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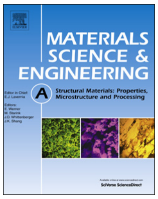

Effect of pre-fatigue deformation on thickness-dependent tensile behavior of coarse-grained pure aluminum sheets

Y. Yan [a], M. Lu [a], W.W. Guo [a], X.W. Li [a,b,*]

[a] *Institute of Materials Physics and Chemistry, College of Sciences, Northeastern University, Shenyang 110819, PR China*
[b] *Key Laboratory for Anisotropy and Texture of Materials, Ministry of Education, Northeastern University, Shenyang 110819, PR China*

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ABSTRACT

To explore the size effect on the mechanical properties of the coarse-grained materials and the relevant influence of sub-structures, the coarse-grained pure aluminum sheets with the thickness spanning from 0.2 to 2.0 mm are selected as experimental materials, on which the pre-fatigue deformation (pre-cycle is equal to 5% of fatigue life N_f) is exerted to alter internal sub-structures. The results show that the uniform strain ε of the annealed sheets almost linearly decreases with the reduction of thickness, and the ultimate tensile strength σ_{UTS} first slowly declines, then quickly drops as the thickness is below 0.5 mm, but the yield strength σ_{YS} does not exhibit an obvious thickness effect. The pre-fatigue deformation not only significantly improves the plasticity, but also decreases the critical thickness t_c (below which the decrease in σ_{UTS} suddenly becomes notable) from 0.5 mm of the annealed state to 0.3 mm, meanwhile, a higher σ_{UTS} is maintained at the thickness ranging from 0.3 to 2.0 mm. For the annealed sheets, the cracks are initiated at grain boundaries (GBs), and with decreasing thickness, the appearance of a lot of straight slip lines leads to the occurrence of single slip separation failure in thinner sheets. The pre-fatigue deformation not only increases the uniform deformation degree in grain interiors, but also promotes the formation of more ill-developed cells in sub-grains and wall-cells and the development of the sub-grains in thinner sheets, so that all the pre-fatigued sheets exhibit ductile failure and a higher σ_{UTS} is obtained at the thickness between 0.3 and 1.0 mm.

1. Introduction

It is well known that the mechanical behavior of bulk materials with thicker or greater dimensions is intensely influenced by their microstructures, and the most typical example is the Hall–Petch relation [1,2]. As the specimen size is scaled down to the range spanning from sub-millimeter to sub-micron, the so-called "specimen size effect" [3] occurs. In order to examine comprehensively the effect of average grain size d and sample size t on the mechanical behavior of materials, Armstrong [3] and Thompson [4] pointed out the ratio t/d effect.

Since then, studies on the t/d effect, as well as on the t and d effects, have been widely conducted [5–15]. A number of research findings have demonstrated that as the t/d or t is decreased to less than a critical value $(t/d)_c$ or t_c, with the continuous decrease of the t/d or t, the mechanical properties of materials may be abruptly changed (e.g., enhanced or weakened). Such changes primarily depend upon the investigated materials [5–10], the strain-gradient levels [5,8], the specimen orientations [10], the free surface state [12], the span of grain and specimen sizes for the same materials [5,11,13–15], etc. Meanwhile, some investigations also revealed that an increase in the average grain size will raise the critical value of t_c, and the materials with large grain size exhibit a more marked specimen size effect. For example, on examining the size effect of tensile strength of the copper sheets with the average grain size from 5 to 50 μm and the thickness between 0.15 and 1 mm, Molotnikov et al. [14] found that the t_c value decreases with the decreasing of the grain size, and the loss of strength also reduces upon thickness reduction, that is to say, a decrease in grain size will delay the onset of size effect [14]. Chen et al. [9] examined the tensile strength of Ag wires with the diameter from 20 to 50 μm and average grain size between 3.5 and 40.6 μm, and found that the Hall–Petch relationship is obeyed in the small grain size regimes from ~3.5 to 10.6 μm; while for the two larger grain sizes of 21.0 and 40.6 μm, the yield strength seems to be higher than that extrapolated from the Hall–Petch relation of the smaller grain sizes. The results suggest that the wires with the two larger grain sizes display evident specimen size effect. In addition, to generate different grain sizes, the mechanical processing and subsequent heat treatment are usually used, which can not only

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[*] Corresponding author at: Institute of Materials Physics and Chemistry, College of Sciences, Northeastern University, Shenyang 110819, PR China. Tel.: +86 24 83678479; fax: +86 24 83683674.
E-mail address: xwli@mail.neu.edu.cn (X.W. Li).

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obtain different grain sizes, but also induce a variation in sub-structure and crystallographic texture. But up to now, more attentions are focused on the ratio t/d effect, as well as the t and d effects, while the internal sub-structure influence on the size effect is rarely considered. Simons et al. [15] examined the effect of interior micro-structures of Cu foils with the thickness from 10 to 250 μm on the fracture strain, and thought that a high dislocation density is responsible for limited work hardening rate in thinner samples.

A variety of studies have demonstrated that some pre-treatment methods, such as severe plastic deformation (SPD) [16,17], induction of residual compression stress [18,19], pre-fatigue deformation [20–24], etc., can improve the mechanical properties of materials by refining grains or changing the internal sub-structures. Therefore, in the present work, to purely consider the "specimen thickness effect", the annealed coarse-grained pure aluminum sheets with a constant grain size and the thickness ranging from 0.2 to 2.0 mm were chosen as target materials. The pre-fatigue deformation to a suitable fatigue life percent was exerted on the annealed pure aluminum sheets with different thicknesses to study the contribution of the sub-structure variation to the size effect.

