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Hot-deformation behaviour of spray-formed 2014 Al + SiC_P metal matrix composites

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Abstract

In the present investigation, discontinuous SiC particle reinforced 2014 Al alloy based metal matrix composites have been produced by spray forming process. The composites contained average particle sizes of 17, 30 and 58 μm in the range of 5–11 vol.%. The composites were tested for their compressive flow behaviour, in unlubricated condition, at strain rates of 0.01, 0.1 and 1.0 s^{-1} and at temperatures of 150, 300 and 450 °C. The flow stress for 30 μm size particle reinforced composite increased with increasing particle content from 0 to 8.5 vol.%, but decreased at 11 vol.%. The flow stress invariably decreased at larger strain values during deformation. The increase in particle size from 17 to 30 μm led to increase in flow stress at 300 °C, whereas, it decreased at 450 °C. The strain rate sensitivity (m) for 30 μm size particle reinforced composite was close to 0.16 up to 8.5 vol.%, whereas, for the composite with 17 μm size particles it decreased to 0.13 with increasing volume fraction up to 8.6 vol.%. The m values increased from 0.13 to 0.15 with increase in particle size from 17 to 58 μm. The variation in flow behaviour has been attributed mainly to particle fracture and debonding at particle/matrix interface, confirmed by microstructural features of the deformed samples. The major particle fracture events were recorded at low temperature and low strain rate of deformation. The composite with 30 μm size particles showed enhanced restoration process based on the low value of calculated apparent activation energy for diffusion (80–100 kJ mol^{-1}). This deformation behaviour of the composites has been discussed in light of microstructural observations and the void formation during deformation.

Keywords: Metal matrix composites; Hot deformation; Strain rate sensitivity; Flow stress; Al alloy; SiC

1. Introduction

Discontinuously reinforced metal matrix composites (MMCs) have seen considerable development in the recent years from the viewpoint of both primary as well as secondary processing. Such composites are attractive for various structural applications in the aerospace and automobile industries due to their unique combination of mechanical, physical and thermal properties [1–6]. The processing of composites is accomplished by several techniques such as stir casting, rheo-casting and powder metallurgy [2–4]. The powder metallurgy method is viable only for critical applications due to the prohibitive cost of production, and also the product size is limited. On the other hand, casting processes lead to a number of processing limitations such as non-uniform distribution of particles, clustering of particles, severe interfacial reactions, large amount of porosity, and finally the inability of the process to incorporate extremely fine size of ceramic particulates. These processing limitations have been addressed in recent times by adopting spray deposition/forming processing route for these composites. This route is capable of low temperature processing and gives rise to uniformity in particles distribution with minimal interfacial reaction products [2–4,7–12]. However, as we all know, the low ductility of composites at room temperature and lower fracture toughness of metal matrix composites, due to easy crack initiation at the interfaces between ceramic particles and matrix, are still the major disadvantage primarily during secondary processing of composites. Ceramic reinforcement in composites increases the hot strength and reduces the hot ductility of composites because they increase the initial dislocation density caused by the difference in the coefficient of thermal expansion and inhibit the plastic flow, due to relative rigidity, during

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deformation [2,4,6,13,14]. The formability of composites is of great concern due to the possibility of the commercial use of the composites in several key areas [15–19]. The deformation behaviour of MMCs is quite different from their base alloys in that the strain rate sensitivity and activation energy change with temperature, deformation rate and microstructural features. It has been observed that a non-uniform deformation pattern develops from the onset of yield, and at lower overall strain than those for unreinforced materials. Generally, ceramic particulates lead to enhanced strain localisation and increase in peak strain [2,4,6,13]. Both these factors combine to yield much higher plastic strain in regions where the majority of the macroscopic deformation is accommodated. The strain hardening of the slip systems in the composite matrix is enhanced compared to that in the unreinforced materials [6]. These effects are governed mainly by distribution, size and volume fraction of particles, and the applied stress conditions. Though a number of studies have been reported on powder processed and conventionally cast composites but the results on the spray-formed composites are limited. A detailed study of the effect of size and volume fraction on the deformation behaviour is required. Therefore, in the present study, 2014 Al alloy based and SiC_p reinforced MMCs, with different sizes and volume fractions, were produced by spray forming process. The hot-deformation behaviour were studied in terms of variation in flow stress behaviour, strain rate sensitivity and activation energy. Attempts have also been made to correlate the deformation parameters with the observed microstructural changes.

