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Optimizing the strength and ductility of spark plasma sintered Al 2024 alloy by conventional thermo-mechanical treatment

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ABSTRACT

In the present paper, we have developed an effective thermal-mechanical process for achieving both high strength and good ductility in a spark plasma sintered Al 2024 alloy. After conventional solid solution treatment, room temperature cold rolling and artificial aging at 175 °C for 3 h, the engineering yield strength and ultimate tensile strength of the Al2024 alloy are 529.6 and 583.1 MPa, respectively, while maintaining a remarkable elongation to failure of 16.2%. The superior of the mechanical properties was discussed.

1. Introduction

During the last decade there has been enormous effort to develop bulk nanostructured (NS) and ultrafine-grained (UFG) aluminum alloys with superior strength for aerospace and automobile applications [1–3]. For structural aluminum alloys, strength and ductility are two of the most important mechanical properties. Generally speaking, high strength aluminum alloy entails strength above 500 MPa at room temperature, while a tensile elongation larger than 5% is required for structural use. However, the two aspects are often in conflict with each other [4].

The bulk fine structured materials can be produced by a number of methods, which broadly fall into two categories: consolidation of nanostructured powders [5–7] and severe plastic deformation (SPD) [8] of bulk micro-structured materials.

For the powder metallurgy method, the nanostructured powders are mostly prepared by mechanical milling, in which kinds of stable or metastable structure will be obtained. Then the milled powders will be consolidated through a variety of ways, such as hot pressing (HP) [9], hot isostatic pressing (HIP) [10] and more recently spark plasma sintering (SPS) [11]. Witkin et al. [12] successfully obtained bulk nanostructured Al–7.5%Mg alloy through mechanical milling at liquid nitrogen temperature and cold isostatic pressing (CIP) followed by hot extrusion process. The ultimate tensile strength and yield strength are 847 and 641 MPa, respectively. But the tensile ductility is very poor (1.4%), which is inadequate for practical applications (5%). This is the nature of nanostructured materials.

For the SPD method, equal channel angular pressing (ECAP) [13], high pressure torsion (HPT) [14] and accumulation rolling bonding (ARB) [15] are proven to be very effective approaches for microstructural refinement, which can increase the strength and ductility simultaneously. For instance, Cheng et al. [16] reported that the combination of solid solutioning, cyro-rolling at liquid nitrogen temperature and artificial aging can increase the yield strength of Al2024 alloy to ~580 MPa, with a good elongation to failure of 16%. Kim et al. [17] found that the combination of ECAP and post-ECAP low-temperature artificial aging can increase the yield strength of Al2024 alloy to 630 MPa while maintaining a respectable 15% elongation to failure. However, the above processes also have weakness, such as sample size limitations, dangerous working environment at liquid nitrogen temperature and the high cost.

Therefore, it is the objective of the present study to develop an improved procedure to increase the strength and ductility simultaneously and to evaluate the mechanism. In this approach, we successfully obtained bulk Al2024 alloy through the combination of SPS, solid solution treatment (SST), room temperature cold-rolling (CR) and artificial aging. The tensile properties of Al2024

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alloy under different processing conditions in this study were compared with those of conventional T3, T4 and T8 heat-treated alloys [18].

2. Experimental

Commercial Al-2024 alloy powder with Cu (4 wt%), Mg (1.5 wt%) and Mn (0.5 wt%) as the primary alloying elements was used as the starting material. The consolidation of the samples was made using a Sumitomo model 1020 SPS apparatus. The SPS experimental setup used in this study consists of a graphite die containing the sample and two punches. The punches are 15 mm in diameter and 25 mm long. The samples were heated to 500 °C at a heating rate of 100 °C/min with a pressure of 50 MPa. The sintering time was 10 min. Such sample is referred as sample 1 hereafter. Solid solution treatment (SST) of sample 1 was carried out at 493 °C in a vacuum furnace for 1 h, and then the materials were immediately quenched in water to room temperature. Such sample is referred as sample 2 hereafter. After SST, cold rolling was performed at room temperature, reducing the thickness from 4 mm to 2 mm, with 0.1 mm reduction for each rolling pass. Rolling in longitudinal and transverse direction alternatively avoids the anisotropy in mechanical properties. Such sample is referred as sample 3 hereafter. The cold-rolled samples were then aged at 175 °C for 3 h and 100 °C for 18 h, respectively, optimizing the strength and ductility combination. Such samples are referred to as sample 4 and sample 5 hereafter. It should be noted that the aging temperature and time in this study are selected based on the traditional heat treatment method for conventional 2XXX series Al alloys and recent literature [19,20].

