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Short Communication

Strength and ductility in ultrafine-grained wrought aluminum alloys

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ABSTRACT

Strength and ductility are two of the most important mechanical properties of engineering materials. In this work, a 6061 aluminum alloy was subjected to multi-directional forging (MF) and aging treatment. The samples possess high strength and high ductility after processing. The strength of samples was enhanced by dispersing ultrafine precipitate particles within the grains, reducing grain-size and increasing dislocation density after MF and aging. The ductility was improved due to reducing the forging stress during aging. Moreover, a mass of dispersing ultrafine precipitate particles widespread within the grains after aging, which helps to accumulate dislocations, increase the dislocation storage capability and resist dislocation slip that lead up to increasing work hardening, the ductility was also enhanced. A linear strengthening elastic–plastic model was developed by simplifying the stress–strain curves. On this basis, the strength and ductility of ultrafine-grained (UFG) materials were discussed. This also provides fundamental insight into the mechanisms that govern the strength and ductility of UFG materials.

1. Introduction

In the conventional grain size regime, usually a reduction in grain size leads to an increase in strength and ductility. However, the UFG materials have high strength, in accordance with the Hall–Petch relation, and a potential for use in a wide of structural applications, their utility is generally restricted because they exhibit disappointingly low ductility [1–4]. The promise of greatly increased strength and ductility for structural materials has been the driving force behind the increasing research effort on the mechanical properties of UFG materials. Some studies have indicated that the low ductility of UFG materials is attributed to insufficient work hardening due to an inability to accumulate dislocations [5,6]. High values of work hardening and strain-rate sensitivity are essential for high ductility because they can help delay localized deformation (necking) under tensile stress [6]. There has been considerable effort to address the pressing need of increasing the ductility of UFG metals and alloys at room temperature [5–10].

A combination severe plastic deformation (SPD) and sequent thermal treatment may be for producing UFG materials with high strength and high ductility [5,9,10]. Moreover, UFG Al–Mg–Si alloys with high strength and high ductility have been produced by cryorolling and heat treating [11–13]. Those works are quite interesting and valuable. However, for UFG materials, correlation between strength and ductility being associated with the toughness is not clear yet. Therefore, it becomes interesting to investigate correlation between strength and ductility of UFG materials. It will be significant both from academic and technological points of view.

Wrought aluminum alloys have attracted attention of many researchers, engineers and designers as promising structural materials for automotive industry or aerospace applications [14]. However, the application range is restricted owing to its low hardness and strength. It is necessary to increase the strength and the ductility for further applications to the industries. MF is also one method to exert severe plastic deformation on bulk materials and may be the most effective way [4,15]. In this work, a 6061 aluminum alloy was subjected to MF and aging treatment. Evolution of microstructure was investigated and mechanical properties were studied in comparison with coarse-grained sample. A linear strengthening elastic–plastic model was developed by simplifying the stress–strain curves. On this basis, the strength and ductility of UFG materials were discussed in detail. This also provides fundamental insight into the mechanisms that govern the strength and ductility of UFG materials.

2. Material and experimental procedure

A commercial 6061 Al alloy rod with a dimension of 40 mm × 40 mm was purchased in T6-treated state (T6). It contained alloy elements of 0.60 Si, 0.70 Fe, 0.25 Cu, 0.15 Mn, 1.00 Mg, 0.20 Cr, 0.25 Zn, and 0.15 Ti balance Al (all in weight percentage). The samples were cut into cubic with starting dimensions of 20 mm × 40 mm × 40 mm and solution heat treated at 520 °C for

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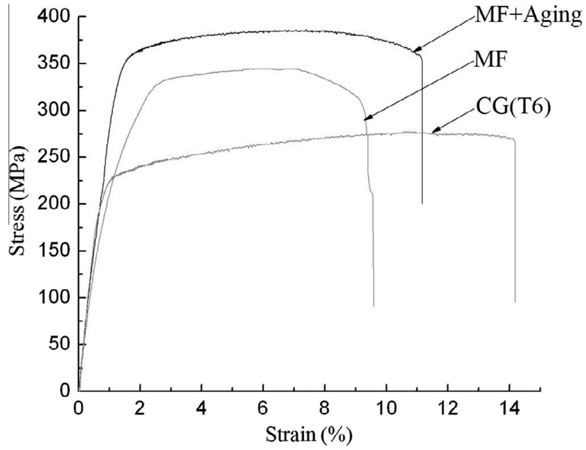

Fig. 1. Stress–strain curves of samples.

1 h and quenched in water. Then the samples were heated at 130 °C for 20 min. The samples were 3 cyclic forged in *x*, *y* and *z* directions respectively, every time of forging produced 50% reductions by 3 passes at a strain rate of approximately 10 s^{-1} by an air rammer. Finally, the samples were forged into the piece with a dimension of 16 mm × 25 mm × 80 mm. MF samples were subjected to aging at 125 °C for 24 h.

