ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
A Peer Reviewed Open Access International Journal

Computational Analysis of Equal Channel Angular Pressing for Aluminum Alloys

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ABSTRACT:

Extrusion is a process used to create objects of a fixed cross-sectional profile. A material is pushed or drawn through a die of desired cross-section. The two main advantages of this process over other manufacturing processes are its ability to create very complex cross-sections and work materials that are brittle, because the material only encounters compressive and shear stresses. It also forms finished parts with an excellent surface finish. Severe Plastic Deformation (SPD) is an innovative process capable of producing uniform plastic deformation in a variety of materials, without causing significant change in geometric shape or cross section. SPD involves simple shear deformation that is achieved by passing the work piece through a die containing two channels of equal cross section that meet at a predetermined angle usually between 90° to 135°. Deformation occurs in the immediate vicinity of the plane lying at the intersection of two channels. The effective strain that is imposed on the work piece increases as the channel angle decreases. An important advantage of SPD process is that a large amount of strain can be imposed without any concomitant change in the cross section of the work piece. This process has ability to refine the grains in materials in bulk quantities. As the cross-section of the material is unaltered, the material can be processed over and over again to achieve very large strain. Multiple pressing of billet by SPD helps to achieve complex microstructures and textures by changing the orientation of the billet during successive pressings. In this project work, a die that executes both extrusion and severe plastic deformation simultaneously is designed, modeled and manufactured.

The indigenous design exploited the benefits extrusion with the properties of the severe plastic deformation. Increased production rate through extrusion and superior material properties by SPD simultaneously, is achieved with the newly built die. Modeling, design and manufacture of the die and to attempt the feasibility level experiments were done in the project work. Computational analysis will be performed using ECAP die having channel angle 90^0, 120^0 and 135^0 in FEA using Deform software and the results will be compared with the experimental results.

I. INTRODUCTION:

Materials processing by severe plastic deformation (SPD) have received vast focus in the research community the last five to ten years due to the unique physical and mechanical properties obtainable by SPD processing. The process of SPD is based on intense plastic deformation of a work piece, resulting in alteration of the microstructure and texture, in principal reduction of the grain size to the sub-micron or the nanometer scale. The most common process of SPD is the equal channel angular pressing (ECAP), which involves pressing a billet through a die consisting of two channels of equal cross sections, intersecting at an angle, typically 90°. The process of ECAP allows us to introduce very large plastic deformations to a work-piece without altering the overall geometry of the work-piece. In the present thesis, the ECAP process has been applied to a commercial 6xxx series aluminium alloy. The deformation characteristics have been investigated by direct strain measurements on ECAP'ed samples. Further, the mechanical properties have been investigated for a series if processing parameters and finally, a detailed study of the texture development and deformation mechanisms have been made.

In the present work, the main focus has been to gain a better understanding of the deformation mechanisms operating in the ECAP process, which leads to the observed intense grain refinement. In this process, a vast amount of EBSD measurements was carried out, including two processing routes (route A and Bc) and eight accumulated strain levels, corresponding to eight ECAP passes. Due to the enormous amount of collected data, it proved impossible to collect all results and observations in this thesis; therefore, the main focus was set on the early stages of grain subdivision, i.e. the first two ECAP passes by route A. However, some results obtained at higher strains, i.e. higher number of passes, are included, such as grain size and misorientation distributions. The most important results on the microstructural development at higher strains will be published in international journals after the submission of the present thesis.

In order to convert a coarse-grain solid into aultrafine grain material, it is necessary both to impose an exceptionally high strain in order to introduce a high density of dislocations and for these dislocations to subsequently re-arrange to form an array of grain boundaries. Conventional metal-working processes, such as extrusion or rolling, are restricted in their ability to produce UFG structures for two important reasons.There is a limitation on the overall strain that may be imparted using these processes because of the reduction in the cross-sectional dimensions of the work-piece.

1. The strains imposed in conventional processing are insufficient to introduce UFG structures because of the generally low workability of metallic alloys at ambient and relatively low temperatures.

