

Incremental ECAP as a novel tool for producing ultrafine grained aluminium plates

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Abstract. Conventional equal channel angular pressing is an efficient technique to obtain bulk ultrafine grained materials (UFG) with extraordinary mechanical properties in the form of rods. In this work, an incremental method of ECAP process which allows to obtain thick sheets with UFG structure is presented. Using this method square plates (62 x 62 mm) were obtained. In this case, a combined route - A+ specific B - with 90 degree rotation along plate normal after each pass keeping other planes in the same positions relatively to the channel - has been applied. The efficiency of this methods was proved for technically pure 1050 aluminium. It was processed by incremental ECAP using 8 passes of A+B route. To characterize microstructure visible light microscopy and transmission electron microscopy were used. Mechanical properties were measured by microhardness test. The results obtained showed that the microstructure and mechanical properties of 1050 aluminium alloy processed by incremental ECAP are comparable to conventional ECAP. However, the new processing method broaden the potential applications of UFG materials.

1. Introduction

Ultrafine grained (UFG) materials are of the great scientific interest because of extraordinary mechanical strength they can reach in comparison to their coarse grained counterparts [1, 2]. Strengthening effect in pure metals is possible due to grain size refinement, as grain boundaries effectively reduce dislocations free path [2]. Among techniques used to produce refined structures only severe plastic deformation (SPD) allows to obtain bulk products with relatively big dimensions that can be applied as structural parts [1]. The most popular SPD processes include high pressure torsion [3, 4] and accumulative roll bonding [5]. However despite the popularity of the mentioned methods and continuous development of new ones equal channel angular pressing (ECAP) [6] and its modifications are still the most promising SPD technique which can be adopted by industry.

It has been proved in numerous papers that significant grain refinement down to UFG regime via ECAP can be obtained with only few passes [7, 8] and a considerable increase in mechanical strength occurs even after a single pass [9]. Different modifications, such as various rotations of billet [10], multiple pass channels [11], applying backpressure [12] or temperature control [13] allows to tailor final properties of ECAPed products.

ECAP is originated in the family of side extrusion processes. This extrusion-like method uses intensive simple shear to deform a billet. Therefore, cross-sectional dimensions of the workpiece can be kept unchanged and single pressing can be repeated many times to cumulate high value of plastic strain. Extrusion is a very popular bulk metal forming technique. That's why ECAP can be easy performed according to bulk metal forming practice

by using common tooling and machinery. However, when ECAP is carried out in its conventional configuration it shares all disadvantages of extrusion process, i.e. feeding of the material into shearing zone is carried out at the same time as plastic deformation takes place. It results in substantial increase in process load because friction forces add to shearing forces. This, in turn, makes impossible to process long billets.

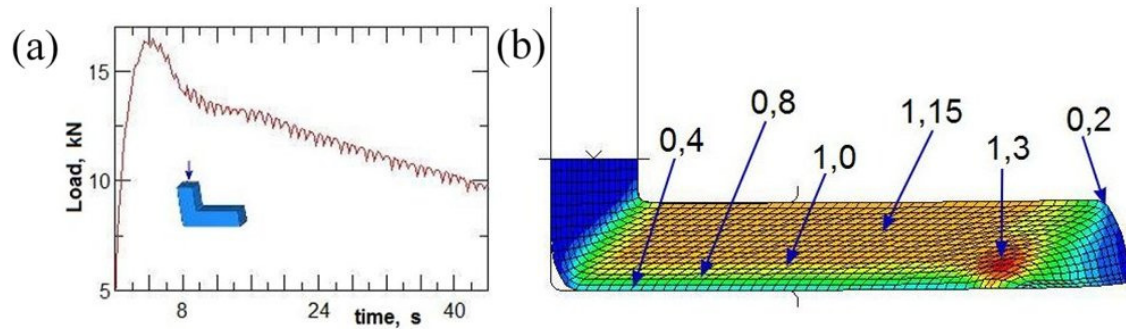


Fig. 1 FE simulation of conventional ECAP: (a) processing load, (b) strain distribution

Some information regarding process load can be obtained by finite element (FE) simulation of the ECAP process. Fig.1(a) confirms that conventional ECAP is a friction intensive metal forming process. Total load at the beginning of the process is 40% greater than final load when the billet is almost completely fed into output channel. This result was obtained for friction coefficient equals 0.05 which means that very good lubrication was assumed for simulation. Friction, despite being kept in ECAP at low level, affects strain distribution substantially, as can be seen from Fig.1(b).

