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Numerical Investigation of AA5053 Through Equal Channel Angular Pressing Technique: An Overview

Nagendra Singh[1,*], Sanjeev Kumar Verma[2], Ashish Kumar Tiwari[3]

Abstract

Equal channel angular pressing is recognized as the predominant method for bulk severe plastic deformation processing and has been employed for refining the grain structure in numerous metals and alloys. This study utilized finite element analysis to examine the processing of metallic billets through simple shear deformation. For the study, the die channel angle was chosen based on achieving the minimum energy consumption to induce maximum uniform strain. Among the favored channel options, it was deemed appropriate. The investigation also examined the maximum load needed to carry out the operation, as well as the distribution of effective stress and strain. The mathematically calculated equivalent plastic strain closely matched the value obtained through finite element analysis. In the process, the die channel angle and friction conditions play a pivotal role in inducing maximum strain in the work material, a fact confirmed by the numerical analysis conducted in this study. Furthermore, these two parameters not only affect the maximum load needed to carry out the operation but also have a minimal impact on the ram rate within the examined range. The study highlights that AA5053 undergoes significant grain-refinement due to the high imposed shear strains accumulated during successive passes. Numerical results indicate that optimized channel angles and processing routes lead to improved deformation uniformity and enhanced mechanical performance. This investigation provides valuable insights into the deformation mechanisms of AA5053 during ECAP and offers a foundation for future experimental validation and optimization of process parameters for lightweight engineering applications.

Keywords: Equal channel angular pressing, severe plastic deformation, AA5083, strain, strengthening mechanism

INTRODUCTION

The continuous progression of materials developed through the ages, from ancient to modern engineering and science, is an ongoing and endless process in the history of human civilization. Throughout the Holocene epoch, the development has traversed various stages, including stones, metals, alloys, composites, ceramics, cermets, and more. With the advent of iron and, subsequently, steel, the manufacturing industry experienced excitement for numerous centuries [1]. In the present situation, as human society grapples with a shortage of energy resources, it appears somewhat unnecessary to engage with bulky machinery. Therefore, there arises a requirement for the advancement and expansion of materials by decreasing weight without sacrificing performance [2]. Intensive research efforts have been undertaken in the past few decades to create lightweight materials. The selection of the appropriate

***Author for Correspondence**
Nagendra Singh
E-mail: singh.mech2008@gmail.com

[1]Assistant Professor, Department of Mechanical Engineering, Ganeshi Lal Agarwal University, Mathura, Uttar Pradesh, India
[2]Assistant Professor, Department of Mechanical Engineering, JS University, Shikohabad, Uttar Pradesh, India
[3]Junior Technical Superintend (JTS), Advanced Centre for Materials Science, IIT Kanpur, Uttar Pradesh, India

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manufacturing process and materials poses significant challenges for scientists and engineers in various applications. Various researchers have reported that secondary operations, such as different heat treatments and forming processes, are utilized to enhance the tribo-mechanical performances of the product [3]. For materials that are not amenable to heat treatment, alternative forming processes are typically applied as secondary strengthening mechanisms. Severe plastic deformation (SPD) is a broad concept encompassing metalworking methods that impart significant strain without altering the overall dimensions [4]. To put it differently, the combination of high strength and specific tool geometry obstructs the smooth flow of material, leading to the generation of considerable hydrostatic pressure. This pressure directs the material to follow the intended path, accompanied by elevated shear strain. The process induces crystal defects, resulting in an increased dislocation density and the formation of fine grains [5]. The deformation of tools or dies is limited. In the field of metal industries, there is a notable focus on Severe Plastic Deformation (SPD) processes due to their practical microstructure refinement at the nanometer or sub-micrometer level. The prevalent method of Severe Plastic Deformation (SPD) is Equal Channel Angular Pressing (ECAP), which imparts shear plastic deformations to a workpiece without changing its overall geometry. Numerous researchers have attempted to induce deformation through ECAP by managing the impact of processing parameters, including die geometry [6], temperature, routes, deformation rate, friction, back pressure, as well as the properties of the work material, such as composition, phase, yield stress, grain size, texture, and so on. The Finite Element Method (FEM) is the sole means to virtually observe and analyze the alterations occurring in the inaccessible zone during deformation. The stress, strain, temperature, etc., generated in the deformation zone can be comprehended more effectively before conducting experiments [7–9]. The crucial data, which is the maximum load needed for the operation and its reduction through customization of variable parameters and die modification, can be achieved through software analysis. According to Patil *et al*., the channel angle and outer corner angle have a noteworthy impact on the load requirement and mean strain, while the outer corner angle exerts minimal influence [10]. The process is also influenced by operating temperatures and friction values. Elevated temperature in conjunction with increased friction conditions results in a higher strain inhomogeneity index. The aim of this study is to examine and explore the impact of various parameters of the ECAP process on strain and its distribution. Finite element analysis was conducted using the die that induces maximum uniform strain with minimal energy consumption [9]. The study delved into the significance of various parameters on flow characteristics, strain generation, and load requirements.

