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Muamar Benisa[1], Galal H. Senussi[2]

INVESTIGATION OF MECHANICAL PROPERTIES FOR BULK NANOSTRUCTURE OF AL-6082 ALLOY MATERIAL PRODUCED BY EQUAL-CHANNEL ANGULAR PRESSING (ECAP)

ISTRAŽIVANJE MEHANIČKIH OSOBINA PAKETA NANOSTRUKTURE LEGURE AL-6082 PROIZVEDENE ECAP TERMOMEHANIČKOM OBRADOM

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Adresa autora / Author's address:
[1] Al-Merghab University, Faculty of Engineering, Alkomes Libya, muamarisa@yahoo.com
[2] Mechanical Engineering Department, Faculty of Engineering, Omar Al-Mokhtar University, El-Baida, Libya

Keywords

- nanostructure materials
- true stress strain curves
- equal-channel angular pressing (ECAP)

Ključne reči

- nanostrukturni materijali
- stvarne krive napon-deformacija
- termomehanička obrada ECAP

Abstract

It is well known that formation of nanocrystalline (NC) structure in different materials leads to remarkable properties. Many investigations of NC materials show that they have substantially different physical and mechanical properties not only because of the grain size but also because of the structure of grain boundaries as well /1-4/.

One of the methods of severe plastic deformation for producing ultra-fine-grained (UFG) material is Equal-Channel Angular Pressing (ECAP). A commercial Al-Mg-Si alloy (6082) is deformed by equal-channel angular pressing (ECAP) to produce a bulk ultra-fine-grained structure using route C technique up to eight passes with a high length to diameter ratio of 15-16. The products were investigated after one, four and eight passes. The upsetting test is used to determine the true stress-true strain curves in all of the three conditions.

The results show that the number of ECAP passes have significant effect on the behaviour of the stress strain curve of the ECAP material. During upsetting, the anisotropy induced by the ECAP technology has led to asymmetrical bulging/buckling.

This phenomenon is reduced by controlling the height/diameter ratio of the upsetting specimens.

Izvod

Poznato je da formiranjem nanokristalnih (NC) struktura kod različitih materijala dovodi do značajnog poboljšanja osobina. Mnoga istraživanja pokazuju velike promene u fizičkim i mehaničkim osobinama NC materijala, ne samo usled veličine zrna, već i zbog strukture na granicama zrna /1-4/.

Jedna od metoda povećane plastične deformacije u cilju izrade materijala ultra finog zrna (UFG) jeste termomehanička obrada ECAP. Komercijalna legura Al-Mg-Si (6082) se deformiše ovim postupkom plastične obrade ECAP kako bi se proizveo paket strukture ultra finog zrna, primenom postupka C sa do osam prolaza, sa odnosom veće dužine prema prečniku od 15-16. Proizvodi su ispitivani posle jednog, četiri i osam prolaza. Ispitivanje deformabilnosti je korišćen za određivanje stvarne zavisnosti napon-deformacija kod sva tri slučaja.

Rezultati pokazuju da broj ECAP prolaza ima značajnog uticaja na ponašanje krive napon-deformacija obrađenog materijala. Tokom ispitivanja deformabilnosti, anizotropija indukovana ECAP tehnologijom je dovela do asimetričnih ispupčenja/izvijanja.

Ovaj fenomen je umanjen kontrolisanjem odnosa visina/prečnik uzoraka pri ispitivanju deformabilnosti.

INTRODUCTION

Nanocrystalline (NC) materials are conventionally processed by a number of methods: gas condensation, ball milling with subsequent consolidation and severe plastic deformation (SPD). The first two methods are often characterized by the presence of some residual porosity or impurities /3, 4, 10/. The SPD methods are free from these disadvantages and more convenient for the investigation of the role of grain boundary on the physical properties in different materials. SPD may be used not only for ductile metals, but also for brittle alloys and intermetallic compounds. Moreover SPD can be used to fabricate bulk material, which makes it possible to measure the mechanical properties. /1, 2, 5, 7, 8, 9, 11, 12/. Severe plastic deformation (SPD) techniques induce large plastic deformation in materials (with true strain ≥ 10) /1, 2/, typically under high applied pressure and at relatively low temperature (usually less than $0.4 \cdot T_m$, where T_m is the melting temperature). They have been used to create ultra-fine-grain (UFG) metals and alloys with grain size in the range 10 to 1000 nm, and it can form nanostructures with a high angle grain boundary. Methods of severe plastic deformation (SPD) should meet a number of requirements which cannot be realised with traditional methods of plastic deformation, such as rolling, drawing or extrusion. First of all it is important to obtain an ultra-fine-grained structure with high angle boundaries to get a change in the properties. The second is the formation of the nanostructure in the whole volume of a sample providing stable material properties. Finally, because the workpiece is exposed to large plastic deformation, it should not have any mechanical damage or a crack before and after the process. While there are different techniques to obtain the nanostructure material, two of them are the most commonly used, the severe plastic torsion staining under high pressure (SPTS) and the equal channel angular pressing (ECAP), Fig. 1, /6, 7/.

