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Mechanical properties and surface characteristics of an AA6060 alloy strained in tension at cryogenic and room temperature

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ABSTRACT

Mechanical properties at 77 K and 295 K and surface characteristics of an AA6060 alloy have been studied. The alloy exhibited significant differences in mechanical properties and fracture mechanisms at 77 K in comparison with that at 295 K. When the temperature decreases, the yield strength, the ultimate tensile strength and ductility to fracture are drastically increased from 217.2 MPa, 252.4 MPa, 14.5% to 251.6 MPa, 335.9 Mpa, 21.5% respectively, and the average diameter of dimples decreases from ~8 μm to ~3 μm. It is proposed that the changed behavior at cryogenic temperature can be attributed to an increased accumulation of dislocations at low temperature. Detailed inspections of the deformed polished sample surfaces show that slip localization in wide slip-bands is not promoted at 77 K, indicating that crystallographic slip is homogeneous, while activation of surface slip systems forming wide slip bands is much easier at 295 K and therefore the surfaces were deformed more in-homogeneously and localized. The homogeneity in slip behavior introduced more topography at 77 K than observed at 295 K and the enhanced topography might be due to more 3-dimensional (3D) lattice rotation in grains having a high Schmid factor, hence introducing more accumulation of local displacements in the thickness direction.

1. Introduction

Aluminum alloy AA6000 series have gained considerable attention due to their beneficial properties such as good corrosion resistance, attractive formability and workability, and high specific strength [1–4]. These alloys are extensively applied in transportation, building industry and in high-voltage electricity power transmission systems, etc. [5,6]. However, such applications still rely on continuous research and development. Hence, these alloys are subjected to numerous investigations aiming to reveal relationships between mechanical properties, deformation behavior, microstructure and technological processing parameters as well as working conditions.

It is well known that the temperature dependence of flow stress is governed by the thermally activated generation and motion of dislocations [7–10]. It therefore becomes important to examine the temperature dependence of mechanical properties as well as the kinetic nature of the deformation. Plastic deformation in crystalline metals occurs by slip on slip planes along corresponding slip directions, leading to lattice rotations and subsequently an evolution of deformation textures. To understand the formation of textures during deformation, some classic models have been developed, e.g. such as Sachs [11], Taylor [12], self-consistent [13] and other mathematical models [14], among others. Main considerations of these models are slip systems [11,12], lattice rotation [15] and the effect of deformation temperature on the work hardening behavior [16], etc. To assess these considerations in demonstrating microstructure-mechanical properties relationships, experimental work including deformation at low temperatures is needed. Over the last decades, considerable efforts have been devoted to clarify the cryogenic temperature performance of aluminum alloys. For instance, in a study involving Al–Li alloys with various Li compositions [17], the authors reported that dispersed particles have an influence on the mechanism of plastic deformation in the temperature region 40–170 K. For a rolled plate of an Al–Li–Cu–Mg–Zr alloy (AA8090), it was reported that the tensile, fracture and strain hardening properties increased when the test temperature was changed from 300 K to 77 K [18]. The latter study also reported that a precipitate distribution close to grain boundaries not forming precipitate free zones (PFZs), showed significantly improvements in mechanical properties, including fracture toughness at the cryogenic test temperature. Here, the fracture process was dominated by slip localization in slip bands promoting the slip band decohesion micro-mechanism [19].

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On the other hand, for a precipitate distribution forming PFZs, the properties increased much less when lowering the test temperature. In a study on the work hardening behavior vs. deformation temperature for pure Al [20], the authors concluded that suppression of dynamic recovery during deformation at low temperatures preserved a high density of dislocations generated by the deformation, i.e. simultaneously improving strength and elongation to fracture. The mechanical properties and fracture behavior of an Al–Mg–Sc–Zr alloy at temperatures below 273 K revealed that a decreasing test temperature resulted in a brittle to ductile transition, and increasing the elongation to failure [21], which was attributed to the ease of formation of thin deformation bands as well as a more extensive accumulation of lattice dislocations. It was also reported that the crystallographic texture formed at lower temperature was weaker than that produced at higher temperature after the same strain in an AA5754 alloy. Consistently, the lattice rotations were suppressed as the deformation temperature declined [22]. Generally for polycrystalline materials, grains rotate towards more stable orientations with increasing plastic deformation. Further, the stable orientation in tension at cryogenic temperature depends upon the initial texture of the material [23]. These previous studies consistently indicate that design of test procedures for Al-alloys at cryogenic temperature has been becoming more and more important along with the materials and their properties themselves, because the material properties as well as the microstructure change dramatically during deformation at cryogenic temperature.