FINITE ELEMENT MODEL

A thermo-viscoplastic material model was applied to the workpiece, while a thermo-rigid material model was used for the tooling setup in the DEFORM-v.6.1 software package. The simulation involved four solid components (billet, punch, ECAP die, and a support plate), all prepared using Solid Works software. Prior to determining the mesh numbers, validation modeling was performed. To examine the material flow behavior and finalize the channel angle of the ECAP die, an analysis of flow characteristics was carried out. The grid pattern analysis option was selected to assess the flow behavior in a 2-D plane [10]. In the analysis, channel angles with and without the outer fillet radius were considered. The impact of the die channel angle on effective strain, strain rate distribution, and flow characteristics is examined in this study. A standard L-9 orthogonal array was designed for the simulation, with the die featuring a channel angle of 70 degree to determine the influence of the parameters. The simulations were carried out by considering three variables: ram rate (mm/sec), operating temperature (°C), and coefficient of friction at three different levels. Table 1 presents the L-9 orthogonal array. Following the completion of the runs, analysis was performed on main effects plots, stress distribution, strain distribution, and load-stroke plots [11].

RESULTS AND DISCUSSION

Confirmatory Test

To establish the mesh density of the models for the finite element investigation, a validation test was carried out. The variable mesh densities considered for the test are listed in Table 2. The simulations were conducted based on various mesh combinations. Figure 1 illustrates the comparative load versus stroke plot derived from the results [12]. With the workpiece identified as AA5083, a coefficient of friction of 0.6, and a die angle of, the maximum load required to complete the operation was determined to fall within the range of 80–85 kN. No significant difference was observed among the three simulations. For a more detailed analysis of flow characterization and the distribution of effective stress and strain at split sections, the mesh density on the higher side (combination-1) was selected for further investigations [13].

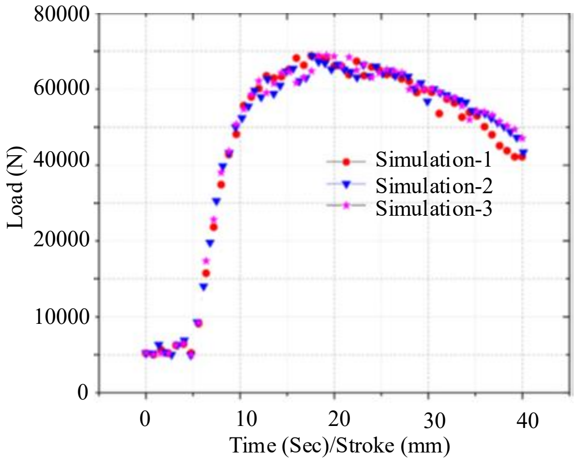

Figure 1. Comparative load versus stroke plot for three simulations [2].

Table 1. L9 orthogonal array.

Run	Ram rate (mm/sec)	Operating Temperature (°C)	Coefficient of friction
i	2.5	20	0.25
ii	2.5	220	0.45
iii	2.5	320	0.65
iv	4.5	20	0.45
v	4.5	220	0.65
vi	4.5	320	0.25
vii	6.5	20	0.65
viii	6.5	220	0.25
ix	6.5	320	0.45

Table 2. Variables mesh densities for the confirmatory test.