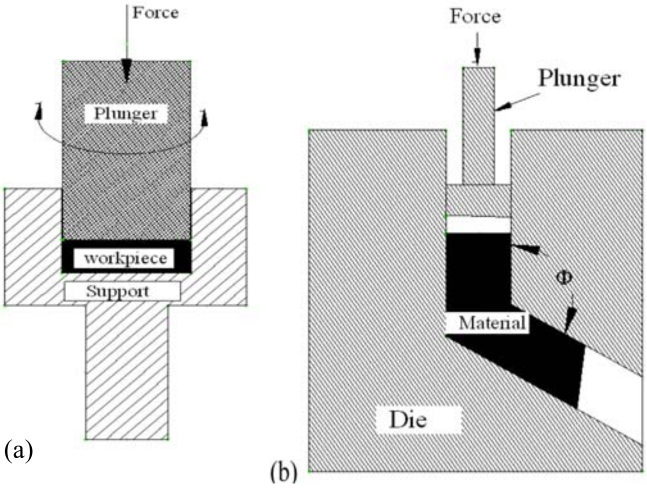

Figure 1. Principles of SPD methods: (a) torsion under high pressure; (b) ECAP method.
Slika 1. Principi SPD metoda: (a) uvijanje pod visokim pritiskom; (b) metoda ECAP

ECAP (EQUAL CHANNEL ANGULAR PRESSING)

This method is used for deformation of large billets by pure shear; the mean feature is to apply intense plastic strain into the material without changing the cross section area. Repeated deformation is possible by this method, the samples can be round or square in cross section with a length from 70 to 200 mm and the cross sectional diameter or its diagonal cannot exceed 20 mm (Fig. 1b).

In ECA pressing, the billet or the sample is pressed multiple times through a special die (one pressing operation is called one “pass”), the intersection angel between the two channels must be considered, it is usually 90° (Fig. 2).

In case it is hard to deform the material, ECA pressing is applied at high temperature to avoid any failure in the channels and make the deformation easier.

When the outer angle Ψ = 0°, and the inner angel Φ is arbitrary, Fig. 2 /1, 5/, according to /6/ the shear value increment at each pass through the channels can be calculated by

$$P/Y = \Delta\varepsilon_i = \frac{2}{\sqrt{3}}\cot(\phi/2) \tag{1}$$

where P is the pressure and Y is the flow stress of the deformed material.

When the sample is pressed through the intersection channels several times during the ECA pressing, the total strain value is:

$$\varepsilon_n = N\Delta\varepsilon_i \tag{2}$$

where N is the number of the passes.

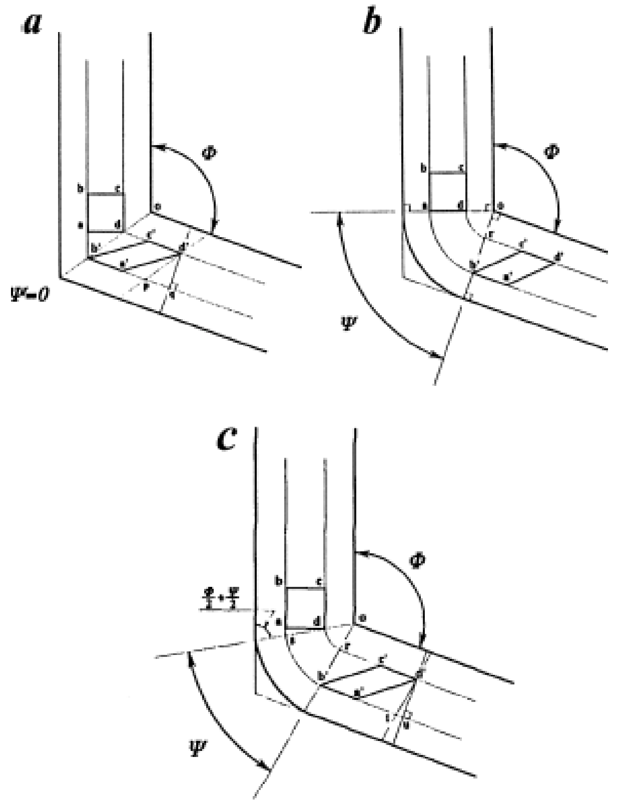

Figure 2. Principles of ECA pressing: (a) Ψ = 0°, (b) Ψ = π – Φ, (c) Ψ is between Ψ = 0 and Ψ = π – Φ.
Slika 2. Principi ECA presovanja: (a) Ψ = 0°, (b) Ψ = π – Φ, (c) Ψ je između Ψ = 0 i Ψ = π – Φ

Generally the strain value for the billet for N passes in ECA pressing can be calculated:

$$\varepsilon_n = N\left[\frac{2\cot(\varphi/2+\phi/2)+\phi\,\mathrm{cosec}(\varphi/2+\phi/2)}{\sqrt{3}}\right] \tag{3}$$

As mentioned above, if we use Φ = 90° and Ψ = 20° as intersection angle, the strain value approximately increases by 1 in each pass. In the ECA pressing, the number of passes and the direction of billet passes through the channel are very important in the refinement of the microstructure /1, 5, 7/.

According to /1, 5, 7/ there are three kinds of passes (routes) (Fig. 3):

– route A if the sample is not rotated around its longitudinal axis.
– routes B, C if the sample is rotated around its longitudinal axis by 90° and 180°, respectively.