During plastic deformation, differently oriented grains can create substantial deformation incompatibilities among neighboring crystals owing to anisotropic plastic flow [24]. Such incompatibilities can affect not only the interactions between interior grains in a material, but also the formation of roughening effects at the free sample surface [25]. So far, a number of experimental studies of surface roughening phenomena at room temperature have been reported, e.g. [26–28], it was suggested that strain hardening, crystallographic texture and the degree of material homogeneity significantly affected surface roughening [26]. By using a crystalline plasticity model combined with finite element analysis, one was able to evaluate surface roughening behaviors of aluminum alloy sheets under various loading conditions [29]. The simulation results showed that surface roughness characteristics could be related to the number of model element layers and the spatial distribution of micro-textures. Similarly, it was revealed that surface strain localization at room temperature was more concentrated in a thin coarse grained Cu samples [28], while plastic deformation was more homogeneous in the fine grained counterpart. In summary, by taking temperature dependence into account, it is expected that a cryogenic test temperature would exert evident effects on mechanical properties and microstructure evolution of deformed surface grains. To the best of the present authors' knowledge, such studies on AlMgSi alloys are still lacking. The present work will therefore extend the understanding of the deformation behavior of AlMgSi alloys at cryogenic temperature. The studied material is an extruded AA6060 alloy subjected to tension along the extrusion direction at 295 K and 77 K. The results reveal new information on obtained mechanical properties and characteristics in the evolution of grains at the surface of specimens.

2. Experimental procedures

The chemical composition of the investigated AA6060 alloy extrusion is given in Table 1. Flat dog-bone tensile specimens having a rectangular cross-section, i.e. 32 mm gauge length, 2 mm thickness and 6 mm width, were taken parallel to the extrusion direction (ED) of a 10 mm thick and 80 mm wide profile. All specimens were solution heat treated at 540 °C for 2 h and then quenched in water, following by a peak aging treatment (T6) at 180 °C for 6 h. The grain structure after the latter treatment was fully recrystallized (Fig. 1a), i.e. having an average grain size of 100 μm. The corresponding orientation distribution functions (ODF) obtained from electron back-scattering diffraction (EBSD) mapping in SEM, are shown in Fig. 1b, The crystallographic texture was dominated by a strong cube accompanied by a minor Goss component.

Table 1
Chemical composition of the present AA6060 alloy (wt%).

Si	Fe	Cu	Mn	Mg	Cr	Al
0.422	0.178	0.002	0.019	0.473	0.001	Balance

The flat surfaces of all the peak-aged samples were polished using standard metallographic techniques, followed by electrochemical polishing to minimize possible effects from deformed surface layers. Thereafter, uniaxial tensile tests were performed using a MTS880 testing machine with an initial strain rate of $10^{-4}\ s^{-1}$ at 295 K and 77 K. The cryogenic temperature tests were conducted by completely immersing samples and grips in liquid nitrogen. All mechanical tests were repeated 3 times to get reproducible results. In addition to the specimens that were strained to fracture, another set of samples were deformed to a fixed strain level of 0.1, which was close to the strain of necking at 295 K. Subsequently, the specimen surfaces were analyzed by EBSD in a Hitachi FEGSEM. These measurements were carried out in the plane defined by the extrusion- and normal directions of the profile. A microhardness indentation was made on this plane before deformation in order to perform the EBSD measurements in the same area. Furthermore, to characterize the three-dimensional (3-D) surface topography of the deformed tensile specimens, a Laser Scanning Confocal Microscope (LSCM; LEXT OLS4000) was used. For the fractured specimens, fractography was performed using a SEM at different magnifications. Finally, hardness measurements were conducted using the Vickers hardness method with 1 kg load and at least 20 measurements were performed on the sample deformed to 0.1 strain for more reliable results.

3. Results

3.1. Mechanical properties and fracture characteristics

Fig. 2 shows the stress–strain and work-hardening curves for the present AA6060 alloy deformed at 295 K and 77 K, and the corresponding mechanical properties are listed in Table 2. It can be seen that the yield strength, ultimate tensile strength as well as ductility are strongly influenced by the test temperature, e.g. increasing from 217.2 MPa, 252.4 MPa and 14.5% at 295 K to 251.6 MPa, 335.9 MPa and 21.5% at 77 K, respectively. To characterize the work hardening behavior, the nominal stress–strain data were firstly transformed to true stress–strain data (σ is the true stress and ε is the true strain) and then plotted as $\partial\sigma/\partial\varepsilon=\theta$ vs. σ and θ vs. ε. The corresponding work hardening rate plots are shown in Fig. 2c and d, respectively. It should be noted that due to serrations in the flow curves, smoothing of the stress–strain data was done. It can be seen that the work hardening rate is improved significantly at 77 K compared with that at 295 K. This behavior is confirmed from Fig. 2b, where the stress–strain curve at 295 K has a lower slope than that at 77 K. Also hardness is higher after deformation at 77 K (Fig. 3), and is probably due to a pronounced dislocation storage contribution.