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The microstructures and tensile mechanical properties of ultrafine grained and coarse grained Al-7Si-0.3Mg alloy rods fabricated from machining chips

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ABSTRACT

Ultrafine grained (UFG) and coarse grained (CG) Al-7Si-0.3Mg (wt%) alloy rods were fabricated by hot extrusion of compacts of a nanocrystalline Al-7Si-0.3Mg alloy powder and coarse grained Al-7Si-0.3Mg alloy granules respectively. Both the nanocrystalline powder and the granules were prepared by processing Al-7Si-0.3Mg alloy (widely known as A356 cast alloy) machining chips produced in machining cast components of this alloy such as car wheels. Samples from the rods were also T6 heat treated with a condition of 535 °C/1 h-water quenching-165 °C/8 h. The as-extruded UFG rod exhibited a yield strength (YS) of 298 MPa, ultimate tensile strength (UTS) of 345 MPa and elongation to fracture (δ_f) of 5.9%, which changed to 223 MPa, 342 MPa and 10.2% respectively after the T6 heat treatment. In contrast, the as-extruded CG rod exhibited a YS of 101 MPa, UTS of 187 MPa and δ_f of 16.6%, which changed to 203 MPa, 275 MPa and 10.8% after the heat treatment. The UFG Al-7Si-0.3Mg alloy sample exhibits a dramatically different precipitation behavior from the CG Al-7Si-0.3Mg alloy sample during the T6 heat treatment, with the formation of fine platelet-shaped pre-β″ precipitates on Al {001} planes in the former sample in contrast of the formation of needle-shaped β″ precipitates along Al < 001 > directions in the latter sample. The change of precipitation behavior leads to a weaker precipitation hardening effect. This work demonstrated that a significantly higher tensile strength can be achieved with heat treated UFG Al-7Si-0.3Mg alloy than CG Al-7Si-0.3Mg without sacrificing tensile ductility.

1. Introduction

Aluminum alloys are important non-ferrous alloys that have been widely used in automotive, aerospace and construction applications due to their low density, good mechanical properties, corrosion resistance, good weldability, good machinability, high formability and relatively low cost [1]. As valuable by-products of manufacturing metallic parts, aluminum alloy machining chips are normally recycled by melting which destroys their microstructure and consumes a substantial amount of energy. On the other hand, if the recycled machining chips are turned into structural members and/or components in solid state without going through melting, the amount of energy consumed and the loss of materials in the recycling process can be significantly reduced [2–5]. It is reported that the stronger and more stable aluminum oxide layers on the surfaces of aluminum alloy chips make it difficult to obtain recycled materials with good mechanical properties for practical use [6]. In order to achieve strength and ductility of the recycled materials which are at least comparable with those of the corresponding primary materials of the same composition, many studies on solid-state recycling of aluminum alloys have been conducted.

Chino et al. [7] reported that the content of the oxide particles in the recycled 5083 aluminum alloy produced by consolidation of machining chips by hot extrusion followed by hot rolling increased with increasing the surface areas of the machining chips, and had a detrimental effect on the ductility and formability of the recycled material. Suzuki et al. [6] found that differential speed rolling was effective in reducing the defects at the inter-chip boundaries, and caused improvement of the mechanical properties and corrosion resistance of 6061 aluminum alloy recycled by hot extrusion and hot rolling of machining chips. Sherafat et al. [8] found that better chips bonding was achieved by adding Al powder as a soft matrix and binder in the recycled 7075 aluminum alloy, and the strength decreased and ductility increased with increasing Al powder content. Tang et al. [9] reported that defect free 2050 and 2195 aluminum alloys produced from machining chips by the