The given routes are influenced in their shear direction at repeated passes of the workpiece through the intersection channel when ECA pressing is applied.

As shown in Fig. 4a, at the place of intersection of channels, the cell takes a shape of an ellipsoid during the first pass, if route A is used. As the result of repeated pass, the length of axis 1 increases and the ellipsoid is elongated, where the shear direction is turned around the axis perpendicular to the longitudinal section of the channels with angle 2Φ, Fig. 4b.

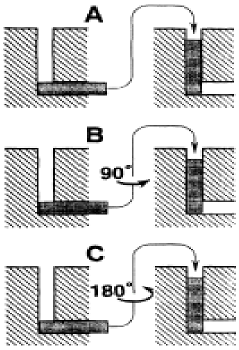

Figure 3. Versions of ECAP method (a) route A, (b) route B, (c) route C.
Slika 3. Verzije metoda ECAP: (a) pravac A, (b) pravac B, (c) pravac C

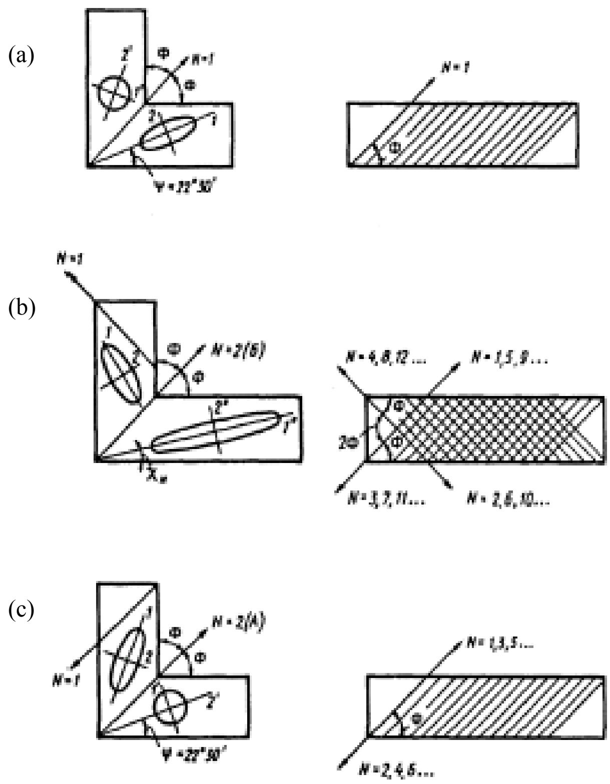

Figure 4. Regimes of simple shear during one cycle ECAP: (a) route A, (b) route B, (c) route C.
Slika 4. Režimi prostog smicanja pri jednom ciklusu ECAP: (a) pravac A, (b) pravac B, (c) pravac C

The repeated passes in route B lead to a change in the direction of the shear, and shear plane is turned with angle 120º, Fig. 5b, and during the deformation using route C repeated pass leads to shear in the same plane but opposite direction, Fig. 4c, and Fig. 5c.

The application of these three ECA pressing routes through several passes produces an increase in the value of the yield stress and strength of the material till it achieves a saturation state. It should be noted that the formation of homogeneous nanostructures in bulk samples requires optimization of temperature, strain conditions of SPD, friction condition between the sample and the die and the magnitude and character of deformation (it is specific for each material), /2/.

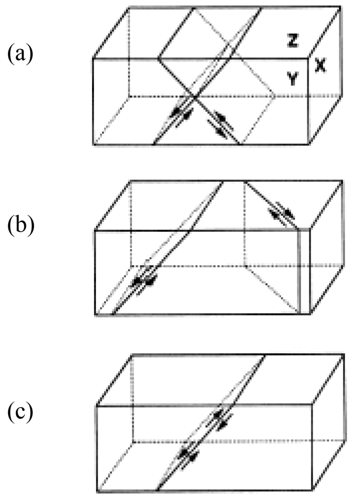

Figure 5. Direction of shear during ECAP according to routes: (a) route A , (b) route B, and (c) route C.
Slika 5. Pravci smicanja pri ECAP a prema pravcima: (a) pravac A, (b) pravac B i (c) pravac C

EXPERIMENTS AND DISCUSSIONS

Experiments with ECAP

The material used in this study is a commercial Al-Mg-Si alloy (Al6082). The main components of the alloy are Al (97%), Mg (0.6-1.2%), Si (0.7-1.3%) and Mn (0.4-1%). Before the ECAP deformation the material was annealed at 420ºC for 40 minutes. The annealed specimens are regarded as the as-received material.

Cylindrical billets of 15 mm in diameter and 230 mm in length were pressed through an ECAP die set having 90º inter-sectioning channels with identical cross section. One, four and eight passes were performed by route C (rotation of the billets around its longitudinal axes after each pass by 180º clockwise) as mentioned above. An experimental setup and schematic representation of ECAP die are illustrated in Fig. 6.

