the direction of centerline and prepared by the conventional methods for the optical microstructural observations on MM-6 metallographic microscope (OM).

3 Results and discussion

3.1 Flow stress behavior

A series of typical true stress–true strain curves of spray-deposited 7075Al/15%SiC_p composites obtained during hot compression at strain rate of 0.001−1 s^{-1} and deformation temperature of 300−450 °C are shown in Fig. 1. It can be seen that the true stress−true strain

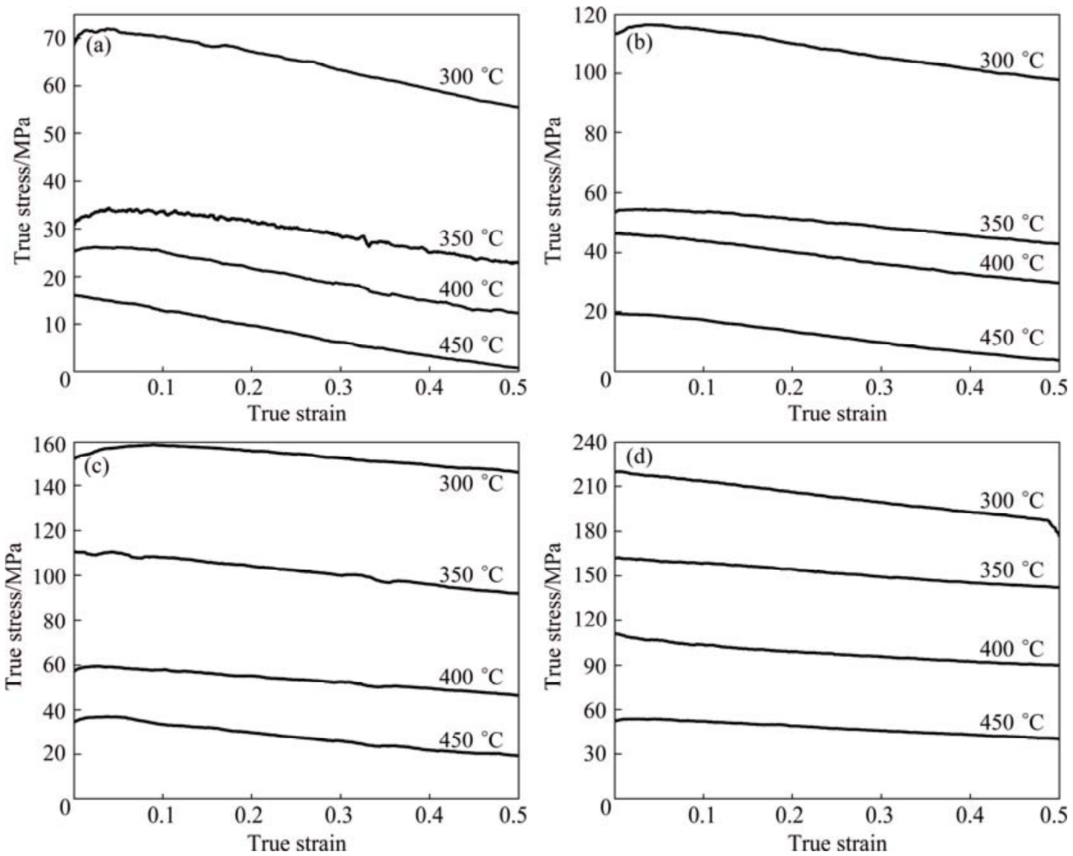

Fig. 1 True stress−true strain curves of spray deposited 7075Al/15%SiC_p composites during hot compression at different strain rates: (a) 0.001 s^{-1}; (b) 0.01 s^{-1}; (c) 0.1 s^{-1}; (d) 1 s^{-1}

curves at strain rate of 0.001−0.01 s^{-1} and deformation temperature of 300−350 °C present a slight work hardening at initial deformation stages, while the others exhibit rapid flow softening without an obvious work hardening at initial deformation stages and the stress decreases with increasing temperature and decreasing strain rate. The flow stress behavior might be related to the presence of concurrent matrix deformation mechanisms such as dynamic recovery, dynamic recrystallization and dynamic precipitates coarsening, which are commonly observed in hot deformation of heat-treatable aluminum alloys [19−21] and the interaction between matrix and SiC particles [9,10]. However, RAJAMUTHAMILSELVAN et al [11] discovered that the work hardening rate of 7075/SiC_p fabricated by stir casting technique is relatively high, and the true strain corresponding to the peak flow stress is greater than 0.1. The difference is that the spray deposition processing method gives the obtained parts a finer microstructure and high supersaturated solid solubility, which leads to the flow stress curves of the studied composite not showing obvious work hardening phenomenon at initial deformation stages.