In order to overcome the limitations of conventional processing techniques, severe plastic deformation techniques were developed. In severe plastic deformation (SPD), high strains are imparted to the material at relatively low temperatures without altering the cross-section of the work piece. Various SPD processes are in vogue today and some of them are listed below.

- Equal Channel Angular Pressing
- Cyclic Extrusion Compression
- Cyclic - closed die forging
- Torsion compression
- Torsion straining
- Multi-axial forging
- Accumulative roll bonding
- Asymmetric Rolling
- Constrained Groove Pressing

All these processes have been designed for particular applications and have different technical characteristics. Except equal channel angular pressing (ECAP) all other methods are restricted either by the amount of strain they can impart or by the size / quantity of material they can process / produce. Among the above mentioned processes, Equal-channel angular pressing is an attractive processing technique for several reasons listed below and has shown a great promise for commercialization as a process for producing fine grained materials in bulk quantities.

II. EQUAL CHANNEL ANGULAR PRESSING (ECAP)

The History of ECAP

Equal Channel Angular Pressing (ECAP) was invented by a Russian scientist Vladimir Segal in 1977 in the former Soviet Union for which he obtained an Invention Certificate of the USSR, similar to a patent. Researchers in the Texas A&M University's (TAMU) Deformation Processing Laboratory in the Department of Mechanical Engineering have been conducting research on the ECAE process since 1992.

Definition of ECAP

ECAP is an innovative process capable of producing uniform plastic deformation in a variety of materials, without causing significant change in geometric shape or cross section. ECAP involves simple shear deformation that is achieved by passing the work piece through a die containing two channels of equal cross section that meet at a predetermined angle usually between 90° to 135°. Of late, channels with acute angles have also been reported.

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International Journal & Magazine of Engineering, Technology, Management and Research
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Deformation occurs in the immediate vicinity of the plane lying at the intersection of two channels. The effective strain that is imposed on the work piece increases as the channel angle decreases. An important advantage of ECAP process is that a large amount of strain can be imposed without any concomitant change in the cross section of the work piece. This process has ability to refine the grains in materials in bulk quantities. As the cross-section of the material is unaltered, the material can be processed over and over again to achieve very large strain. Multiple pressing of billet by ECAP helps to achieve complex microstructures and textures by changing the orientation of the billet during successive pressings.

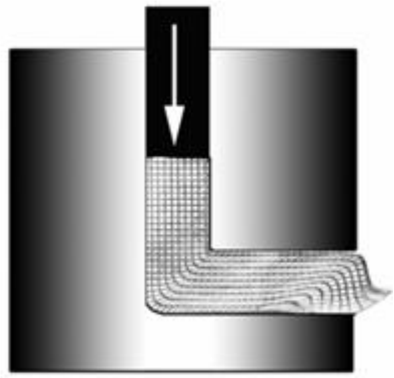

Fig 1: ECAP Die

Square and round cross-section channels have been reported in literature. Channel with a square cross-section is advantageous while carrying out multiple pressings. The orientation of the shear plane can easily be changed by rotating the billet during subsequent pressings. Based on this simple fact, four processing routes (A, B_A, B_C, and C) have evolved. Each processing route is defined by the combination of shear planes that undergo deformation during pressing. The distinction between these routes are important because they introduce different shearing patterns into the sample leading to variations in both macroscopic distortions of the individual grains in the polycrystalline matrices and to develop a reasonably homogenous, equiaxed ultra fine grained microstructure.

ECAP Processing Routes

The four processing routes have been identified are listed below and their schematic representation is provided in Fig.2

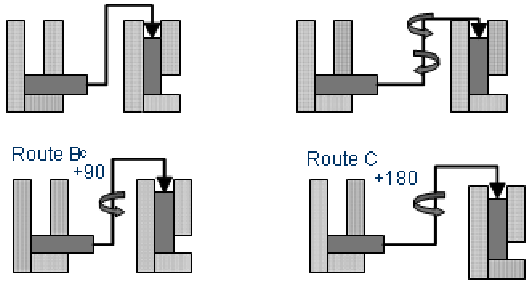

Fig 2: Processing Routes in ECAP

Route A: The sample is pressed repetitively without any rotation between successive pass.

