IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 4 Issue 3, March 2017
ISSN (Online) 2348 – 7968 | Impact Factor (2016) – 5.264
www.ijiset.com

A Study on Effect of Ultrafine Grain Refinement on Mechanical Properties of Non-Heat Treatable Alloys

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Abstract

Among the procedure devised for grain refinement, severe plastic deformation is of particularly interest and the focus of this study. This project work deals with the concept of ECAP used to introduce severe plastic deformation in non-heat treatable alloy. In this work, the non-heat treatable alloy selected is aluminium low alloy 1100 for the study. Detailed FEM analysis has been done using commercial software DEFORM 3D™ for single ECAP pass. Deep literature survey has done to understand correct method to do analysis of the billet using FEM. Results has calculated and collected for different die geometries i.e. die corner angle and die channel angle. Effect of die geometry on strain distribution and strain homogeneity has studied. Also the parameters are compared for in homogeneity index and corner gap introduced during ECAP process. Die has been manufactured using optimum die geometry combination to get better strain homogeneity as well as strain distribution through the billet material. Detail manufacturing process has discussed. Also the difficulties occurs during the experimentation has been explained.

Keywords: *Die geometry, ECAP, FEM, Non-heat treatable alloy, Strain homogeneity.*

1. Introduction

Grain size can be regarded as key micro structural factor affecting all aspects of the physical and mechanical behavior of poly crystalline metals as well as their biochemical and chemical response to the surrounding media. Hence, control on grain size is the effective way to design materials with desired properties. Most of the mentioned properties benefit greatly from grain size reduction. A possible avenue for microstructure refinement of metals is the use of severe plastic deformation (SPD) a principle that is as old as metalworking itself. 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. The general principle for the method is shown in Figure 1. The tool is a block with two intersecting channels of identical cross-section. A well lubricated billet of the same cross-section is placed into one of the channels, and a punch then presses it into the second channel. Under these conditions the billet will move as a rigid body, and deformation is achieved ideally by simple shear in a thin layer at the crossing plane of the channels. When the punch is finished it is retreated and the billet has been uniformly deformed, except for a small zone in the lower part of the sample and in the end regions.

The die geometry is defined by the cross section area and the two angles Φ and Ψ, the angle of intersection between the two channels, and the arc of curvature at the outer point of intersection respectively. It is possible to calculate, from the two angles, the shear strain or the effective von Misses strain resulting from pressing through the die. The advantage with the ECAP method is that it is possible to introduce severe plastic deformation (SPD) by repeated pressing of the billet without any significant change in the cross section. Altering the billet orientation after each press, thereby modifying the shear plane and shear direction, makes it possible to control the microstructure and texture of the material, thus, altering the mechanical properties.

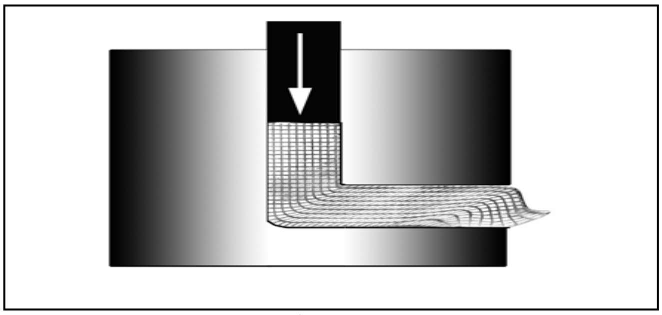

Fig.1. Sketch of ECA pressing [11]

The aim of project is to study ECAP process, improvement in properties of non-heat treatable alloys, simulation, determination of optimum die geometry for ECAP, and validate the results experimentally.

2. Literature Survey

Estrin et al [5]. presented their take on the area of bulk ultrafine-grained materials produced by severe plastic deformation (SPD). A brief overview of the available SPD technologies is given, along with a summary of unusual mechanical, physical and other properties achievable by SPD processing.

Huang et al [6].Their review addresses new developments in the processing and properties of ultrafine-grained (UFG) materials. These materials are produced through the application of SPD to conventional coarse-grained metals and typically they have grain sizes within the sub-micrometer or even the nanometer range. The review concentrates on the major procedures of equal-channel angular pressing and high-pressure torsion. It is shown that UFG materials exhibit both excellent strength at ambient temperature and, if the grains are reasonably stable, outstanding superplastic properties at elevated temperatures.

