

Hot Deformation mechanisms in 7075Al/10%SiC_p metal matrix composites

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Abstract: The high-temperature deformation behavior of Al 7075/SiC_p Composites was investigated by carrying out compression tests for determination of the optimum hot deformation conditions. The tests were carried out in the temperature range of 300 – 500 °C and strain rates ranging from 0.001 – 1.0 s⁻¹ with a height reduction of 50%. The optimum hot-working conditions were decided from the processing map based on the dynamic materials model (DMM). Dynamic recrystallization (DRX) occurred over the entire temperature and strain rate range. However, uniformly sized grains were formed at the temperature range of 300 – 500 °C and strain rate range of 0.001– 0.01 s⁻¹, which are the optimum condition for hot working of this material. The characteristic microstructures predicted from the processing map agreed well with the results of microstructural observations.

Keywords: Metal-Matrix Composites (MMCS), Hot Deformation, Dynamic Recrystallization, Processing Map

1. Introduction

Discontinuously reinforced aluminum matrix composites exhibit unusual combinations of mechanical, physical and thermal properties-high stiffness and strength, high elastic modulus, good wear resistance, and good dimensional stability while retaining relatively low density, are attractive for many structural applications, especially in the aerospace and automobile industries [1-3]. However, a significant disadvantage of these materials is their low room temperature ductility and poor toughness because of the existence of a large amount of reinforcement particulate or whisker, i.e., silicon carbide particles (SiC_p) or silicon carbide whisker (SiC_w), and silicon nitride particles (Si₃N_{4p}) or silicon nitride whisker (Si₃N_{4w}). Their elongation to failure is typically less than 10% at room temperature. Consequently, conventional forming processes for metal matrix composites are relatively difficult in comparison with their monolithic alloy (matrix) counterparts. Hence, high temperature forming properties of aluminum based composites need to be studied [4].

The 7075 aluminum alloy is widely used in the aerospace application for its light-weight and high stiffness. To further improve the mechanical properties, particle or whisker-reinforced 7075 MMCs have been developed, and the mechanical properties and deformation behavior of these

MMCs are quite different from their base alloy. Many studies on these topics have been carried out in the past decade [5]. However, the mechanical properties and workability of 7075/SiC_p MMCs have not been well studied. Therefore, the purpose of this study was to investigate the workability of 7075/SiC_p MMCs at elevated temperature by employing the upset forming technique.

A processing map based on the dynamic materials model (DMM) is used to understand and constitutively analyze the hot workability of the 7075 Al/10% SiC_p composites. In the DMM model [6], the work piece subjected to hot-working conditions is considered to be a power dissipator. The instantaneous total power dissipation P consists of two complementary parts G and J , that is,

$$P=G+J \quad (1)$$

or

$$\sigma \dot{\epsilon} = \int_0^{\dot{\epsilon}} \sigma d\dot{\epsilon} + \int_0^{\sigma} \dot{\epsilon} d\sigma \quad (2)$$

where G represents the power dissipated by the plastic work and is known as the dissipater content. J represents the dynamic metallurgical mechanisms that occur during hot deformation and is known as the dissipater co-content.

σ and $\dot{\epsilon}$ represent the flow stress and the strain rate, respectively. At any given temperature and strain, the power dissipation between G and J is given by:

$$m = \frac{\partial \log \sigma}{\partial \log \dot{\epsilon}} \bigg|_{\epsilon, T} = \left(\frac{\sigma}{\dot{\epsilon}} \right)_{\epsilon, T} \quad (3)$$

where m is the strain rate sensitivity of flow stress.

The efficiency of dissipation η is given by:

$$\eta = J/J_{\max} = 2m/(m+1) \quad (4)$$

Here, η represents the efficiency of power dissipation occurring as a result of microstructural changes in the workpiece and η along with temperature and $\dot{\epsilon}$ is used to construct a processing map.

DRX, dynamic recovery (DRV), superplasticity, void formation, and precipitation from metastable phase are observed during hot deformation. Because of this, the microstructure of the workpiece changes remarkably. The values of the dissipation efficiencies are high, irrespective of whether or not the microstructural changes are beneficial to hot workability of the alloy. Therefore, it is necessary to separate the power dissipation from the harmful ones when using the power dissipation maps for deciding the optimum hot-working conditions. The “safe” mechanisms include DRV, DRX, and superplastic deformation while the microstructural “damage” mechanisms include void formation, wedge cracking, intercrystalline cracking, and other types of cracking processes [7]. The other phenomena are considered to be unstable because they give rise to shear bands or inhomogeneity in the microstructures of the alloy as a result of flow instability. A criterion based on continuum principles that is applicable to large plastic flow proposed by Ziegler was developed for delineating the regimes of flow instability; accordingly, instability occurs when the following condition is satisfied:

$$\xi(\dot{\epsilon}) = \frac{\delta \ln(m/m+1)}{\delta \ln \dot{\epsilon}} + m \leq 0 \quad (5)$$

where ξ is the instability parameter. The onset of flow instability was observed when $\xi \leq 0$ [8].

