Comprehensive study of effect of process parameters in equal channel angular pressing

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In present work, comprehensive study of equal channel angular pressing (ECAP) process is attempted for analyzing the influence of process parameters, viz., channel angle ($\Phi$), the angle of curvature ($\Psi$), plunger velocity ($v$), processing routes ($R$), shear friction ($m$) at die and billet interface and the number of ECAP passes ($N$). This study will help to understand ECAP process with a better insight into influence of multiple process parameters and develop improved ECAP process with two objectives, i.e., (i) high and uniform distribution of equivalent strain in ECAPed billet and (ii) minimum pressing requirement during the process along with selection of best process parameters without committing to expensive tooling and machinery. ECAP study is performed on the AA6061 aluminum alloy. ECAPed billet is mechanically tested. The usefulness of experimental and FEM analysis in developing practical ECAP process is demonstrated in this paper. The outcome of this work certainly provides momentum in the commercialization of ECAP process.

Keywords: Equal channel angular pressing, Finite element method, Severe Plastic Deformation

Ultrafine grain materials/bulk nano materials are among the interest areas of research today to meet present engineering challenges. Traditionally bulk nano materials are made by nano scale synthesis, i.e., self-assembly, non-traditional lithography, template growth and biomimetics. In these processes, nanoparticles, delivered in the form of nanotubes, nano powders, quantum-dots, and biomaterials are stacked into final product in a designed way. These processes are quite expensive, time consuming and chemically unstable\(^1\). Recently, a top down grain refinement approach known as severe plastic deformation (SPD)\(^2\) has been adopted to produce bulk nano material at a commercial level. Among different SPD approaches, one approach known as equal channel angular pressing (ECAP) (Fig. 1)\(^3\) attracted a lot of attention recently because of its potential to be used at an industrial level.

Though ECAP process has a potential to be employed at a commercial level, but still its applications are restricted to laboratory level only. Larger pressing load, heavier dies, large experimental setup and labour intensiveness are the major hurdles before the commercialization of an ECAP process\(^4\).

It is observed that ECAP process efficiency and industrial feasibility is influenced by two process constraints, i.e., equivalent strain distribution\(^5\) and pressing force\(^6\). These constraints depend on six process parameters\(^7\)-\(^14\), i.e., die geometry\(^15\)-\(^16\), plunger velocity, repetitive ECAP passes, die billet interface friction and processing routes (Fig. 2).

This study is a step forward in selecting process parameters in order to get uniformly distributed average equivalent strain across the ECAPed billet with lower pressing force. In first step process parameters are numerically analysed on the basis of ECAP constraints. Best value of each process parameter is transferred to next set (Fig. 3), on the

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basis of best process parameters experimental ECAP dies are designed and tested.

Further, result validation and mechanical testing are performed. It is confirmed by the experimental results that yield strength and ultimate tensile strength of AA6061 aluminium alloy processed with best process parameters increased up to 49% after 4 repetitive ECAP passes at an average pressing load of 8 tonnes.

Finite element modelling

An industrial version of FE modelling software “FORGE2013” is used for FEM analysis. Five intersection angles (i.e., 90°, 105°, 120°, 135°, and 150°), four outer arc angles (ψ = 0°, 20°, 30°, 40°), three plunger velocities (i.e., 1 mm/s, 5 mm/s, 10 mm/s), two shear frictions (i.e., medium (m = 0.1) and high (m = 0.4)), four processing routes were numerically modelled and analysed in this work.

FEA predictions give useful information regarding pressing load and equivalent strain; these results will be used further for experimental setup and die designing.

Experimental Procedure

Billet fabrication for experimental analysis

Circular cross-section billets with 10 mm diameter and 100 mm length are used for analysis. Tolerance between plunger and ECAP channel kept very low to prevent material flow through the joint cavity. To avoid cup formation at top portion of the billet, top and bottom portion is grinded into a conical shape.

Experimental setup

Split ECAP dies are used for the experimentation. Since AA6061 is ductile in nature, all forming experiments are carried out at room temperature.

Plunger speed kept low (2 mm/s), to avoid heating up the material, which could lead to the grain growth. A computerized hydraulic press with a pressing capacity up to 100 tonnes is used for experimentation analysis. A 80 kg weight cast iron fixture is used for holding the vertically split ECAP die. This fixture had added...
extra strength to the ECAP die for hard material to processed. The fixture also facilitates the rapid engagement and disengagement of an ECAP die for multiple passes. All experiments are carried out at room temperature with or without molybdenum disulfide (MoS$_2$) lubricant.