The strength and ductility of samples were tested according to test standard [16]. All of the samples were cut into dog-bone-shaped specimens with a gauge length of 30 mm, and a cross section of 2.5 mm × 10 mm. Uniaxial tensile tests were conducted at room temperature using an Instron 8801 Materials testing machine with an initial strain rate of 1.1×10^{-3} s^{-1}. Microstructure features of the samples were characterized by a JEM-2100F transmission electron microscope (TEM, operating at a voltage of 200 kV).

3. Results and discussion

Stress–strain curves of these samples are compared in Fig. 1. The coarse-grained sample has a low yield stress but exhibits significant work hardening and a large elongation to failure. This behavior is typical of coarse-grained metals. The elongation to failure is a quantitative measure of ductility, and is taken as the strain at which the sample broke. It can be found that the MF increases significantly the strength but decreases dramatically the ductility. This is consistent with the mechanical behavior of metals and alloys that are processed by other SPD techniques [15,17]. However, after being processed by aging treatment for 24 h, the strength and ductility of MF sample were improved simultaneously. The tensile strength and elongation of sample are 385.7 MPa and 11.17%, respectively.

Fig. 2a shows a cross-sectional optical microscopic microstructure of the sample before the processed (T6). A coarse-grained structure in sample can be easily observed. Fig. 2b shows optical microscopic microstructure of the sample after MF. SPD can be easily observed in the sample. The microstructure of alloy was refined markedly. Fig. 2c shows optical microscopic microstructure of the MF sample after aging. To our surprise, there is relatively minor concurrent grain growth in MF sample after aging.

Fig. 3 shows the TEM micrographs of the MF samples. The heavily deformed microstructure with high dislocation densities and a

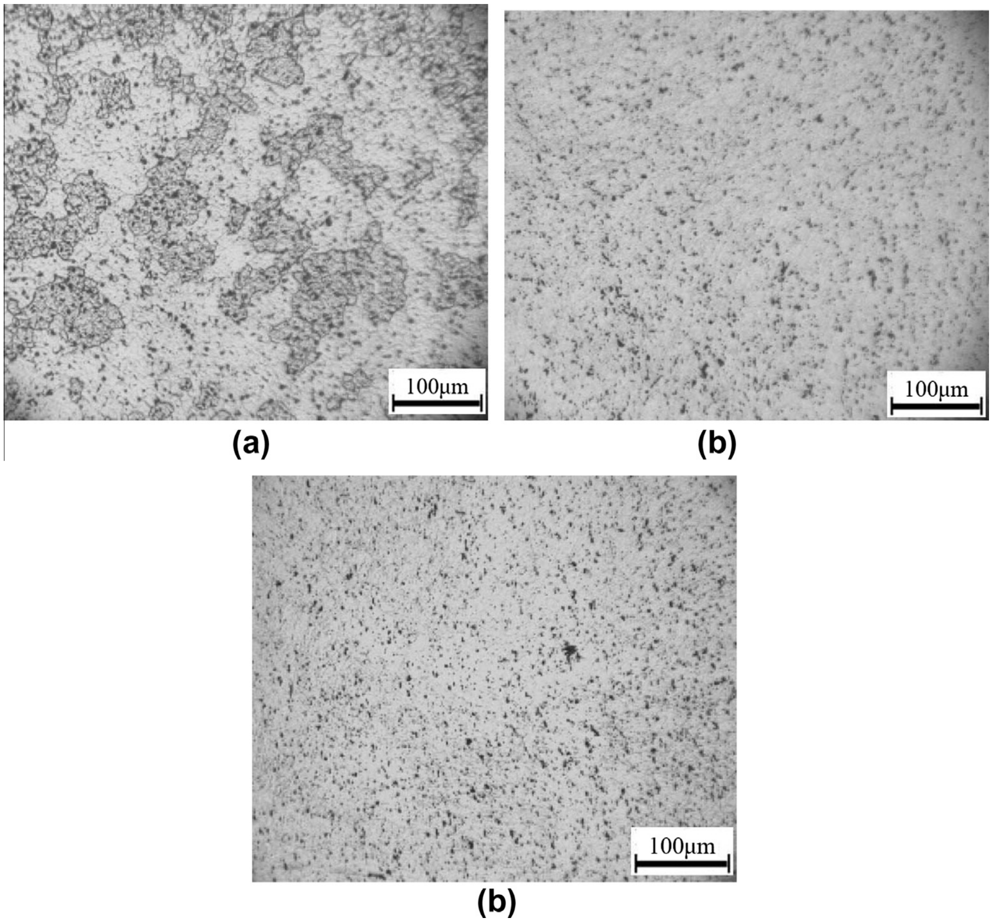

Fig. 2. Cross-sectional optical microstructure of samples: (a) before the processed (T6), (b) after MF process and (c) after MF and aging process.