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Flow stress analysis of ultrafine grained AA 1050 by plane strain compression test

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ABSTRACT

Plane strain compression (PSC) test was used to study the flow stress of ultrafine grained commercially pure aluminum at large strains. AA 1050 sheets were processed by various Accumulative Roll-Bonding (ARB) cycles up to 10 cycles as the initial specimens for the test. An approach was developed to measure the coefficient of friction and to suppress its effect on the results. It is shown that as a result of having an anisotropy parameter (*R*-value) of less than one, Von-Mises tensile strengths are significantly higher than PSC strengths. Comparing these strengths, the *R*-value as an average anisotropy parameter of rolling and transverse directions is estimated for the ARBed sheets, where it is decreased by 6 ARB cycles and increased by the following 8–10 cycles. Estimated *R*-values are used for drawing the flow curves based on the Hill's 1948 anisotropic plasticity. While the flow curves display a steady state flow stress for all samples, a flow softening is observed at the beginning of the curves for 8 and 10-cycle specimens up to strain of 0.3. It is revealed that despite evidence for shear banding, the softening has a microstructural reason due to different strain rates during pre-straining by ARB and PSC. In other words, since the grain refinement during ARB up to 8 and 10 cycles has exceeded the smallest possible grain size of the PSC test, post-ARB deformation of these two specimens result in a microstructural revolution toward the preferred steady state conditions along with a gradual work softening.

1. Introduction

Grain size is one of the major effective parameters on the mechanical properties of polycrystalline metals. The effect of grain size on strength is quantified through the Hall–Petch equation in which the yield or flow stress of polycrystalline metals is proportional to the inverse square root of the grain size, i.e.,

$$\sigma_y = \sigma_0 + Kd^{-1/2} \tag{1}$$

where σ_0 is the friction stress and K is a constant [1,2]. That the strength of polycrystalline metals is enhanced by a decrease in the grain size into the ultrafine or even the nanostructured regime, has been an interesting way to produce a promoted version of conventional metals and alloys. During the last decade, it has been well illuminated that Severe Plastic Deformation (SPD) is a very effective way to achieve such a Ultrafine Grained (UFG) [3,4] and bulk nanostructured [5,6] metals. Among various SPD processes, Equal Channel Angular pressing (ECAP) [7], Accumulative Roll-Bonding (ARB) [8] and High Pressure Torsion (HPT) [9] have been the most investigated processes on bars, sheets and disk shaped metals, respectively. As it can be applied by means of a conventional rolling facility, ARB overcomes limitations of the two other processes, i.e. low productivity of ECAP and small work-piece size of HPT [3]. Grain refinement and its remarkable effect on enhanced strength and hardness has been reported by doing this type of SPD process on various aluminum alloys [10–14]. Along with such an increased strength, unfortunately, low ductility and elongation are reported as inevitable consequences of ARB. While tension test is performed almost in all studies to define mechanical properties of the ARBed sheets, the low elongation has been a barrier of full mechanical characterization. Of particular interest is determination of the trend of flow stress not only for its own importance, but also for its capability in revealing micro and macrostructural aspects of the metal flow during post-processing deformation. Flow stress versus the post-processing strain up to large strains may provide a very helpful knowledge on the microstructural response of the ultrafine grained and nanostructured metals to applied stress. However, as a result of necking, a big and important part of this curve is lost in tension test. Furthermore, some aspects of deformation are difficult to observe at very small strains. Although strain rate sensitivity [15,16] and

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anisotropy [17] are measured by tensile data before necking, there is no guarantee that the related values are reliable at larger strains. In order to overcome the limit of necking in tension test of ECAPed aluminum samples, several researchers have used the uniaxial compression test [12,18–20]. While it is not practical to apply uniaxial compression test for ARBed sheet metals with small thicknesses, plane strain compression (PSC) test is a potentially applicable test [21]. The current study aims to examine such a test and cover the lack of data for stress of ARBed AA 1050 sheets at large strains.

2. Experimental procedure

Commercially pure aluminum sheets, AA 1050, with thickness of 1.5 mm and composition shown in Table 1 after annealing at 330 °C for 1 h with a mean grain size of 28 μm have been used as primary material. Sheets were cut in dimension of $60\times 160\ \text{mm}^2$ for ARB processing. Two rollers with diameter of 150 mm and rotational speed of 50 rpm were used for roll-bonding process with 50% of thickness reduction with approximate strain rate of $25\ \text{s}^{-1}$. The surface of rollers were degreased and cleaned by acetone before roll bonding process in which no lubricant was used. As for surface brushing, a 55 mm diameter stainless steel circumferential brush with wire diameter of 0.35 mm was used at rotational speed of 2500 rpm. ARB cycles have been performed at room temperature up to 10 cycles. Each cycle included cutting, degreasing with acetone, wire brushing, stacking and roll-bonding.