Route B_A: The sample is rotated through 90° in the alternate directions between successive pass.

Route B_C: The sample is rotated by 90° in the same sense between each successive pass

Route C: The sample is rotated by 180° between successive pass.

The Strain Imposed during ECAP

The strain is estimated by assuming a fully-lubricated specimen so that any frictional effects may be neglected. Several conclusions may be reached from the above equation. The angle at the arc of curvature, Ψ, has a relatively minor effect on the equivalent strain except only for channel angles less than 90°. Exceptionally high strains may be achieved in a single pass by constructing a die with very low values of φ and Ψ. For conventional dies where the channel angle is generally equal to 90°, the equivalent strain is close to $\sim$1 for a single pass and this strain is essentially independent of the angle representing the arc of curvature, Ψ.

The Processing Routes in ECAP

As noted briefly, there are four basic processing routes (Route # A, B_A, B_C and C) in ECAP and these routes introduce different slip systems during the pressing operation so that they lead to significant differences in the microstructures produced by ECAP. The four different processing routes are summarized schematically in Fig.2. Various combinations of these routes are also possible, such as combining routes B_C and C by alternating rotations through 90° and 180° after every pass, but in practice the experimental evidence obtained to date suggests that these more complex combinations lead to no additional improvement in the mechanical properties of the as-pressed materials. Accordingly, for the simple processing of bars or rods, attention is generally devoted exclusively to the four processing routes.

Influence of Pressing Speed and Temperature

Processing by ECAP is usually conducted using hydraulic presses that operate with relatively high ram speeds. Typically, the pressing speeds are in the range of $\sim$1–20 mm s^{-1}. Nevertheless, it is feasible to construct dies for use in conventional mechanical testing machines and this provides the capability of extending the pressing speeds over a very wide range. The pressing speed has no significant influence on the equilibrium size of the ultrafine grains formed by ECAP but, since recovery occurs more easily when pressing at the slower speeds, these lower speeds produce more equilibrated grains.

Influence of Back Pressure

In an ECAP process when the material extrudes out of the deformation zone and enters the exit channel some amount of pressure can be applied to the work piece in the exit channel thereby increasing the resistance to material movement. An important advantage in imposing a pressure called back-pressure is that it leads to a considerable improvement in the workability of the processed samples since it alters the state-of-stress in the main deformation zone. In the absence of a back-pressure it is generally found that cracks appear on the billet surface after about 12–13 passes. A sample of a quenched aluminum failed in the first pass during ECAP at room temperature in the absence of a back-pressure but during pressing with a back-pressure, the sample was processed up to 4 passes without any cracking.

Another important advantage of back-pressure is the visible enhancement introduced in the uniformity of the metal flow during the ECAP operation.

Strength Improvements in ECAP

In grain-boundary strengthening, the grain boundaries act as obstacles to the motion of dislocations. Since the lattice structure of adjacent grains differs in orientation, it requires more energy for a dislocation to change directions and move into the adjacent grain. The grain boundary is also much more disordered than inside the grain, which also prevents the dislocations from moving in a continuous slip plane. Impeding this dislocation movement will hinder the onset of plasticity and hence increase the yield strength of the material.

Effect of ECAP on Structure and Property

With the ECAP process, material can be deformed to very high strains without any significant changes in cross-sectional area, resulting in various combinations of microstructure, texture and mechanical properties. Very high strains can easily be imparted to the starting material by repeated passes of the billet through the die. In addition, by changing the orientation of the billet from one pass to another, different processing route effectively changes the strain path to which the material is subjected during deformation In practice, experiments have demonstrated that the micro structural characteristics introduced by ECAP (including the structural homogeneity, the average shapes of the individual grains, and the disorientation angles of the boundaries between adjacent grains) are dependent up on experimental conditions such as

- The numbers of passes through the die
- Shearing directions in each separate passage as manifested by a rotation of the sample between separate pressings and
- Temperature

Advantages of ECAP

The equal channel angular pressing is a unique industrial process for the following reasons.