Han et al [7]. They investigated deformation behavior within the deformation zone of a work-piece during equal channel angular pressing (ECAP) using the finite element method. The effects of die geometry on the variations of normal and shear deformations were studied with a deformation rate tensor. The zero dilatation line, at which the normal components of the deformation rate tensor are zero, in the die coincided with the line of intersection of the two die channels irrespective of die geometry such as curvature angle (ψ) and oblique angle (ϕ), while the maximum shear line, at which the shear components of the deformation rate tensor have maximum value, is dependent on the die geometry.

Moradi1 et al [9].Explained severe plastic deformation (SPD) by equal channel angular pressing (ECAP) has been used as a reliable method to achieve an ultra-fine and homogenous microstructure in the bulk materials. In their research, study was conducted on the structures and mechanical properties of A356 (7%Si) Al alloy produced by severe plastic deformation through ECAP. The results show near 114% improvement of the ultimate tensile strength (UTS) and 166% elongation from the as-cast structure.

Lua et al [12]. Studied influence of channel angle on deformation behavior and strain homogeneity of aluminum alloys HS6061-T6 during ECAP by conducting finite element simulations for a range of channel angles $50\sim150^0$ by COSMOS, along with the consideration of strain hardening of material and friction. The deformation behavior is more complicated and taking place in three stages with channel angles $\Phi < 110^0$. It is smooth and taking place in two stages with $\Phi \geq 110^0$. Comparatively thin and adequate length of plastic zone at the die diagonals is observable with $\Phi=110^0$ and 130^0 by indicating the possibility of strain homogeneity. Effective strain contours across the width at the center of the sample show that strain homogeneity is greater with $\Phi = 110^0$ compared to all other channel angles. The effective plastic strain index of inhomogeneity decreased with the number of ECAP passes. From the experimental and FEM results, $\Phi = 110^0$ and 130^0 was found to give higher homogeneity than $\Phi=70^0$ and 90^0 The 3D FEM simulation can be successfully used to find the variations of strain with the number of passes, processing route, and Cu content in HS6061-T6 alloys.

3. Research Gap

From the literature review it is seen that most studies on ECAP process had focus on the experimental validation of the process, however very less research done on the optimization study of the die geometry such as curvature angle (Ψ) and oblique angle (Φ).

4. Specification of the problem

From the above research gap we clearly saw there is very less work done on the optimization study of the die geometry such as curvature angle (Ψ) and oblique angle (Φ) using FEA and its validation by manufacturing the die and comparing its results using comparison study of grain refinement.

5. Objectives

a) Study the existing system ECAP
b) Selection of billet material.
c) Choose optimum die geometry by carrying out computer analysis using FEA packages
d) procurement of material and Manufacturing of die.
e) Carrying out ECAP & validate the results experimentally.

6. Estimation Of The Strain In ECAP

The shear strain γ for simple shear is defined as in Figure 2, γ = a/h. Simple shear involves a shape change produced by displacement along a single set of parallel planes. The shear strain introduced by the ECAP will first be derived for the case of simple shear, assuming a square cut die and neglecting the friction effects. Figure 3 shows a cubic element abcd along the centre line in the ECAP die. The die is defined by the angles Φ and ψ. If we follow the element through the die, we will end up with the orthogonal element a'b'c'd', deformed by shear during the passage through the die. Following the notation in Figure 3.3, it follows that the shear strain γ is given by,

$$\gamma = \frac{a'u}{d'u} = \frac{rc' + as}{ad}$$

$$= \frac{\Psi.ad.cosec\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right) + ad.\cot\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right) + ad.\cot\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right)}{ad} \quad (1)$$

This reduced to,

$$\gamma = \Psi\,\mathrm{cosec}\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right) + 2cot\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right) \quad (2)$$

Fig. 2. Schematic drawings of a deforming element moving through the ECAP die [8]

Also, the magnitude of equivalent effective plastic strain (ε_{eq}) after N passes is given by the following relationship,

$$\text{at } \varepsilon_{eq} = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\Phi+\Psi}{2}\right) + \Psi cosec\left(\frac{\Phi+\Psi}{2}\right)\right]$$

(3)