Moreover, it can also be seen that the stress levels of the studied composite are higher at temperature below 400 °C but lower at 450 °C compared with the spray deposited 7075Al alloy [20]. The flow stress values of the composites are close to the result reported by SU et al [10], but are slightly lower than that of the 7075/SiC_p fabricated by stir casting technique at the same deformation condition [11]. The difference of flow stress values between this composites and the matrix alloy at low deformation temperature is influenced in the composites by the nonuniform constraints from the rigid particles and the high density dislocations induced by the difference of coefficient of thermal expansion ($\Delta\alpha$) between SiC particles and the matrix [9]. At higher temperature, the finer grains in matrix may play an important role in grain boundary sliding (GBS) and interface sliding (IS) between SiC particles and the matrix, and hence lead to the change of deformation mechanism.

The strain rate sensitivity m, which is calculated according to the variation of flow stress with strain rate at different test temperatures, is shown in Fig. 2. The value of m increases with increasing temperature and is slightly higher than that reported by SU et al (m=0.11−0.15) [10]. Especially, the maximum of the strain rate sensitivity is obtained to be 0.74 at strain rate of 0.001−0.1 s^{-1} and deformation temperature of 450 °C,

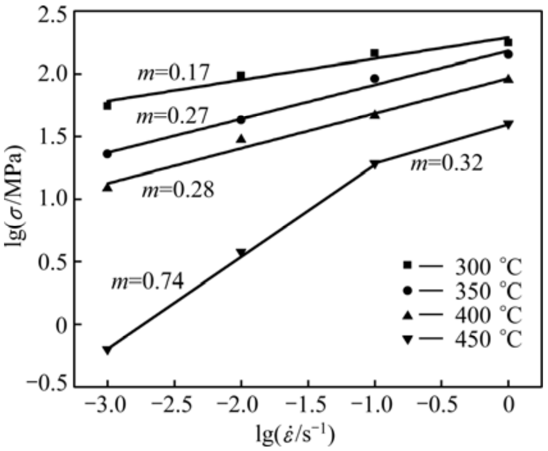

Fig. 2 lg σ versus lg $\dot{\varepsilon}$ curves for spray deposited 7075Al/15%SiC_p composites at true strain of 0.5

indicating that the composite exhibits superplasticity in the present deformation conditions. LI and CHEN [22] reported the superplastic deformation mechanics of SiC_p/2024Al composite fabricated by spray atomization and co-deposition, and noted that the composite fabricated by spray atomization and co-deposition contains fine grains and well-distributed SiC particles after pretreatment, and hence exhibits superplasticity. Superplasticity has been observed in aluminum matrix composites even at high strain rates (higher than 0.1 s^{-1}) [23−25]. With a relatively stable thermal structure, the optimum superplastic strain rate for particulate reinforced aluminum based composites was found to be even higher than that of the modified aluminum alloys [23]. Grain boundary sliding and interface sliding were considered to be the primary superplastic deformation mechanisms for metal matrix composite materials [24,25]. MISHRA et al [25] studied the mechanism of high strain rate superplasticity in aluminum alloy composites and noted that the requirement of very high temperatures for high strain rate superplasticity is connected to the accommodation rate required for non-deforming second phase particles. And the higher the temperature, the faster the accommodation process, which this leads to an increase in the ductility with the increase of temperature. Therefore, the superplasticity of the spray deposited 7075Al/15%SiC_p composites is related to the ultrafine grains formed in the spray deposited matrix and the accommodation ability of interface between SiC particles and the matrix. And the accommodation ability is enhanced by the ultrafine grains formed in the spray deposited matrix. When compared to the matrix material, the studied composite exhibits two different deformation mechanisms during hot deformation. The mechanism at strain rate of 0.001−1 s^{-1} and deformation temperature of 300−400 °C is similar to that of the matrix material, including dynamic recovery, dynamic recrystallization and dynamic precipitate coarsening during deformation [19−21], while superplastic deformation mechanism is observed at strain rate of 0.001−0.1 s^{-1} and deformation temperature of 450 °C.

