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Effect of alumina nanoparticle on strengthening of Al-Si alloy through dendrite refinement, interfacial bonding and dislocation bowing

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ABSTRACT

The present investigation evaluates the effect of varying percentage of alumina nanodispersions in strengthening and interfacial bonding with cast A356 aluminum alloy by modified compocasting followed by solidification using squeeze casting. Addition of 0.5 wt% Al_2O_3 nanoparticles to cast alloy shows remarkable enhancement in the yield strength from 204 to 323 MPa. They also exhibit higher hardness, UTS, compressive strength, thermal, tribological and corrosion properties. HRTEM image showed the insertion of Al lattice into the Al_2O_3 crystalline lattice contributing to strengthening of the alloy. The Al_2O_3 nanoparticles and the β" are involved in the Orowan strengthening of Al nanocomposite. The presence of hard Al_2O_3 nanoparticles and the stronger bonding between particle and alloy constrain the dislocation motion leading to dislocation bowing. The theoretical estimation of Al −0.5 wt% Al_2O_3 nanocomposite yield strength shows that the contribution of Hall-Petch is predominant followed by Orowan and solid solution strengthening.

1. Introduction

Aluminum alloys with nanodispersions are gaining considerable attention as lightweight metallic materials in high-performance application areas of aerospace and defense sectors. Aluminum Nanocomposites (ANC) exhibits excellent mechanical properties, resistance to creep at the higher temperature and good fatigue strength compared to base aluminium alloys [1,2]. The nanoscale reinforcement has more reinforcing effect than micron size in metallic systems due to the strong bonding at atomic level between the matrix and nano reinforcement [3]. Furthermore, since the distribution of nano-reinforcement in metal matrix is inter and intra-granular types, the concepts of Hall-Petch and Orowan mechanism contribute for material strengthening [4]. However, the major challenge while developing metallic nanocomposite is on uniform distribution of dispersoids in the matrix and the properties of the final composite depend on the same [5,6]. A variety of techniques have been developed to integrate nanoscale reinforcements with metal matrix like powder metallurgy [7], stir casting [8], compocasting [9], infiltration [10], ultrasonic technique [11] etc. Among them, stir casting is attractive due to its simplicity and low cost in processing. However, the disadvantages are the agglomeration of reinforcement due to low wettability with the matrix and the formation of interfacial reactions. In recent years, researchers have identified compocasting as one of the effective methods for fabricating ANC over other conventional methods due to its advantages like uniform distribution of reinforcement without agglomeration, good wettability and better matrix-reinforcement bonding [12]. Compocasting is a solid-liquid state method in which a vortex is created in the semisolid molten metal and the reinforcements are added into the vortex under stirring [13].

Sajjadi et al. reported the studies on Al A356nanocompositesprocessed by the compocasting process, however the mechanical properties reported are 162 MPa for 3 wt% of alumina nanoparticle addition [14]. Mazahery et al. identified that the porosity level of nanocomposites increases with increasing nanoparticles content, fabricated by stir casting process [15]. Squeeze casting technique has great potential in reducing the porosity level in final composite [16]. The literature survey shows that most of the works on Al-nanocomposites have been focused on improving the mechanical properties with the high weight percentage of nanoparticles without tailoring the process parameters. Hence, the basic

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study on the effects of tailoring the process parameters in strengthening the Al-nanocomposites at the atomic level is almost non-existent. One of the major requirements of composite materials is a strong interface bonding for effective load transfer from the matrix to the reinforcement [17]. Accordingly, in the present investigation Al-Al_2O_3nanocomposites are processed by modified compocasting technique and solidified under squeeze casting process. The paper deals with the evaluation of interfacial characteristics between the nanoparticles and aluminum matrix, and the influence of interfacial bonding on the strengthening of cast aluminum alloys. The nanocomposites are characterized with respect to structural, interfacial, physical, mechanical, tribological, and corrosion characteristics.

2. Experimental procedure

2.1. Processing of Al-Al_2O_3nanocomposite

Al A356 cast alloy supplied by Sargam Metals, India was used as the matrix material with a chemical composition of Al–7Si–0.35 Mg (in wt%). The Al_2O_3 nanoparticles with the weight percentage of 0.25 wt%, 0.5 wt%, and 1 wt% were used as the reinforcement with average particle size of 40 nm obtained from Alfa Aesar. The density of Al_2O_3 nanoparticles used was 3.6 g/cc with a melting point of 2045 °C. The stir casting and modified compocasting routes were used for fabricating Al-Al_2O_3nanocomposites and solidified using squeeze casting by 25T hydraulic press. The Al_2O_3 nanoparticles were preheated at 200 °C for 1 h. Stir casting process involves the incorporation of Al_2O_3 nanoparticles into the vortex of mechanically stirred molten metal and solidified by squeeze casting above the liquidus temperature of the matrix material (730 °C). In modified compocasting process, the Al_2O_3 nanoparticles were incorporated into the vortex of semisolid metal at a temperature between the solidus and liquidus (585–595 °C) range of the matrix material and solidified the composite melt using squeeze casting above the liquidus temperature of the matrix material (730 °C). To ascertain better dispersion of nanoparticles, the compocast ingot was reprocessed by remelting, stirring and squeeze casting. The effects of modified compocasting over compocasting were described in our previous study [16]. The squeeze casting of Al A356 alloy was carried out for comparison of properties. During the fabrication of composites, 1 wt% Mg in pure form was added into the molten aluminium metal to improve the wettability between the nanoparticles and the matrix.