Results and Discussion
Equivalent strain distribution along the length of billet based on intersection angle ($\Phi$) and repetitive passes

Equivalent strain distribution in ECAPed billet processed through different ECAP dies with intersection angle $90^\circ$, $105^\circ$, $120^\circ$, $135^\circ$, $150^\circ$ and constant outer arc angle ($\Psi$) = $0^\circ$ at medium shear friction coefficient ($m = 0.1$), 5 mm/s plunger velocity and ambient temperature is shown in Fig. 4, graphs revealed that for smaller intersection angle (i.e., $90^\circ$ and $105^\circ$) higher variation in equivalent strain distribution is achieved. With an increase in intersection angle $\Phi=120^\circ$, $135^\circ$ and $150^\circ$ variation in equivalent strain distribution reduces and strain gets more uniformly distributed along the length of the billet. Plots revealed that with repetitive ECAP pass better uniformity in equivalent strain distribution has been achieved for higher intersection angles (i.e., $\Phi=120^\circ$, $135^\circ$ and $150^\circ$) ECAP dies. FE results (Fig. 5) indicated that first two intersection angles ($\Phi = 90^\circ$, $105^\circ$) poses a non-uniform distribution of equivalent strain across the top middle and bottom sections. However, billet processed through dies with intersection angle $120^\circ$ or greater shows more
uniform distribution of equivalent strain throughout the cross-section.

Dead zone formation at the bottom surface of ECAP die is the main reason behind this non-uniformity in equivalent strain distribution. Larger strains get accumulated near the dead zone at the bottom segment of the billet and thus cause the uneven distribution of equivalent strain across the cross-section.

The dead zone formation is associated with an occurrence of corner gap at the junction of inlet and exit channel (Fig. 6). From FE results it can be observed that occurrences of this corner gap formation reduces with an increase in intersection angle (for \( \Phi > 105^\circ \)), thus leads to the uniform distribution of equivalent strain.

From FEM results it is evident that corner gap depends on outer arc angle (\( \Psi \)), with an increase in outer arc angle formation of corner gap reduces (Fig. 7). Billet processed with four outer arc angles (i.e., 0\(^\circ\), 10\(^\circ\), 20\(^\circ\) and 30\(^\circ\)) are presented; it can be observed because of large curvature at corner, billet can easily slide and chances of corner gap formation reduces. At outer arc angle \( \Psi = 30^\circ \) equivalent strain is more uniformly distributed across the cross-section of the billet at top middle and bottom layers.

**Experimental Procedure**

Average equivalent strain value for five intersection angles (i.e., \( \Phi = 90^\circ, 105^\circ, 120^\circ, 135^\circ, 150^\circ \)) at shear friction \( m = 0.1 \) and at three plunger velocities (i.e., 1, 5 and 10 mm/s) are given in Table 1.

**Variation of pressing force distribution along the length of billet based on intersection angle (\( \Phi \)) and repetitive ECAP passes**

The pressing force flow direction and variation at different intersection angle dies are shown in Figs 8 and 9, respectively. It is depicted that initially large pressing force is required as the plunger tries to push the billet towards a different channel. With continued pressing, shear deformation occurs as billet slides along the length of exit channel, and value of pressing force decreases continuously as the end of the process is reached. Nearly, same trend is observed for all the channel angles (Table 2). The numerical result of variations of pressing force for multiple ECAP passes are shown in (Fig. 10). It was observed that with repetitive ECAP passes peak pressing load increases because of strain hardening. During experimentation, contradictory results have

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**Table 1** — Average equivalent strain obtained for different intersection angles (i.e., \( \Phi = 90^\circ, 105^\circ, 120^\circ, 135^\circ, 150^\circ \)), at 3 plunger velocities and shear friction (\( m = 0.1 \))

