EFFECT OF ECAP ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF SOLID STATE RECYCLED 413.0 ALUMINUM ALLOY CHIPS

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Abstract

The main objective of severe plastic deformation (SPD) methods is to obtain material with ultra-fine grained microstructure. Large deformations introduced during SPD processes result in extensive refinement of initial coarse microstructure which has significant influence on overall mechanical properties of such materials. In this work 413.0 aluminum alloy has been subjected to extrusion and equal channel angular pressing (ECAP). Metal chips obtained from machining process have been pre-compacted into a form of cylindrical billets and then extruded at elevated temperature into longitudinal square profile with cross section of 10 x 10 mm. In the second part of the experiment samples cut from this extrudate has been subjected to ECAP deformation through the 90° die. Mechanical properties were determined by uniaxial tensile tests and microhardness measurements has been performed. Structural observations did not reveal any significant changes in particles size after ECAP but enhancement of mechanical properties has been noticed and attributed to the work hardening of the aluminum matrix.

Keywords: ECAP, extrusion, mechanical properties, aluminum alloys, solid bonding

1. INTRODUCTION

Constant efforts to improve mechanical properties by structure refinement resulted over the recent years in a development of different SPD methods like e.g. ECAP, HPT, ARB or high speed machining. These processes enable to obtain UFG materials with an average grain size far below 1 µm [1]. In this group ECAP, developed in 1980s, is one of the most extensively used processes among all of SPD. In this method small portion of material usually in a cylindrical or cuboid form is being pushed through a steel die assembled by two channels intersecting at an angle Φ from 90° to 150°. Magnitude of shear strain γ that can be applied during only one ECAP pass is relatively small [2], but by applying multiple passes total deformation can be significantly increased. Because of this SPD methods can be used to improve mechanical properties of materials, which are characterized, by poor ductility and toughness such as Al-Si alloys. Various studies [4-5] show that use of ECAP on Al-Si alloys leads to microstructure refinement and improves their strength. In contrast to ECAP machining processes like turning or milling allow to obtain large shear strain (>>1) in just a single pass however small dimension of fabricated chips enforce need for additional material consolidation.

The main aim of this studies was to examine limitation of microstructure refinement and properties improvement of AlSi alloy by combine turning and ECAP process. In order to eliminate negative effect of cooling liquid during consolidation of chips after cutting dry machining was carried out. Due to simplicity, low costs and variety of suitable material forms (powders, RS ribbons etc.) solid state bonding has been accomplished by extrusion [7-10].

2. EXPERIMENTAL MATERIALS AND PROCESSING

Experimental studies were divided into two consecutive steps. At first 413.0 aluminum casting alloy in a form of round rods and with chemical composition presented in **Table 1** were subjected to turning. As a result large chips (**Fig. 1a**) with an average size of 21.6 x 3.7 x 1 mm were produced. Cutting was performed with tool feed rate of 0.2 mm/s and rotation speed of 315 rev/min. Received chips were subjected to cold compaction under the pressure of 240 MPa. Cylindrical billets, 10 mm in height, 40 mm in diameter, weight of 25 g and density of 2.07 g/cm^3 were produced. Seven of such billets were finally hot extruded into a form of 10 x 10 mm square profile. Temperature and ram speed during extrusion were 450 °C and 3 mm/s respectively. At the second stage of experimental procedure samples from solid bonded (SB) profile were cutted and ECAP procedure with different number of passes (1-4) was performed. In order to acquire relatively high plastic strain 90° channel die was used. Additional rotation (90°) of sample was performed after every pass.

Table 1 Chemical composition of 413.0 alloy

Element	Si	Fe	Cu	Mn	Mg	Zn	Ni	Ti	Total others	Al
Weight %	10.58	0.38	0.51	0.24	0.28	0.1	0.12	0.06	0.08	Balance

Uniaxial tensile tests were performed for samples machined from as extruded profile and specimens after ECAP deformation. Tensile tests were carried out at room temperature at a constant strain rate of 8×10^{-3} s^{-1} using Zwick Z050 testing machine. Moreover, additional hardness measurements were performed on longitudinal cross section under the indenter load of 9.807 N. Average HV value was calculated based on at least 10 measurement results.