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friction extrusion process demonstrated an equiaxed recrystallized grain structure, and the average grain size increased with increasing die rotation rate. Güley et al. [10,11] showed that good inter-chip bonding and improved mechanical properties can be achieved in the recycled 6060 aluminum alloy produced by hot extrusion of chips by both increasing extrusion ratio and using a porthole die instead of a flat die. Chiba et al. [12] reported that the mechanical strength and uniform elongation of the recycled Al-7Si-0.4Mg alloy were both positively correlated with the plastic strain produced during extrusion, and good density and ductility were acquired in the recycled materials extruded with an extrusion ratio of 18:1. Haase et al. [13] found that fine equiaxed grains and improved inter-chip bonding can be achieved in the recycled AA6060 aluminum alloy produced by hot extrusion of machining chips by using integrated equal channel angular pressing (iECAP) die which imposes a high pressure and strain during extrusion. Recently, we [14] reported that plastic deformation during extrusion caused recrystallization and growth of new grains and rapid establishment of good inter-granule bonding of the solid-state recycled Al–7-Si–0.3Mg (wt%) alloys.

In the present study, we investigate the microstructures and mechanical properties of ultrafine grained (UFG) and coarse grained (CG) Al-7Si-0.3Mg alloy rods fabricated by hot extrusion of compacts of a nanocrystalline (NC) Al-7Si-0.3Mg alloy powder and coarse grained Al-7Si-0.3Mg alloy granules respectively. Both the NC powder and the granules were prepared by processing Al-7Si-0.3Mg alloy (widely known as A356 cast alloy) machining chips produced in machining cast components of this alloy. Al-7Si-0.3Mg alloy is of high interest for two reasons. Firstly, this alloy is a typical casting aluminum alloy which is used widely by manufacturing industry to produce aluminum alloy components such as wheels for automobiles by casting, so a large amount of machining chips of this alloy is produced each year. Secondly, the microstructure of the alloy consists of eutectic Si particles, Al(Mg,Si) solid solution matrix and, depending on heat treatment condition, Mg_xSi ($x = 1$ or 2) precipitates, so it would be interesting and valuable to investigate the microstructures and mechanical properties of this alloy.

2. Experimental procedure

Table 1 shows the chemical composition of the Al-7Si-0.3Mg alloy (also known as A356 cast alloy) machining chips produced in machining cast components. An UFG Al-7Si-0.3Mg alloy rod was fabricated by vacuum hot pressing of a NC Al-7Si-0.3Mg alloy powder produced by mechanical crushing and high energy ball milling (HEMM) of the chips followed by hot extrusion of the hot pressed powder compact. The details of the mechanical crushing and HEMM processes used to make the NC Al-7Si-0.3Mg alloy powder were reported in Ref. [13]. The vacuum hot pressing of the NC Al-7Si-0.3Mg alloy powder was performed at 450 °C for 30 min and under a pressure of 100 MPa to obtain a cylindrical compact with a diameter of 28 mm and height of 25 mm. Then the hot pressed compact was hot extruded at 500 °C with an extrusion ratio of 25:1 to produce a cylindrical rod with a diameter of 6 mm. Prior to hot extrusion, the compact was induction heated to 500 °C with a heating rate of 150 °C/min, and held at the temperature for 2 min. Both the heating and extrusion were carried out under argon to avoid oxidation of the compact. A CG Al-7Si-0.3Mg alloy rod with a diameter of 10 mm was fabricated by hot extrusion of a granule compact produced by cold pressing of Al-7Si-0.3Mg alloy granules. The granules were made by mechanical crushing the same Al-7Si-0.3Mg alloy machining chips as those used for making the NC powder. The hot extrusion parameters for making the CG rod were similar to those for making the UFG rod except that a smaller extrusion ratio of 9:1 was used. Samples were cut from the extruded rods, and heat treated under a typical T6 heat treatment condition: solid solution at 535 °C for 1 h, water quenching and aging at 165 °C for 8 h.

Table 1
The chemical composition (wt%) of the Al-7Si-0.3Mg alloy machining chips used as the starting material for preparing the samples in the study.

Element	Si	Mg	Ti	Fe	Cu	Al
Content	7.4	0.28	0.11	0.14	0.01	Bal.

