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An overview of severe plastic deformation as an extrusion processing technique for alloys and metal matrix composite materials

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Abstract

Severe Plastic Deformation (SPD) is gaining a remarkable prominence for grain refinement of alloy-based materials. Equal Channel Angular Extrusion (ECAE), C-Shaped Equal Channel Reciprocating Extrusion (CECRE), and Equal-Channel Angular Drawing (ECAD) are the major SPD methods used for extrusion processing of materials. In this review, an attempt is made to highlight pertinent issues on ECAE as a candidate SPD technique for enhancing properties of alloys and metal matrix composites. This overview shows that ECAE has manifested tremendous improvement in the mechanical and microstructural properties of materials depending on the experimental conditions been utilised. Furthermore, factors affecting the extrusion processed materials (such as friction, die geometry, extrusion velocity), all have deterministic effects on the post-experimental analysis of materials under the technique after several passes of extrusion. This can either increase or reduce the quality of the material under investigation irrespective of the geometry. SPD techniques have gained wide attention in the manufacturing and automobile industries through the production of bulk Ultra-fine Grain (UFG) materials where materials with an average grain size of about 100 nm to 1 µm have been produced. Grain refinement of large size microns in metals and alloys have also been improved when such materials are subjected to SPD, thereby causing reduction of grain size within the equiaxial and peripheral region on the extruded materials without causing any change in material isotropic nature. Thus, it is also worthy of note that the material grain size of up 1 µm has been achieved using ECAE (either experimentally or numerically) with a tremendous improvement of their mechanical properties on the extruded product. In conclusion, the SPD technique still offers the unique benefit of imposing shear strain on engineering materials, thereby causing significant changes in material properties without altering its isotropy (physical properties) and geometric characteristics. Therefore, stress-strain agglomeration commonly situated at the die corner angle in SPD techniques which normally led to material wear should be properly addressed using multiple-stage extrusion processes at reasonable lubrication conditions.

1.0 Introduction

The adoption of Severe Plastic Deformation (SPD) as a candidate technique for enhancing the mechanical response of alloy-based materials through grain refinement is attracting a rapidly growing researchers' interest. This is based on the observation that the grain boundaries act as a pinning point that impedes dislocation movement within the microstructure of an alloy. Refinement of grains within the microstructure provides a scenario where the grain boundaries act as a barrier and impede dislocation movement that requires substantial force to overcome and thus strengthening the alloy-based material [1-3]. Accumulative Roll Bonding (ARB), Cryogenic Rolling (CR), High-Pressure Torsion (HPT) and Repetitive Corrugation Straightening (RCS), Friction Stir Processing (FSP), Equal Channel Angular

Swaging Extrusion (ECASE), C-Shaped Equal Channel Reciprocating Extrusion (CECRE), Equal Channel Angular Drawing (ECAD) and Equal Channel Angular Extrusion (ECAE) are among the leading SPD methods [2, 4-5].

ECAE was invented by Vladimir Segal of the former Soviet Union (USSR) in 1974 [6]. It is an effective process to produce materials with increased mechanical properties and no change in billet size [7]. It is a method employed to impose a large strain on the material without changing the shape or size of the workpiece. It can also be referred to as one of the most promising material processing techniques which involves the imposition of severe plastic deformation on metals and its alloys for strain accumulation in materials without any change in cross-section [8]. The mechanical and microstructural property of the billet is altered as a result of the large plastic deformation of the material. Recently, the importance of severe plastic deformation and Equal Channel Angular Pressing (ECAP) has been increasingly recognised due to the unique physical and mechanical properties inherent in various ultrafine-grained materials [9-10]. Thus, the combination of ECAP and Equal Cross Section Lateral Extrusion (ECSLE) brings about the process commonly called ECAE.

It is well known that an ECAE consists of two dies of equal channels and a plunger. The die is formed from two equal channel cross-sections intersecting to form a shear corner. Deformation occurs as the billet is punched through die along the shear plane as shown in Fig. 1. Thus, the specimen experiences change in its mechanical and microstructural properties as the shear strain is imposed on the billet giving an increase in the material strength and production of Ultrafine-equiaxed Grains (UFG) with complex microstructure and better material compact [11]. ECAE also entails a new technique in the Severe Plastic Deformation (SPD) method which is used by introducing a potential shear strain on the billet using a ram in order to enhance the entrance channel of the die where multiple alloy specimen passage is possible [12].