Several reports on producing UFG aluminium plates have been published. However, in every case process of plastic deformation include rolling, in cryogenic temperature [14, 15] or combined with ECAP [16]. It always led to noticeable increase of mechanical properties caused by grain refinement. Markushev et al. has shown in Ref [17] that initial microstructure does not influence final size of refined grains in aluminium alloys but strengthening effect is stronger in non-heat treatable ones. Additionally it was suggested that thermal stability of UFG structure depends on alloy composition.

The aim of the present work was to design a new ECAP tool capable to produce long and flat product without any additional post-processing. By using this new ECAP tool, deformation is applied incrementally to reduce friction forces and allow to process long products and control its thickness. Construction of IECAP machine makes it possible to produce UFG plates with no limitations connected with thickness or length of billet.

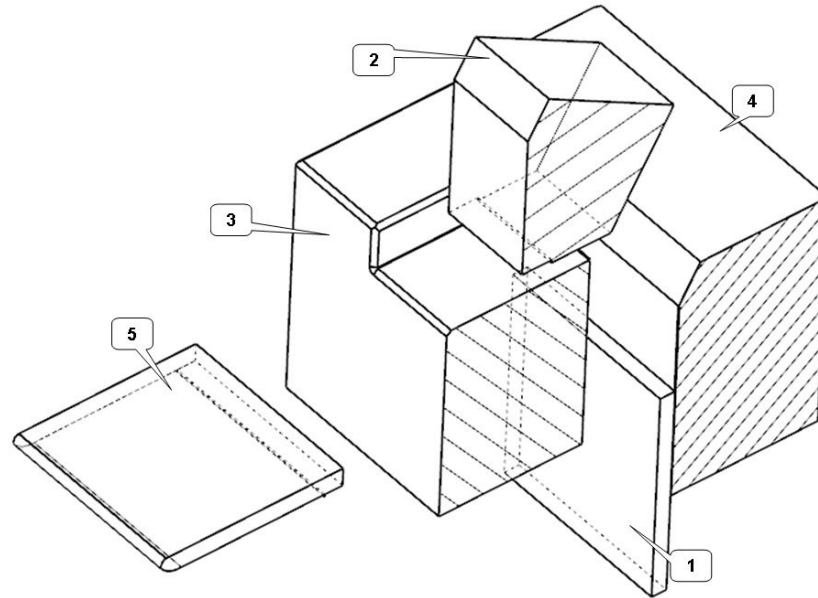


Fig. 2 Tool arrangement of IECAP at the ISx machine (1) pusher (2) punch (3) die (4) clamp (5) billet

2. Materials and methods

2.1 Incremental ECAP

It is widely known that most of plastic deformation techniques could be performed in steady or incremental flow. In this paper we present modification of ECAP in which billet is deformed with series of small deformations. Idea of such technique has already been reported in Ref. [18] as FE modeling of possibility of applying incremental deformation to ECAP. First application for processing of plates has been described in Ref. [19]. The deformation was performed on hydraulic press with a manual handling of plate. Now the process has been automated on an ISx (Incremental Shear for any of x-products) machine built for efficient manufacturing of UFG metal plates. The machine is equipped with replaceable set of forming tools. This device allows to produce plates with dimensions of $8 \times 70 \times 200$ [mm]. However, the thickness of the plate depends on available punch load which is limited to 100kN for the ISx machine. The tool arrangement has been changed over for pressing square plates with dimensions of $3 \times 62 \times 62$ [mm] at present.

