Hardening mechanisms of aluminum alloys under dynamic-channel angular pressing

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Abstract. An experiment on high-speed deformation of aluminum alloy A3003 by dynamic channel angular pressing is described. During dynamic pressing, the material is exposed to two deformation modes. They are compression-tension due to the interaction of shock and rarefaction waves when the sample hits the bottom of the first channel, and a simple shear localized at the joint of the channels. The features of structure formation under the action of each deformation mode are determined. It was found that a high dislocation density and the presence of localized deformation zones caused by shock-wave loading, have a significant influence on the formation of the structure upon dynamic channel-angular pressing. The mechanisms of hardening and the contribution of dislocation and grain-boundary components to the overall hardening of the alloy are determined.

1. Introduction

It was found earlier [1-3] that dynamic channel angular pressing (DCAP) is an effective technique for refining the structure and hardening of commercial aluminum alloys. The enhancement of structural and phase transformations in aluminum alloys is due to the high strain rate (10⁴-10⁵ s⁻¹) and two acting deformation modes. The deformation modes are compression-tension on account of the circulation of shock and rarefaction waves emerged when a sample hits the bottom of the first channel and a simple shear is localized at the joint of the channels. The aim of the present work is to study the nature of the hardening of an aluminum alloy with an ultrafine-grained (UFG) structure and to determine the contribution of each deformation mode to the strength of the material produced by DCAP.

2. Experimental

During DCAP, a cylindrical Al-Mn (A3003 alloy) billet with a diameter of 30 mm and a length of 200 mm with a coarse subgrain structure with an average size of the subgrains 1-2 µm was stopped when it was crossing the intersecting area of the channels with a velocity of 200 m s⁻¹. For the study, two cross-sectional samples were cut from the obtained DCAP L-shaped sample. Sample A was cut from the vertical part and sample B from the horizontal part.

Structural characterization of the samples was carried out using a Neophot-32 optical microscope, a Philips CM-30 Super Twin transmission electron microscope (TEM) and a Quanta-200 Pegasus scanning electron microscope (SEM) equipped with an EBSD analysis system. TEM investigations were carried out at an accelerating voltage of 200 kV. Quantitative analysis of the size of structural
fragments was done from dark field TEM images by means of Siams-700 image analysis software. X-ray diffraction analysis was performed using a DRON-3 diffractometer with Cu Kα radiation. The dislocation density was calculated with respect to the mean-square lattice microdeformation and the size of coherent scattering region. Microhardness was measured using a PMT-3 device. Brinnell hardness was determined as well using standard techniques.

3. Results

Studies by SEM and TEM show that the coarse subgrain structure is preserved in sample A. The influence of high strain rate deformation results in the formation of a generous amount of defects accumulated as near the boundaries of subgrains, as well as in the subgrain body. Figure 1 shows the dislocations pile-up within subgrains. The originally plane subgrain boundaries are distorted, their width increases due to aggregation of dislocations in the boundary regions (figure 1a, b). The single-crystal type of the microdiffraction pattern obtained from three neighboring subgrains with low angle-boundaries (LAGBs) shows reflections with low azimuthal misorientation (figure 1a). According to X-ray data, the average dislocation density in this sample is \( \rho_d = 6.0 \times 10^{13} \text{ m}^{-2} \) and is 1.5 times higher than that of the initial material. Moreover, localized deformation bands with the UFG structure (500-700 nm) were detected in sample A (figure 1 c). These bands appear due to the plastic flow instability during loading of the shock wave. The UFG structure of the bands consists of grains separated by high-angle boundaries (HAGBs) which is evidenced by the ring-like shape of the selected-area diffraction pattern and subgrains with LAGBs (figure 1 c). Thus, X-ray and TEM data show that the accumulation of structural defects and minor structural refinement already occur in sample A due to the shockwave induced deformation.

