Materials Science & Engineering A 639 (2015) 519–525

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

In-situ investigation of the anisotropic mechanical behavior of rolled AA 7020-T6 alloy through lattice strain evolution during uniaxial tension

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ARTICLE INFO

Article history:
Received 29 October 2014
Received in revised form
15 May 2015
Accepted 15 May 2015
Available online 22 May 2015

Keywords:
AA 7020-T6 alloy
Anisotropy
Lattice strain
Texture
High energy X-ray diffraction

ABSTRACT

The texture-induced anisotropic mechanical behavior of a highly textured AA 7020-T6 (maximum orientation density of 29.7 multiple random distribution), was characterized by the lattice strain evolution along rolling direction (RD), 45° to RD and 90° to RD, respectively, under uniaxial tension using high energy X-ray diffraction. The uniaxial tensile tests were done till ultimate tensile strength (UTS), which show different yield strengths (YS), UTS and elongations along the three directions on a macroscopic level. On micromechanical level, the lattice strain evolution explains the correlation between crystallite orientation and different mechanical behavior, leading to the macroscopic anisotropy. In the elastic region, the sample 45° to RD has the lowest lattice plane dependent Young's modulus compared to the other two directions. In the elastic plastic transition region, lattice strain differences among different {hkl} lattice planes are highest for sample 45° to RD and lowest for sample 0° to RD. Moreover, the 45° to RD sample has the lowest lattice dependent YS. In the plastic region, the work hardening behavior of different {hkl} lattice planes in all three directions can be divided into two groups, corresponding to two types of dislocation combinations. However, {200} planes of samples 45° and 90° to RD behave abnormally due to the stress along $<110>$ of the {200} planes and the orientation density of {200} planes parallel and perpendicular to the loading direction (LD).

1. Introduction

Engineering components may exhibit anisotropic mechanical behavior as a function of the angle from the RD due to the producing processes that give rise to preferred orientations, which is considered to be the main contributing factor for the elastic and plastic anisotropy of rolled aluminum alloys [1–3]. The anisotropic mechanical behavior includes different Young's Moduli, yield strengths, UTS and elongations along different directions with respect to RD, which lead to the occurrence of earing during deep drawing of a textured sheet [4]. Literature reported that the 7000 series aluminum alloys have such anisotropic behavior on a macro scale due to texture [5,6].

AA 7020 alloy belongs to the 7000 series alloys and is widely used in welded engineering structural components due to the high strength, good weldability and low producing costs. However, AA 7020-T6 exhibits mechanical anisotropy due to the texture resulting from the producing procedures. In industry, the anisotropy is normally characterized by the plastic strain ratio (*r*-value), which only shows the anisotropic behavior on a macro scale [7]. In contrast, lattice strain evolution reveals that in a textured material, crystallites oriented in a given direction possess specific mechanical behavior, which gives insight into mechanical anisotropy from a micromechanical level.

The lattice strain of individual lattice planes under external load depends on the single crystal properties, on how the lattice planes are oriented with respect to the loading axis and on how they interact with the neighboring crystallites [8]. The first factor belongs to the intrinsic properties of the material, while the last two are extrinsic factors, both of which exert influence on the geometry of dislocation slips. The lattice strain evolutions of face-centered cubic (fcc) materials with random orientations or with weak texture during uniaxial tension were investigated by several researchers [9–15]. In the elastic region, elastic anisotropy, which is expressed by $2C_{44}/(C_{11}–C_{12})$, plays an important role in lattice strain evolution [9–11]. However, the ratio of Young's moduli E_{111}/E_{200} in a polycrystalline material may be different from that

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http://dx.doi.org/10.1016/j.msea.2015.05.050
0921-5093/

calculated by the Kröner model, because of the interactions with neighboring crystallites, resulting in different lattice plane dependent stress–strain behavior [12]. Furthermore, the measured lattice strains of individual lattice planes imply that the E_{111} is not the largest one in a textured polycrystalline copper, even though the E_{111} is the largest one in copper with random orientations [13]. From elastic–plastic transition region on, lattice strains are dominated by both elastic and plastic anisotropy, the latter of which is dependent on the easiness of dislocation slip. Load redistribution at the elastic–plastic transition region causes lattice strains of different lattice planes to possess different magnitudes. Experimental results show that the lattice planes which yield firstly carry smaller load than the other ones which still deform elastically. For randomly oriented aluminum which has small elastic anisotropy, the crystallites with the normal of {111} planes parallel to LD possess larger lattice strain than the other crystallites, while for copper and stainless steel which have large elastic anisotropy, the crystallites with the normal of {200} planes parallel to the LD possess larger lattice strain [7]. Moreover, the lattice strains of other lattice planes are bounded by those of {111} and {200} lattice planes [9,10]. Besides, simulation results of lattice strain evolution of weakly textured material can only qualitatively capture the characteristics of the measured results, and Daymond et al. [10] attributed the differences between the simulated results and the measured results to the texture (with maximum orientation density smaller than 3 mrd). By contrast, in the present study, the emphasis is on the lattice plane behavior along different orientations of a highly textured AA 7020-T6 alloy characterized by high energy X-ray diffraction, to understand the mechanisms contributing to the mechanical anisotropy.