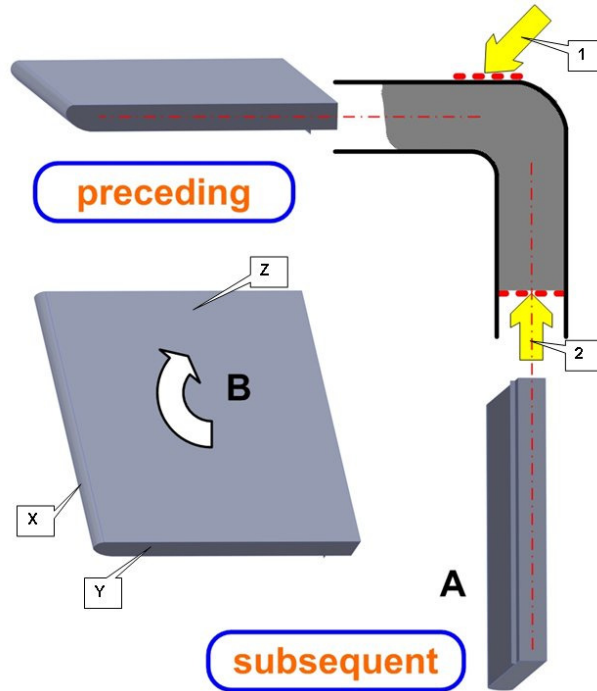


Fig. 3 Schematics of route A+B and planes X,Y,Z for workpiece investigation applied for IECAAP of rectangular plates: 1- punch (shearing), 2- pusher (feeding)

Fig. 2 shows schematically operation principles of IECAAP on the ISx machine. A plate is moved horizontally by pusher (1) and deformed by punch (2) by simple shearing. Angular channel is in a stationary die (3). The plate is kept in stable position relatively to tools by clamp (4) while being sheared. After a single deformation pusher change the position of the plate in the input channel and another cycle goes on. Finally the processed workpiece (5) is removed from the output channel when incremental forming is completed.

Geometry of tools built for IECAAP processing allows to produce a rectangular plates which can be rotated around plate normal. Schematics of applied rotation of the plate regarding preceding and subsequent pass through the angular channel is shown in Fig.3. Such a route has never been applied to ECAP processing because tools arrangement in a conventional ECAP machine do not enable such a rotation because thickness of the channel cannot be changed. Applied route is called A+B because it is combination of route A in which placement of billet do not change relatively to channel and route B with 90 degree rotations. Thickness of product depends on punch motion and can be easily controlled.

2.2 Material and methods

In this study, technically pure aluminum 1050 was used to investigate efficiency of IECAAP. 8 passes were performed to obtain ultrafine grained structure. Each pass is equivalent to true strain of $\epsilon=1.15$. As mentioned in the previous section, route A+B with 90 degree rotation around normal to plate's plane was applied. A pressing direction in every odd pass was in agreement with rolling direction of material's initial condition while in was perpendicular to rolling direction. The deformation was carried out with 0.6 mm pusher step so the plastic deformation zone in every stage overlapped one from the previous cycle.

Material was investigated in terms of mechanical properties (by microhardness measurements) and microstructure (using visible light microscope and transmission electron microscope - TEM). Series of microhardness measurements were performed to verify

homogeneity of mechanical properties on different planes (X, Y, Z as marked in Fig.3). Metallographic investigations were performed on Y plane on planes close to punch and die to check influence of a punch motion on the surface of the billet. TEM observations were performed on electropolished thin discs on Y plane to investigate grain refinement. JEOL JEM 1200EX transmission electron microscope with accelerating voltage of 120kV was used for structural characterization. Grain size was determined in terms of equivalent diameter i.e. the diameter of a circle with the same area as investigated grain and grain size diversity expressed as the variation coefficient CV which is a ratio of standard deviation to the mean value.

3. Results and discussion

3.1 FE modelling

During incremental ECAP deformation conditions are the same as in conventional ECAP. Shearing takes place and spread through the whole thickness of the plate. Fig.4 shows strain distribution in longitudinal cross-section of the plate pressed incrementally using tool configuration specific for ISx machine. Shearing process results in almost uniform plastic deformation field which is similar to those for the conventional ECAP (as compared to Fig.1 (b)) except a layer close to the punch which moves at 60°. Punch load was not calculated because mechanical properties of the metal are not known at present.