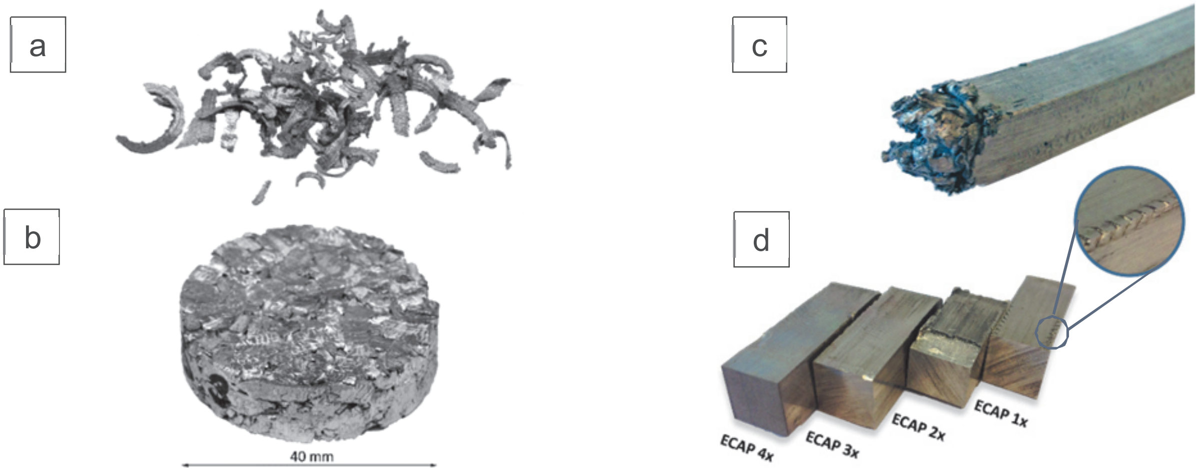

Fig. 1 a) Macro view of chips after machining process; (b) cylindrical billet after cold compaction c) SB profile d) ECAP samples after every pass

In order to evaluate effectiveness of consolidation process as well as overall influence of the ECAP deformation on the microstructure refinement scanning electron microscopy observations were performed by using Hitachi SU-70 microscope. Samples for SEM studies were prepared by grinding and polishing of longitudinal cross-sections of tested materials.

3. RESULTS AND DISCUSSION

3.1. Surface quality

Fig. 1 shows profile surface after extrusion (**Fig. 1c**) and ECAP samples (**Fig. 1d**) after different number of passes. Due to lower shear strain and temperature at the beginning of extrusion process consolidated profile in its front section revealed lack of sound bonding between individual chips which can be observed as small serrations on a surface (**Fig. 1b**). This roughness diminishes with profile length and after ≈35 mm, smooth and glossy face of a profile can be observed. In addition, ECAP sample after first pass exhibit small and shallow cracks on the sample top edges (**Fig. 1d**). As can be observed successive pressing through the ECAP die did not enforce any further fractures propagation. Densities of all examine samples exhibit constant value of 2.66 g/cm^3 which indicates lack of critical voids inside material.

3.2. Microhardness and mechanical properties

Results of Vickers hardness tests are presented in **Fig. 2**. One can observe that profile after extrusion exhibit the lowest HV value among all tested materials. By applying only single ECAP pass microhardnes increases to ~100 μHV while following second, third and fourth pass gains additional ~10 μHV. Such microhardness relation is a direct result of two strengthening mechanism cooperation. Primarily, severe plastic deformation during machining leads to refinement of brittle phases while at the same time matrix strengthening due to dislocation multiplication occurs. Following processing of the material by hot extrusion, results in activation of recovery processes, which in turns trigger off material softening. Further application of ECAP deformation restores matrix hardening and continue phase refinement.