The as-extruded and heat treated samples were characterized by using scanning electron microscopy (SEM) (FEI Nova NanoSEM 230), electron backscatter diffraction (EBSD) (Carl Zeiss AURIGA® CrossBeam® Workstation) and transmission electron microscopy (TEM) (JEOL JEM-2100F). The TEM specimens were prepared by cutting thin slides from the as-extruded and heat treated samples along the extrusion direction, mechanically grinding them to a thickness of 30 μm, punching 3 mm disks from the thin slides and then dimpling the disks to a thickness of about 10 μm. The final thinning of the disks was carried out using a Gatan PIPS 691 ion milling system under a voltage of 5 kV. Flat dog-bone shaped tensile test specimens with cross section dimensions of $3 \times 2\ \mathrm{mm}^2$ and a gauge length of 25 mm were cut from the as-extruded and heat treated samples along the extrusion direction. Tensile testing of these specimens was carried out with a strain rate of $5 \times 10^{-4}\ \mathrm{s}^{-1}$ using a materials testing machine (Zwick/Roell Z020). Three specimens were tested for each of the as-extruded and heat treated samples.

3. Results

As shown in Fig. 1, the microstructure of the as-extruded UFG Al-7Si-0.3Mg alloy rod consisted of ultrafine Al grains with sizes in the range of 200–600 nm, ultrafine equiaxed and rounded Si and Al_3FeSi particles with sizes in the range of 150–250 nm, and coarse Si particles with sizes in the range of 1–4 μm. As shown in Fig. 2, after T6 heat treatment, the number density of the ultrafine and rounded Si and Al_3FeSi particles became larger, and their sizes changed to the range of 50–250 nm. The Si and Al_3FeSi particles were distributed along the Al grain boundaries as well as inside the Al grains. As determined from the Al grain size distributions of the as-extruded and T6 heat treated UFG samples shown in Figs. 1(d) and 2(f), the average size of Al grains increased from 468 to 576 nm as a result of the T6 heat treatment.

As shown in Fig. 3, the Al grains in the T6 heat treated UFG sample contained a high number density of small precipitates, but they did not take the typical needle shape of the β″ precipitates which are expected to form as a result of T6 heat treatment of an CG Al-7Si-0.3Mg alloy [15]. As shown in Fig. 3(a), with the electron beam parallel to the [001] zone axis of the Al grain examined, the precipitates exhibited a discus-like shape with diameters of 5–10 nm. As shown in Fig. 3(b), with the electron beam parallel to the Al [110] zone axis, the images of the precipitates became thin plates with a thickness of about 1 nm and lengths in the range of 5–10 nm, and the plates are parallel to the {001} planes of the Al grain. The HRTEM images and corresponding FFT patterns of the precipitates with the electron beam parallel to the Al [001] zone axis (Fig. 4(a)) demonstrated the crystal structures of the precipitates and the Al matrix were coherent. The FFT patterns of the precipitates and the Al grains showed extra diffraction spots in addition to the diffraction spots of the Al grains, suggesting that the crystal structure of the precipitates is different from that of Al matrix. Fig. 4(b) shows a HRTEM image of a precipitate in the T6 heat treated UFG sample with the electron beam parallel to the Al [110] zone axis. It again demonstrated that the crystal structures of the precipitate and the Al matrix along the $(002)_{Al}//(002)_{precipitate}$ interfaces were coherent. Based on the FFT patterns shown in Fig. 4(c), the crystallographic orientation relationship between the precipitates and the Al matrix was determined to be $[110]_{Al}//[010]_{precipitate}$, $(002)_{Al}//(002)_{precipitate}$, Al $(2\bar{2}0)_{Al}//(200)_{precipitate}$.

As shown in Fig. 5(a), the microstructure of the as-extruded CG Al-7Si-0.3Mg alloy sample consisted of Si particles with sizes in the range of 0.5–10 μm and coarse elongated and equiaxed Al grains with sizes in the range of 30–100 μm and 2–10 μm. Based on the size distributions of