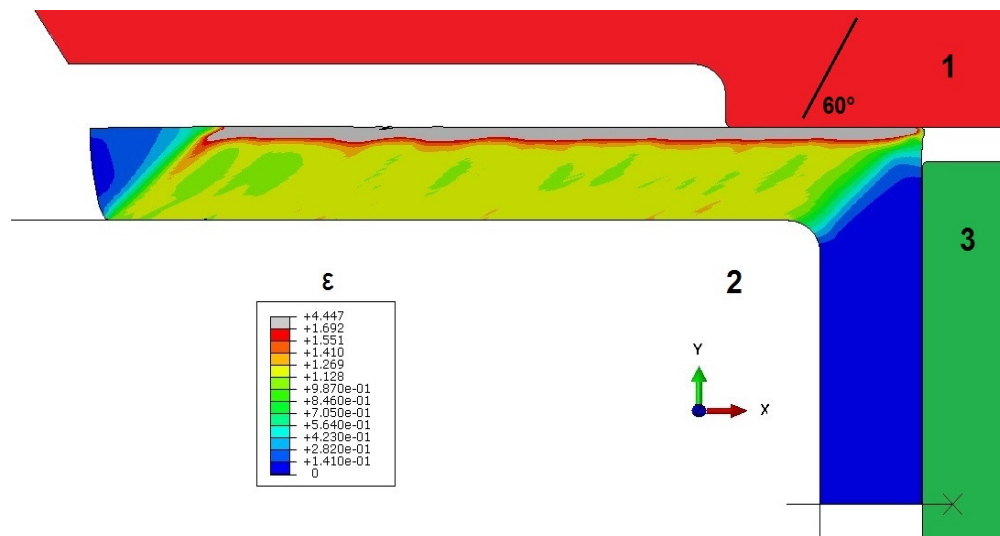


Fig. 4 FE simulation of incremental ECAP: 1-punch reciprocating at 60°, 2-stationary die, 3-clamp

3.2 Influence of punch motion

Construction of IECAP machine allows to control thickness of the billet. Due to punch motion it is possible to reduce the smallest dimension by applying additional strain on the surface on a punch side. Results presented in this section refer to the first pass of IECAP since subsequent passes leads to blurring of observed microstructures.

As shown in Fig. 5 some near surface effect can be noticed close to the punch side of Y plane. Punch motion is oblique relative to billet surface, as can be seen in Fig.4. It causes shearing, as in conventional ECAP, but also surface deformation due to friction between the tool and material. Consequence of this phenomena can be seen on Fig. 5 (b) as Z-contour near a 'punch' surface. Such a microstructural feature is not visible on 'die' side of billet, Fig. 5(a).