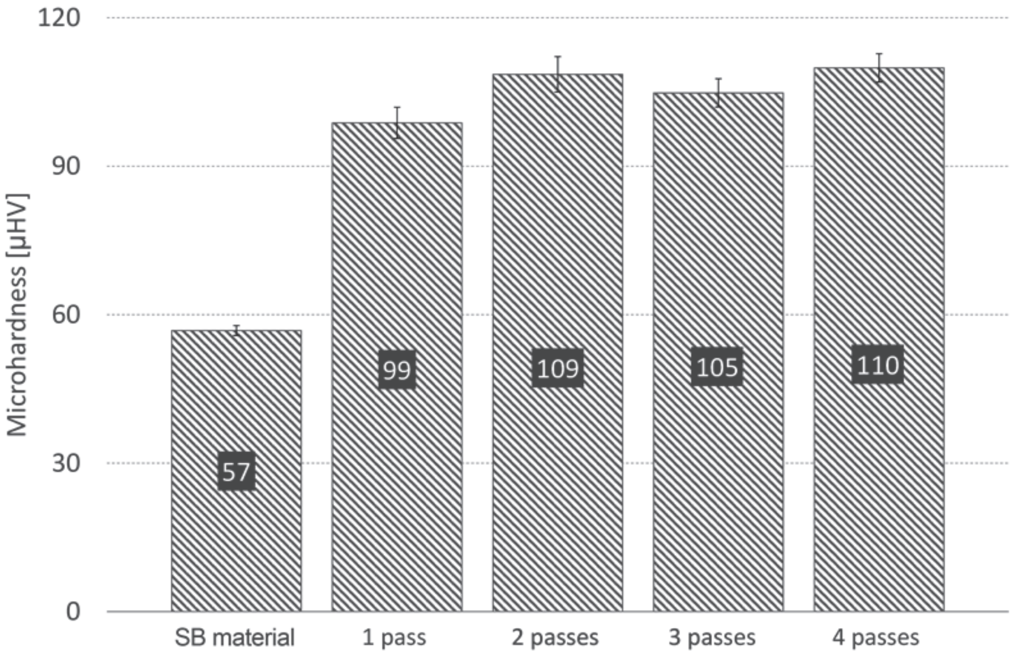

Fig. 2 Microhardness evolution during number of ECAP passes for 413.0

Similar effect can be observed for samples after tensile test. Typical tensile curves have been presented in **Fig. 3**. Yield stress (YS), Ultimate Tensile Strength (UTS) and strain (ε) were determined from as received tensile characteristics. Results in **Table 2** represent an average value of YS, UTS and ε, which were determined for at least three tensile measurements. One can observe that similarly to microhardness tests results, SB material exhibit the lowest strength properties, however plasticity of the material is the highest among all tested alloys (**Fig. 3, Table 2**). Significant increase in mechanical properties after first and second ECAP pass has been observed (**Fig. 3, Table 2**). Further ECAP deformation induced by third and fourth pass did not effect on mechanical properties. Plasticity of the material decreases drastically after just one pass and remains at constant level through further ECAP deformation (**Fig. 3, Table 2**).