In the present study, the hot deformation characteristics of 7075 Al/10% SiCp composites are investigated using hot compression tests. Using the load-displacement data obtained from the hot compression tests, processing map will be constructed using the load-displacement obtained from the tests used for interpreting the experimental stress-strain curve and determining the optimum hot-working conditions. The hot-workability parameters such as m , η , and ξ are evaluated by using the experimental data. The experimental results are discussed and compared with those of microstructural observations.

2. Material Flow Instabilities during Hot Deformation

In general, occurrence of microstructural processes in metals and alloys during hot deformation are: dynamic recrystallization (DRX), super plastic deformation, dynamic recovery, Wedge cracking, void formation, intercrystalline cracking, prior particle boundary (PPB) cracking and flow instability processes. On the basis of Raj maps [8,9] the deformation characteristics of materials are interpreted as follows. In the low temperature ($T \leq 0.25T_m$), high strain rate regime ($10-100 \text{ s}^{-1}$), void formation occurs at hard particles leading to ductile fracture. In the high temperature ($T \geq 0.75T_m$), low strain rates ($\leq 10-3 \text{ s}^{-1}$) regime, wedge cracking caused by grain boundary sliding occurs (except in super plastic materials in which wedge cracking is at a minimum). In high temperature ($T_m \approx 0.75$) and high strain rate regime (10^{-1} to 10 s^{-1}), dynamic recrystallization occurs in low stacking fault energy materials. At intermediate temperatures and strain rates dynamic recovery process occurs. At very high strain rates ($\geq 10 \text{ s}^{-1}$) there is a possibility for the occurrence of adiabatic shear bands and these lead to flow localization. Out of all the above mechanisms, DRX and super plastic deformation are ‘safe’ mechanisms for hot working while dynamic recovery is preferred for warm working. All other mechanisms either cause microstructural damage or in homogeneities of varying intensities and hence are to be avoided in the microstructure of the component. This section highlights briefly on the existing instability theories for identifying the temperature strain rate domains of flow instabilities during hot deformation of materials.

3. Experimental Studies

Stir casting technique was used to fabricate 7075Al alloy reinforced with 15% volume fraction of silicon carbide Composites. The matrix material was 7075 Aluminium Alloy (Composition in wt% Cu 1.66, Mg 2.10, Si 0.14, Mn 0.21, Fe 0.40, Cr 0.18, Zn 5.67, Ti 0.01 and rest Al) and the reinforcement was SiC_p with average size of 5 μ m. The aluminium alloy was melted by using an Electric Furnace. Preheated SiC_p (250°C) was added to the melt and mixed by using a rotating impeller in Argon environment and poured in permanent mould. The cast billets were soaked in the temperature of 400°C for 30 minutes and hot extruded. The cylindrical specimens of dimensions, 10 mm in diameter and 10 mm in Height were machined from the extruded rods.

The hot compression tests [10] were performed on a IOT servo controlled universal testing machine for different strains (0.1 – 0.5), strain rates (0.001s⁻¹ - 1.0s⁻¹) and temperatures (300 - 500°C). Temperature of the specimen was monitored with the aid of a chromel/alumel thermocouple embedded in a 0.5mm hole drilled half the height of the specimen as stated by Yi Liu et al[6]. The

thermocouple was also used for measuring the adiabatic temperature rise in the specimen during deformation. The specimens were effectively lubricated with graphite and deformed to a true strain of 0.5. After compression testing, the specimens were immediately quenched in water and the cross section was examined for microstructure. Specimens were deformed to half of the original height. Deformed specimens were sectioned parallel to the compression axis and the cut surface was prepared for metallographic examination. Specimens were etched with Keller's solution. The microstructure of the specimens was obtained through Versamet 2.0 optical microscope with Clemex vision Image Analyser and mechanism of deformation was studied. Using the flow stress data, power dissipation efficiency and flow instability were evaluated for different strain rates, temperatures at a constant strain of 0.5. The processing maps were developed for 0.5 strains for 7075Al/15% SiC_p composites.