<table>
<thead>
<tr>
<th>Angle(( \Phi ))</th>
<th>Ram velocity mm/s</th>
<th>I(^{st} )</th>
<th>II(^{nd} )</th>
<th>III(^{rd} )</th>
<th>IV(^{th} )</th>
</tr>
</thead>
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<tr>
<td>90°</td>
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<td>1.3</td>
<td>2.32</td>
<td>3.3</td>
<td>4.1</td>
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<td></td>
<td>5</td>
<td>1.4</td>
<td>2.5</td>
<td>3.4</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.42</td>
<td>2.6</td>
<td>3.52</td>
<td>4.34</td>
</tr>
<tr>
<td>105°</td>
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<td>1.85</td>
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<td></td>
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<td>10</td>
<td>0.98</td>
<td>2</td>
<td>3</td>
<td>3.78</td>
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<td>120°</td>
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<td>0.7</td>
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<tr>
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</table>
been observed. It was observed that with repetitive ECAP passes pressing load has decreased, it happened because pressing force required for extruding the material billet depends on billet length, with larger length more pressing load is required to extrude the billet, but with continued passes the length of billet has been decreased (because of material removal and flash generation) thus peak pressing load also reduced.

Effect of plunger velocity and die billet interface friction

Effect of friction on the deformation behaviour of the processed material is studied by many researchers\(^{17,18}\). Many of the reported results are contradicting. Yang et al.\(^ {19}\) have reported that strain is independent of friction. Domlin et al.\(^ {20}\) and Suo et al.\(^ {21}\) have reported that strain homogeneity increases with friction. Prangnellet et al.\(^ {22}\) has reported that strain concentration and inhomogeneous deformation increases with friction. In present work a shear friction \((m)\) model is adopted for FE analysis. FE results concluded that for medium die billet interface friction \((m = 0.1)\) at die angles \((\Phi = 90^\circ\) and \(\Psi = 0^\circ)\), after fourth ECAP pass, average equivalent strain obtained is 4.2 at pressing load of 8 tonnes. FEM iso-contours of the same combination also indicate the dead zone formation with the accumulation of strain at the bottom layer. Alloy processed with ECAP die with angles \((\Phi = 90^\circ\) and \(\Psi = 30^\circ)\) at die billet interface friction \((m = 0.1)\) gives approximately similar average equivalent strain \((\varepsilon = 4)\) at pressing load of 7.2 tonnes, but with this combination uniformity in equivalent strain distribution has considerably improved. FE results indicated that at higher plunger velocity \((v = 10 \text{ mm/s})\) slightly higher value of average equivalent strain is obtained, but experimentally plunger velocity \(v = 10 \text{ mm/s}\) is more prone to plunger and die failure. For safety and economic point of view 1-5 mm/s plunger velocity is preferable.

Effect of multiple passes

AA6061 billet is numerically simulated for 8 repetitive ECAP passes through ECAP die with \(\Phi = 90^\circ\) and \(\Psi = 30^\circ\) with processing route \((B_C)\) at medium shear friction coefficient \((m)\) and 1 mm/s plunger velocity. It is
observed that average equivalent strain induced in the billet increases with each pass until it reached to the saturation limit (for this case saturation point obtained at $7^{th}$ pass (strain =7.2). Further increase in ECAP passes after saturation point, results no further increase in equivalent strain rather gives incorrect hypothetical values. This phenomenon is also experimentally analysed with similar experimental conditions, experimentally it was noticed that billet after $4^{th}$ pass loses its strength and during $6^{th}$ ECAP pass it get fractured. It is apparent that FEM and experimental results are in agreement and both results show an excellent agreement with Hall-Petch relationship.

**Processing routes**

ECAP process has four basic routes (Fig. 11); these routes induced different slip system in the ECAPed billet. In route ‘A’, sample is processed between two consecutive passes without rotation. In route ‘$B_A$’ the sample is rotated $90^\circ$ in alternate directions between consecutive passes. In route ‘$B_C$’ the sample is rotated by $90^\circ$ in the same direction (clockwise or anticlockwise) between each passes. In route ‘$C$’ sample is rotated $180^\circ$ between the consecutive passes in the same direction. Numerically, no significant effect of pressing route have been observed, but microstructural and mechanical testing results indicate that processing route ‘$B_C$’ helps in getting equiaxed grain with high angle grain boundaries and also helps in retaining the ductility.