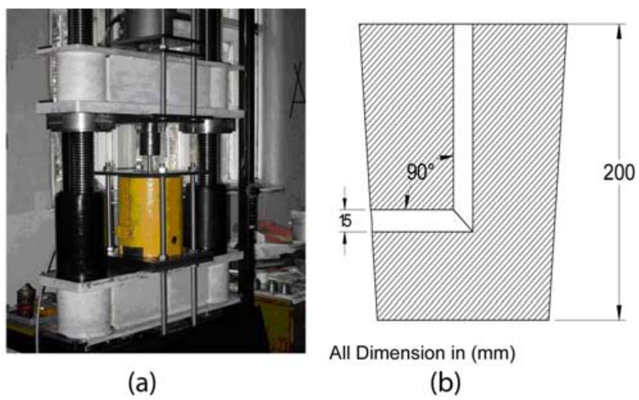

Figure 6. (a) Experimental tool setup, (b) schematic of ECAP die.
Slika 6. (a) Postavljanje eksperimenta, (b) shema ECAP kalupa

The well lubricated billets, having slightly smaller cross-section than the die channel, are placed into the vertical channel and then a punch extruded them through the intersection and the second channel. This technology is performed at room temperature with a constant displacement rate of 8 mm/min. The length to diameter ratio of specimens is relatively high (more the 15). Under these conditions the sample moves inside the channels as a rigid body and deformation is achieved only at the intersection by simple shear. After the extrusion stroke, the punch returns to its initial position. Another short billet (made of lead) is inserted first into the channel then the next work piece. The punch makes the second stroke by which the first billet is pressed out of the horizontal second channel. Then the procedure is repeated. Figure 7 shows the billets after different passes, from left, zero, one, four, and eight passes.

Figure 7. From left: zero pass, one pass, four passes, eight passes, respectively, using route C technique.
Slika 7. S leva: bez prolaza, jedan prolaz, 4 prolaza, 8 prolaza, respektivno, primenom postupka C pravca

Upsetting test

A common method for the determination of flow curves is the application of the compression test. Using this method, friction at the interface between the die and the specimen leads to the bulging of the sample and thereby to an inhomogeneous stress and strain rate.

Besides the simplicity of this method, a correction technique is needed to get the flow stress from the true stress by excluding the effect of friction. As it can be seen later, problems occurred during the compression tests because of the strong anisotropy of the pieces after using the ECAP passes. Therefore the true stress–true strain curve was measured only as an approximation of the flow curve. To improve the approximation, the best available lubricant is used to minimize the effect of friction.

To determine the true stress–strain curve of Al6082 alloy in the normal (as received) microstructure and in nanostructured condition after different number of passes (one, four and eight) by route C technique, the compression tests are carried out by using an electro-mechanic testing machine. The tests are performed at room temperature to avoid the recrystallization of the nanostructure; speed of the clamping head was 2 mm/min. The specimens all had the same diameter of 10 mm and were machined from the pressed material along the longitudinal axis. Three sets of three specimens were prepared with the initial height dimensions of 15, 10 and 5 mm, respectively.

The two flat surfaces of the specimens (contacting surface) were well lubricated by a suitable lubricant (white lubricant) and placed in the centre of the compression die between two parallel smooth surfaces. The die was fixed in the centre of the TIRA test 2300 machine (Fig. 8). Compression loading is applied on the specimen up to 500 N, then the specimen is unloaded. After cleaning the end surfaces of the specimen, the height and the maximum and minimum diameter are accurately measured by a Mitutoyo equipment having 1/100 mm resolution. Then the specimen is reloaded by a load increment of 0.5 kN over the initial load and the procedure is repeated until the equivalent strain achieved 0.7, then the load increment was increased to 1 kN. The procedure continued up to the agreed load limit.

Figure 8. Upsetting machine with the die set.
Slika 8. Mašina za ispitivanje sa sklopom kalupa

The true stress values are calculated for each load value using the area obtained from the constant volume relationship ($A_0h_0 = Ah$, where on the left hand side are the initial area and height respectively, and on the right hand side are the actual values). The equivalent true strain is calculated by using the equation

$$\varepsilon = \ln\left(\frac{h_0}{h}\right) \quad (4)$$

where h_0 and h are the initial and final height, respectively.

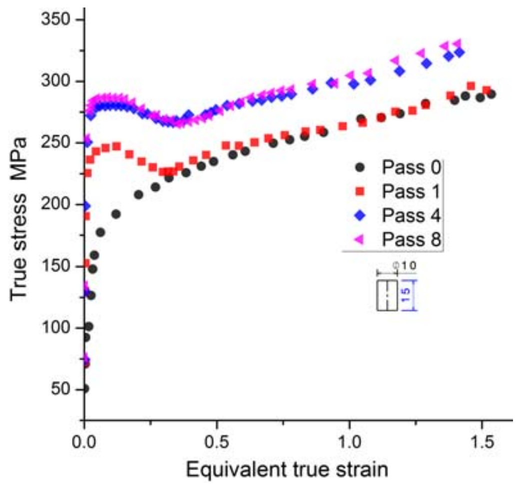

Figure 9. True stress–true strain curves of Al6082 after different passes, initial specimen size 10×15 mm ($h_0/d_0 = 1.5$).
Slika 9. Krive stvarni napon–stvarna deformacija za Al6082 posle različitih prolaza, početne dimenzije uzorka 10×15 mm ($h_0/d_0 = 1.5$)

Figure 9 presents results with the 10 × 15 mm specimens (length to diameter ratio of 1.5 (h_0/d_0 = 1.5). True stress–true strain curves of normal structure and nanostructure in one, four and eight passes, route C, are shown.