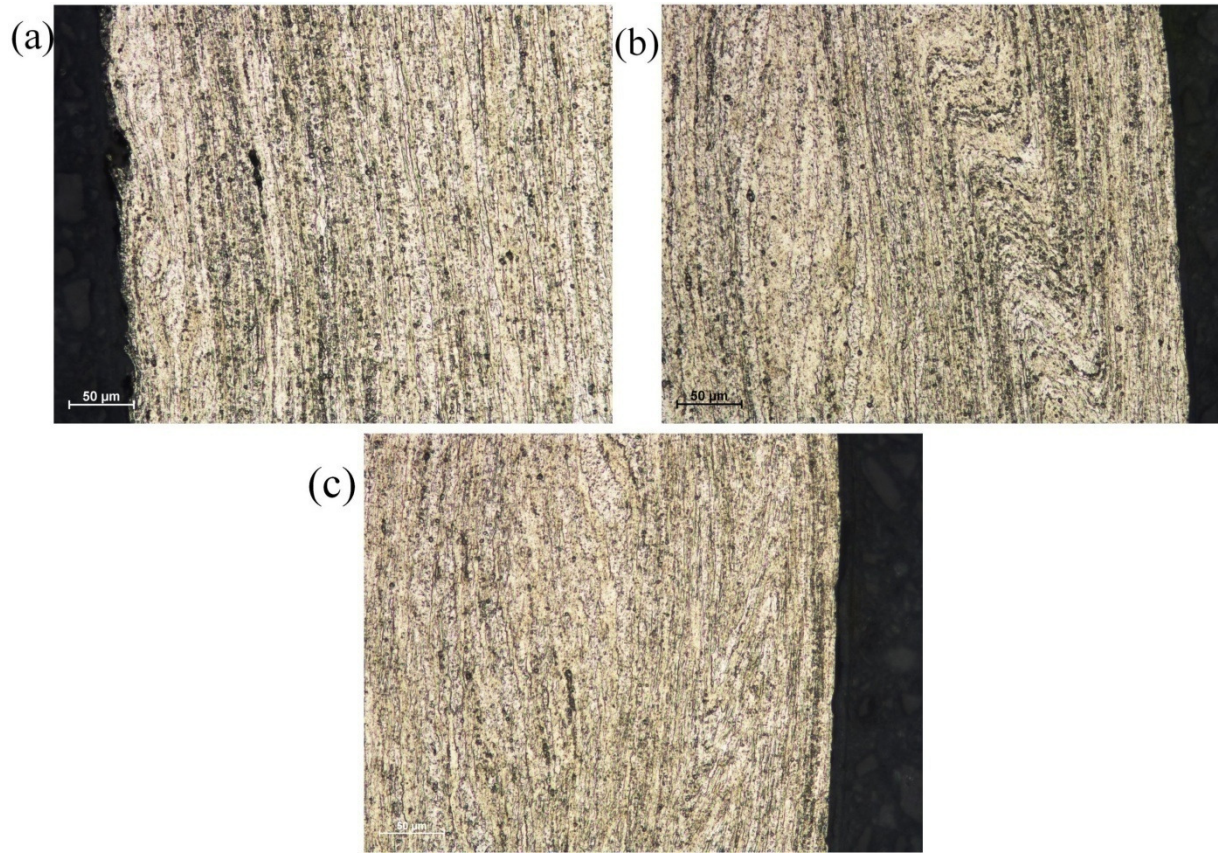


Fig. 5 Microstructure of 1050 aluminium alloy near (a) 'die' surface (b) 'punch' surface after first pass of IEAP with pure shearing (c) 'die' side with shearing and additional stress

Control of punch motion allows to enhance stress that is needed for deformation what reduces the thickness of entire billet. Microstructure investigations using visible light microscope (Fig. 5 (c)) shows that distance between Z-contour and specimens surface is smaller than in deformation without additional stress. In both cases microstructure become more elongated along pressing direction when approaching to the centre of specimen.

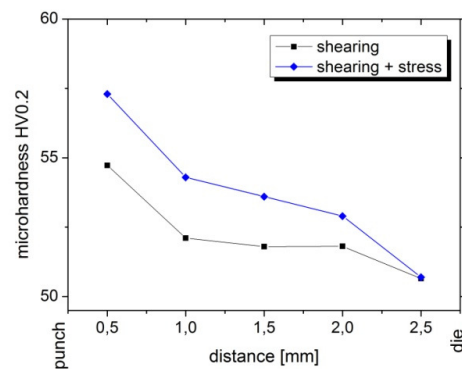


Fig. 6 Microhardness HV0.2 distribution on Y plane after first pass of IEAP

Impact on microhardness measured on the Y plane is shown in Fig. 6. It can be noticed that in standard deformation, without additional strain, microhardness distribution from 'punch' to 'die' surface seem to be non-uniform what is standard for the first ECAP pass due to non-homogenous distribution of strain. However, applying additional stress causes a strength

increase intensification on ‘punch’ side what is also visible on microhardness distribution curves.

3.3 Microhardness

Table 1 gathers the average values and standard deviations of microhardness HV0.2 measured on different planes.

