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ENHANCEMENT OF MECHANICAL PROPERTIES OF THE AA5754 ALUMINUM ALLOY WITH A SEVERE PLASTIC DEFORMATION

IZBOLJŠANJE MEHANSKIH LASTNOSTI ALUMINIJEVE ZLITINE AA5754 Z VELIKO PLASTIČNO DEFORMACIJO

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Mechanical properties of materials with ultrafine grain (UFG) size have attracted considerable scientific attention and technological interest during the last few years. It was well established that the grain size of metallic alloys may be substantially refined with a severe plastic deformation (SPD). The present work focuses on equal-channel angular pressing (ECAP) as the most used method of SPD for grain refinement inducing a significant enhancement to the mechanical and functional properties of the commercial AA5754. ECAP with up to 6 passes resulted in a substantial grain-size reduction from 70 µm of an as-received sample to 5 µm. The aforementioned reduction of the grain size increased the microhardness by a factor of 4. These results were compared to those of AA3004.

Keywords: severe plastic deformation, equal-channel angular pressing (ECAP), mechanical properties, microhardness (HV), tensile test

Zadnjih nekaj let vzbujajo pozornost znanstvenikov in tehnologov mehanske lastnosti materiala z ultradrobnimi zrni (UFG). Ugotovljeno je bilo, da je z uporabo velike plastične deformacije (SPD) mogoče močno zmanjšati velikost zrn v kovinski zlitini. To delo poroča o metodi "equal-channel angular pressing" (ECAP) kot najpogosteje uporabljeni SPD za zmanjšanje zrn, ki povzroči občutno povečanje mehanskih in funkcionalnih lastnosti komercialne zlitine AA5754. ECAP povzroči občutno zmanjšanje velikosti zrn iz 70 µm pri dobavljeni zlitini na 5 µm po 6 prehodih. Omenjeno zmanjšanje velikosti zrn je povečalo mikrotrdoto za faktor 4. Rezultati so bili primerjani z rezultati pri zlitini AA3004.

Ključne besede: velika plastična deformacija, equal-channel angular pressing (ECAP), mehanske lastnosti, mikrotrdota (HV), natezni preizkus

1 INTRODUCTION

The processing, structure and properties of metallic materials with ultrafine grain size have been of increasing interest over the past few years. Grain-size reduction is one of the most attractive ways of improving the mechanical properties of metallic materials. It is known that the strength of all the polycrystalline materials is related to the grain size, through the Hall-Petch equation, predicting an increase in the yield strength (σ_y) with a decrease in the grain size (d):

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

Severe plastic deformation (SPD)[1–5] has gained importance since it offers a direct conversion of bulk metals and alloys with conventional grain sizes to even nanoscaled materials with outstanding new mechanical properties. In order to convert a coarse-grained solid into a material with fine grains, it is necessary to impose an exceptionally high strain in order to introduce a high density of dislocations and to subsequently rearrange the dislocations, forming an array of grain boundaries.[4,6–11] The following are the three SPD methods that attract most of the scientific attention: high-pressure torsion (HPT),[6,7] accumulative roll-bonding (ARB)[10,11] and equal-channel angular pressing (ECAP),[4,8,9] introduced by Segal and co-workers in 1980.[4]

The aim of this paper is to present a grain refinement and the resulting improvement in the mechanical properties using ECAP on the commercial AA5754 Al-alloy. The improvement in the mechanical properties and the grain refinement were studied as functions of the number of ECAP passes.