Figure 9 illustrates the usual shape of true stress–true strain curves for the as-received material (zero pass). The nanostructure specimens have different curve shape and show higher stress than the conventional alloy. The shape of the curves in all three cases is typical, non-monotonous, and needed further study.

As Fig. 9 shows, after the initial increase of all the three ECAP (one, four and eight passes), specimens have shown an anomaly by the decreasing true stress, which increases again only from true strains of about 0.4 value. For strains over the 0.4 value, pass one ECAP procedure caused only slight increasing in the true stress, less than estimated. Pass four showed significant increase while the further four passes up to eight caused just a slight increase.

The reason for the anomaly phenomenon in the shape of curves after ECAP is the strong anisotropy which leads to the buckled specimen shape (Fig. 10) that has lost the axial symmetry in straining. Additional lines on Fig. 10 show the deviation of longitudinal axes and the typical sliding layers. This sliding to aside might be the reason of the only slight difference between the curves of the zero and one pass.

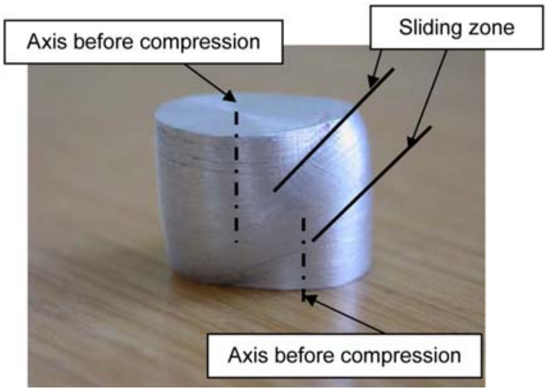

Figure 10. Typical shape (caused by the anisotropy) of compression specimen with 1.5 initial height to diameter ratio.
Slika 10. Tipičan oblik (usled anizotropije) epruvete za pritisak sa odnosom početne visine i prečnika od 1,5

The effect of this phenomenon decreases as the strain increases, but does not cease. It is supposed that for a decrease of the initial height to diameter ratios (h_0/d_0) the effect of this phenomena will decrease. On the other hand it is known that for smaller h_0/d_0 ratios the effect of friction for the strain state of the specimen is increasing, therefore the difference between the true stress–true strain and flow curves is increasing. Contrary to this fact, two further series of measurements are performed for ratios of 1 and 0.5, respectively.

Figures 11 and 12 present curves obtained by using 10×10 mm (h_0/d_0 = 1) and 10×5 mm (h_0/d_0 = 0.5) size specimens. The phenomenon observed for the 1.5 geometrical ratio nearly disappeared at the ratio of 1 and disappeared at the ratio of 0.5. It does not mean that anisotropy is not present, but the effect for the strain state of the compressed specimens was much less pronounced.

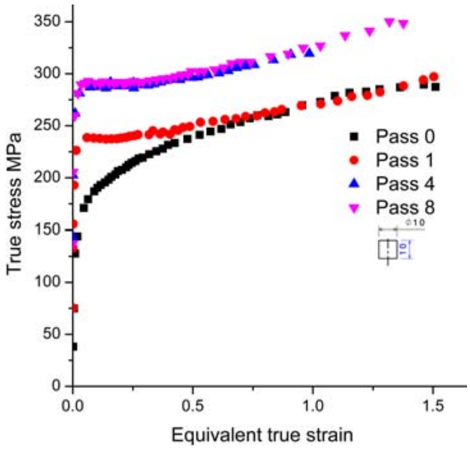

Figure 11. True stress–true strain curves of Al6082 after different passes with initial specimen geometry of 10×10 mm (h_0/d_0 = 1).
Slika 11. Krive stvarni napon–stvarna deformacija za Al6082 posle različitih prolaza, početne dimenzije uzorka 10×10 mm (h_0/d_0 = 1)

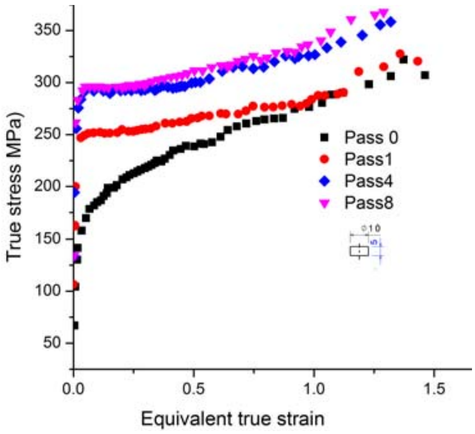

Figure 12. True stress–true strain curves of Al6082 after different passes with initial specimen geometry of 10×5 mm (h_0/d_0 = 0.5).
Slika 12. Krive stvarni napon–stvarna deformacija za Al6082 posle različitih prolaza, početne dimenzije uzorka 10×5 mm (h_0/d_0 = 0.5)

Except for the missing deviation behaviour, these curves show the same changes caused by the ECAP passes as for the geometrical ratio of 1.5. It can be said that the anomaly on true stress–true strain curves on specimens exposed to ECAP can be avoided by the h_0/d_0 geometrical ratio not exceeding one. From these figures the general shape of the curves have about right angle shape in case of the ECAP exposed specimens and on the other hand, for the conventional material, the curve has a power shape as usual.

