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Processing map and microstructure evaluation of AA6061/Al_2O_3 nanocomposite at different temperatures

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Abstract: Hot compression behavior of Al6061/Al_2O_3 nanocomposite was investigated in the temperature range of 350−500 °C and the strain rate range of 0.0005−0.5 s^{-1}, in order to determine the optimum conditions for the hot workability of nanocomposite. The activation energy of 285 kJ/mol for the hot compression test is obtained by using hyperbolic sine function. By means of dynamic material model (DMM) and the corresponding processing map, safe zone for the hot workability of AA6061/Al_2O_3 is recognized at temperature of 450 °C and strain rate of 0.0005 s^{-1} and at temperature of 500 °C and the strain rate range of 0.0005−0.5 s^{-1}, with the maximum power dissipation efficiency of 38%. Elongated and kinked grains are observed at 400 °C and strain rate of 0.5 s^{-1} due to the severe deformation.

Key words: nanocomposite; hot compression test; processing map; dynamic recrystallization; instability flow

1 Introduction

Metal matrix composites (MMCs) have been an amazing subject during the past decades and aluminum alloys have assumed the most attractive title in this sphere [1−3]. Not only because of their low density and high specific strength, but also due to the incredible ability for strengthening by reinforcement particles, many researchers endeavored to develop aluminum alloy properties either in the experimental scale or for industrial purposes [4,5]. Furthermore, the costs of production and manufacturing of aluminum metal matrix composites (AMMCs) are much more affordable and reasonable in comparison with other lightweight metals such as magnesium and titanium alloys [6,7]. Accordingly, there are a wide volume of applications which are undoubtedly dependent on the enhancement of this sort of alloy, particularly in automotive and transport industries [7,8].

Metal matrix composites (MMCs) that comprise a uniform dispersion of reinforcements in the size range of nanometers are defined as metal matrix nanocomposites (MMNCs) [9,10]. MMNCs are the predominant materials for the future of several applications because of their capacity in the improvement of toughness and ductility, which are the most challenging disadvantages of MMCs [6,8,9]. By decreasing the size of reinforcement particles, it is very likely to achieve a finer grain microstructure due to the suppression of grain growth during solidification stage which can result in the enhancement of mechanical properties [11−13]. Meanwhile, the trapping of air and formation of bubbles increase with reduction of the size of particles, which dramatically decrease the mechanical properties of composite [9]. Therefore, substituting micro ceramic particles with nanoparticle reinforcements is also accompanied with some challenges [14].

AA6061 alloy, a precipitation hardened aluminum alloy, in which magnesium and silicon are the fundamental alloying elements [15,16], exhibits unique welding, extrusion and forging abilities, and it is considered as one of the most widely used aluminum alloys for the construction of automotive parts such as

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wheel spacer [17,18]. Many studies have been conducted in order to reinforce AA6061 matrix by silicon carbide [19], aluminum oxide [15,20−24] and zirconia [25], and aluminum oxide is considered as the most compatible ceramic reinforcement for aluminum matrix composites [15]. Moreover, it is reported [26] that the application of aluminum matrix composites has been improved to 1000 °C due to the high melting point of Al_2O_3 and its remarkable compatibility with the matrix. It is noteworthy to indicate that the bonding of ceramic particles through the matrix can be improved by reducing the interface between particles and matrix [9,27].

Hot deformation is a process, in which the work piece is deformed plastically above its recrystallization temperature [21,28]. The recrystallization phenomenon can result in the increase of ductility while strain hardening process has decreased [29]. Predicting the appropriate temperature range and strain rate is necessary by investigating the alternation of large plastic flow irreversible thermodynamics for a prosperous isotherm forging of metals and MMCs [30]. Dynamic material model (DMM) is a thermodynamic approach based means for obtaining the optimal conditions of hot deformation process [30]. Dissipated and stored energies in the work piece are two fundamental criteria in this model in order to assess the microstructural evolutions [31]. According to Eq. (1), the overall power (P) received by the specimen is divided into two distinct terms, where G is the value of energy dissipated by the plastic deformation and J demonstrates the role of other metallurgical mechanisms, also σ and $\dot{\varepsilon}$ are defined as the instantaneous stress and strain rate, respectively [21].

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

SPIGARELLI et al [21] investigated the hot workability of AA6061 reinforced by micro particles of Al_2O_3 by constitutive equations. They have considered the climb of dislocations as the major mechanism for controlling the hot deformation behavior of this alloy. Furthermore, FAN et al [32] studied the hot deformation of AA6061 by uniaxial compression tests in the temperature range of 400−500 °C and strain rate of 0.01−1 s^{-1}. Their results consider dynamic recovery (DRV) and dynamic recrystallization (DRX) as the main mechanisms for hot deformation at high temperatures [32]. Dynamic precipitation is also observed at 400 °C and it has been considerably dependent on the variation of temperature [32]. MROWKA-NOWOTNIK et al [33] reported that the stress level reduced with the increase of temperature and decreasing strain rate, and the activation energy of deformation process was noticeably dependent on the process parameters. Moreover, they also mentioned DRV and DRX mechanisms as the ruling factors for dynamic flow softening [33]. However, there is still no report concerning the characterization of AA6061/Al_2O_3 nanocomposite hot workability. Moreover, previous researches in the field of hot deformation process of aluminum-based nanocomposites, microstructural evolutions and a comprehensive connection between optimal hot deformation parameters and microstructural observations were insufficient. Hence, investigation with more details is necessary to clarify the microstructure evolutions during hot deformation of aluminum metal matrix nanocomposites and develop optimal conditions for hot workability of such materials [34].

In the current study, AA6061/0.5%Al_2O_3 nanocomposite was produced by stir casting method and extruded as a secondary process for the improvement of mechanical properties. Hot deformation behavior of AA6061/Al_2O_3 nanocomposite was investigated in the temperature range and strain rate range of 350−500 °C and 0.0005−0.5 s^{-1}, sequentially. Hot deformation data and microscopic observations were used to determine the optimal conditions for hot working of nanocomposite in a practical manner.

2 Experimental

Aluminum oxide (Al_2O_3) nanoparticles were prepared by Merck Company with the mean size of 40 nm and used as the reinforcement additive. The metal matrix consists of 0.65% Si, 0.7% Fe, 0.25% Cu, 0.15% Mn, 0.9% Mg, 0.07% Cr, 0.25% Zn, 0.15% Ti, and balance aluminum.

A combination of stir casting and extrusion procedure was employed for the production process. Firstly, the amount of 0.5% nanoparticles were injected through the molten aluminum by the pressure of pure argon gas at 750 °C for 20 min followed by a 15 min extra stirring in order to achieve a more homogenized mixture. The stirring speed was 450 r/min. Afterwards, a solution heat treatment was performed at 550 °C for 2 h on the manufactured bars prior to the extrusion process. The extrusion ratio η ($\eta=(D_0/D_1)^2$) was chosen as 2.8, where D_0 is the initial diameter and D_1 is the final diameter. High magnification SEM micrograph of nanocomposite is shown in Fig. 1.

All the samples, for the hot compression studies, were machined by automatic cutting device with height and diameter of 15 mm and 10 mm, respectively. Subsequently, a T6 heat treatment was accomplished after the extrusion with solution temperature and time of 550 °C and 2 h, while age hardening temperature and time were 200 °C and 3 h, respectively.

Hot workability of samples were investigated by

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