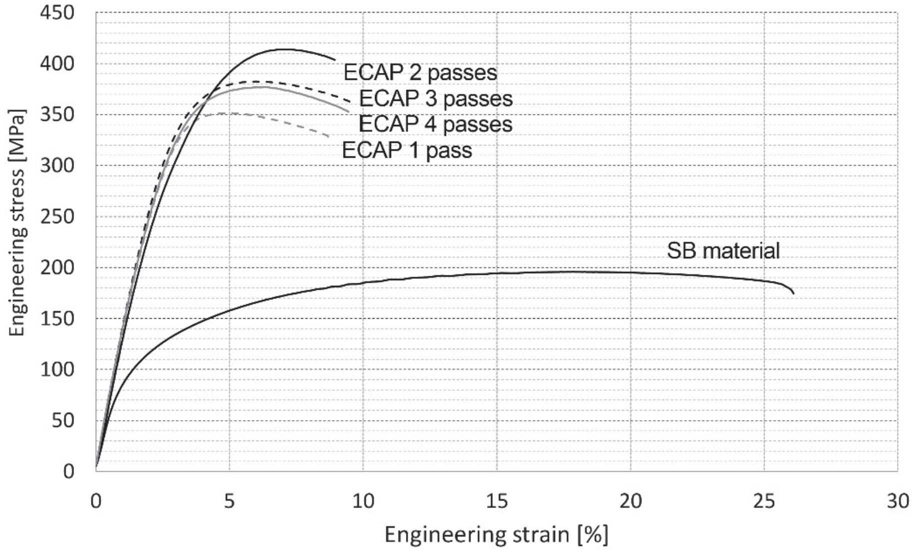

Fig. 3 Typical engineering stress-strain curves for 413.0 samples.

Table 2 Mechanical properties of 413.0 before and after ECAP process. Every value in the table represents an average value determined from three separate tensile tests

Sample	YS (MPa)	UTS (MPa)	ε (%)
SB material	109	218	26
1 ECAP pass	293	355	9
2 ECAP passes	314	391	9
3 ECAP passes	309	383	9
4 ECAP passes	311	387	8

3.3. Structure evolution

Microstructure observations of SB profile alongside with a material after first and fourth ECAP pass has been presented in **Fig. 4**. Exanimated materials revealed no signs of discontinuities which suggest sound bonding of as-extruded profiles. White particles visible on the picture represent Al-Fe-Si phases, while light grey corresponds to Si primary crystals. These brittle and hard phases crack during machining and are directly responsible for chips breakability [11].

In addition, thin-foils observations of samples after extrusion and four ECAP passes (**Fig. 5**) revealed noticeable differences. As-extruded material is characterized by clear defined and uniform structure which may suggest occurrence of recovery processes during hot extrusion. At the same time sample after ECAP posses highly deformed, inhomogeneous microstructure which in general can be attributed to work hardening and large distortions imposed during pressing through the die.

Silicon particle size distribution after extrusion and first and last ECAP passes is shown in **Fig. 6**. It can be seen that particles size gradually shifts to lower values after each operation. The largest difference in size can be observed between SB and first ECAP pass. Distribution after four passes shows only slight decrease in overall particles size. The mean size of Si particles after solid bonding were found to be 2.54 μm, while after 1st and 4th ECAP pass size of particles was 2.00 μm and 1.99 μm respectively. Similar analysis performed for Al-Fe-Si particles revealed no significant differences in size.

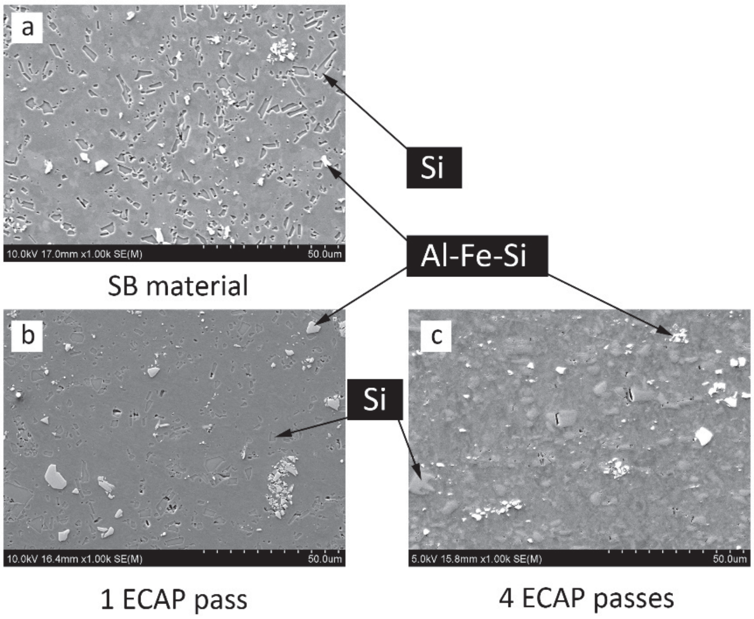

Fig. 4 Microstructure of 413.0 alloy after a) extrusion, b) first and c) fourth ECAP pass