The structure formed due to the shock wave loading undergoes shear deformation when the billet crosses the intersection area of the channels. Features of the structure formation upon additional simple shear deformation (sample B) are shown in figure 2. One can see a fragmented severely deformed structure. The dark field TEM image shows that the shear bands are oriented at an angle of 45-50º to the longitudinal axis and consist of grains/subgrains with HAGBs and LAGBs. A ring-like diffraction pattern (figure 2 a) proves the formation of such a mixed structure. The average lateral and longitudinal size of the structural fragments calculated from the dark field images are 370 and 420 nm, correspondingly. The DCAP pressing results in an increase in the dislocation density up to \( \rho_d = 5.0 \times 10^{13} \text{ m}^{-2} \). EBSD studies were performed on the deformed alloy to obtain more detailed information about its structure. A typical EBSD map of a sample after one DCAP cycle is presented in figure 3 a, b. An analysis of the distribution of the misorientation angle (figure 3c) shows that the shock-wave loading and shear deformation cause an increase in the number of LAGBs up to 70-75\%, while approximately two thirds of which are boundaries with misorientation angles from 2 to 5 degrees. It was found [4-6] that these boundaries make a significant contribution to the material hardening.

![Figure 1. Bright field TEM images of the structure of the sample A (a and c combined with the selected area diffraction patterns): dislocations in the subgrain body (a); subgrain boundaries (b), localized deformation area (c).](image-url)
Analysis of the structure of the A3003 alloy after four cycles of DCAP showed that 60-65% of the grain boundaries were HAGBs [1, 3].

The mechanisms of material hardening upon DCAP were determined by means of hardness measurements. One can see how the microhardness and hardness change after shock-wave loading and additional shear deformation (figure 4). According to figure 4, the first increase in the microhardness value (by 15%) is associated with a high accumulation of dislocation density and its evolution under shock-wave impact. At the next stage of simple shearing, the formation of a grain/subgrain structure resulted in further increase in microhardness values by 20%. Thus, the total increase in microhardness values is 35% or 190 MPa relative to the initial state. Brinell hardness is increased by 46% during DCAP. However, the primary increase in Brinell hardness by 35% occurs only after shear deformation, i.e. due to the formation of the UFG structure (figure 4). Considering these data and the results of TEM, we can conclude that the main contribution to the hardening of the alloy under shock-wave loading is due to the dislocation evolution. Hardening after shear deformation increases by means of the additional accumulation of defects and refinement of structural fragments, i.e. due to the hardening of grain boundaries. Therefore, a different contribution to the formation of the structure and hardening was revealed in two deformation modes of DCAP.

4. Discussion
The experiment, when the sample was stopped in a DCAP die, showed that the shock-wave loading in the initial state of dynamic pressing has a great influence on the structural formation of aluminum

Figure 2. TEM images of the structure of sample B: bright field image combined with the selected area diffraction pattern (a), dark field image of aluminum matrix (b).

Figure 3. EBSD analysis data of sample B: a – EBSD map, b – boundaries pattern, red lines - 2-5°, green lines- 5-15°, blue lines - > 15°, c - misorientation angle distribution.
alloys and strength properties. The increase in the number of structural defects occurs due to the circulation and interaction of compression and rarefaction waves under shock-wave loading. At this stage, the value of the dislocation density increases in 1.5 times. High dislocation density leads to the material hardening and intensifies the structural refinement at the stage of shear deformation. Moreover, instabilities of the plastic flow under shock wave loading cause the formation of localized deformation bands. Their development and intersection during the shock wave propagation result in the dislocation assembly evolution and in the cell structure formation, which transforms in to the UFG structure with HAGBs and LAGBs under the shear deformation. Upon DCAP, both of these factors accelerate the transformation of the structure of aluminum alloys from coarse grained to UFG states. These aspects determine a higher efficiency of DCAP compared to static channel-angular pressing.

Considering X-ray and EBSD data, two hardening mechanisms of the alloy were distinguished. Firstly, these are dislocations hardening due to the accumulated high dislocation density and LAGBs with misorientation angles from 2 to 5 degrees. Secondly, it is the grain boundaries hardening due to the formation of LAGBs with a misorientation angle of 5-15 degrees and the UFG structure with HAGBs.

The experimental results of the present study are in good agreement with the numerical simulation of the DCAP process based on the plastic flow dislocation model [7].

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