The behaviour of nanostructure specimens as compared to conventional specimens is characterized by two significant features: firstly, by significantly much higher value of yield stress, that is higher as the number of passes increases, and secondly, by less pronounced strain hardening. The latter is evidently caused by the change in the deformation behaviour of UFG metallic materials, when, along with intergranular dislocation strain, grain boundary sliding occurs, /8/.

For sake of better comparison, the following figures illustrate the effect of the geometry of specimens (different height/diameter ratio) on the behaviour of true stress–true strain curves for the three ECAP exposed cases (one, four and eight passes), where the diameter of all specimens equals to 10 mm.

The curves obtained for one ECAP pass are shown on Fig. 13 that clearly shows the effects that were described before. At the (h_0/d_0) ratio of 1.5 the valley caused by the anisotropy on the curve is present while it nearly disappears at the ratio of 1 from the slightly higher curve position. On the other hand the effect of friction can be clearly seen by a rather higher curve position for the ratio of 0.5.

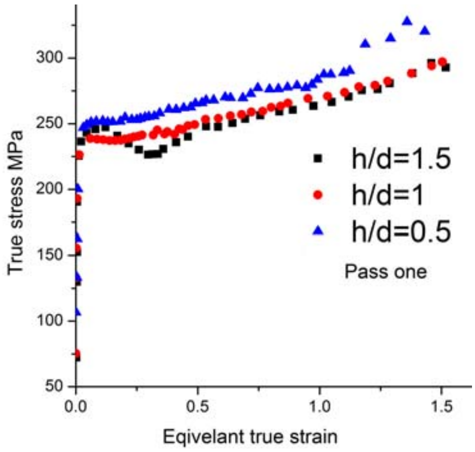

Figure 13. True stress–true strain curves for one ECAP pass at different height/diameter ratio.
Slika 13. Krive stvarni napon–stvarna deformacija za jedan ECAP prolaz kod različitih odnosa visina/prečnik

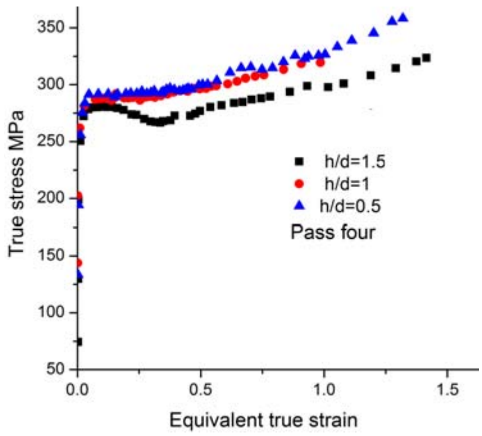

Figure 14. True stress–true strain curves for four ECAP passes at different height/diameter ratio.
Slika 14. Krive stvarni napon–stvarna deformacija za četiri ECAP prolaza kod različitih odnosa visina/prečnik

The same behaviour can be seen on Figs. 14 and 15 for ECAP passes of four and eight, respectively. At a higher number of passes the difference between curves obtained for ratios 1.5 and 1 is bigger than in the case of only one pass. The effect of friction can be observed again.

The shape of one full set of compression specimens can be seen on Fig. 16 after the last load increment is applied when the maximum force is the same. The top row shows the pieces having 0.5 initial height/diameter ratio in cases of zero, one, four and eight ECAP passes. For the middle row the initial geometry ratio is 1 and for the bottom row it is 1.5.

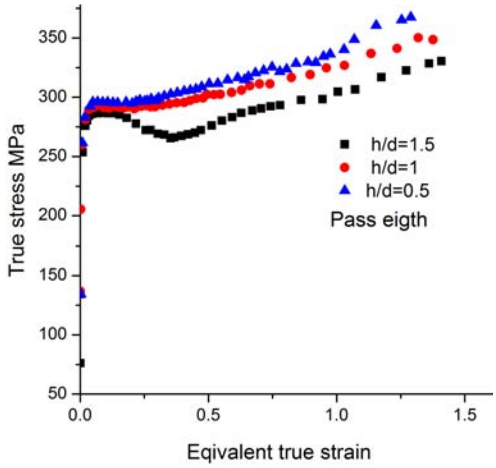

Figure 15. True stress–true strain curves for eight ECAP passes at different height/diameter ratio.
Slika 15. Krive stvarni napon–stvarna deformacija za osam ECAP prolaza kod različitih odnosa visina/prečnik