4. Results and Discussion

The flow stress data was generated covering the temperature range of 300 - 500 °C and strain rate range 0.001 - 1.0 s⁻¹ from compression testing of solid cylinders of size 10 mm in diameter and 10 mm in height using servo hydraulic testing machine capable of imposing constant true strain rates on the specimen. Adiabatic temperature rise during high strain rate testing was measured and the flow stress was corrected for the temperature rise. The specimens were compressed to 50% of their initial height and the load-stroke curves obtained in the hot compression were converted in to true stress-true plastic strain curves by subtracting the elastic portion of the strain and using the standard equations for the true stress and true strain calculations. The values of the efficiency parameter (η) and the strain rate sensitivity parameter (m) to use the instability condition ^[11] are determined from the flow stress test data of the material.

4.1. Flow Behavior

The flow stress data obtained at different temperatures, strain rates and strains were corrected for adiabatic temperature increment. The shape of stress-strain curves indicates some features helping to identify the mechanisms of the hot deformation.

The typical flow curves obtained at 450°C for different strain rates are shown in Fig. 1. The curves are corrected for deformation heating. At strain rates lower than 0.1 s⁻¹, the curves are consistent with the generally reported behavior of other materials under hot deformation conditions. There is initial work hardening, which leads to a pronounced peak stress followed by steady-state deformation at large strains. Such behaviors have been shown to be typical for dynamic recrystallization taking place under hot deformation [6]. At strain rate of 0.1 s⁻¹, the flow curves exhibited continuous flow softening after a

peak stress whereas other curves shown steady-state behavior. Dynamic recrystallization, flow instability and cracking may be shown as flow softening behavior [12].

Fig.2. shows the true stress-true strain curves obtained at a constant strain rate of 0.1s⁻¹ and at various temperatures. Flow stress decreases with the increase in temperature and decrease in strain rate. Work hardening characteristic decreases with increase in temperature. The flow curves exhibit nearly steady state behavior and the critical strain to the steady state increases with temperature decrease. The flow curves exhibit flow softening behavior at 450°C, and the steady state flow behavior was not observed at large strain. Further, the flow curves exhibited a peak at the beginning of plastic deformation at 450°C.

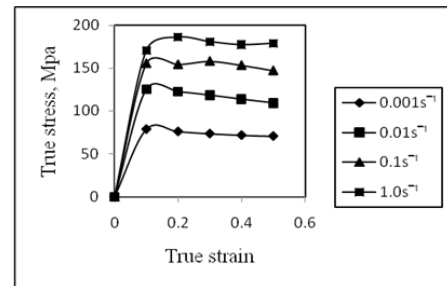


Figure 1. The flow curves for different a strain rates at constant temperature of 400 °C

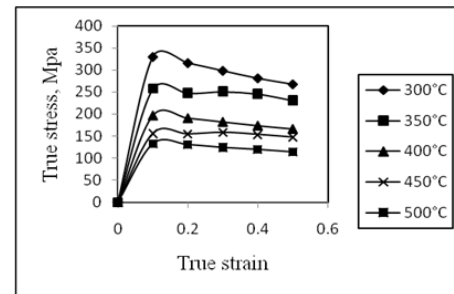


Figure 2. The flow curves for different temperatures at constant strain rate of 0.1s⁻¹

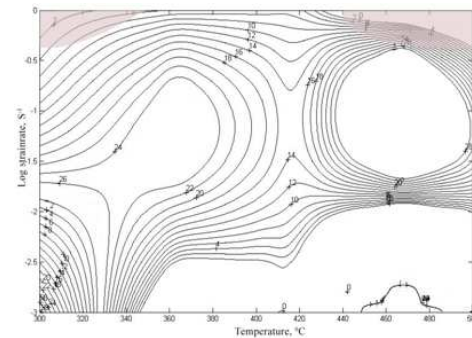


Figure 3. Processing map for 7075Al/10% SiC_p composites at 0.5 strain.

The true stress-true strain curves show a peak and subsequent decrease in flow stress, indicating that the material undergoes DRX over the entire range of temperatures and strain rates. Since the deformation, behavior is affected by adiabatic heating.

Flow curves presented in Fig. 1 and Fig.2., the increase in temperature and the subsequent softening of the specimen are well pronounced at high strains and strain rates. In the present study, the observed temperature increase caused by the adiabatic heating is maximum at 450 °C and at a strain rate of 0.1 s^{-1} ; when the true strain was 0.5.