Tension samples were cut from center of the sheets at longitudinal direction and machined according to the ASTM E8 standard. The test was done at room temperature with initial strain rate of $1\times 10^{-3}\ \text{s}^{-1}$. PSC samples were also prepared from center of the sheets at rolling direction, so that the groove was aligned with the transverse direction, in which no spreading was imposed during the test. Sample location and dimensions of the test specimen and tools are depicted in Fig. 1. In order to minimize the friction, both of the samples and the indenters were finely polished and covered by a PTFE lubricant grease. The indenters were constrained in one degree of freedom within the walls of a jig to move vertically. It has been confirmed that the results of PSC test are reliable and redundant strains are negligible as long as the strip thins within the following range [22,23].

$$2\le \frac{b}{t}\le 4 \text{ and } 5\le \frac{w}{b}\le 12 \qquad (2)$$

Table 1
Chemical composition of the material (mass%).

Al	Si	Fe	Cu	Mn	Mg	Zn	Other
99.27	0.18	0.41	0.066	0.015	0.011	0.0234	0.029

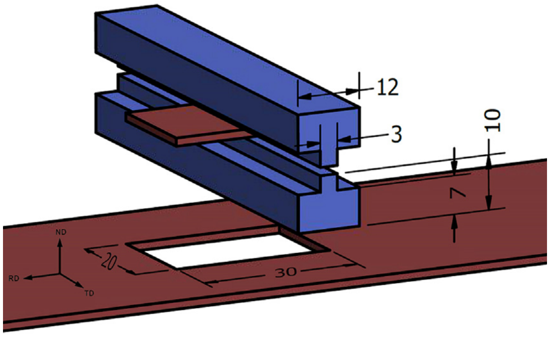

Fig. 1. Geometries and dimensions (mm) of the PSC sample and indenters.

where b is the indenter breadth, t is the current sample thickness beneath the indenter and w is the sample width. Taking into account the dimensions (Fig. 1), compression up to the Von-Mises equivalent strain of 0.8 is acceptable in the required range. Initial strain rate of this test was $4\times 10^{-3}\ \text{s}^{-1}$. For 8 and 10 cycle specimens, initial strain rate of $10^{-1}\ \text{s}^{-1}$ was also used to study the effect of strain rate on the trend of flow stress curves.

Macrostructure analysis of the specimens was performed in an optical microscope using cross polarized mode to observe the possible shear bands. For this purpose, transverse surface of the samples were polished and etched in a 59% Poulton's reagent, 30% HNO_3, 3% chromic acid and 8% H_2O solution [24].

2.1. Correction procedure for friction

Generally, registered data of PSC test needs 4 types of correction due to effect of friction, redundant work, spreading and temperature change. It was mentioned in the previous section that up to a Von-Mises equivalent strain of 0.8 no considerable redundant strain interfere and therefore no relevant correction is necessary. Also, due to a large sample width compared to the indenter breadth, no spreading was observed within the range mentioned in Eq. (2). Regarding the temperature change, since the test was done at room temperature with a small strain rate, no heating up due to heat of deformation or cooling down due to thermal contact was involved. However, the friction still plays an inescapable role in the measured force and its relevant correction is vital to have a trustworthy flow stress.

Although one can calculate the effect of friction by Finite Element Method (FEM) [25] or slip line field analyses [26], slab analysis [26–28] is the most straightforward method to estimate the role of friction on required force in various deformation processes including the PSC test. Based on this analysis, material shear strength or shear flow stress (K) is related to the current average pressure of PSC ($\overline{p}$), current thickness of sample (t), coefficient of friction (μ) and indenter breadth (b) as follows [28]:

$$\frac{\overline{p}}{2K}=\frac{t}{\mu b}\left[\exp\left(\frac{t}{\mu b}\right)-1\right] \qquad (3)$$

Having the coefficient of friction, Von-Mises flow stress (σ_{VM}) can be obtained as a function of Von-Mises equivalent strain (ε_{VM}) using the following relations for PSC [28]:

$$\sigma_{VM}=\sqrt{3}K=\frac{\sqrt{3}}{2}\overline{p}=\frac{\sqrt{3}F}{2wb} \qquad (4)$$

$$\varepsilon_{VM}=\frac{2}{\sqrt{3}}\varepsilon_t=\frac{2}{\sqrt{3}}\ln\left(\frac{t_0}{t}\right) \qquad (5)$$

where F is the compression force during PSC test and ε_t is the thickness strain. It is obvious that an accurate μ is the key to successful correction. Since the coefficient of friction is affected by many factors such as surface condition, lubricant, temperature, pressure and relative velocities and direction of the surfaces, the only credible way to determine its value correction is the direct measurement at the exact conditions of the test.

A technique is described by Watts and Ford [22] and used by Alexander [26] in which it is possible to estimate the coefficient of friction through comparison of the PSC pressure at a finite strain of for example 10% for the same strips under two identical conditions, except that the ratio of b/t is 3 in one case and 7 in the other. Such a technique is modified and used in the current study. In this approach an increasing linear coefficient of friction with two constants is used:

$$\mu=\mu_0+C\varepsilon_t \qquad (6)$$