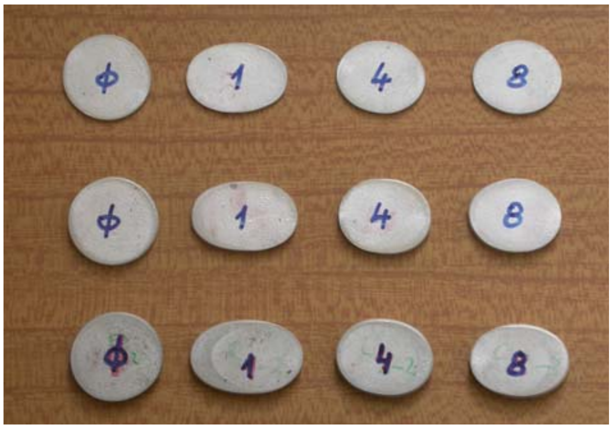

Figure 16. Compression ECAP specimens with initial diameter 10 mm and height from the top 5, 10, 15 mm, and from the left zero, one, four and eight passes.
Slika 16. Pritisni ECAP uzorci sa početnim prečnikom 10 mm i visinom od vrha 5, 10, 15 mm, i prolazi sa leve strane jedan, četiri i osam

The specimen cross section tended to change from circle to oval after ECAP passes, showing the presence of the induced anisotropy caused by this operation, and the maximum of this ovalizing is obtained after pass one. This can be explained by the fact that the cell shape returns back to original after double passes when route C is used.

Figure 17 shows the side view (from perpendicular direction to the maximum diameter) of three upsetting specimens, from top to bottom the specimens having eight, four and one pass. The figure shows the maximum ovalizing is obtained by one pass and there is only a slight difference between the pieces made by four and eight passes when the latter had the lower value.

The ratio of maximum and minimum diameters is calculated for each pass (one, four and eight) of ECAP. Figures 18 and 19 show the dependency of this ratio in the form of "ln(*a*/*b*)", where "*a*" is the half of the maximum and "*b*" is the half of the minimum diameter. The figures show the curves for different passes in case of 10×10 ($h_0/d_0 = 1$) and 5×10 ($h_0/d_0 = 0.5$) initial geometry respectively. (It should be noted that because of the barrelling and sliding aside of the specimens, the measurement of the maximum and minimum diameter is not fully accurate, therefore the diameter ratio is informative only. It can be seen on these figures, the maximum anisotropy is obtained by pass one and on the other hand the ratio has a lower value by four and eight passes, and they are approximately the same.

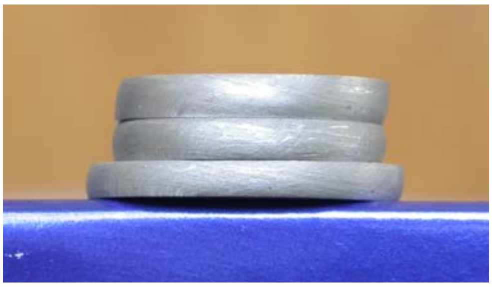

Figure 17. Pieces with 1.5 h_0/d_0 ratio of the three different passes, from top: eight, four and one pass (largest diameter).
Slika 17. Uzorci odnosa h_0/d_0 od 1,5 kod tri različita prolaza, odozgo: osam, četiri i jedan prolaz (najveći prečnik)

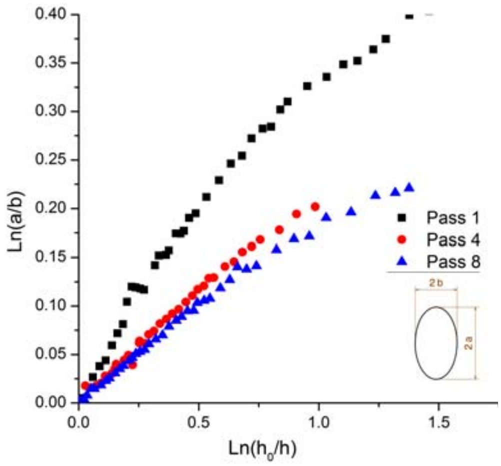

Figure 18. Diameter ratio vs. upsetting strain at room temperature for Al6082 after various ECAP passes ($h_0/d_0 = 1$).
Slika 18. Promena odnosa prečnika sa deformacijom na sobnoj temperaturi za Al6082 posle ECAP prolaza ($h_0/d_0 = 1$)

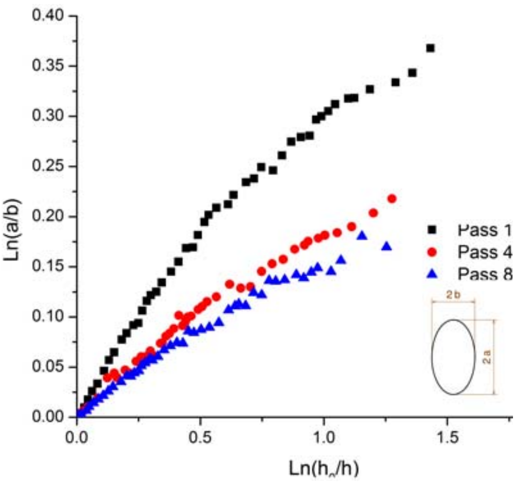

Figure 19. Diameter ratio vs. upsetting strain at room temperature for Al6082 after various ECAP passes ($h_0/d_0 = 0.5$).
Slika 19. Promena odnosa prečnika sa deformacijom na sobnoj temperaturi za Al6082 posle ECAP prolaza ($h_0/d_0 = 0,5$)

As it was mentioned above, the characteristic features of these nanostructured pieces is the anisotropic flow that leads to oval shape, which is not symmetrical but has some egg-like shape as it can be seen on Fig. 20, on the photos of the top and bottom surface of the same specimen.