Third generation synchrotron radiation provides high-energy X-rays with high brilliance, which makes it possible to get the microstructure information of a material in a short exposure time by transmission technique [16]. It allows in-situ lattice strain measurements to be carried out without stopping the loading machine at a relatively low loading speed. During the measurement, complete Debye–Scherrer rings are collected by an area detector, from which one can get the lattice spacing of individual {hkl} lattice planes in both parallel and perpendicular to the LD simultaneously.

2. Experimental

2.1. Material

The investigated material was from a rolled AA 7020-T6 aluminum block with thickness of 29.7 mm. The as-received AA 7020-T6 block, which is used for military use, was got from a French company called CNIM (Constructions industrielles de la Méditerranée) [17]. The AA 7020 block went through T6 heat-treatment (solution heat-treated and artificially aged) after rolling, to get the maximum strength [18]. Its chemical composition of the material is listed in Table 1, which was obtained using atomic emission spectroscopy. Three flat samples were cut from the center layer of as-received AA 7020-T6 block along rolling direction (RD), 45° to RD and 90° to RD, respectively. The sketch of the flat sample is shown in Fig. 1. The thickness of the sample is 3 mm, and the X-ray was parallel to the thickness direction during the measurement. The center layer of the as-received block shows the strong plane-strain rolling texture of high stacking fault energy fcc materials. The orientation distribution function (ODF) analysis results of the center layer are shown in Fig. 2. One can see that the orientations are mainly concentrated along the β fiber which runs from copper component {112} < 111 > through S component {123} < 634 > to brass component {011} < 211 > in Euler space [19]. The maximum orientation density is 29.7 multiple random distribution (mrd). The optical microstructure of the sample exhibits that grains are elongated along RD, as shown in Fig. 3. The sample was etched in the solution consisted of 200 ml distilled water and 5 g 35% tetrafluoroboric acid for 2 min under 30 V voltage, which produced different colors on grains with different orientations [20], and the microstructure image was obtained using optical microscopy Olympus-PMG3. The black spots in the Fig. 3 are the precipitates consisting of η′, η and T′ which were formed after T6 heat-treatment [21].

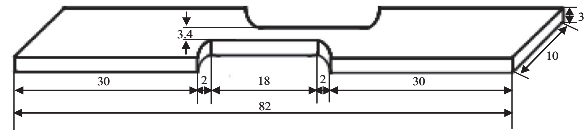

Fig. 1. Sketch of the flat sample (mm).

2.2. Lattice strain measurement

The lattice strain measurements were carried out at the High Energy Material Science beamline HEMS, P07B, at PETRA III (DESY, Hamburg). The X-ray beam from the storage ring was monochromatized by a single bounce monochromator (SBM) comprised of two flat water-cooled Laue crystals Si(111) and Si(220), with which the energy can be changed between 53 and 87 keV, respectively. In the present work, the 87 keV X-ray beam (X-ray wavelength of 0.1420 Å) was chosen to characterize the lattice strain evolution with beam size 0.5×0.5 mm^2 and sample-detector distance of 1119 mm. The flat sample was fixed in a universal testing machine (UTM) which can reach the maximum load of 20 kN [22]. The in-situ tensile measurements were performed at room temperature with a loading speed of 5×10^{-4} mm/s till UTS. The diffracted beams, Debye–Scherrer rings, were recorded by Perkin Elmer XRD 1622 flat panel, a fast data-collecting area director which has 2048×2048 pixels with pixel size of 200×200 μm^2. The misalignment of the area detector was corrected by the LaB_6 standard powder using the software package FIT2D [23], and the tilting angle of the detector was 0.12°.

The LD of the three samples with respect to the Al (111) pole figure is shown in Fig. 4. In-situ tensile tests along these three directions can give insight into the initial texture effects on the lattice strain evolution. The load-elongation curves of the three samples and the measured points are shown in Fig. 5. The elongation is the length change of the whole loading system, which was recorded by the software coupled with the tensile loading machine. The texture dependent yield strengths are 317.8 MPa, 297.5 MPa and 303.5 MPa for the LD parallel to RD, 45° to RD and 90° to RD samples, respectively. The texture leads to the lowest yield strength in the 45° to RD sample.

Table 1
Chemical composition of the studied material in weight percent.

	Zn	Mg	Fe	Mn	Zr	Cu	Si	Ti	Al
AA 7020-T6	4.172 ± 0.014	1.215 ± 0.006	0.319 ± 0.009	0.300 ± 0.001	0.148 ± 0.004	0.078 ± 0.001	0.033 ± 0.001	0.013 ± 0.001	Balance