Table 1 Microhardness measurements on different planes of IECAped 1050 aluminium alloy plates

Condition	X		Y		Z	
	HVo.2	SD	HVo.2	SD	HVo.2	SD
Initial	47	2.55	45	2.12	46	1.91
1 st pass	53	2.83	53	1.67	51	2.72
2 nd pass	57	2.28	55	2.28	56	2.14
3 rd pass	57	2.31	56	2.92	56	2.20
4 th pass	55	1.25	54	1.66	54	1.75
8 th pass	56	1.06	58	1.92	58	1.92

The biggest increase in microhardness is observed for the first pass of IECAp. For the next passes one can observe continuous but slight strengthening effect with the highest value for the sample after eighth pass. The hardness homogeneity is relatively high, as shown by the values of variation coefficient measured for all planes. They stay at a constant level of about 0.05 and is at similar level as rolled material (initial condition). It clearly shows homogeneity of mechanical properties on every plane.

Table 2 Grain/subgrain size in IECAped 1050 aluminium alloy

IECAP pass	d ₂ [nm]	CV(d ₂)
1	909	0.33
2	855	0.27
4	842	0.43
8	599	0.41

3.4 Microstructure

Fig. 7 shows representative TEM micrographs taken from the Y plane of IECAped billets after different number of passes. After the first pass (Fig.7 (a)) one can notice small grains elongated along deformation direction with a dislocation substructure inside them. Such a structure is typical for fcc metals with high stacking fault energy because of frequent dislocation intersections. The second pass (Fig.7 (b)) causes rearrangement of the dislocation structure observed in previous condition. In several grains dislocation walls are visible but incidental dislocations within grain interior are not so abundant. After the third pass (Fig. 7 (c)), grains are more developed. Neighbour grains vary in contrast what clearly indicates higher misorientation angle between them. Microstructure after the fourth pass is even more developed since no dislocation cells were noticed. However, grain/subgrain size reduction in comparison to second pass is not clearly distinguishable, see Table 2. The sample after the final eighth pass (Fig. 7 (e)) shows fully refined grains which are still elongated with deformation direction but their size is significantly reduced.

Diffraction patterns taken with a large aperture (effective diameter of 10 µm) presented as insets in images in Fig. 7 also confirm the grain refinement process. At initial stages, the patterns reveal strong texture as scattering occurs only at a specific set of planes what is visible as two spots on opposite sides of a central spot. After the third and four pass

development of an arc can be noticed what is an outcome of increasing misorientation angle between grains. At final, eighth pass, full ring pattern is present what confirms a variety of orientations.