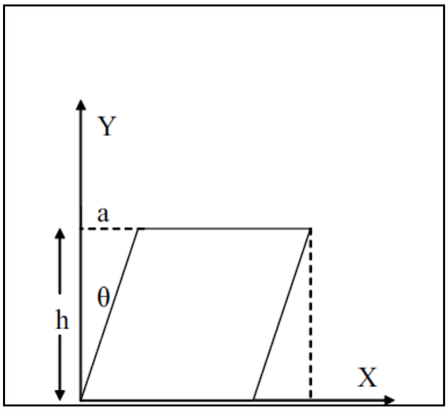

Fig. 2. Deformed rectangle element [8]

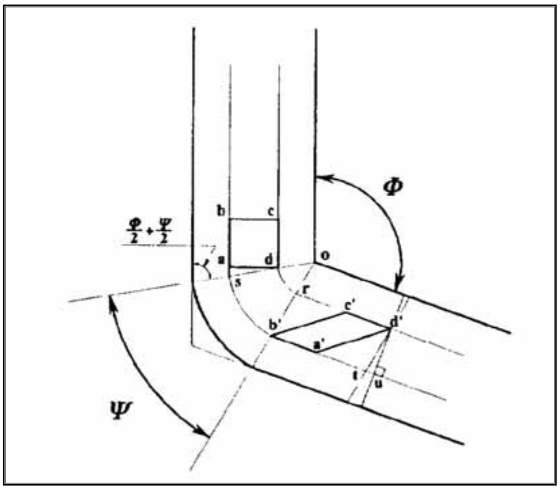

Fig. 3. Schematic drawings of a deforming element moving through the ECAP die [8]

7.Aluminium Alloys And Selection Of Billet Material

A. Non Heat Treatable Alloys-

Non-heat treatable aluminium alloys constitute a class of alloys that owe their strength mainly to elements in solid solution, but also to some types of particles. A heat-treatment of such an alloy will generally not produce any strengthening precipitates as in the heat treatable alloys (an exception is the dispersoids formed in Al-Mn alloys). The strength may in fact decrease during heat treatment due to the removal of solute atoms. The alloy systems belonging to this class are the AA1xxx system (commercially pure with small amounts of mainly Fe and Si), the AA3xxx system (as AA1xxx with manganese and magnesium additions), the AA5xxx system (as AA1xxx with magnesium addition) and the AA8xxx system (as AA1xxx, but with higher alloy additions).

The strength of these alloys depends strongly on the content of alloying elements. In Figure4.1, the ultimate tensile strength of a number of commercial non-heat treatable alloys are shown as a function of the amount of alloying elements. An interesting observation is that the tensile strength is approximately linearly dependent on the total alloying addition in wt. %, irrespective of element type. It is here distinguished between the O-temper, i.e. annealed condition, and the H18/H38 condition, i.e. cold rolled or cold rolled and stabilized of the same alloys. These curves indicate a large work hardening potential in

ISSN (Online) 2348 – 7968 | Impact Factor (2016) – 5.264
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these alloys. The dotted and the full lines illustrate the difference between the alloys where solution hardening is most important (AA5xxx) and where the particle hardening dominates (AA1xxx, AA8xxx). In the AA3xxx alloys the strength results from both Mn and Mg in solid solution and particles/dispersoids.

B. Material selected for billet

1100 aluminium alloy is an aluminium-based alloy in the "commercially pure" wrought family (1000 or 1xxx series). With a minimum of 99.0% aluminum, it is the most heavily alloyed of the 1000 series. It is also the mechanically strongest alloy in the series, and is the only 1000-series alloy commonly used in rivets. At the same time, it keeps the benefits of being relatively lightly alloyed (compared to other series), such as high electrical conductivity, corrosion resistance, and workability. It can be strengthened by cold working, but not by heat treatment.
Aluminum 1100 alloy is widely used in fin stock, heat exchanger fins, spun hollowware, dials and name plates, decorative parts, giftware, cooking utensils, rivets and reflectors, and in sheet metal work.

C. Geometric Modeling And Simulation

1.Die

Die is modeled using part design in CATIA. The die is modeled into two symmetric parts as shown in Figure 4. At the time analysis the inner surfaces of die kept as bonded.