Figure 1 shows a schematic illustration of the ECAP procedure. In the present experiment a die was constructed as a channel bent at an angle close to 90°. A sample was machined to fit into the channel. The sample was then pressed through the die, using a plunger. The strain imposed on the sample in each passage through the die depended primarily upon the angle, Φ, between the two parts of the channel (90° in **Figure 1**) as well as, to a minor extent, upon the angle of curvature, φ, representing the outer arc of curvature where the two channels intersect (0° in **Figure 1**). If the samples are pressed repeatedly, different slip systems may be introduced by rotating the samples between the consecutive passes through the die. In practice, four separate processing

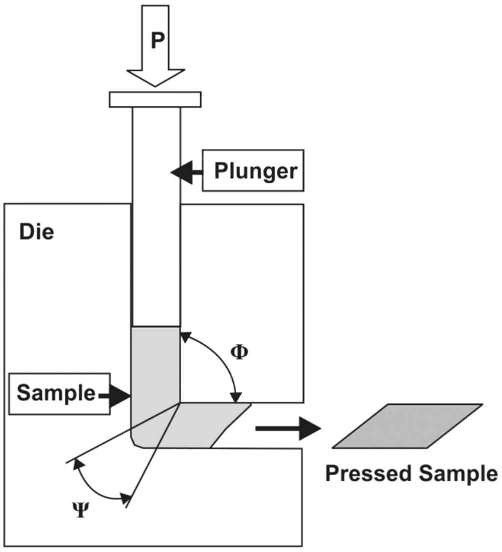

Figure 1: Sectional view of the ECAP die
Slika 1: Prerez skozi ECAP-orodje

routes have been identified for use in ECAP (**Figure 2**). Between each two consecutive passes, a sample can be rotated around the longitudinal axis through the angles of 0° (route A) and 90° in the alternate direction (route B_A), by 90° in the same manner for each pass (route B_C) or by 180° (route C). These different processing routes, along with the number of passes, strongly determine the final microstructure.[4,8,9]

The structural features of the SPD-processed metal are quite complex and they are characterized not only by the formation of ultrafine grains, but also by the presence of non-equilibrium grain boundaries, having a high density of dislocations and vacancies,[12,13] high lattice distortions and possibly also the changes in the local phase composition.[12–14]

In order to examine the potential for using route B_c ECAP for the grain-size refinement and, thus, for the improvement of the mechanical properties, the commercial 5754 Al-alloy was selected for this study. For the sake of comparison, certain results for the AA3004 Al-alloy, the subject of our former research,[15] are given. The AA5754 alloy was chosen because of its technological importance and its relatively low presence in the available ECAP literature.

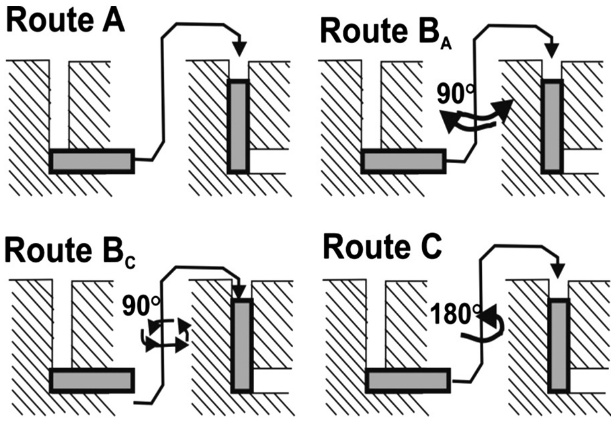

Figure 2: Four processing routes in ECAP
Slika 2: Štiri vrste predelave pri ECAP

2 EXPERIMENTAL WORK

The experiments were conducted on a light-weight commercial Al-alloy, AA5754, supplied from STAMPAL-Torino, Italy, having the composition presented in **Table 1**. According to the manufacturer's declaration, the grain size of the as-prepared samples is about 70 μm. The samples were in a cylindrical form, 10 mm in diameter. Being subjected to ECAP, up to a total of 6 passes at room temperature, they retained the same diameter. Small rectangular pieces suitable for the HV tests were cut from the as-pressed cylinders,[16–21] polished and then subjected to the Vickers-microhardness (HV) measurements, using a load of 300 g, applied for 15 s. For the tensile tests, the samples 100 mm in length and 10 mm in diameter were produced. The samples suitable for the scanning electron microscopy (SEM) were prepared to fit in the sample holder (a diameter of 10 mm and length of 12 mm). Their surfaces were polished with a fine polishing paste and then etched in a 5 % HF solution for 0.5 min to 1 min in order to obtain the visibility of the grain boundaries. The results for the HV and tensile tests performed on the AA3004 aluminum alloy (reported elsewhere)[18] are also given for comparison with the present results for AA5754, the subject to this research. The compositions of both alloys are given in **Table 1**.