3.2 Processing maps

The flow stress values obtained at true strain of 0.5 were used to establish the processing maps on the basis of DMM. The strain rate sensitivity m at different temperatures and different strain rates can be calculated according to Eq. (3). The efficiency of power dissipation η and the instability parameters at the strain of 0.5 can be calculated using Eqs. (4) and (5).

Figure 3 shows the processing map (power dissipation efficiency contours and the instability regions) of spray deposited 7075Al/15%SiC_p composites at strain of 0.5 during hot deformation. The numbers on contour lines represent the efficiency of dissipation and the shaded regions denote flow instability. These regions where the values of flow instability parameter are negative are characterized by the possibility of unstable flow. It can be seen that the processing maps (Fig. 3) exhibit only one peak power dissipation efficiency of 0.72 occurring at 450 °C and 0.01 s^{-1}, which is obviously higher than that in other studies [11−14]. The efficiency of dissipation decreases with decreasing temperature and increasing strain rate, which suggests that hot workability of this composites becomes worse with decreasing temperature and increasing strain rate.

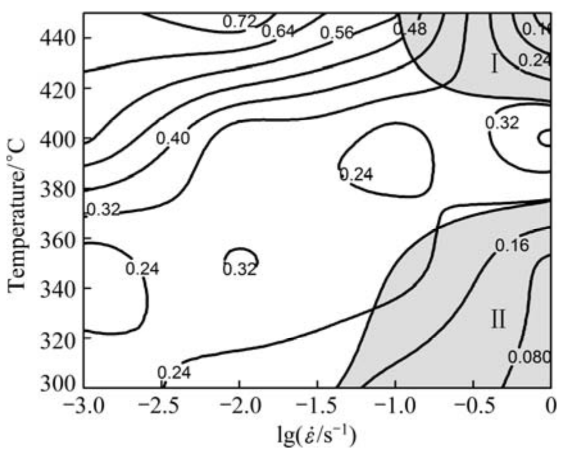

Fig. 3 Processing map of spray deposited 7075Al/15%SiC_p composites at true strain of 0.5

In addition, it can also be seen that there are two instable domains in the processing maps (Fig. 3): (I) 400−450 °C and 0.05−1 s^{-1} and (II) 300−390 °C and 0.05−1 s^{-1}. The instability domain (I) exhibits higher power dissipation efficiency of 0.48. Such high dissipation efficiency resulting instability is possibly caused by various mechanisms of material damage at different temperatures and strain rates [26]. Hence, these two domains are undesirable for processing and should be avoided. At low temperature and high strain rate (domain (II)), limited dynamic recovery allows dislocation to accumulate and cause an increase in stress, and the associated stress concentrations could cause particle/matrix detachment [9]. At high temperature (domain (I)), the occurrence of stress concentrations should be reduced by straining with low stress. However, when a composite is exposed to high temperature for a long period, reactions between the reinforcement and the matrix may degrade the material for different thermal expansions [9]. In stable region, the domain corresponding to deformation temperature of 430−450 °C and strain rate of 0.001−0.05 s^{-1}, in which the peak power dissipation efficiency of is higher than 0.64, is the optimum domain of present composite for hot working.

3.3 Microstructural observation

Figure 4 shows the optical microstructures of spray deposited 7075Al/15%SiC_p composite at strain rate of 0.001−1 s^{-1} and deformation temperature of 350 °C. It can be seen that the distribution of SiC particles in 7075Al matrix is streamline and tends to be inhomogeneous with increased strain rate. Figure 4(b) presents well-distributed particles and less voids, but Fig. 4 (d) shows nonuniform reinforcements with more and bigger voids. According to the processing map (Fig. 3), Figs. 4 (a) and (b) respond to stable region while Figs. 4 (c) and (d) respond to instability zone described by Eq. (5). The power dissipation η increases from 0.24 to 0.32 when the strain rate increases from 0.001 s^{-1} to 0.01 s^{-1}, but decreases to 0.08 when the strain rate increases to 1 s^{-1} at the temperature of 350 °C. So the result received from processing map is consistent with that obtained from microstructural evolution.

