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Microstructural refinement and wear property of Al–Si–Cu composite subjected to extrusion and high-pressure torsion

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ABSTRACT

The effect of high-pressure torsion (HPT) on the microstructure and the mechanical properties, especially the wear properties, of an Al–Si–Cu alloy (represented by Al–15%Si–2.5%Cu–0.5%Mg) and its composite, which was reinforced by SiC particles (SiC_p) at a volume fraction of 5%, was investigated systematically in this study. The Al–Si–Cu/SiC_p composite is produced in a powder metallurgy process followed by hot extrusion (EXTR) at 565 °C. The EXTR specimen is also subjected to HPT processing at an anvil rotation speed of 0.5 rpm under a quasi-hydrostatic pressure of 5 GPa.

HPT processing leads to a nanostructured microstructure comprised of equiaxed α-Al grains (60–70 nm) and secondary particles and phases; the SiC_p with a damaged facet, the phase exhibiting high Mg content and the intermetallic $CuAl_2$ phase, for the Al–Si–Cu/SiC_p composite. The values of the tensile strengths and hardness of the HPT specimens are nearly twice higher than those of the EXTR specimens for the Al–Si–Cu alloy and the Al–Si–Cu/SiC_p composite. Ball-on-disc tests were used to examine the wear resistance of the processed materials. The wear test results indicated that HPT processing significantly reduces the wear loss, thereby leading to improvement in the load bearing capacity and the wear resistance of the Al–Si–Cu alloy and the Al–Si–Cu/SiC_p composite. This behavior is linked to HPT processing, based on the refined and homogenous microstructure that results in an increase in the hardness.

1. Introduction

The Al–Si alloys are widely used especially for tribological applications, due to their low density, good formability and process flexibility [1–9]. Compared to the other alloys, the Al–Si structure containing hard eutectic Si particles dispersed in a relatively soft Al matrix phase is desirable for the improvement of wear resistance, because the hard second phase prevents the removal of material from the part under loaded conditions. The anti-friction and wear properties of these hard particles are strongly linked to their shape, size and size distribution, and cohesion with matrix, all of which play an important role in effectively sustaining the load [10,11].

To achieve the enhanced load bearing capacity of such alloys used for tribological applications, the incorporation of hard particles, i.e., SiC, Al_2O_3, TiB_2 etc., in micron or nanometer scale is a widely accepted method for the improvement of the anti-wear performance of relatively soft Al alloys [12,13]. Numerous studies exist regarding Al alloys reinforced by incorporation of hard particles, in which their alloys and composites were tested under various tribological conditions to reveal the improved wear performance in comparison to the Al–Si–Cu alloy [14–17]. The explanation of the findings of such studies is mainly based on the role of hard particles, i.e., the particles intrinsically impede material wear loss by resisting further plastic deformation compared to the soft matrix Al alloy. Regarding, the worsening of the wear performance in such composites, the cracking of the reinforcement due to the high contact stress developed during the test, the particle removal/pull out, and the reinforcement/matrix de-cohesion are generally attributed to the acceleration (inferior) of the wear rate (resistance).

There is an increasing demand to develop Al matrix composites (AMCs) that withstand the higher stresses encountered in service conditions as well as improved wear resistance. Recently, severe plastic deformation (SPD), e.g., via high-pressure torsion was successfully applied to the AMCs [18–20], resulting in a good microstructural refinement and homogeneity for both the secondary phase/particles and the matrix phase, which is a promising result for enhancing the composite properties. To obtain similar improvement in AMCs that

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are reinforced with fine particles, the application of conventional secondary thermo-mechanical processes such as extrusion is limited due to the induced low strain, which is insufficient to improve the microstructural refinement and homogeneity. The improvements of Al–Si alloys regarding the wear properties via HPT processing can potentially increase their use in the manufacturing of engine parts for which high friction and wear is expected. Therefore, this study focuses on the effects of HPT processing on the microstructure and consequently on the mechanical properties, especially the wear properties, of the Al–Si–Cu matrix (Al–15%Si–2.5%Cu–0.5%Mg) composite reinforced by SiC particles.

2. Experimental procedures

2.1. Materials and preparation

Al–15%Si–2.5%Cu–0.5%Mg alloy powder (Al–Si–Cu alloy) that has an average diameter of $<157\,\mu m$ (ECKA Granulate Velden GmbH) is used as the Al–Si–Cu alloy. The alloy composite reinforced with SiC particles (SiC_p) was fabricated using a powder metallurgy process. First, the SiC_p with a diameter of $<53\,\mu m$ (Aldrich) were added into the Al–Si–Cu alloy powders with a volume fraction of SiC_p of approximately 5%. Next, they were mixed in a three-dimensional mixer (Turbula-Model T2F, Willy A. Bachofen AG Maschinenfabrik, Switzerland) for 30 min at 60 rpm. The blended powders of both the Al–Si–Cu alloy and the Al–Si–Cu/SiC_p composite, which were placed in a die, were cold unidirectionally cold compacted at a pressure of 200 MPa to produce billets of 100 mm in diameter and 200 mm in height. The compacted matrix and the composite billets were then sintered at a temperature of 565 °C for 60 min in argon atmosphere. Subsequently, the billets were then immediately processed using the hot extrusion process with an extrusion ratio of 4:1 to produce bars of 90 mm in diameter and 250 mm in length (the extrusion direction). After the extrusion process was performed at 565 °C, the samples were allowed to air cool.