2. Experimental details

2.1. Spray forming of composites

Aluminium alloy (2014) based metal matrix composites, containing different sizes of silicon carbide particles with various volume fractions, were produced by spray forming technique. The particle size and volume fraction were varied in the range of 17–58 μm and 5–12 vol.%, respectively. The spray forming setup employed in the present investigation is described elsewhere [7,9]. To describe it briefly, elemental components of the 2014 alloy was melted in an induction furnace under a nitrogen cover at 750 °C and atomized at a melt flow rate of 330 kg h^{-1}. Cylindrical billets of 200 mm diameter and 400 mm height were produced with three different volume fractions of SiC_p. The SiC content and porosity formed in the billets have been reported earlier by the authors [9].

Radial slabs were machined from each of the cylindrical billets and were rolled to 50% thickness reduction at 500 °C in five roll passes. Specimen samples of 5 mm diameter and 10 mm length were machined from the rolled stocks for the deformation tests. Before these tests the density of each sample was measured using Archemedes principle. The amount of SiC_p was already known from the respective samples utilised for the measurement of SiC_p mass fraction. Tests were carried out on the samples containing 17, 30 and 58 μm size particles and with different volume fractions. Temperatures of 300 and 450 °C were chosen for this study using strain rates of 0.01, 0.1 and 1.0 s^{-1}. During deformation, the heating rate was kept at 8 °C s^{-1}, and then dwell was for 60 s. Before placing the samples in the holder a chromel–alumel thermocouple was diffusion bonded with the sample using a high current through a copper electrode so as to ascertain that the bond does not fail during heating of the samples. The density measurements were performed after the deformation tests also so as to infer the void formation during deformation process.

Deformed samples were prepared for metallographic examination using standard technique and were observed under scanning electron microscope to see the morphological changes occurred at different deformation conditions.

2.2. Determination of deformation parameters

The deformation behaviour of any metallic material is governed by the internal constitution of the material and the rate of strain hardening. The strength of materials increases with increase in the plastic strain rate. The strain rate sensitivity of a metal matrix composite is controlled by rate sensitivity of the matrix and the interaction between particle and the matrix. As the matrix flow is restricted, the channelled flow of matrix between two reinforcing particulates increase the composite flow stress. This effect becomes stronger as the deformation rate increases. The rate sensitive flow behaviour is given by [20,21]

$$\sigma = K\dot{\varepsilon}^m \tag{1}$$

where K is a parameter that depends upon structure of the material and temperature and, m is the strain rate sensitivity parameter. The value of m is determined by a variant of the Eq. (1) given at a constant strain and temperature [22]

$$m = \left.\frac{\partial \log \sigma}{\partial \log \dot{\varepsilon}}\right|_{\varepsilon,T} \tag{2}$$

The deformation behaviour of composites is influenced by the complexity of the dynamic microstructural processes. This can be understood by using activation energy (Q) for microstructural mechanisms that relates the steady state flow stress (σ) with applied strain rate (ε) and temperature (T) by an Arrhenius-type rate equation given as [23,24]

$$\dot{\varepsilon} = A\sigma^n \, e^{-Q/RT} \tag{3}$$

where A is a constant, n the stress exponent, which is also equal to $1/m$ [24], R the gas constant and Q the activation energy. At a given strain rate, the slope of the $\log \sigma$ and $\log (1/T)$ gives the activation energy.

The deformation process is accompanied by two power dissipation routes (1) the power required to bring in microstructural changes in the workpiece and (2) the dissipation in heat generation during deformation. For an ideal plastic flow, the flow stress is proportional to the strain rate at any strain and temperature. The efficiency is defined as the ratio of the heat dissipated in the microstructural changes and the maximum dissipation possible.