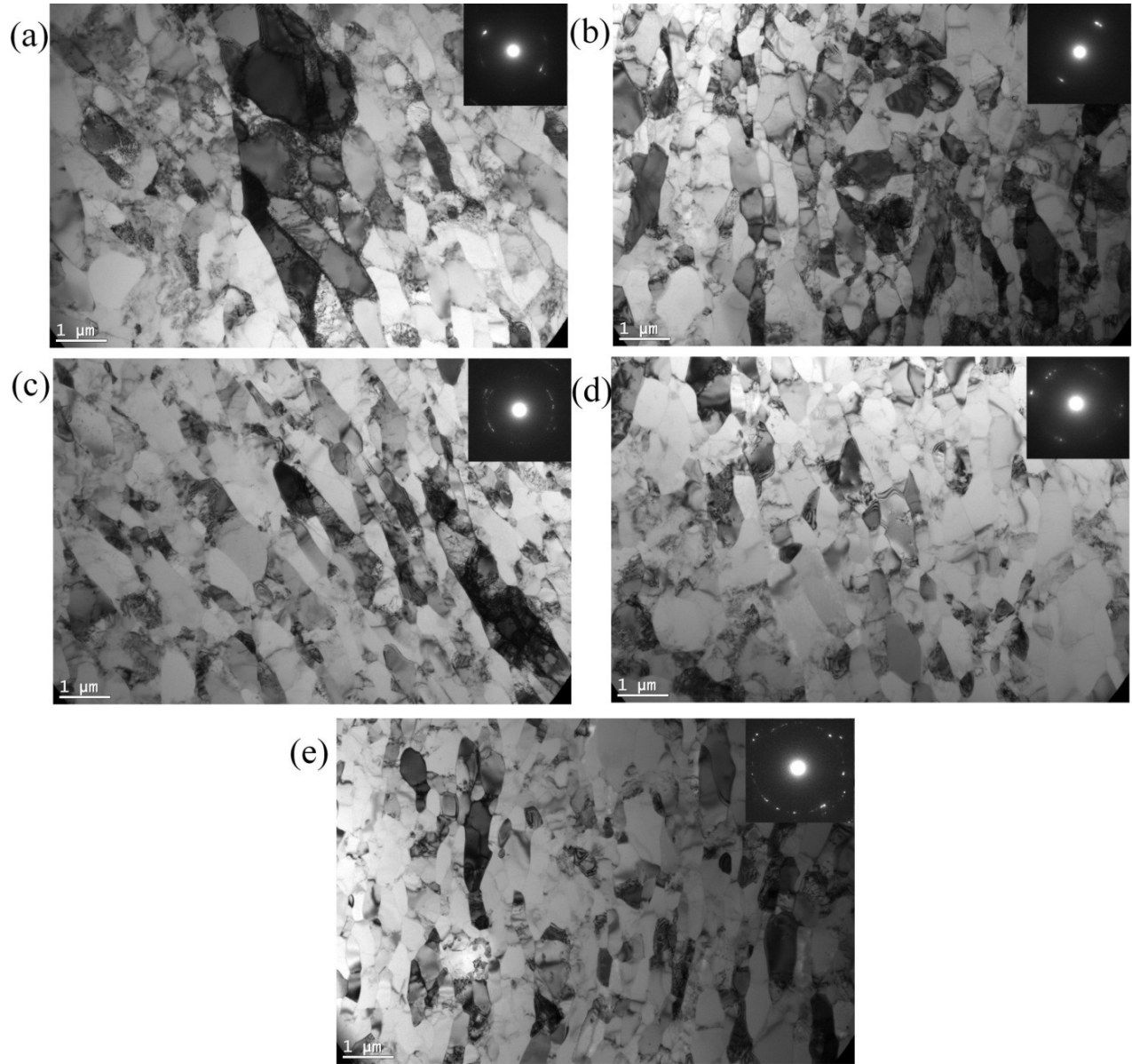


Fig. 7 Microstructure on Y plane of IECAPed 1050 aluminium alloy at different stages (a) 1st pass (b) 2nd pass (c) 3rd pass (d) 4th pass (e) 8th pass

Table 2 summarizes the results of grain/subgrain size measurements for 1st, 2nd, 4th and 8th IECAP pass. Following reduction of equivalent diameter it can be noticed that changes between the first and fourth pass are not so significant as for the fourth and eighth pass. It can be attributed to the formation of dislocation structures in early stages of IECAP and their further transformations. When they approach to their smallest size subsequent deformation increases misorientation angle between them. These transformations can be visualized by changes in variation coefficient CV. Range of distribution of grain/subgrain size increases in later passes with advancing deformation process.

As microstructure investigations have shown, IECAP process leads to a significant grain size reduction via formation of dislocation walls and further increase of their misorientation angles. Such a mechanism has been previously proposed [7, 8] and is commonly accepted. According to FEM calculations, the strain state is similar to conventional ECAP processing. As a result, the microstructure obtained also does not differ significantly from the one typical for ECAP, for which average grain size of about 500-800 nm has been obtained for pure aluminium [17,20]. As for the fraction of high angle grain boundaries, detailed quantitative studies are in progress and this topic will be discussed in a separate communication. The major advantage of the new method is a significant load reduction in comparison of conventional ECAP and even more importantly possibility of tailoring shape of IECAP-ed plates in one machine only by precise control of punch motion. Such a tool arrangement allows to change thickness of single plate along its length with keeping UFG structure by fully automated IECAP press.

4. Summary

It has been demonstrated that for aluminium 1050 efficient grain size refinement can be achieved using IECAP processing. By using automated machinery it was possible to process rectangular 3 mm thick plates and after 8 passes with a specific route A+B, reduce the grain size to less than 600 nm.

The major advantage of IECAP process is the possibility of processing relatively large billets in the form of plates with various dimensions. IECAP significantly reduces friction forces which enables homogenous microstructure to be obtained. A strain distribution is uniform across the thickness of the plate except a layer close to the punch because material under punch tends to flow backward to the workpiece movement. This feature should be a subject of further investigation in terms of the process parameter optimisation.

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