For HPT processing, the extruded bars were cut into disk specimens with a diameter of 20 mm and a thicknesses of 0.80 mm parallel to the extrusion direction using electro-discharge machining (EDM). The disk specimens of both the Al–Si–Cu alloy and the Al–Si–Cu/SiC_p composite were subjected to HPT processing between two anvils in opposition vertically by rotating the lower anvil at 0.5 rotations per minute (rpm) for 5 rotations under a pressure of 5 GPa at room temperature. The HPT processing is schematically illustrated and explained in detail in Ref. [21,22]. Hereafter, the specimens subjected to extrusion and HPT processing are referred to as the EXTR and HPT specimens.

2.2. Microstructural characterization

The microstructure of each specimen was examined using a scanning electron microscope (SEM; JSM–6060, JEOL, Japan) and a transmission electron microscope (TEM; Jeol JEM 2100F, Japan). The specimens examined using the SEM were wet-polished using waterproof emery papers of up to #4000 and then buff-polished to obtain a mirror surface by colloidal SiO_2 suspension. In addition to the SEM observations, TEM observations were performed at the half radius, r_h, position, $r=r_h=5$ mm, i.e., where a medium strain is imposed via HPT processing, along a cross section of the disk specimens. For TEM observations of the cross section of the samples, each half specimen of a disk specimen was adhered between two silicon substrates using epoxy at the surface and then cut to a thin slice parallel to the cross section of length that is approximately the diameter of the disk specimen. Each slice was wet polished to the thickness below 50 μm using waterproof emery papers up to #2400. Subsequently, a copper ring, 3 mm in diameter, was adhered onto the polished slices at the r_h position using epoxy. Subsequently, the sample was further thinned to below 20 μm using a dimple grinder and via ion milling. The TEM sample preparation was illustrated in a previous study [23]. The TEM analysis was performed using a field-emission TEM operating at 200 kV and equipped with an energy dispersive X-ray spectroscopy (EDS) attachment. The grain diameter in the HPT specimen was measured quantitatively using TEM bright-field images in this study.

2.3. Mechanical tests

The apparent densities of the EXTR and the HPT specimens for the Al–Si–Cu alloy and the Al–Si–Cu/SiC_p composite were evaluated using the standard Archimedes' method. Hardness (*HV*) measurements were performed using a micro-Vickers hardness tester (Shimadzu HMV–2TADW–XY, Japan) with a load of 200 g for a dwell time of 10 s along the surface of the HPT specimen. The measurements along the surface of the HPT specimen were performed at the intervals of 2.5 mm between the measurement positions in the radial direction. The average hardness value was determined at every point from three separate measurements clustered around the selected point. The tensile properties of the specimens were evaluated using a testing machine at a crosshead speed of 0.2 mm/min on a servo-hydraulic test frame (AG-50kNG, Shimadzu, Japan) at room temperature. The dimensions of the tensile specimens, machined at the r_h position of the disk specimens, were mentioned and illustrated in a previous study [23]. The fracture surface was analyzed using the SEM.

The wear behaviors of the specimens were examined according to the ASTM G133–05/2005 standard by using Tribotech™ Oscillating Tribotester-ball on disc machine (Fig. 1). The tests performed under atmospheric conditions at 25 °C and 40–50% humidity by applying a load of 3.0 N a long a wear track length of 5 mm. The wear tests were performed against the Al_2O_3 ball with a diameter of 6 mm and a sliding speed of 5 mm/s for a total sliding distance of 25 m. Prior to testing, the specimens were polished using emery paper and cleaned in ethanol. The surfaces of the specimens were metallographically prepared to a surface finish of 1.6 μm (Ra) prior to the wear tests. At least three repetitions of each test were performed. The depths of the wear tracks were measured using a stylus profilometer (Mitutoyo, SJ-301, Kawasaki, Kanagawa, Japan) at 10 intervals. The volumetric wear loss was determined by means of optical 3D profilometry and software-aided analysis of the wear tracks (MicroCAD compact stripe profilometer). The worn surfaces of the specimens were examined using a SEM to elucidate the wear mechanism of the tested specimens.

3. Results and discussion

3.1. Microstructure

Fig. 2 shows changes in the porous structures of the EXTR and the HPT specimens of the Al–Si–Cu alloy and the Al–Si–Cu/SiCp

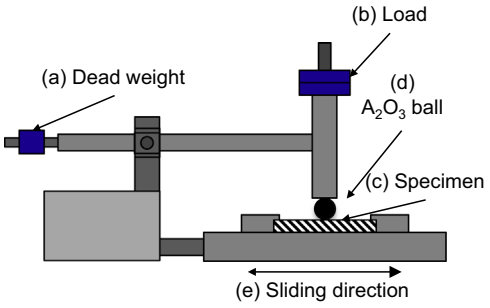

Fig. 1. Schematic drawing of the wear tester utilized in this study; (a) dead weight, (b) load, (c) specimen, (d) A_2O_3 ball and, (e) sliding direction.