Table 1: Chemical compositions of AA5754 and AA3004 (for comparison) in mass fractions, *w*/%
Tabela 1: Kemijska sestava AA5754 in AA3004 (za primerjavo) v masnih deležih, *w*/%

Al-alloy	Al	Mg	Mn	Cr	Fe	Si	Zn
AA5754	96.1–95.4	2.4–2.6	0.1–0.6	0.4	0.4	0.4	0.2
AA3004	97.8	1.2	1	0	0	0	0

A digitalized scanning-electron-microscopy (SEM) system of a JEOL JSM-T220A SEM was used as an imaging tool for three samples (obtained after 2, 5 and 6 passes) to estimate the grain size. The calculations were made with the SPIP V3.2.6.0 software.

3 RESULTS AND DISCUSSION

Figure 3 shows a variation in the microhardness with the number of passes, where the measurements were taken on two orthogonal planes on a specimen surface. The first point in **Figure 3** (the zero passes) refers to the as-received alloy. **Figure 3** shows that HV is essentially independent of the plane of sectioning (longitudinal and perpendicular). HV increases abruptly after the first pass, but thereafter it increases slowly with the progress in the

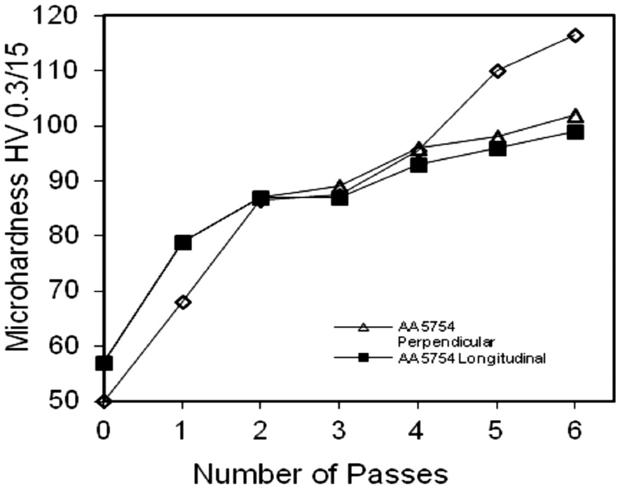

Figure 3: Improvement of the microhardness (HV) depending on the number of ECAP passes measured in two orthogonal planes for AA5754 (70 microns in as-received condition). Evolution of AA3004 (50 microns in as-received condition) is given for comparison.

Slika 3: Povečanje mikrotrdote (HV) v odvisnosti od števila ECAP-prehodov, izmerjeno na dveh ortogonalnih ravninah za AA5754 (70 µm v dobavljenem stanju). Za primerjavo je prikazana mikrotrdota za AA3004 (50 µm v dobavljenem stanju).

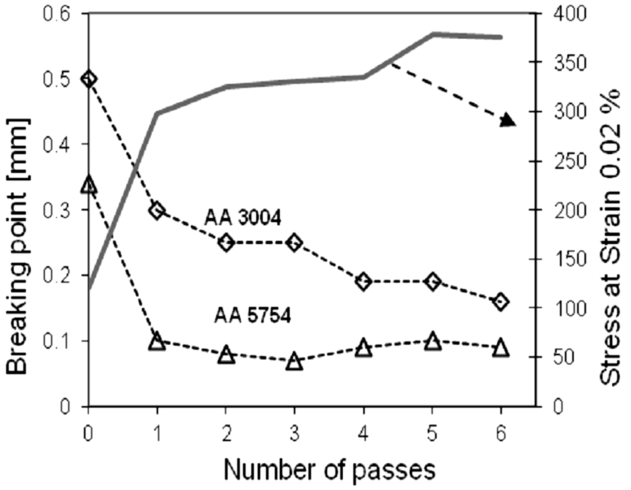

Figure 5: Left *y*-axis: the breaking point changes with the number of ECAP (B_c) passes for AA5754. The change for AA3004 is given for comparison. Right *y*-axis with a gray line: presentation of the stress at a strain of 0.02 % (elastic region, governed by the Hook's law) for the as-received sample and after 1–6 passes.