Combination	Workpiece mesh	Punch mesh	ECAP-die mesh	Coefficient of friction	Ram rate (mm/sec)	Operating temperature (°C)
1	55000	50000	90000	0.65	2	50
2	45000	40000	60000	0.65	2	50
3	35000	30000	50000	0.65	2	50

Flow Characteristic and Strain Distribution with Different Channel Angles

In the study of metal forming, flow analysis plays a crucial role in comprehending the forming characteristics of the process. The flow characteristics of the material during ECAP in the finite element analysis with various die channel angles were examined using the split billet grid pattern technique and are illustrated in Figure 2. In the straight die, a considerable dead metal zone was noted at the outer corner zone. Introducing an outer fillet corner reduces the zone, but a sticky layer appears prominent in the material at the bottom areas, indicating a non-uniform strain distribution [14]. In the die with an angle and a fillet, the flow is relatively improved. As the die angle increases, the flow seems to become smoother. For die angles and, a negligible amount of non-uniformity in the flow was identified, with a reported minimum inhomogeneity index [15]. The smoothness of the flow has a detrimental impact on the objective of Severe Plastic Deformation (SPD). To achieve uniform maximum strain induction without compromise, the die design must ensure that the flow does not incorporate any redundancy. Figure 2 illustrates the effective strain distribution in the finite element analysis at the split section of the billet along the billet axis. The distribution evidently supports the earlier discussions on the flow characteristics. Achieving a uniform strain distribution in a single pass is challenging, but a die with appropriate corner angles can reduce the inhomogeneity index (Figure 3) [16]. The Von-Mises equivalent strain for ECAP was derived considering the die channel angle and the angle associated with the arc of curvature, as shown in Figure 4, and the corresponding relationship is presented in Eq. (1) (Figure 5) [17].

$$\varepsilon = \frac{2N\cot\left(\frac{\psi}{2}\right)}{\sqrt{3}} \qquad (1)$$

$$\varepsilon = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\phi+\psi}{2}\right) + \psi\,\mathrm{cosec}\left(\frac{\phi+\psi}{2}\right)\right] \qquad (2)$$

$$\varepsilon = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\phi+\psi}{2}\right) + \psi\right] \qquad (3)$$

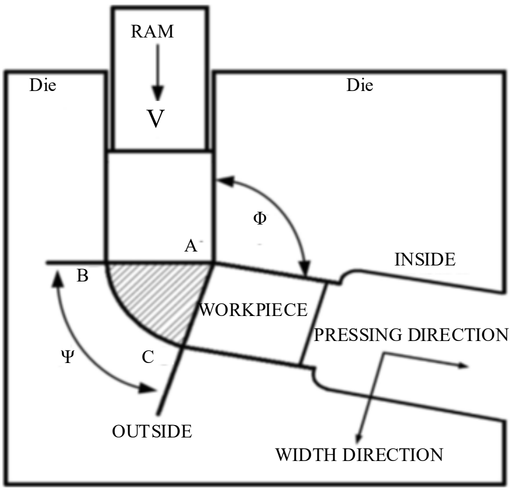

Figure 2. ECAP in 2-dimension [3].

The relationship overlooks the impact of outer die angle, ram rate, and operating temperature in estimating strain generation. It suggests that a smaller die angle (70 degree) will induce more strain, resulting in higher dislocation densities, and a channel with a die angle will have zero strain. However, Salcedo *et al.* modified the relationship by introducing the outer corner angle, as represented in Eq. (2) [13]. This equation was subsequently further modified by Goforth *et al.* and presented in Eq. (3) [15]. Using Eqs. (2) and (3), the maximum strain values were calculated for the designed die and found to be 0.76 and 0.74, respectively.