- Uniform structure and properties are developed throughout the worked materials.
- A large equivalent deformation per pass and an extremely large total effective deformation after multiple passing occur without any appreciable change of the initial billet cross-section.
- Relatively low pressures and loads are sufficient for pressing.
- The creation of special structures and textures are possible because of strict control over the direction of shear, the homogenous stress-strain state, the capacity for extremely large deformations in massive products and the opportunity to modify the shear plane and direction during a multiple extrusion sequence.

Disadvantages of ECAP

- ECAP is a batch process i.e., limited by the length of the material it can handle.
- Designing a die suitable to process a variety of engineering materials has been identified as a major bottle neck in commercialization of the process.

ECAP Tool Design

ECAP dies are the most complex tooling to design. The complexity arises as the channel is to be machined which is usually at an angle varying from 90°-150°. It is difficult to fabricate the required angle and also the corner angle in a single piece of die. Single piece die is always ideal and easy to handle in the press facility but is practically difficult to fabricate from the machining point of view. Often split dies are used, which enable an increased flexibility in providing required design features in same die-set.

Die Design

One of the most important factors for the design of extrusion dies is the selection of adequate channel, corner angle and fillet radii. Channel angle for the die set were chosen as 90°, 105°, 120° with a corner angle was of 30°. The corner angle was decided based on literature survey carried out. Based on the above factors, three dies were designed, the design parameters are

Channel angle/Corner angle/parting plane

- 90°, 30°,varying parting plane
- 120°, 30°,same parting plane
- 105°, 30°,same parting plan

Project Methodology

The work material is selected as aluminum AA6351 and the corresponding cross section to be extruded with severe plastic deformation properties is considered as circular cross section. The die was designed for a 40 ton hydraulic press, based on the load it has to withstand and for the decided extrusion ratio. The SPD properties are decided based on the die angle as the strain rates depends on the die angle. More acute the die angle, superior are the mechanical properties and more obtuse the die angle less will be the extrusion load required. To balance between the expected superior mechanical properties produced by high strain rates caused by the die angle and the extrusion load required to create the strain rates, 135^0 120^0 and 90^0 angles were decided. The die is modeled in solid works software and analyzed in COSMOS. The computed displacement, von misses stress and strains were recorded. The procedure adopted for the dies with different die angles and the comparison of the results obtained are presented.

III. SELECTION OF THE MATERIAL FOR THE WORKPIECE

AA6351 Aluminum Alloy

Aluminum in general (and extruded aluminum profiles in particular) offers a number of advantages over other materials (and other forming processes). Other materials may offer some of the beneficial characteristics of aluminum profiles, but aluminum can offer a complete range of benefits at once. Aluminum extrusion is a versatile metal-forming process that enables designers, engineers, and manufacturers to take full advantage of a wide array of physical characteristics: Light weight, Strong, Exhibits High Strength-to-Weight Ratio, Resists Corrosion, Excellent Thermal Conductor, Conducts Electricity, Non-magnetic, Resilient, Reflective, Suited to Extreme

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Cold, Recyclable, Accepts a Variety of Common Finishes, Seamless, Can be Joined in Many Ways, Economical.

Applications

There are three basic categories of applications for aluminum extrusion:

Building and Construction: a wide range of products from residential windows to high-rise curtain wall Transportation: covers numerous component parts in the automotive, truck, rail, aerospace, and marine sectors Engineered Products: includes all other products from consumer goods (air conditioners) to electrical items (power units) to machinery and equipment (irrigation pipes) to food display and refrigeration.