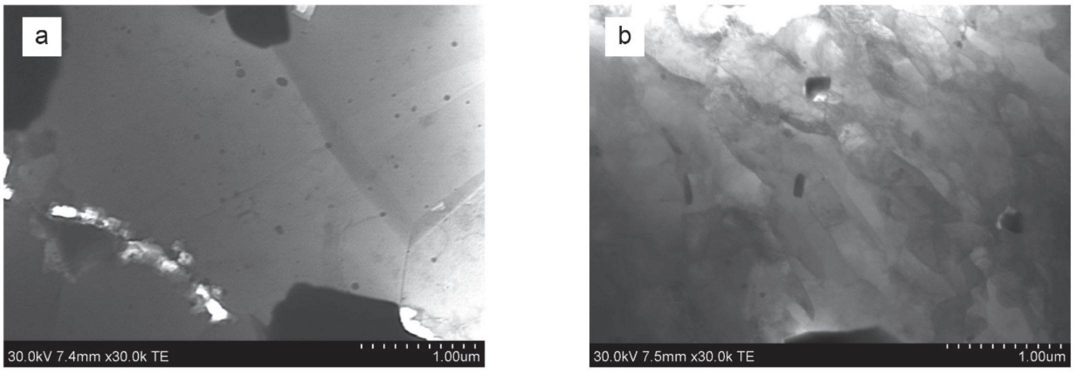

Fig. 5 Thin-foils microstructures prepared from samples after a) extrusion and b) fourth ECAP pass

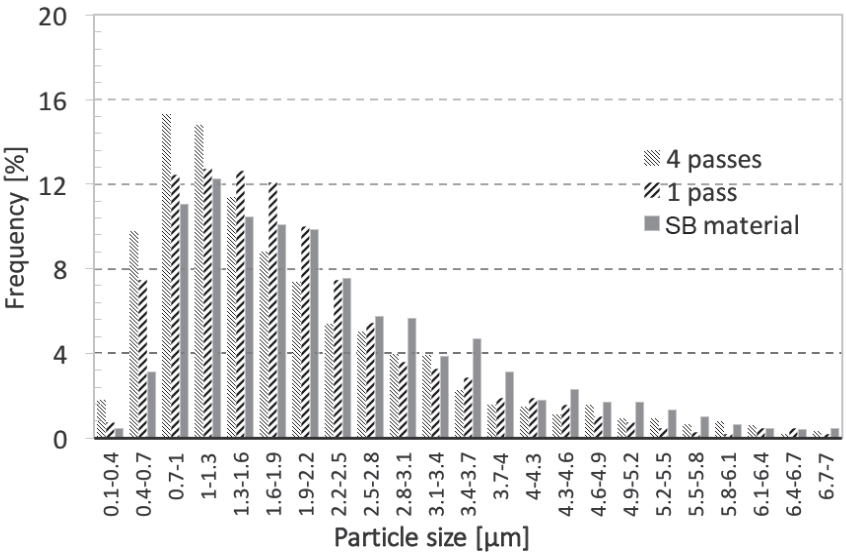

Fig. 6 Size distribution of Si particles in as-extruded material, after 1st and 4th ECAP pass

CONCLUSIONS

1) Plastic consolidation of 413.0 metal chips at temperature of 450 °C and ram speed of 3 mm/s results in material with good solid bonding and surface quality.
2) One ECAP pass contributed to significant increase in mechanical properties. This can be ascribe to deformation of aluminum matrix and brittle phase refinement. However, due to small changes of Si and intermetallic phases major part of material strengthening effect can be ascribed to the work hardening process.
3) Further deformation (2-4 ECAP passes) has negligible influence on mechanical properties.

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