However, the equation was derived under the assumption of a rigid perfectly plastic material, zero friction conditions at the contact surfaces, uniform plastic flow in the channel, and isotropic work material. In simulations with lower friction values, the maximum strain found closely approximates the numerical value. However, in cases where the coefficient of friction is on the higher side, specifically 0.6 for runs 3, 5, and 7, the induced strain is greater, as clearly stated in Table 3. Under elevated temperature and increased friction conditions, the deformation is more extensive, leading to a higher observed strain. Figure 3 displays the load versus stroke plot for different channel angles. The maximum load is required for a right-angled channel die due to redundant work and a highly non-uniform strain distribution. The load requirement decreases with the smoother flow. The die with a channel angle necessitates a comparatively minimal load to complete the process. However, the maximum strain induction decreases with the increase in die angle [18–20]. The primary goal of Severe Plastic

Deformation (SPD) is to induce more strain and, consequently, dislocation density. The die that minimizes redundant work due to non-uniform strain generation and is capable of providing the maximum strain is selected for further investigation. The die with a channel (20°) angle is deemed suitable and chosen for further investigation. The variation of the inner corner angle has a very negligible impact on the load requirement [12], and therefore, it is neglected. A suitable outer fillet with a radius of 10 mm is chosen.

Table 3. Simulation results.

Run	Ram rate (mm/sec)	Operating temperature (°C)	Coefficient of friction	Maximum Load (N)	Maximum strain
1	2.5	20	0.25	24936	1.17
2	2.5	220	0.45	39824	1.27
3	2.5	320	0.65	32288	2.30
4	4.5	20	0.45	62970	1.2
5	4.5	220	0.65	61127	2.34
6	4.5	320	0.25	7532	1.28
7	6.5	20	0.65	96589	2.24
8	6.5	220	0.25	142331	1.2
9	6.5	320	0.45	22293	1.35

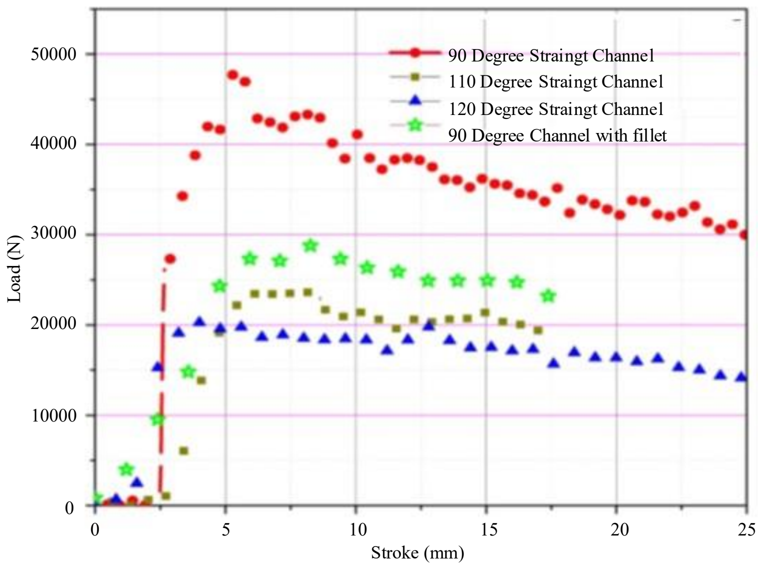

Figure 3. Load versus stroke [5].

Simulation Analysis Based on Taguchi Philosophy

Taking into account the parameters mentioned in Table 1, simulations were carried out with a focus on outputs such as the maximum load requirement and maximum strain distribution. The simulation results tabulate the maximum load and maximum induced strain for each run in Table 3. The progressive plot of load versus ram displacement, derived from the simulation results, is presented in Figure 4. The maximum load requirement for the material is influenced by factors such as strain, strain rate, and operating temperature [21]. For each curve, the load value increases rapidly, reaching a maximum rate of rise. The rate of decrease after the peak point is dependent on strain rate and friction. Higher friction conditions result in a noticeable decline in the load requirement. In the case of run-7, with lower operating temperature and higher friction and ram rate, the load requirement is at its maximum. Under higher friction conditions, the strain inhomogeneity is significantly elevated [22].