Table.1 Chemical composition of the experimental AA6351Aluminium alloy

Composition	Si	Fe	Cu	Mn	Mg	Zn	Cr	Al
Standard	0.07–.3	0.5	1.2– 2.0	0.4 - 0.8	2.1– 2.9	5.1– 6.1	0.18–28	Remaining
Experimental	0.93	0.47	1.5	0.61	2.62	5.42	0.19	Remaining

Table.2 Mechanical Properties of the experimental AA6351Aluminium alloy

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Elongation (mm)	Hardness (BHN)	Shear Strength (MPa)	Fatigue Strength (MPa)
AA6351	380	150	20	150	330	160

Table.3 Physical Properties of the experimental AA6351Aluminium alloy

Density	Melting Point	Modulus of Elasticity	Electrical Receptivity	Thermal Conductivity	Thermal Expansion
2.81 g/cm^3	555°C	70 GPa	0.038 ×10^{-6}Ωm	172 W/mK	46 ×10-6 /K

SELECTION OF THE MATERIAL FOR THE DIE

H13 DIE STEEL

Properties of H13 die steel

Table.4: Chemical composition of H13

Elements	C	Mn	Mo	Si	Ni	Cr	V	Fe
% by weight	0.32 – 0.45	0.20 – 0.50	1.1 – 1.75	0.8 – 1.2	0.3 Max	4.75 – 5.5	0.8 – 1.2	Remaining

Table.5: Physical Properties of H13 Die Steel

Density (kg/m^3)	Melting Point, deg C	Modulus of Elasticity, GPa	Poisson's Ratio
7850	2600	200	0.27 – 0.3

Table.6: Mechanical Properties of H13 Die Steel

Yield Stress, MPa	Allowable Shear Strength, MPa
415	250

Table.7: Thermal Properties of H13 Die Steel

Thermal Conductivity, W/mK	Thermal Capacity, J/KgK
24.3	460

DIE Design Calculations

During pressing the axial stress on the sample is being translated to pressure exerted on the inner surface of the inlet channel .The maximum pressing load is taken to be around 700 tons

$$\sigma = \frac{F}{A},$$

Where σ is the stress acting of the components

A is the sample cross section area,

F is the force applied due to the application ofpressing load of plunger

1 ton force = 9.96 KN

700 Ton force = 6974 KN

Design calculations of solid die:

$$\sigma = \frac{F}{A},$$

Where σ is the stress acting of the die component

A is the die cross section area,

F is the force applied due to the application of pressing load of plunger

A= Upper surface of the die

= (250×250) = 62500 mm^2

$$\sigma = \frac{F}{A} = \frac{6974 \times 1000}{62500}$$

ISSN No: 2348-4845
International Journal & Magazine of Engineering, Technology, Management and Research
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$= 111.584\ N/mm^2$

$\tau = \frac{F}{A}$,

where τ is the shear stress of the die component

A is shear area

A = (shear area of the die)-(total channel area)

$= (250\times350)-(25\times387.5)$

$= 77812.5\ mm^2$

$\sigma = \frac{F}{A} = \frac{6974\times1000}{77812.5}\ N/mm^2$

$= 89.625\ N/mm^2$

The tensile strength(yield) of the die material H13 is 1650 MPa.

The stress developed on the upper surface of die is calculated to be around 111.584 N/mm^2, hence the die is considered to be safe.

The shear stress developed on the die is calculated to be 89.625.

The shear strength of the die material H13 is 990 MPa.

Hence the die components are safe in compression as well as in shear.

The dimensions of the die can be considered as 250mm×250mm×350mm.

Design calculations of split die:

$\tau = \frac{F}{A}$,

where τ is the shear stress acting of the die component

A is the die cross section area,

F is the force applied due to the application ofpressing load of plunger

A = (shear area of the die)-(total channel area)-(total area removed for all bolts)

$A= (250\times350)-(25\times387.5)-(5\times\frac{\pi}{4}\times d^2)$

$= (250\times350)-(25\times387.5)-(5\times\frac{\pi}{4}\times 25^2)$

$=75358.13\ mm^2$

$\tau = \frac{F}{A} = \frac{6974\times1000}{75358.13}\ N/mm^2$

$= 92.544\ N/mm^2$

The shear stress developed on die is calculated to be 95.544N/mm^2

The shear strength of the die material H13 is 990 MPa.

Hence the split die components are safe in shear.