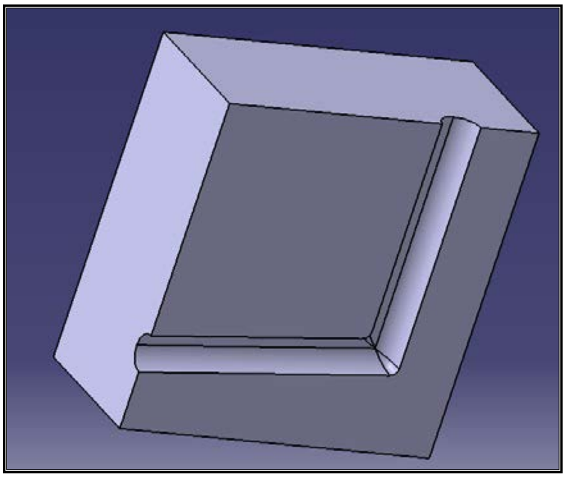
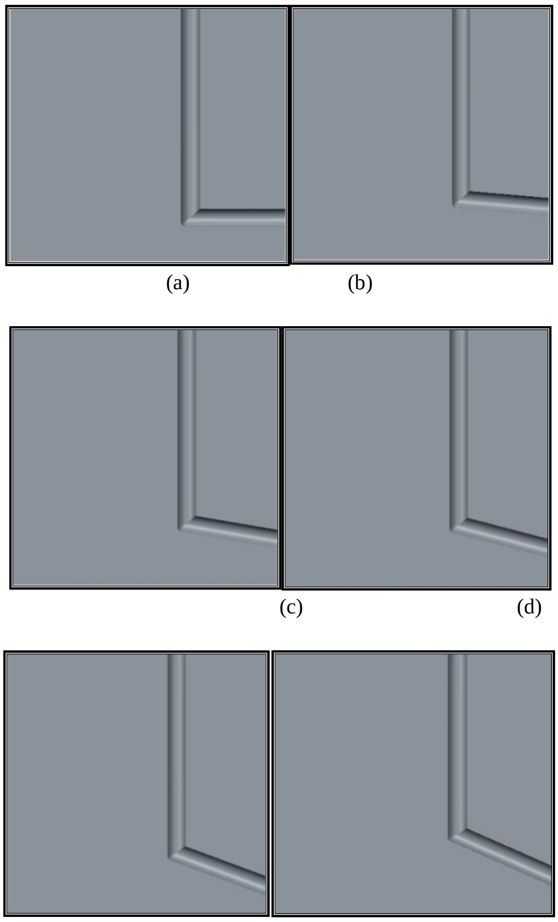


Fig. 4. Solid model of Die

Modeling has done for constant angle $\psi = 15^0$ and for Φ with increment of 5^0 starting from $90^0$to 120^0 as shown in Figure 5. To make the file suitable to import to the Finite element analysis software, model was saved with extension .part, .igs, .stp.



(a) (b)

(c) (d)

(e) (f)

Fig. 5. Solid model of die with different channel angle (a)90º (b)95º (c)105º (d)110º (e)115º (f)120º

2. Billet

Billet was also modeled in module part design in CATIA with the specified dimensions, and saved with extension .part, .igs, .stp. The model is shown in Figure 6.
Billet dimensions Diameter = 9.8 mm, Length = 100 mm.

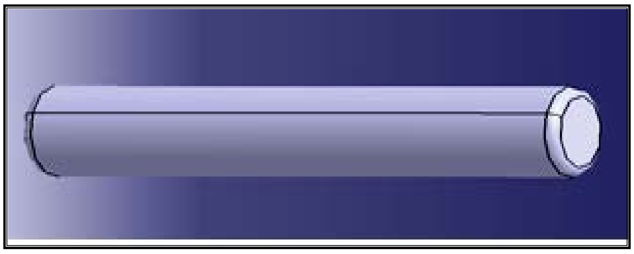


Fig.6. Billet modeled in CATIA

Simulation using DEFORM3D™

For choosing the optimum die dimension as well to find out the stress developed in the billet during the process, the amount of force require to press the billet through the die channels for number of channel angles, simulation has done in commercial FEM software DEFORM3D^{TM}-F23. Results were collected for die channel angle starting from 90º with the increment of 5º. We were more focused on billet, therefore only billet is kept as plastic .The die and punch were kept as rigid. The value of 2 mm/s was assigned to the ram speed. The optimum mesh element numbers were chosen as 20,000 and automatic re-meshing was used to accommodate large deformation in analyses. The value of 0.12 was selected as a friction coefficient and all analyses were performed at the ambient temperature.