4.2. Processing Maps

The processing maps have been developed based on the procedure explained earlier [13,14,15]. The processing map at a strain of 0.5 is shown in Fig.3. The contours represent constant efficiency of power dissipation marked as percent. Shaded region corresponds to flow instability and the numbers against each contour represent efficiency of power dissipation, which characterize the rate of microstructure evolution in the hot working process. There is no marked change in the iso-efficiency contour maps at different strains, but the flow instability regions increases with the development of deformation and expand towards higher strain rates and higher temperatures regions. The map exhibited domain with higher value of power dissipation: Domain occurs in the temperature range of 435–495°C and strain rate range of $0.01\text{--}0.25 \text{ s}^{-1}$, with a peak efficiency of about 28%. Which indicating that the region is an optimum condition for thermo mechanical processing of this composites. As per the instability criterion Eq. (5), the material is expected to show some unusual features like flow localization at strain rates higher than 1.0 s^{-1} . A domain of unstable region has occurred at 300°C and 1.0 s^{-1} . Another unstable region occurs at temperatures higher than 500°C and strain rates higher than 1.0 s^{-1} . Microstructures of the specimen deformed at that region exhibited flow localization. Strain rates higher than 1.0 s^{-1} may be avoided in processing this material. Unstable regions are observed in two areas.

4.3. Microstructural Evolutions

4.3.1. Stability Zones

The predictions of deformation stability are validated by microstructural observations. Typical microstructures obtained on the specimens deformed to a true strain of 0.5 at temperature of 450 °C and strain rate of 0.1 s^{-1} are shown in Fig. 4. which indicates the complete dynamic recrystallization (DRX), has occurred. The complete DRX microstructure appears as equiaxed grains and grains size becomes finer compared with that of undeformed grains. These microstructures exhibited fine equiaxed grains structure with wavy or serrated grain boundaries, which are typical of a DRX process. The domain of DRX is favoured for hot working since the process of softening enhances the intrinsic workability. In DRX domain, the dissipator power co-content J is dissipated by formation and migration of grains interfaces through dislocation generation and on the simultaneous recovery. Although shape and size of grains of deformed materials are changed during deformation, grains interface can be restructured by DRX.

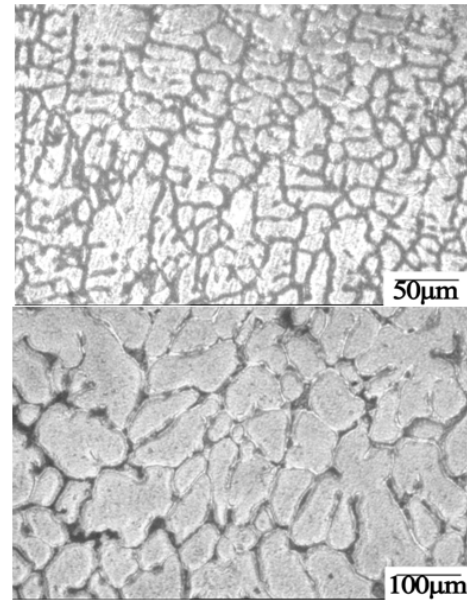


Figure 4. Dynamic recrystallization at 400 °C at a strain rate of 0.1 s^{-1}

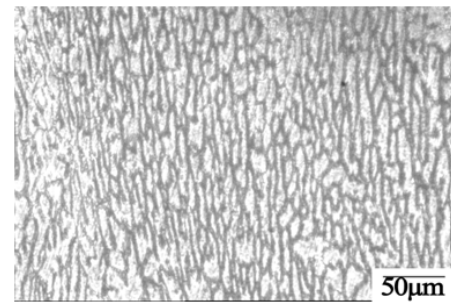


Figure 5. Grain elongation at 400 °C and at a strain rate of 0.01 s^{-1}

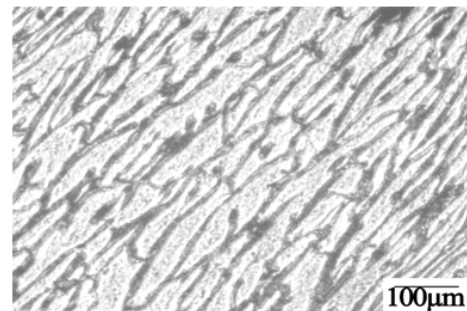


Figure 6. Shear band formation at 300 °C and at a strain rate of 1.0 s^{-1}

Therefore DRX domain is safe and desirable for hot processing [16]. Elongation obtained specimens deformed at temperature of 450°C and strain rate of 0.1 s^{-1} are shown in Fig. 5.