The final dimensions can be taken as 250mm×250mm×350mm

Design of bolts:

Shear stress across the threads:

The average thread shearing stress for the bolt (τ_s) is obtained by using the relation:

$\tau_s = (\frac{F}{\pi d\times l})/5$

d = diameter of bolt = 25mm

l = length of bolt = 325 mm

$\tau_s = (\frac{6974\times1000}{\pi\times25\times325})/5 = 54.64$ Mpa

The shear stress developed on each bolt is 54.64 Mpa

The shear stress of bolts made of mild steel is given by

Hence the bolts can be taken as safe.

The die is modeled in solidworks software and the set up is shown in figure 8

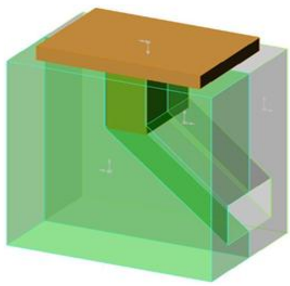
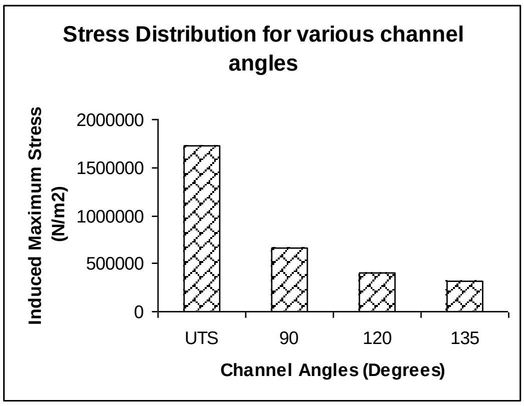


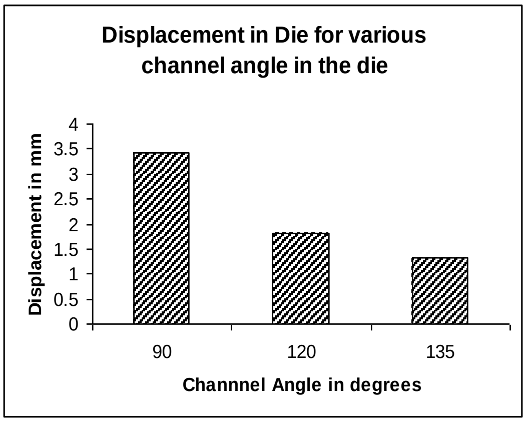
Figure 3: die is modeled in solid works software

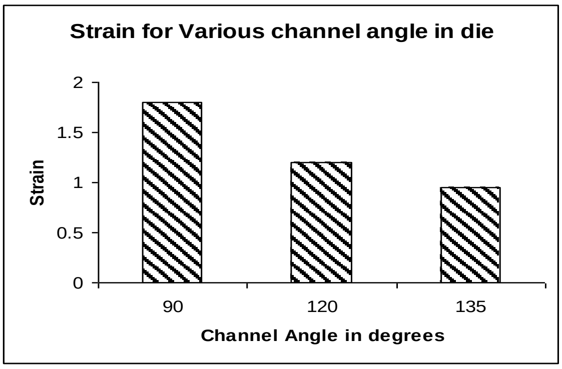
IV. COMPUTATIONAL ANALYSIS

The von-mises-stress, strain and displacement of the ECAP die for superplastic forming the AA6351 billet material is shown in the figures below. As per the results, the die with 135^0 degree channel angle undergoes less displacement and stress as compared to the other dies. The results show better stress, strain and displacement levels all within the safe limits much below the yield points. The extruded part is expected to have excellent mechanical properties in all directions due to high strain rate achieved in the severe plastic deformation zones in the initial and final stages. The product manufactured through this die is predicted to have superior mechanical and metallurgical properties compared to a conventionally extruded part due to the high strain rates produced during processing the material in the die for simultaneous operations, with the same extrusion force.

Channel Angle (Degrees)	90	120	135
Displacement (mm)	3.42	1.814	1.384
Maximum Induced Stress (N/m^2)	663045	398761	312677
Yield Strength (N/m^2)	1723390	1723390	1723390
Strain (No Unit)	1.8	1.195	0.95







V. SIMULATION STUDIES USING DEFORM SOFTWARE

Material:

The material selected for the present study is cast aluminum and commercial pure aluminum. Cylindrical rods were made out of cast aluminum and commercial pure aluminum.