DEFORM3D^{TM} has three steps- Pre, Simulate, Post. Pre stage is initial stage before running simulation, model is created into the Pre module. Generated database file is used in simulate module. 'Run simulation' command starts doing simulation. Results obtained from simulation were displayed in post module. These results has used for further calculations

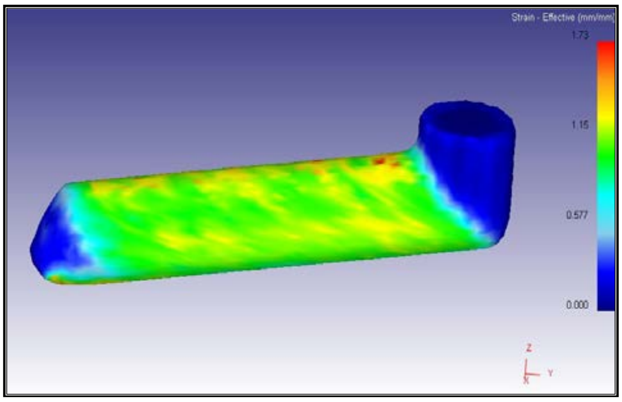


Fig.7. Billet after simulation

Figure 7. shows deformed billet and the values of effective strain developed in 100º die channel angle.

Figure 8. shows the effective stress disribution in the ECAPed bilet for 100º die channel angle. It can be observed that the max stress area lies near to the intersecting line of channels and at the contact area of billet and plunger.

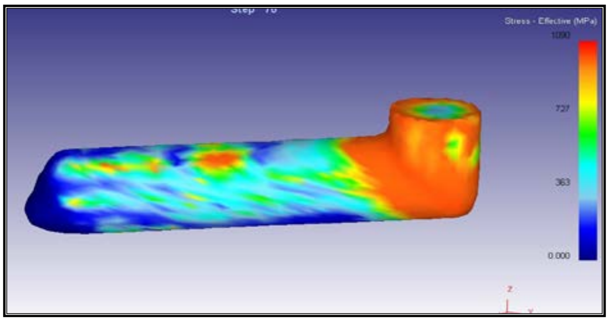


Fig.8. Stress variation in billet

One of the objectives of simulation is to find out the ramming force. We can directly plot graph of time v/s load in z direction which gives value of load at every point of displacement of plunger through die.

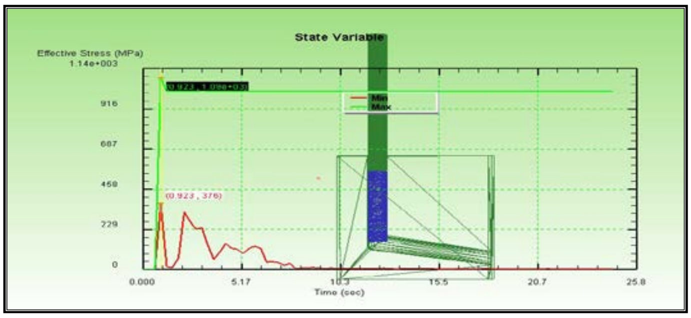


Fig.9. Load prediction

. Figure 9. shows the graph of time v/s load in z direction, this load is nothing but the amount of force required by the billet to pass through the die channel. We can take it directly as ramming force, i.e. force required to provide by plunger. We could see from the graph that max stress is developed at the starting of the process and the amount of stress reduced and remains constant once the process got started.

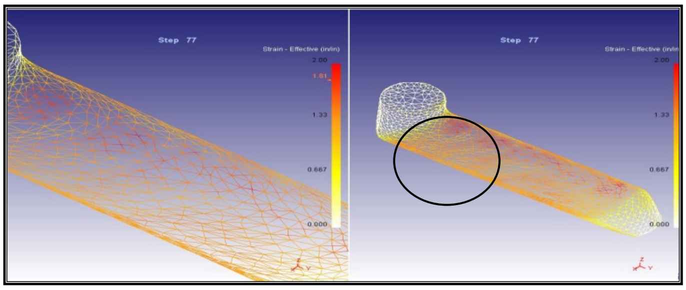


Fig.10. Maximum strain node for ϕ =90°

Figure 10. shows the nodes from where values of strain are taken as reference and also maximum for ϕ=90°, 95°, 100°,105°, 110° respectively. The maximum strain was observed at the inner edge of the billet material and mostly the area which got passed by the inner edge of the die channel at intersection. The Figure 16 shows the node at which the value of effective strain is maximum i.e. 1.83 for die channel angle 90º. Similarly the strains calculated for 95°, 100°,105°, 110° die channel angle its result is tabulated in table 1.