At higher strain rates since the time is short, the heat generated by plastic deformation is not conducted away to the colder parts of the body, a drop in the flow stress occurs locally and therefore slip becomes localized. This is called adiabatic shear bands and this generally occurs at 45° with respect to the principal stress axis.

The SiCp present in the aluminium matrix are disturbed due to the flow of matrix in the shear direction. Shear bands are unevenly and intensely deformed regime with

non-crystallographic features. Shear bands as a deformation mode widely occurs in various metals and its alloys, especially in those with low Stacking Fault Energy or those with FCC structure when deformed at low temperatures or at high strain rates [17]. Shear bands provide the potential path for flow localization [18].

The shear bands were observed at a temperature of 300 °C and a strain rate of 1.0 s⁻¹ as shown in Fig.6. Since deformation of metals and alloys is localized in shear bands, in which there remain still large numbers of twins which are difficult to be deformed. It would induce micro cracks, flow instability and non-homogeneous microstructures. So it should be avoided in hot working.

Voids generated by particle cracking and debonding causes macroscopic crack propagation from the surface to the interior linking the voids. The presence of voids seems limited to clustered regions, where the presence of very large triaxial tensile stresses during compression can induce nucleation of voids at the interface [19], which is shown in Fig. 7. at the temperature of 350 °C and at a strain rate of 1.0 s⁻¹.

Localization usually occurs at peak load but sometimes it may occur before reaching peak. Beyond the peak, the material may experience softening or degradation in its load carrying capacity but still continue to carry reduced load compared to peak load while growth and coalescence of micro cracks continue during the falling region of the curve. Finally, the micro crack growth leads to a macro crack and fracture [20].

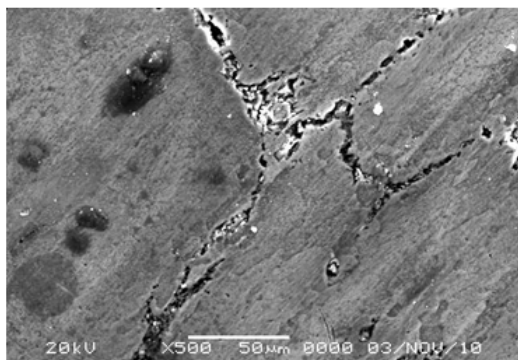


Figure 7. SEM image of voids formation at 350 °C and at a strain rate of 1.0 s⁻¹

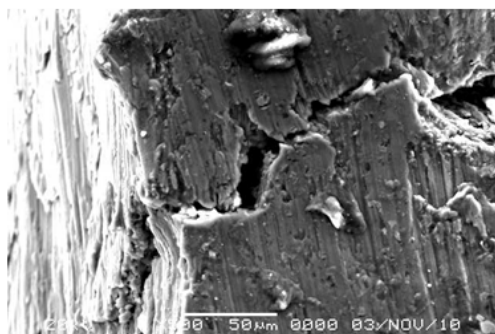


Figure 8. SEM image of interface cracking at 500 °C and a strain rate of 1.0 s⁻¹

At high strain rate, the heat generation due to local temperature rise by plastic deformation is not easily conducted away, the flow stress in these deformation zones will decrease and further plastic flow will be localized [13,21]. Discontinuous reinforced Al matrix composites are more sensitive to processing variables such as temperature and strain rate than unreinforced alloys.

This is due to the presence of hard particles in the soft matrix, which cause plastic flow localization at the particle–matrix interface at the temperature of 500 °C and at a strain rate of 1.0 s⁻¹ as shown in Fig.8.

5. Conclusions

Hot compression tests were performed on Al/15% SiC composites produced through Stir casting technique. The flow stress was evaluated for a temperature range of 300 - 500 °C and a strain rate range of 0.001–1.0 s⁻¹. The power dissipation efficiency and instability parameters were evaluated and processing maps were constructed for 0.5 strains. The optimum domains and instability zone were obtained for the material. The domains for hot working significantly differ from that of pure aluminium. The microstructure evaluation leads to debonding, adiabatic shear band formation and matrix cracking which led to flow instability of the composites. The super plastic deformation and dynamic recrystallization zones correspond to optimum working regions were identified.

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