Slika 5: Leva *y*-os: prelomna točka s številom ECAP-prehodov za AA5754. Za primerjavo je prikazana AA3004. Desna *y*-os s sivo linijo: prikaz napetosti pri raztezku 0,02 % (elastično področje, ki ga določa Hookov zakon) za dobavljeno stanje in po 1–6 prehodih.

pass number (up to 6). A comparison with another widely utilized Al-alloy, AA3004, shows that both alloys achieve the same microhardness after three passes. The results of the tensile testing are shown in **Figure 4**, where the stress is plotted against the strain for a sample in the as-received condition and for the samples after 1 to 6 passes. These curves show that the elongations due to the applied force were significantly reduced after the ECAP processing. It is obvious that the unpressed (as-received) alloy revealed an increase in the stress from about 80 MPa to about 240 MPa after a single ECAP pass, i.e., an increase by a factor of 3. It is also evident that further ECAP passes (2–6) resulted in another stress increase up to 340 MPa (an improvement of more than 4 times). **Figure 5** presents a change in the strength at fracture due to the pass number in the ECAP processing (the results derived from **Figure 4**). It is evident from **Figure 5** that the strength at fracture was substantially reduced with the ECAP processing, from 0.35 mm for the strain of the as-received sample to about 0.11 mm for the sample after a single pass. **Figure 5** revealed that further ECAP (B_c) processing with 2 to 6 passes caused further deterioration of the strength at fracture.

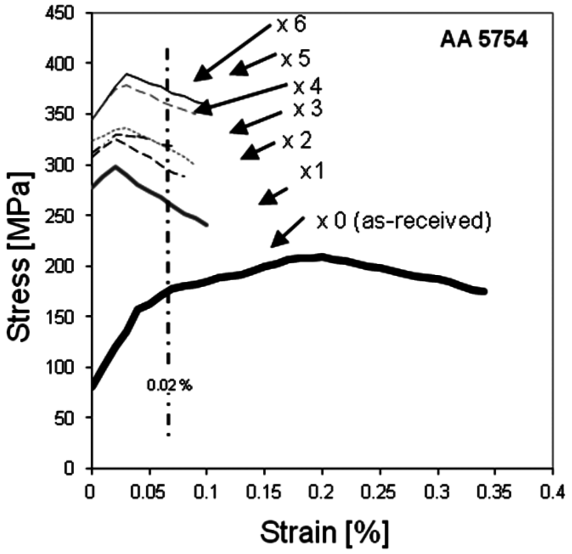

Figure 4: Tensile test: stress versus strain of AA5754 at room temperature for the as-received sample and the samples subjected to 1–6 passes

Slika 4: Natezni preizkus: napetost proti raztezku za AA5754 pri sobni temperaturi za dobavljeno stanje in po 1–6 prehodih

SEM micrograms of the AA5754 surfaces are presented in **Figure 6**. The image in **Figure 6a** shows a network of grain boundaries with thin edges, suggesting small voids among the grains. Furthermore, the calculations of the grain size from **Figure 6** indicate that a single pass causes an abrupt fall from the mean grain size of 70 microns (the value declared by the manufacturer) to about an average of 10 microns, where the standard deviation (SD) appears to be 0.4 µm, suggesting a rather uniform refinement. The following ECAP passes, as seen from **Figures 6b** and **6c**, caused further grain refinement.