TABLE I
RESULT DATA

ϕ(Die channel angle)	Ψ(Die corner angle)	strain effective Max.	stress effective MPa
90º	15º	1.81	1113
95º	15º	1.77	1100
100º	15º	1.73	1090
105º	15º	1.13	1020
110º	15º	1.11	1020

7. Die Manufacturing

A) Die manufacturing

The die is vertically split. We are only interested in ECAP process so the die channel angle and corner angle are of prime importance. The dimensions of die selected according to the simulation results. Many parameters had to be taken into consideration regarding sample shape, sample size and maximum work load. We decided to use 100° die channel angle, 15° corner angle and 100 mm sample length which should be capable of bearing 500kN load.
Dimensions of the dies are 145mm x 145mm x 35mm (2 Quantity)

1. Material selected for die

WPS DIN 1.2379 /ASTM A681 (D-2) / HCHCr (High carbon high chromium steel)

TABLE III
CHEMICAL COMPOSITION OF HCHCr

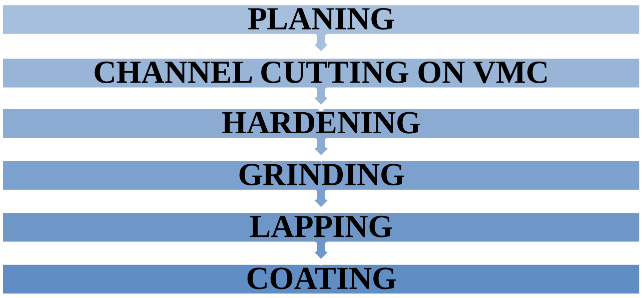
Element	C	Cr	Mo	V
%	1.50	12.00	1.00	1.00

Mechanical properties
E (elastic modulus) - 190-210 GPa
Compressive Yield Strength - 1900MPa

It is used mostly for dies and long run tooling applications. The reason to select this material is it has high wear and abrasion resistant properties and dimensional stability. It is heat treatable and will offer hardness in the range 55-62 HRC. High chromium content gives it mild corrosion resisting properties in the hardened condition. The advantages of using this material are,

- High wear resistance
- High compressive strength
- Good through-hardening properties
- High stability in hardening

2. Die manufacturing flow



3. Planing

This operation is used to machine straight open mainly external surfaces of die. Planing has done on the every surface of the blocks purchased, to get perfect square shape blocks.

4. Channel cutting on VMC

It was the most important task in manufacturing of die, because the channel dimensions are the factors which will affect the deformation of billet material. Therefore the dimensions of channel should be perfect. Channel has cut using ball cutter on VMC (vertical machining center).VMC used the coding generated from modeled die.

5. Hardening

Hardening is a metallurgical and metalworking process used to increase the hardness of a metal. The hardness of a metal is directly proportional to the uniaxial yield stress at the location of the imposed strain. A harder metal will have a higher resistance to plastic deformation than a less hard metal, which helps material to be dimensionally stable. Hardening is done by heating die slowly to 850°c and kept it at same temperature for 1hour and then quenched into water.

6. Grinding

Grinding is a type of machining using an abrasive wheel as the cutting tool. Each grain of abrasive on the wheel's surface cuts a small chip from the workpiece via shear deformation. After hardening, small dimensional changes has occurred due to shrinking which result into imperfect match of the inner surfaces of the die. To eliminate these changes grinding has to be done.

7. Lapping

Lapping is a machining process, in which two surfaces are rubbed together with an abrasive between them, by hand movement or using a machine. Channel surface should be

IJISET - International Journal of Innovative Science, Engineering & Technology, Vol. 4 Issue 3, March 2017
ISSN (Online) 2348 – 7968 | Impact Factor (2016) – 5.264
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smooth enough to promote movement of billet and plunger. Abrasive paste of 400 microns is used for lapping of channel surface.

8. Coating

Due friction between plunger and channel surface, there are chances of wear out of channel surface. To increase the wear resistance, coating of MgO is applied to the channel surface.

9. Design and manufacturing of plunger

Plunger is the key part of the ECAP test, because all the force required to pass the billet material through the channel is transferred with plunger. Plunger is designed to sustain the high stresses induced during the ECAP process. Diameter of plunger was fixed and equal to 10mm.