2.2. Characterization

Structure and properties of Al-Al_2O_3nanocomposites were characterized by different techniques and compared with base alloy. The T6 heat treatment condition was used for base alloy and Al-Al_2O_3nanocomposites, i.e., solution treatment (525 °C for 12 h) followed by quenching in warm water (80 °C) and then precipitation or age hardening at 165 °C for 8 h. The microstructures were investigated by Leica DMRX optical microscope, JEOL Scanning electron microscope and JEOL-JEM-2100 transmission electron microscope with Oxford energy dispersive X-ray spectroscopy (EDS). The secondary dendrite arm spacing (SDAS) values were measured using linear intercept method. The coefficient of thermal expansion (CTE) was measured using EXSTAR-TMA/SS6100 thermo mechanical analyser at a heating rate of 10 °C/min. The differential thermal analysis (DTA) was carried out using Hitachi STA7300 (TG–DTA) instrument at a heating rate of 10 °C/min in the argon atmosphere. The density was measured using Archimedes principle method. Heat-treated samples were used for mechanical properties and wear characterization. The tensile and compression tests were carried out using universal testing machine (INSTRON 1195–5500R). The hardness was measured using ZwickBrinell hardness testing machine with a 2.5 mm ball indenter and 62.5 kg load. The dry wear tests were carried out in DUCOM (TR20LE) pin-on-disk tribometer with applied loads of 10 N, 20 N, 30 N, 40 N and 50 N at a sliding velocity of 2 m/s for the constant sliding distance of 1500 m. The corrosion tests were carried out using electrochemical workstation (CH Instruments, 680) with three-electrode cell system. The Al A356 alloy and Al-Al_2O_3nanocomposites were used as the working electrode, platinum was used as the auxiliary electrode and calomel as the reference electrode. In all the tests the working electrode under study was subjected to 3.5 wt% NaCl solution and the scan rate was 1 mV/s.

3. Result and discussion

3.1. Microstructural characteristics

Fig. 1(a) showed the optical microstructure of squeeze cast Al A356 base alloy, in which the formation of primary phase α-Al dendrites (white region) and Al–Si eutectic mixture (gray region) between the dendrite arms during solidification is observed. The elimination of porosities and the formation of fine grains are perceived in the microstructure (secondary dendrite arm spacing of 17 μm) since solidification takes place under pressure with the higher degree of heat dissipation during squeeze casting process. Fig. 1(b, c, and d) shows the microstructures of Al A356–0.25 wt%, 0.5 wt%, and 1 wt% Al_2O_3 nanoparticles reinforced composites respectively, prepared by modified compocasting process. It is clear from the microstructures that the incorporation of Al_2O_3 nanoparticles into the aluminium matrix refines the phases of the composites compared to squeeze cast A356 base alloy. As the sizes of Al_2O_3 particles are in nanometer scale, the surface area of particles in the matrix increases thereby enhancing the grain nucleation sites and breaking of dendrites resulting in refined grain size of the composite microstructure during solidification. The addition of 0.25 wt% Al_2O_3 nanoparticles into the aluminium matrix alters the grains size (Fig. 1(b)) with a secondary dendrite arm spacing of 13.5 μm. When 0.5 wt% Al_2O_3 nanoparticles are added into the matrix aluminium, the size of aluminium dendrites and eutectic Al-Si morphology gets refined significantly (Fig. 1(c)) compared to the former one. The SDAS value of Al-0.5 wt % Al_2O_3 nanocomposite is 9 μm, which is lower compared to all other variants due to the incorporation of optimum weight percentage of nanoparticles into the matrix with better dispersion and distribution of particles. Further addition of Al_2O_3 nanoparticles (1 wt %) into the matrix increased the secondary dendrite arm spacing to 11 μm (Fig. 1(d)) compared to 0.5 wt% Al_2O_3nanoparticles added composite due to the agglomeration of nanoparticles in the matrix aluminium. Al A356-0.5 wt% Al_2O_3 nanoparticles reinforced composite processed by stir casting technique also results in the agglomeration of particles in the matrix, which extensively increase the grain size of the composite with a secondary dendrite arm spacing of 15 μm (Fig. 1(e)). During compocasting process, the higher viscosity of semisolid aluminium molten metal slurry transmits shear force over the agglomerated nanoparticles which lead to better dispersion and distribution of reinforcement in the matrix [13]. Also, good wettability between the nanoparticles and the melt is maintained in the semisolid state.

3.2. Strengthening by nanodispersion

HRTEM images of Al-0.5 wt% Al_2O_3 nanoparticles reinforced composite by modified compocast method is shown in Fig. 2, in which the distribution of Al_2O_3 nanoparticles in the aluminum