The main effects plot is examined to identify the significant factors influencing the response. Taguchi suggests visually analyzing the main effect plot using conceptual approaches to understand the impact of various parameters without resorting to ANOVA. Figure 5 illustrates the main effects plot for the maximum load requirement, depicting the key factors influencing the load requirement for Severe Plastic Deformation. It is evident from the figure that an increase in temperature leads to a decrease in the load requirement. The opposite effect was observed for the friction condition. Examining the slopes of the plots, it is evident that the effect of ram rate on load requirement is significantly less compared to operating temperature and coefficient of friction. Figure 6 presents the main effects plot for the maximum induced strain under various variable conditions [23]. It is noted that an increase in both temperature and coefficient of friction leads to an increase in the maximum strain. However, the maximum strain induced due to the friction condition is primarily observed around the surface, resulting in strain inhomogeneity. Examining the slopes of the plots, it is evident that the effect of the coefficient of friction on effective strain induction is higher than that of ram rate and operating temperature.

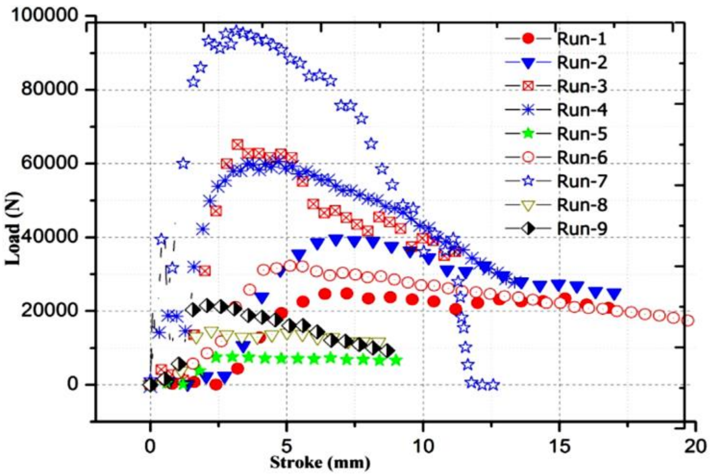

Figure 4. Schematic diagram of load vs. stroke [9].

