ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 16 (2016) 805–812

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Efficiency of the compression with oscillatory torsion method in grain refinement in Al

Kinga Rodak [a,*], *Jacek Pawlicki* [b,1]

[a] *Institute of Materials Science, Silesian University of Technology, Krasińskiego 8, 40-019 Katowice, Poland*
[b] *Silesian University of Technology, Krasińskiego 8, 40-019 Katowice, Poland*

ARTICLE INFO

Article history:
Received 6 October 2015
Accepted 29 May 2016
Available online

Keywords:
Metals
Severe plastic deformation
Grain refinement
Mechanical properties
Scanning electron microscopy

ABSTRACT

Experiments were conducted to investigate the development of an ultrafine grain structure during compression with oscillatory torsion processing of high-purity aluminum (99.9%) with an initial grain size of 75 μm. The samples were processed using different deformation parameters: torsion frequency (f) and compression rate (v). The samples were examined using a scanning electron microscope equipped with a field emission gun and an electron backscattered diffraction detector. The results suggest that for high-purity aluminum an ultrafine-grained microstructure was obtained after a total effective strain (ε_{ft}) of 45 in samples deformed at $f = 1.6$ Hz and $v = 0.04$ mm/s. A quantitative study of the microstructural parameters showed that the area fraction of the ultrafine grains (<1 μm) ($A_{1\mu m}$) was 44%, the fraction of high-angle boundaries was 53%, and the average diameter of the grains was about 600 nm. The yield stress and ultimate tensile stress reached 127 and 137 MPa, respectively, after deformation at a total effective strain of 45. When the total effective strain reached 120, the mechanical strength of the material decreased. This suggests that the decrease in strength is associated with the operation of the recovery mechanism that decreases the boundary volume.

1. Introduction

Large plastic deformation can be obtained by classical formation techniques like cold rolling and drawing, but these techniques follow a continuous strain path and led to cellular and fibrous structures with low-angle boundaries (LABs) [1]. Severe plastic deformation (SPD) methods are known to result in significant refinement of the initially coarse-grained structure. Metals with grains <1 μm (ultrafine) are interesting because they have excellent mechanical and physical properties. Some SPD techniques offer the possibility to change the strain path during deformation, and are classified as cyclic deformation methods (CDMs). The main CDMs are cyclic extrusion compression (CEC) [2], equal channel angular pressing (ECAP) with sample rotation [3,4], and multiaxial forming (MF) [5]. These processes lead to the formation of equiaxed nano- and ultra-fine grains with high-angle boundaries (HABs). However, for grain refinement higher values of effective strain must be used [6,7] than for monotonic methods

* *Corresponding author*. Tel.: +48 32 6034408; fax: +48 326034400.
E-mail addresses: kinga.rodak@polsl.pl (K. Rodak), jacek.pawlicki@polsl.pl (J. Pawlicki).
[1] Tel.: +48 32 6034205.
http://dx.doi.org/10.1016/j.acme.2016.05.004
1644-9665/

of deformation such as high-pressure torsion (HPT) [8,9] and hydroextrusion (HE) [10], where an effective strain of ~4 is sufficient for grain refinement [10].

The compression with oscillatory torsion (COT) is a SPD method that allows large deformations [11], and therefore grain refinement is possible [12]. The basis of this method is the deformation of a massive sample by simultaneously applying compression and oscillatory torsion. COT offers the possibility to change the strain path during deformation by changing the parameters of torsion frequency, compression rate, torsion angle, and true reduction. From earlier researches [12] is known that comparable values of the total effective strain ε_{ft} obtained with different parameters do not guarantee the same final structure. For example, the fragmentation process in Cu was faster for sample deformed at torsion frequency f = 1.6 Hz and compression rate υ = 0.04 mm/s than these for sample deformed at torsion frequency f = 0.2 Hz and compression rate υ = 0.015 mm/s, despite comparable value of deformation ($\varepsilon_{ft} \sim 14$). Consequently, the formation of the structure is controlled not only by the total effective strain ε_{ft} but also by the deformation path. The deformation path which affects the structural effect can be expressed as the proportion of strain due to torsion deformation from parameter changes as torsion frequency and torsion angle vs that due to compressional deformation from changes in compression rate. It should be emphasized that the presented in [12] results from the COT process do not exhaust all of the possibilities that can be attained from this method. In particular, a large range of strains, achievable by changing the parameters proportion, is need for refining grain structure.