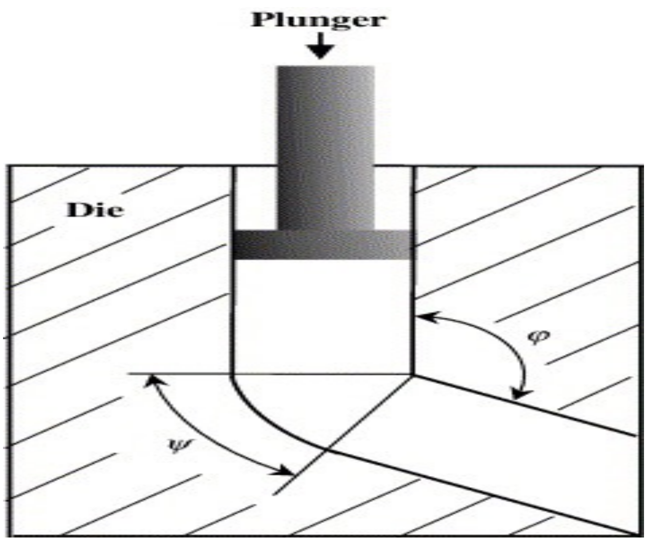

Figure 1: Schematic Diagram of the ECAP process with Die Inner and Outer angles [11, 12]

However, ongoing studies have shown that the strain level of alloys during ECAE processes can be obtained through conventional working techniques such as straight extrusion whose product can be compared with the properties of materials made from other conventional extrusion processes [13-14]. Thus, it can be affirmed that the ECAE process still offers the unique benefit of straining a material without changing its initial cross-sections. Past studies have also shown that the ECAE process can improve the as-extruded specimens after constant subjection to severe plastic deformation. It has also been revealed that the optical micrograph of most alloy specimens as recorded on the extrude plates at ECAE have shown great improvement in the grain refinement and general homogenization of the microstructure of the specimens [15]. Also, previous studies have indicated that the ECAE processed metallic alloys have been carried out at relatively high temperatures, low pressing speeds, and high die angles as the ECAE process is widely used for grain refinement process for titanium, Nickel, Magnesium, Aluminium, and Iron alloys [16]. The Importance and uses of ECAE include:

i. Achievement in powder consolidation and compaction
ii. The impartation of a tremendous increase in material strength
iii. Reduction in material grain size up to 1 μm
iv. Unusual increase in properties (i.e., ductility and tensile strength) at low temperature)
v. Increase in material hardness
vi. Prediction of Ultrafine-equiaxed grain materials
vii. Formation of complex microstructures due to non-uniform strain distribution.

Research conducted so far on metal forming over the past few decades have shown that SPD technique have attained wide attention in the manufacturing and automobile industries for the production of bulk UFG materials where materials with an average grain size of about 100 nanometers to 1 micrometer have been produced [17-19]. Thus, the high-level non-uniform strain distribution of the billet even after multiple extrusion passes as the material undergoes plastic deformation have become a research concern. This concern may be due to the presence of a dead zone within the extrusion channel which is far more concentrated at the shear plane region of the inner die angle which in turn results in no plastic flow along the strain path [20].

Over a decade, research regarding the SPD technique known as the ECAE has been recorded in literature [21,22]. The justification for this interest lies in the fact that the ECAE of deformed metals and alloys exhibit a very small grain size and subsequently their tensile strength is remarkably improved. ECAE is one of the most applicable SPD processes which leads to strength and ductility improvement through the grain refining and development of a suitable texture [23]. The process can also be referred to as a SPD developed to improve the microstructure and consequently the production of metals and alloys with proper microstructure and high strength and ductility. The parameter used so far in carrying out numerical and experimental analysis of ECAE process materials has a tremendous effect on the overall outcome of the specimen properties after subjection to SPD giving obvious changes in the mechanical and microstructural properties of the billet. This includes:

i. Temperature ranging from -150^{o}C to 1200^{o}C depending on the material test condition (isothermal or non-isothermal)
ii. Die inner and outer corner angles ranging from 60^{o} and 135^{o} have also been reported
iii. A varied amount of strains in difficult corners
iv. Multiple extrusion or passes
v. Change in billet orientation between successive extrusions.