2. Experimental materials and methods

The polycrystalline aluminum ingot of 99.996 purity was selected as the original material. The ingot was first cold-rolled and then annealed at 350 °C for 20 min. Fig. 1 shows the initial optical microstructures of annealed sheet along the rolling direction and the rolling plane. The average grain size is approximately 550 μm.

The specimens for pre-fatigue tests were cut from the annealed sheet, and their gauge dimensions are 10 mm in length, 5 mm in width and 7 mm in thickness. Fully reversed push–pull stress-controlled fatigue tests were performed under a stress amplitude of 30 MPa at room temperature in air using a 20 kN HUF-2020 CARE servohydraulic tester. A sinusoidal waveform signal with a frequency of 1 Hz was applied. The total fatigue life N_f was measured to be ~30,000 cycles as the sample was cyclically deformed to fracture. In order to obtain the sub-structure, which is somewhat different from that of the annealed sheet, the pre-cyclic test was interrupted just at 1500 cycles (i.e., 5% N_f) [23].

All the tensile specimens were cut from the annealed sheet and the pre-fatigued specimen. Their gauge dimensions are 10 mm in length, 5 mm in width and the different thicknesses from 0.2 to 2.0 mm. The tensile tests were carried out at a strain rate of $10^{-3}\,s^{-1}$ to the final fracture. Before tension, all the specimens were electro-polished to obtain smooth surfaces. The deformation features on the lateral surfaces near the fracture, the fracture surfaces and microstructures were observed using SSX-550 SEM and Tecnai G^2 20 TEM, respectively.

3. Experimental results

3.1. The thickness dependence of tensile properties and the relevant effect of pre-fatigue deformation

Fig. 2 shows the engineering stress–strain curves of the annealed sheets with different thicknesses and the corresponding tensile properties. It is clear that the uniform strain ε almost linearly decreases with the reduction of thickness, while the ultimate tensile strength σ_{UTS} first slowly declines, then quickly drops after the thickness is less than 0.5 mm, which approaches to the average grain size of annealed sheet. There is no obvious change in the yield strength σ_{YS} with decreasing thickness.

The tensile stress–strain curves of different-thickness sheets pre-fatigued to 5% N_f, and the variation of tensile properties with thickness are displayed in Fig. 3. The ε still linearly decreases with the reduction of thickness, except for a dramatic decrease occurring at 0.2 mm thickness. The σ_{UTS} first slowly reduces with decreasing the thickness to 0.3 mm, and then rapidly reduces at the 0.2 mm thickness. The σ_{YS} also does not exhibit noticeable thickness-dependence.

For the comparison of tensile properties of the annealed and pre-fatigued sheets at the same thickness, the combined results from Figs. 2 and 3b are demonstrated in Fig. 4. Two important aspects are worthy to be mentioned. First, the pre-fatigue leads to a significant increase in the uniform strain ε at the thickness range from 0.3 to 2.0 mm, but dramatic decrease occurs at the 0.2 mm thickness. Second, the σ_{UTS} is almost the same at the thickness ranging from 1.0 to 2.0 mm, with continuously decreasing thickness, the σ_{UTS} of the pre-fatigued sheets is higher than that of the annealed sheets, and the critical thickness t_c decreases from 0.5 mm of the annealed state to 0.3 mm of the pre-fatigued state.

On the whole, the ultimate tensile strength and the uniform strain of the coarse-grained pure aluminum sheets exhibit a strong thickness dependence, especially for thinner sheets. The pre-fatigue deformation not only improves the plasticity largely, but also decreases the t_c (below which the decrease in σ_{UTS} suddenly becomes notable) from 0.5 mm of the annealed state to 0.3 mm, meanwhile, a higher σ_{UTS} is maintained.

3.2. The deformation characteristics on the lateral surfaces

The deformation characteristics on the lateral surfaces near the fracture surfaces after the annealed sheets with different thicknesses were loaded to tensile rupture are displayed in Figs. 5 and 6. With decreasing thickness, the elongation of grains

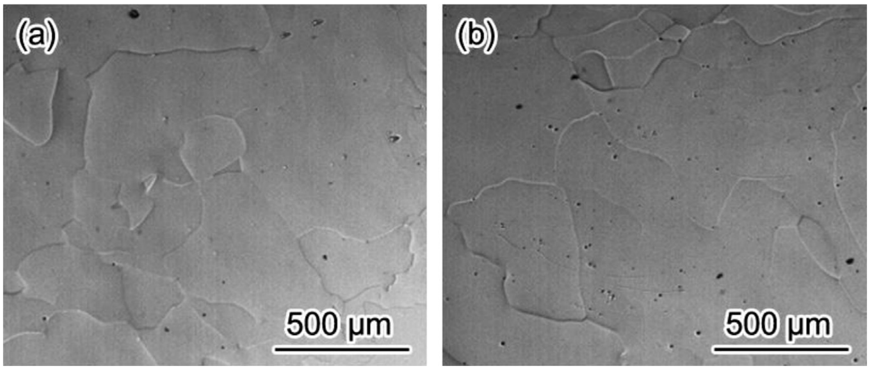

Fig. 1. Metallographic microstructures of as-annealed aluminum sheet along the rolling direction (a) and the rolling plane (b).