For this reason, in this study, different deformation parameters of the COT process were adopted to study their effects on the microstructure refinement and mechanical properties of Al.

2. Experimental

The tests were performed on high-purity aluminum (99.9%). The samples were taken from 12 mm diameter aluminum bars and annealed at a temperature of 200 °C for 2 h. After this treatment, the average diameter of the grains was 75 μm. The heat treatment allowed removal of structural effects resulting from the previous technological treatments and a homogenous grain structure in the whole volume of the material to be obtained.

The principle of COT methods is the deformation of samples by simultaneously applying compression and oscillatory torsion. Fig. 1 is a schematic presentation of the COT set up. The apparatus consists of upper and lower anvils made from high-strength tool steel. Torsion straining was achieved by rotating the lower anvil, and compression was simultaneously achieved by linear strain from the upper anvil.

The COT method has been described in more detail in [11]. Samples for deformation were prepared in accordance with the dimensions presented in Fig. 2. All tests using the COT method were conducted at room temperature.

Because the deformation process is complex, the effective strains were calculated from the Huber–Mises–Hencky hypothesis according to the formula

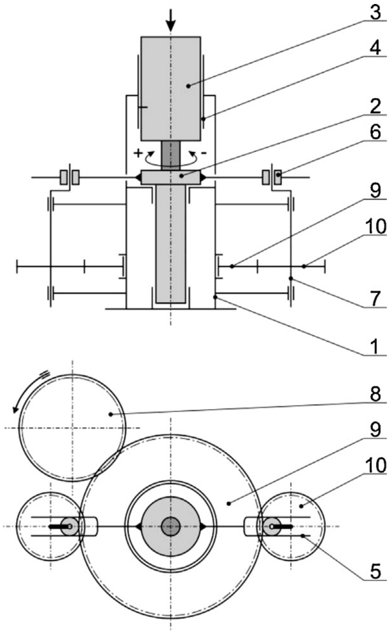

Fig. 1 – Scheme of the COT method: (1) frame, (2) lower punch, (3) upper punch, (4) non-rotating slidable bearing, (5) lower punch arm, (6) roller, (7) crankshaft, (8) driving gear, (9) ring gear, (10) gear wheel.

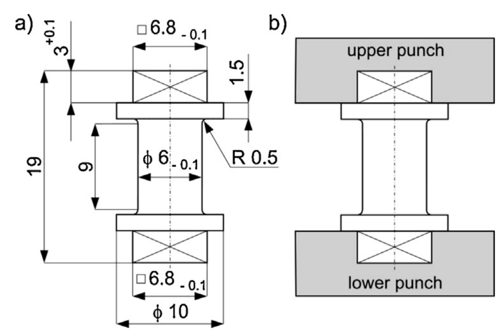

Fig. 2 – Geometry and dimensions (a) of samples used in the experiment and (b) sample in the anvils.

$$\epsilon_f = \sqrt{\epsilon^2 + \frac{\gamma^2}{3}} \tag{1}$$

where ε is the deformation induced by the uniaxial strain and γ is the shearing strain.

The total effective strain ε_{ft} is expressed as a sum of effective strains from Eq. (1) in a single phase of deformation as

$$\epsilon_{ft} = \sum_{n=1}^{n} \epsilon_{fn} \tag{2}$$

where n is the number of deformation phases. The single phase comprises a torsion of the sample in one direction with a simultaneous decrease of height.

The value of the total effective strain ε_{ft} could be controlled by changing the proportions of the following parameters: torsion frequency f, in the range of 0–1.8 (Hz), compression rate υ, maximal – 0.66 (mm/s), torsion angle α, in the range of 0–±8