The mechanical performance of the samples was characterized using Vickers microhardness and tensile testing. All the samples were polished by abrasive paper and silica suspension carefully before testing, minimizing the surface residual stress. Vickers microhardness tests were performed on the samples at a load of 100 g and a dwell time of 15 s using a SHIMADZU HMV-1T microhardness tester. The reported values are the average of 15 indentations for each sample. For tensile testing, all of the samples were cut and polished into dog-bone-shaped specimens with a gauge length of 3 mm and a cross section of 1 mm × 1 mm. The operation of the testing machine was computer-controlled and the digital data of load and displacement from the gage section were recorded. Tensile specimens were tested at a quasi-static strain rate of 5×10^{-4} s^{-1}, with direct measurement of the displacement of the tensile gage section by a dual-camera video extensometer. The values of strength and ductility are taken from an average of three samples.

Thin foil samples for transmission electron microscopy (TEM) investigations were prepared using standard ion milling techniques. To understand the relationship between the mechanical behavior and microstructures, systematic TEM, selected area electron diffraction (SAED), high-resolution TEM (HRTEM) and energy dispersive spectroscopy (EDS) analyses were performed using a JEM 2100 microscope operated at 200 kV.

3. Results

3.1. Mechanical properties of the Al2024 alloy

The typical tensile stress–strain curves and mechanical properties values of Al 2024 alloy at different processing states are shown in Fig. 1 and Table 1, respectively. For comparison, ultimate tensile strength (UTS), yield strength (YS) and elongation of T3, T4 and T8 heat-treated Al2024 alloy are also provided in Table 1. As shown in the engineering stress–strain curves (Fig. 1(a)), after solution treatment at 493 °C for 1 h sample 2 has a YS of 280.5 MPa, an UTS of 452.8 MPa and an elongation to failure of 27.9%, indicating that SST improved the strength of the Al2024 alloy significantly. The above result is also much better than the SST casting alloy reported by Zhao et al. [20]. That is why we choose SPS alloy other than the casting alloy. Optical images (not shown here) indicate

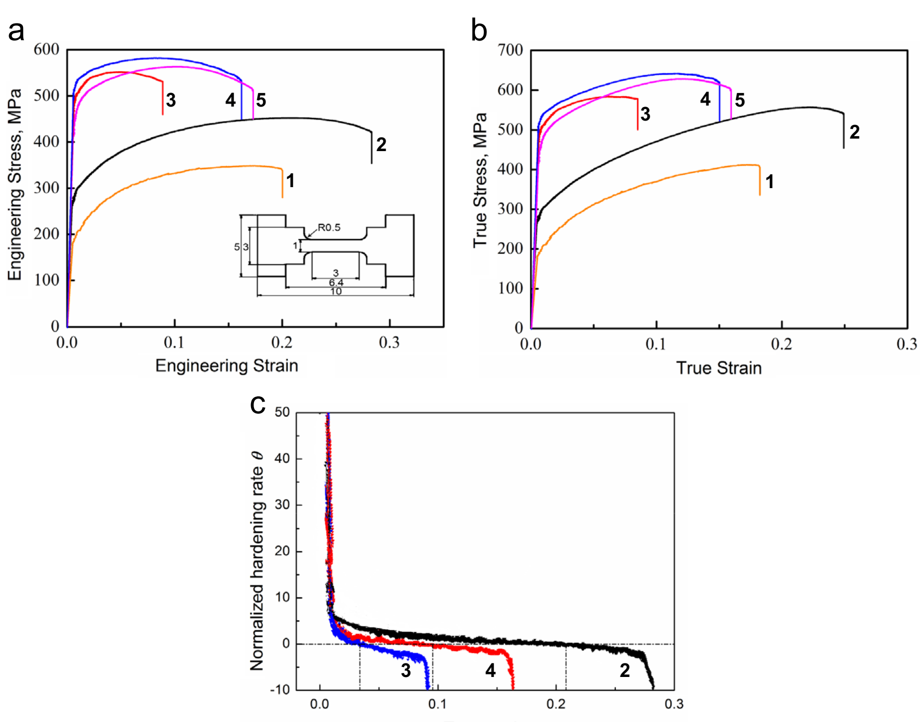

Fig. 1. (a) Typical tensile engineering and (b) the corresponding true stress–strain curves of Al 2024 alloy under different processing conditions. (c) Comparison of the work-hardening rate curves of three samples. The curves correspond to different processing states: (1) SPS; (2) SPS+SST; (3) SPS+SST+CR; (4) SPS+SST+CR+aging at 175 °C for 3 h and (5) SPS+SST+CR+aging at 100 °C for 18 h.