Figure 20. Anisotropic flow where red shows the upper side and blue the lower side of ECAP billet, (a) upper surface of the upsetting specimen, (b) lower surface of the upsetting specimen.
Slika 20. Anizotropno tečenje, gde crvena tačka predstavlja gornju stranu a plava donju stranu ECAP uzorka, (a) gornja površina i (b) donja površina deformisane epruvete

The direction of the maximum diameter of the oval shape during upsetting test is the direction of “Z” shown on Fig. 21 on the ECAP billet. This characteristic is proved by signing the direction of the upper and lower side of the ECAP billet on the specimen surface after machining along the longitudinal axis (Fig. 21, Y-direction). The red sign shows the upper side of the billet and the blue sign shows the lower side as they are situated after the last pass.

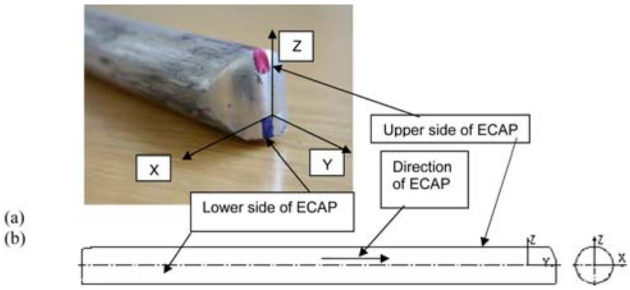

Figure 21. Direction of ECAP and its axes, (a) The anterior view of billet after pass one (red is upper and blue is lower side) and its axes, (b) Billet with the axes of coordinates.
Slika 21. Orijentacija ECAP sa osama, (a) pogled sa strane i (b) epruveta sa koordinatnim osama

As it was supposed, the egg-like shape is situated in a way that the “top side” of the egg (smaller radius on the egg curve) is at the top (red) side of the billet. The reasons for this is maybe the fact that the lower radius “R” of the ECAP channel is larger than the upper one “r” (Fig. 22), so the flow at the upper side happens in a thinner layer than at the lower side. This arrangement of the egg shape is most significant after the first pass. After several double passes, the “egg-like” shape is less significant, because during consequent passes (using route C) the shearing direction at the intersection plane is the opposite at each pass (see also Fig. 23).

Moreover, the same results are observed when some specimens are machined along the other two axes (X and Z directions) and the ECAP directions are signed on each specimen, but further study is needed to investigate the anisotropy of the materials produced by ECAP.

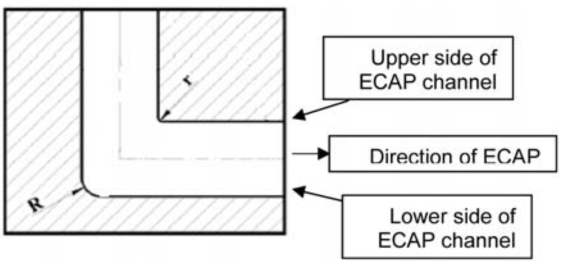

Figure 22. Section of the ECAP die set.
Slika 22. Presek ECAP sklopa kalupa

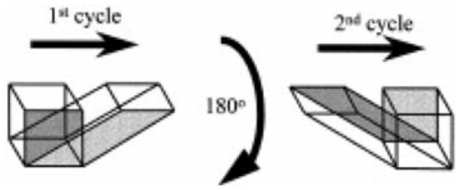

Figure 23. The cell transformation during ECAP passes using route C technique.
Slika 23. Transformacija rešetke pri ECAP prolazima sa metodom C pravca

CONCLUSION

The ECAP (equal channel angular pressing) method was used to produce nanostructure cylindrical products by route C (the rod is rotated 180° around the longitudinal axis between each deformation steps). The test material is the Al6082 commercial Al-Mg-Si alloy.

Upsetting test is used to determine the true stress–true strain curves in four conditions (annealed raw material and after one, four and eight ECAP passes). Three series of conventional upsetting specimens are used with three different heights to diameter ratio (h_0/d_0), the following conclusions can be drawn:

- Nanostructure specimens have different stress strain curve shape, where the general shape of ECAP materials have about right angle shape, while for the conventional material the curve has power shape as usual.
- ECAP specimens illustrate higher value of yield stress, that increases as the number of ECAP passes increase compared with the conventional alloy.
- Unusual phenomenon in the shape of stress strain curves after ECAP is strongly effected by anisotropy and maximum anisotropy is obtained by pass one. Moreover, the maximum ovalizing in ECAP specimens are observed after ECAP pass one.
- The valley shape, caused by anisotropy, on stress strain curves after ECAP technique almost has disappeared with low h_0/d_0 upsetting ratio and it has nearly disappeared at ratio of 1 or less.
- The direction of maximum diameter of the oval shape during upsetting test is the direction of “Z” (perpendicular to horizontal ECAP channel, and parallel to vertical axis).

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