Work piece with dimensions:

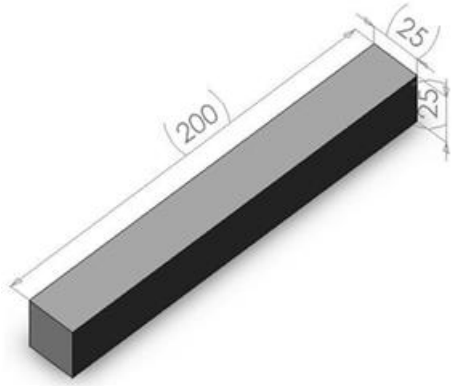


Fig 4:Work piece with dimensions

Die with dimensions(2D)

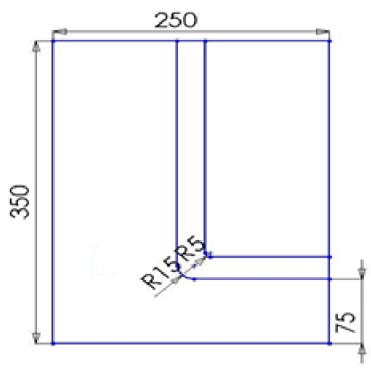


Fig 5: Die with channel angle of90^0

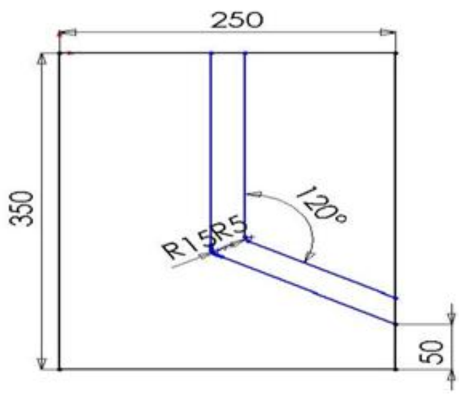


Fig 6: Die with channel angle of120^0

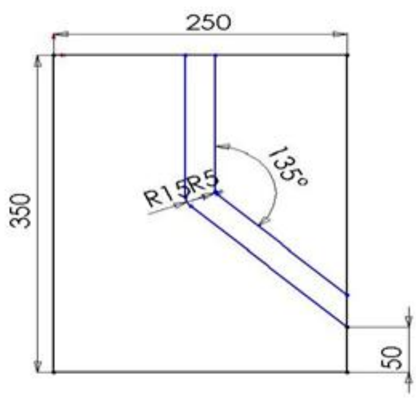


Fig 7: Die with channel angle of 135^0

Experimental Unit:
The complete ECAE Experimental setup is shown in figure.

The setup consists of following Parts:

- Mechanical press of 700 ton capacity
- Die
- Plunger
- Bolts and nuts(for split die)

5.5 Specifications of die and sample:
Die:

Material – H13 die steel

Dimensions – 250mm×250mm×350mm

Die: Solid and Split

Angle between the channels: 90^0, 120^0 and 135^0

Angle of curvature: 25^0

Inner fillet radius of channel in the die = 5 mm

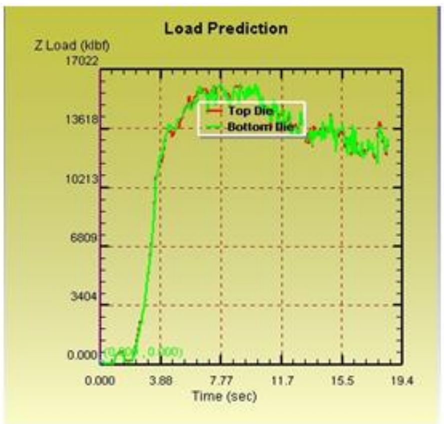
Outer fillet radius of channel in the die = 15 mm

Work piece:

Material - Aluminium

Cross-section of channel = 25mm×25 mm

VARIATION OF EFFECTIVE STRAIN FOR SOLID AND SPLIT AND MICRSTRUCTURAL DEVELOPMENT



(a)