The microstructure corresponding to superplastic deformation region is shown in Fig. 5(a). It reveals that there are few and small voids and fractured particles relatively uniformly distribute in the matrix. The optical microstructure under 400 °C and 0.01 s^{-1} is shown in Fig. 5(b), and it is characterized by well-distributed particles and less voids. Figures 5(c) and (d) show the optical microstructure under 350 °C, 0.1 s^{-1} and 300 °C, 1 s^{-1}, which correspond to the instability domain. They are characterized by big voids at the interfacial between SiC particles and Al matrix in aggregation area of many broken SiC particles, as shown by the arrow at Fig. 5(d). It can be seen that the lower deformation temperature and higher strain rate lead to more serious segregation of broken particles. After analyzing the microstructure of the sample in four deformation conditions shown in Fig. 5, it is obvious that the microstructure at temperature of 450 °C and strain rate of 0.01 s^{-1} has little damage and more homogeneous particles. It is concluded that the processing map can exactly predict the hot workability of the material.

In order to predict damaging mechanism under different deformation conditions, processing maps were

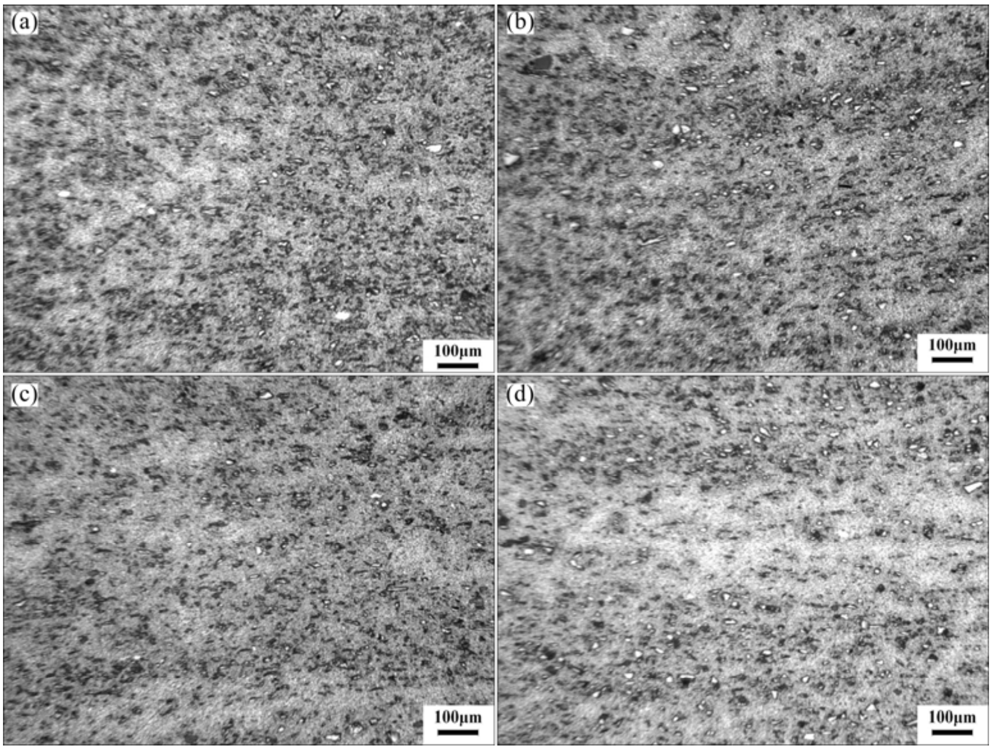

Fig. 4 Optical microstructures of spray deposited 7075Al/15%SiC_p composites at 350 °C and strain rates of 0.001 s^{-1} (a), 0.01 s^{-1} (b), 0.1 s^{-1} (c) and 1 s^{-1} (d)