9. Equipment And Experimental Setup

This chapter presents the details of the experimental work conducted during this study and equipment used. Experimental work constitutes the execution of the following tests and examinations of the material

- Chemical composition
- ECAP

The details of each of the tests are given in the following sections along with some details of the equipment used for the test. The main equipment used in the testing and examination of the material includes the following

1. Chemical analysis spectrometer
2. Universal testing machine

A) Chemical composition

The material used in this study was in the form of circular bar. The material was analysed on chemical analysis spectrometer. The material was annealed, which included a heat treatment at 350°C, furnace cooling up to room temperature. Chemical analysis spectrometer is used to determine the chemical composition of material.

B) ECAP

1. Preparation of billet

Billet is machined to required size, 100 mm in length, 9.5 mm diameter, and fillet of 1mm at the edges. It is then polished using abrasive paste of 400 microns. Annealing has been done on the machined billet to get homogeneous properties throughout the length of the material. Billets are held at 350°c temperature for 1hr in the electric furnace and then allowed to cool in furnace itself. Prepared billets are shown in Figure 22.

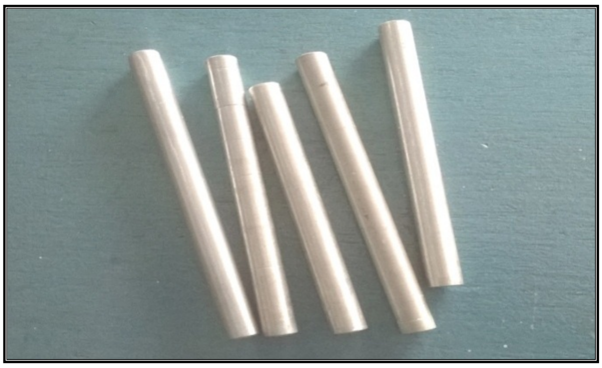

Fig. 22. Prepared billets

2. Procedure for ECAP

UTM TUE-C-400 servo is used to perform ECAP. Experiment is performed at room temperature. Die channel is lubricated to avoid friction between surface of billet and channel. Well lubricated billet is inserted into the die channel. Mineral oil based grease is used as lubricant. Load has applied manually to the billet through plunger. Single pass is carried out and the passed billet is used for study. Actual setup is shown in Figure 23.

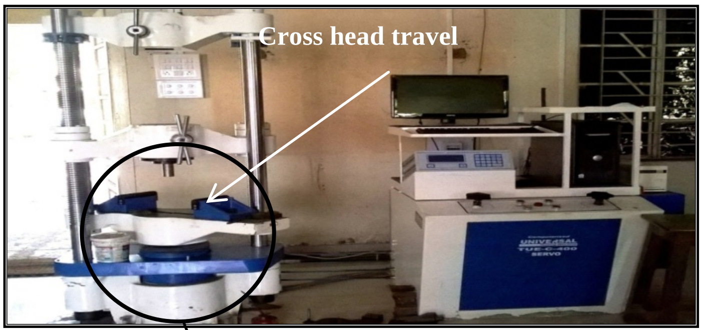

Fig.23. Test Setup

10. Conclusion

The detail study of severe plastic deformation by ECAP has been studied.
1. It is concluded that the degree of severe plastic deformation depends upon the geometry of the die. It has been seen that the strain introduce in billet material is high at channel angle equal to 900and reduces with the increase in channel angle.

2. Plastic deformation zone depends upon the die corner angle. For small die corner angle, plastic deformation zone accumulate near pure shear plane and spread away from pure shear plane as die corner angle increases.FEM analysis has successfully done for different die geometry.

3. With the combination of corner angle equal to 15^o and die channel angle 100^o, optimized result have observed in FEM analysis. ECAP die has been manufactured for die corner angle equal to 15^o and die channel equal to 100^o.

Acknowledgment

The authors of this present work acknowledge the support given by GES R. H. Sapat College of Engineering, Management Studies and Research for guidance and use of labs.

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BIOGRAPHY

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Professor Vidyadhar C. Kale has completed his Metallurgical Engineering and masters in Metallurgy (Powder metallurgy) from COEP Pune University, M.S.India in the years 1986 and 1988 respectively. Later he did his M.E.Engg. at Queen`s university, kingston, Canada, He has published several research papers on his research work. Author has total 24 years industrial and teaching experience His research interest includes advanced materials, Design, stress analysis and composite materials.