**Experimental results**

Commercially available AA6061 aluminum alloy is used for numerical and experimental analysis. Circular cross-section billets with 10 mm diameter and 100 mm length are used for analysis. Raw specimen billet has been grinded up to 0.5-1.0 mm in diameter to permit loose fit in the die channel. It facilitates billet to slide properly into the tightly closed ECAP die. Before placing the processed billet into die for next pass, processed billet needs to be finished properly and extra flash is removed by filing, as shown in (Fig. 12 (a)), removal of the flash is necessary because this flash gets inserted into the die’s joint cavities, and tightly sticks with the die and leads to plunger failure.

Extrusion process has been carried out using a tool steel plunger guided by a hydraulic press. Tolerance between plunger and ECAP channel kept very low to prevent material flow through the joint cavity and cup formation at top portion of the billet. To avoid cup formation at top portion of a billet, top and bottom portion of billet is grinded into a conical shape as shown in Fig. 12 (b).

**Mechanical testing**

The engineering stress-strain curves of AA6061 alloy before ECAP and after ECAP are presented (Fig. 13). Ductility and strength are measured by...
uniaxial tensile test. As illustrated in stress-strain curve, yield strength increases after two ECAP passes but ductility decreases. However, alloy processed with route (B_c) shows slight retention in ductility in comparison with route (A). There is no further reduction in ductility with addition ECAP passes but strength and ductility both increases. This satisfies the effect called “Paradox of Strength and Ductility in SPD processed material”. It is also observed that pressing route also helps in retaining ductility; route (B_c) shows greater retention of ductility than route (A).

Microstructural analysis

Scanning electron microscope is employed to study the microstructure produced in the processed billet. For microstructural analysis, a segment is cut from the processed billet and properly electro-polished.

Microstructural results of unprocessed billet before ECAP and ECAPed billet after 4 passes with route ‘B_c’ are presented in Fig. 14. Results showed that the
unprocessed billet (extruded rod) contains grain with size of 10 to 15 µm and after four passes with processing route ‘B_C’, the average grain size reduces to 0.4 to 0.5 µm.

**Hardness measurements**

In this work evolution of hardness measurement in AA6061 aluminium alloy after 4 repetitive ECAP passes with route B_C are presented. The Vickers microhardness (Hv) recorded at top, middle and bottom layers of processed billet along longitudinal direction (Fig. 16). In every traverse there was approximately 25 readings taken along 50 mm billet length for top, middle and bottom surface.

The dash line in each plot represents the microhardness of the unprocessed billet. The plot
indicate that hardness increases from an initial value 80 Hv to 135 Hv after four repetitive ECAP passes with processing route B_c, an increase of approximately 68% (Fig. 15).

Surface profile analysis

The surface finish of a processed billet is important not only for dimensional correctness, but also for other physical properties such as corrosion resistance and fatigue life. In present work, the surface roughness (R_a) was measured up to 3 mm length for the billet subjected to different ECAP pass and route (B_c). The surface profiles of unprocessed and processed billet are shown in Fig.17. Result indicates that with increase in ECAP passes surface roughness decreases.

Conclusions

In this paper ECAP process is modeled and analyzed for five intersection angles (Ψ), four outer arc angles (ψ), three plunger velocities, two shear frictions for producing ultra-fined grained materials. FE results obtained are experimentally validated.

Each process parameter is tested by making other process parameters constant and the optimal value at which better objective parameter are achieved, is transferred to next set of simulation (Fig.18). The research outcomes are summarized as follows:

Numerical and experimental analysis performed in this work indicates that for attempting ECAP on AA6061 aluminum alloy the best shortlisted parameters are: Ψ = 90°, ψ = 30°, plunger velocity (v) = 2 mm/s, friction = medium (m = 0.1), processing route = ‘B_c’ and number of passes is = 4. With these parameters the average equivalent strain induced in the billet is 4.2 at pressing load of 8 tonnes.

Tensile test results indicate that the yield strength and ultimate tensile strength of ECAPed AA6061 alloy has increased to 470 and 550 MPa respectively after 4th ECAP pass. It was an increase of 49%. It was also observed that processing route B_c shows better retention of ductility (15% elongation) as compared to route A (12.5% elongation) and with microstructural analysis, it was also observed that route ‘B_c’ shows the presence of equiaxed grain with high angle grain boundaries.

Micro-hardness measurements and surface profile analysis indicates that after 4 ECAP passes with processing route ‘B_c’ the hardness (Vickers hardness) is improved from initial value of 80 Hv to 135 Hv, and also smoothness in surface profile after 4th pass is considerably improved.

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