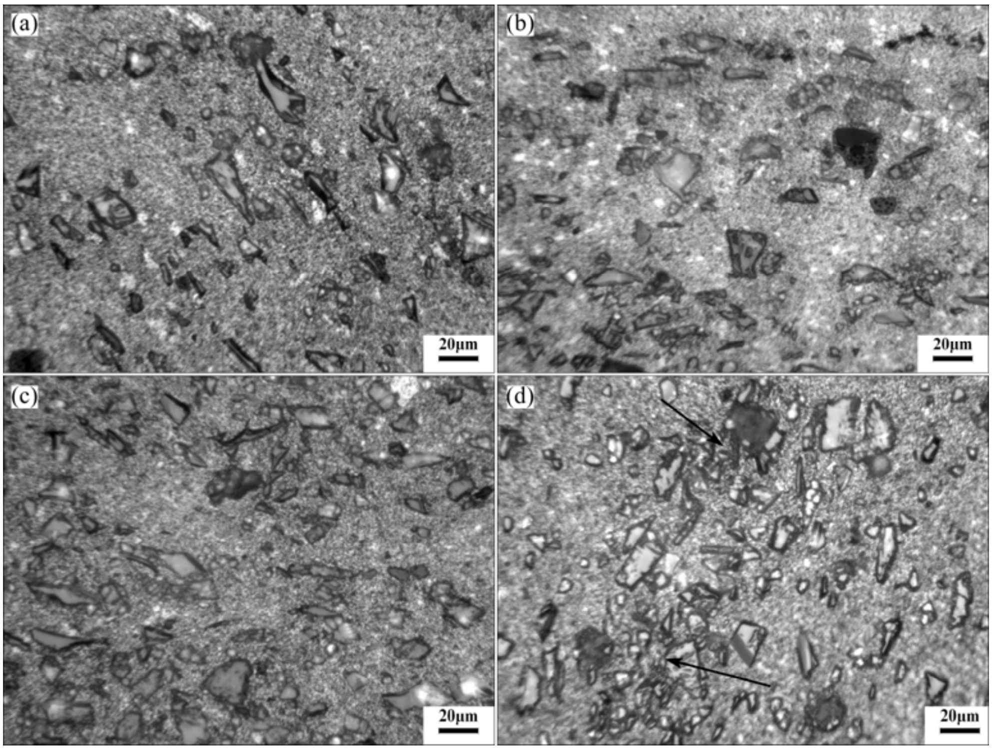

Fig. 5 Optical microstructures of spray deposited 7075Al/15%SiC_p composites under different conditions: (a) t=450 °C, $\dot{\varepsilon}$=0.01 s^{-1}; (b) t=400 °C, $\dot{\varepsilon}$=0.01 s^{-1}; (c) t=350 °C, $\dot{\varepsilon}$=0.1 s^{-1}; (d) t=300 °C, $\dot{\varepsilon}$=1 s^{-1}

obtained in this work. By analyzing the microstructure of the sample and the processing maps (Fig. 3), it is found that the instability zones correspond to high levels of damage and absence of restoration mechanisms, while the higher efficiency dissipation regions in the stability zones correspond to the optimum parameters for hot deformation of spray deposited 7075Al/15%SiC_p composites.

4 Conclusions

1) The true stress−true strain curves spray deposited of 7075Al/15%SiC_p composite at strain rate of 0.001−0.01 s^{-1} and deformation temperature of 300−350 °C present a slight work hardening at initial deformation stages, while at other strain rates and temperature, the curves exhibit rapid flow softening without an obvious work hardening at initial deformation stages. The stress decreases with increasing temperature and decreasing strain rate. Moreover, the stress levels are higher at temperature below 400 °C but lower at 450 °C compared with the spray deposited 7075Al alloy.

2) Superplastic deformation characteristics of spray deposited 7075Al/15%SiC_p composites are found at temperature of 450 °C and strain rate range of 0.001−0.1 s^{-1} with strain rate sensitivity of 0.72.

3) There are two instable domains in the processing maps of the composite: (I) 400−450 °C and 0.05−1 s^{-1} and (II) 300−390 °C and 0.05−1 s^{-1}. The optimum parameters of hot working for the composites are obtained to be temperature of 430−450 °C and strain rate of 0.001−0.05 s^{-1} based on processing maps and optical microstructural observation.

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挤压态喷射沉积 7075Al/SiC 颗粒增强复合材料热压缩流变应力行为及加工图

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摘 要：在 Gleeble−1500 热模拟机上对挤压态喷射沉积 7075Al/15%SiC 颗粒增强复合材料进行热压缩试验，变形温度为 300~450 °C，应变速率为 0.001~1 s^{-1}。结果表明：复合材料的真应力−真应变曲线几乎呈现快速流动软化特征，没有明显的加工硬化；其应力值随着变形温度的增加和应变速率的减小而减小，且当变形温度在 400 °C 以下时，其应力水平较喷射沉积态基体 7075Al 合金的高，但在 450 °C 时，其应力水平比基体合金的低。当变形温度在 450 °C 和应变速率为 0.001~0.1 s^{-1} 时，其应变速率敏感系数达 0.72，呈现超塑性变形特征。加工图以及金相显微组织观察表明：该复合材料最合适的热加工参数为变形温度 430~450 °C，应变速率 0.001~0.05 s^{-1}。

关键词：7075 铝合金；SiC；颗粒增强复合材料；热压缩变形；流变应力；加工图；超塑性变形

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