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International Journal & Magazine of Engineering, Technology, Management and Research
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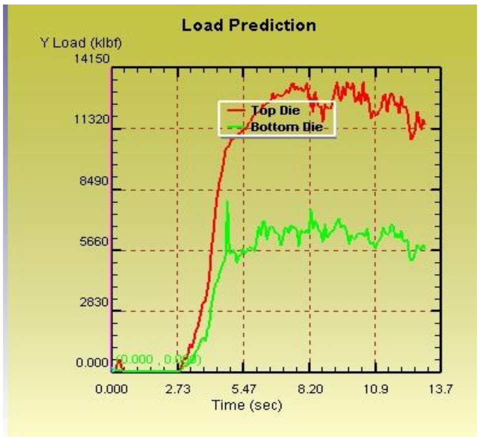
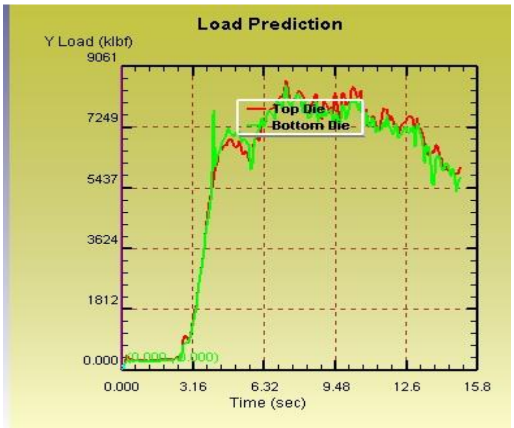


(b)

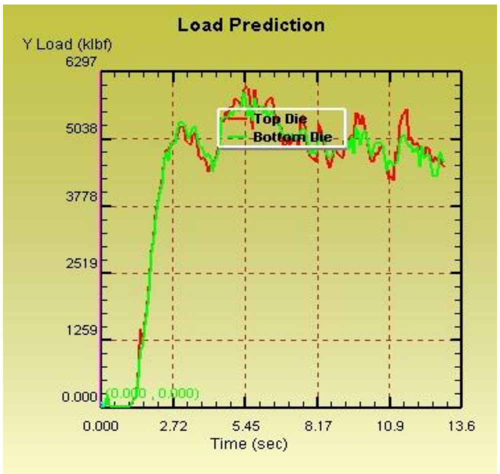
Fig 8: Load prediction on plunger and bottom die of solid(a) and split(b) for 90^0



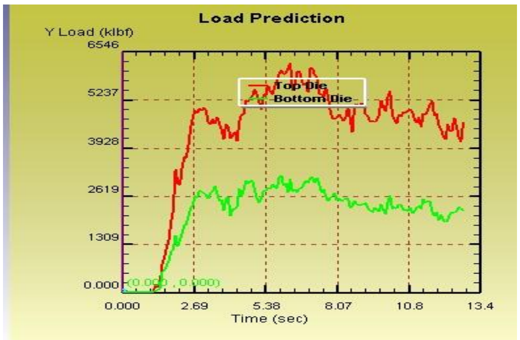
(a)

(b)

Fig 9: Load prediction on top die and bottom die of solid(a) and split(b) for 120^0



(a)



(b)

Fig 10: Load prediction on plunger and bottom die of solid(a) and split(b) for 135^0

VI. CONCLUSION

Dimensional and Structural changes in materials subjected to SPD and their effect on properties have been improved by the ECAP die. Structural integrity of the severe plastically deformed product subjected to dimensional changes is achievable in this die. The designed die is modeled and analyzed in COSMOS and the vonmises stresses, strain and displacement of the die are recorded.The die with more channel angle is less vulnerable towards displacement, stress and strain as per the computational analysis conducted. Effect of different channel angles on Aluminum, Estimation of effective strain, effective strain rate for aluminum on passing through different channel angles, Estimation of maximum principal stress and effective stress on the die components(solid and split) with different channel angles.Variation of load on top die and bottom die is plotted on graphs.

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