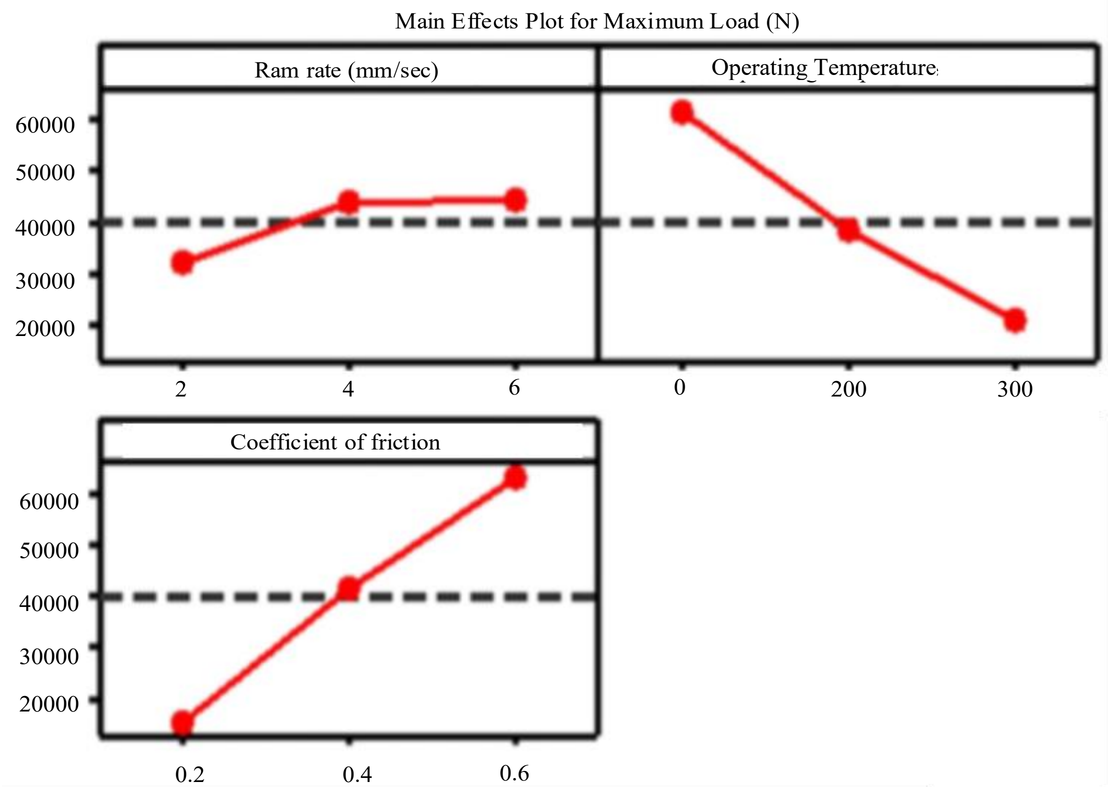

Figure 5. Main effects plot for the maximum load requirement [12].

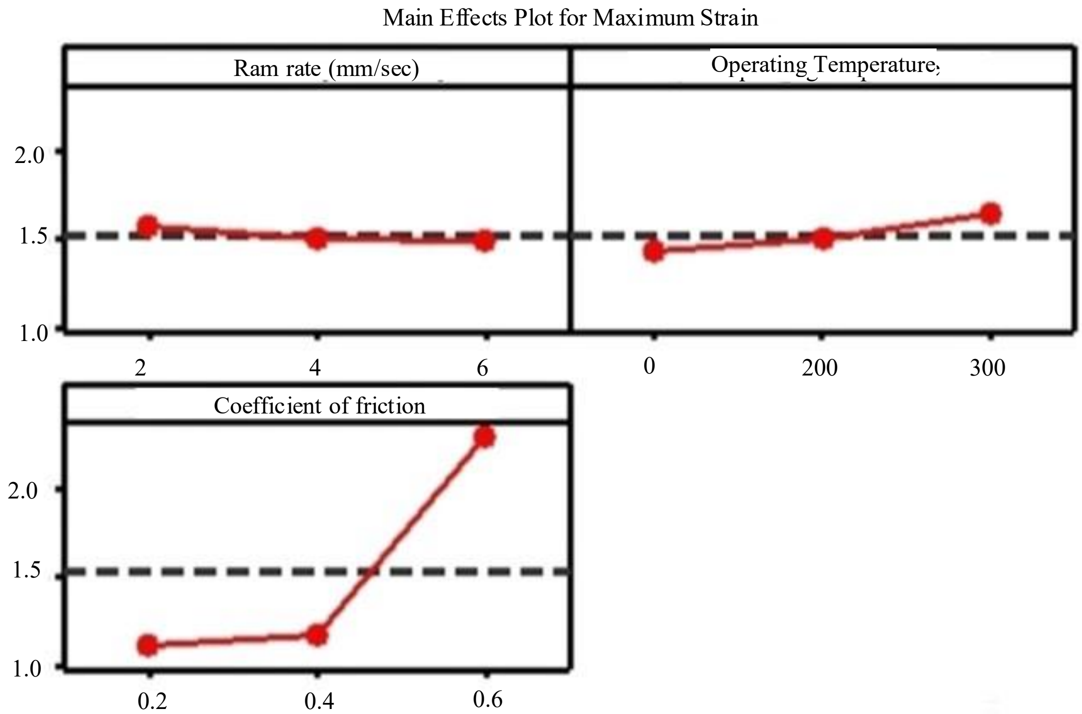

Figure 6. Main effects plot for the maximum strain [15].

CONCLUSION

This study presents the outcomes of a 3-dimensional rigid viscoplastic finite element analysis of AA5083 during Equal Channel Angular Pressing in a single pass. The die channel angle significantly influences the magnitude of induced effective strain and its distribution. Reducing the angle results in a higher magnitude of strain induction as well as a more inhomogeneous strain distribution. Operating temperature and the friction coefficient have a significant impact on the maximum load requirement for the operation, while the strain rate has a comparatively negligible effect. Among the three variables, operating temperature, ram rate, and coefficient of friction, the friction value, along with the die channel angle, plays a significant role in strain induction.

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