A presentation of the grain size versus the pass number, given in **Figure 7**, shows an abrupt fall after the first pass, and thereafter a tendency for saturation at a grain size of 4–5 µm, which is an expected result, in agreement with the Hall-Petch equation (1). Another observation is obvious: further treatment with ECAP cycles (4 and 6 passes) result in a decrease in the grain size.

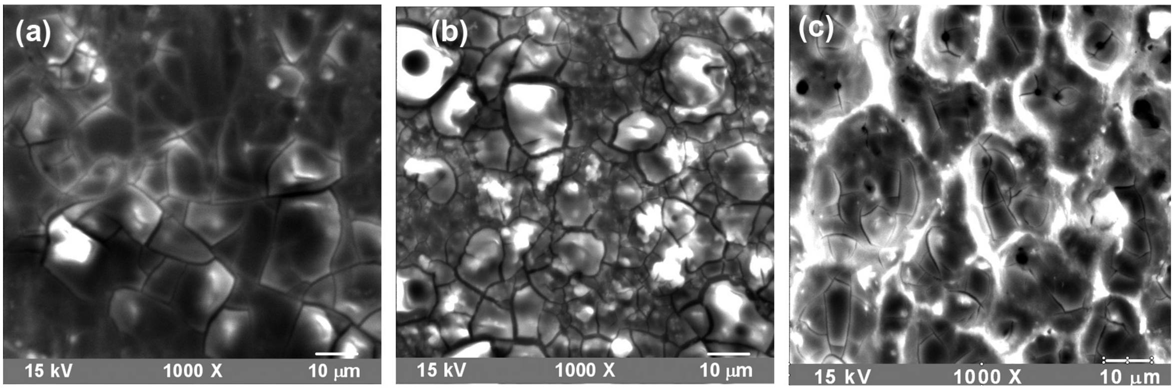

Figure 6: SEM images of the surface of AA3004: a) after a single pass (grain size of (10.3 ± 0.410) μm), b) after 4 passes (grain size of (6 ± 1.9) μm), c) after 6 passes (grain size of (5 ± 2.1) μm)

Slika 6: SEM-posnetki površine AA3004: a) po enem prehodu (velikost zrna (10,3 ± 0,410) μm), b) po 4 prehodih (velikost zrna (6 ± 1,9) μm), c) po 6 prehodih (velikost zrna (5 ± 2,1) μm)

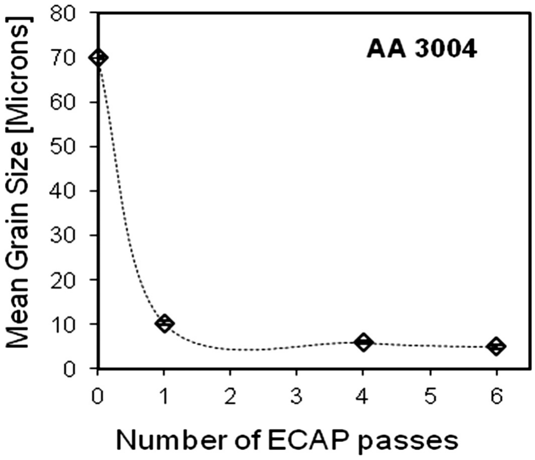

Figure 7: Grain-size evolution of AA3004 with the number of ECAP passes

Slika 7: Spreminjanje velikosti zrn pri AA3004 s številom ECAP prehodov

4 CONCLUSION

In summary, this investigation demonstrates that ECAP was an effective tool for achieving a substantial reduction in the GS of the commercial 5754 Al-alloy from 70 μm to about 5 μm due to 6 passes. The microhardness (HV) of the alloy increased abruptly after the first pass, but thereafter it increased slowly with the following passes (up to 6). The observed increase in the HV of the alloy obviously resulted from the grain-size refinement, followed by an advanced spatial grain packing. The HV of AA5754 increased 3–4 times upon 5–6 ECAP passes, while the grains were refined from 70 μm to about 5–6 μm. The tensile tests showed that the elongations due to the applied force were significantly reduced after the ECAP processing. The stress grew from about 80 MPa to about 240 MPa upon a single pass.

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