The ECAP/ECAE has been established as an SPD method that refines the microstructural properties (i.e. grain size) of metals and alloys through SPD [24], thereby improving its strength according to the Hall-Petch relation and other model equations. The ECAE process is shown schematically in Fig.1 . A workpiece is placed in a die consisting of two channels of equal cross-section joined at an angle φ. The sharpness of the outer angle at the intersection of the two channels is quantified by the angle ψ. As shown in Fig. 2, the billet or specimen is pushed from the top as it undergoes simple shear during passage through the shear plane between the two channels [25].

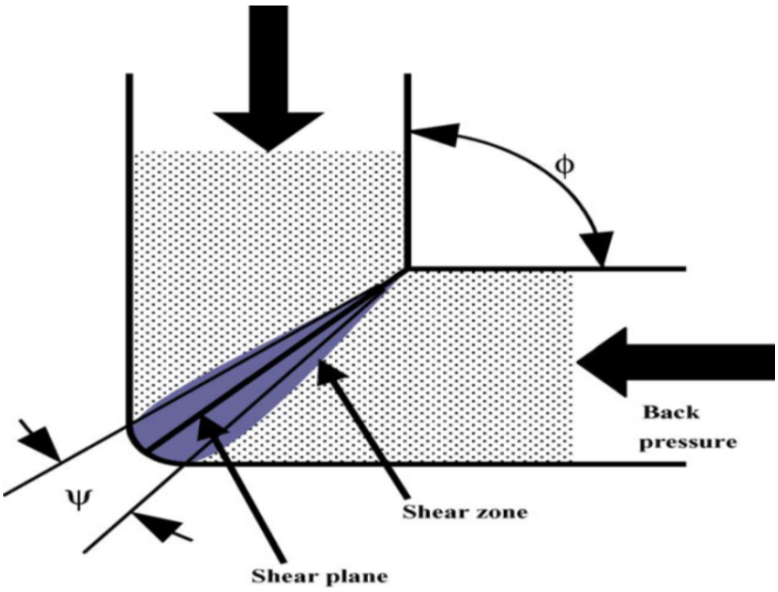

Figure 2: Schematic of ECAE Process showing the Inner Planes with Inner and Outer Angles [33, 36]

Backpressure may be applied to the other end of the workpiece. This helps to produce better workability and more uniform strain distribution around the billet. The amount of imposed shear strain can be determined theoretically by the angle and sharpness of the intersection using the relation below

$$\gamma_N = 2\cot\left(\frac{\psi}{2}+\frac{\varphi}{2}\right) + \psi\, cosec(\frac{\psi}{2}+\frac{\varphi}{2}) \quad (1)$$

The accumulated equivalent strain value can be calculated using the die-channel and inner and outer angles as extracted from Equation 2 [22, 32].

$$\varepsilon_N = N\frac{1}{\sqrt{3}}[2\cot\left(\frac{\varphi}{2}+\frac{\psi}{2}\right) + \psi\, cosec\left(\frac{\varphi}{2}+\frac{\psi}{2}\right)] \quad (2)$$

Consequently, other subsequent models such as the Segal strain model which was derived as the path of independent strain relationship for a sharp corner at $\psi = 0$ to the total strain is given as:

$$\varepsilon_N = 2N\frac{1}{\sqrt{3}}\cot\left(\frac{\varphi}{2}\right) = 1.16\, Ncot\varphi \quad (3)$$

Therefore, for 1 pass of extrusion at $\varphi = 90^{o}$, equation 3 becomes:

$$\varepsilon_N = 2N\frac{1}{\sqrt{3}} = 1.155 \quad (4)$$

Other strain model equation as employed so far in the literature includes the Iwahashi's strain model as shown in equation 5 which depicts the generalised relation for total strain imposed on an alloy material for a case where $\psi \neq 0$

$$\varepsilon_N = 2\frac{N}{\sqrt{3}}[\cot\left(\frac{\varphi}{2}+\frac{\psi}{2}\right) + \frac{\psi}{2}\, cosec\left(\frac{\varphi}{2}+\frac{\psi}{2}\right)] \quad (5)$$

Goforth's strain model also analysed metal flow during the ECAE process using the plane method by taking the punch pressure required into consideration for non-hardening materials as sourced from [27] as depicted in Equation 6:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\cot\left(\frac{\varphi}{2}+\frac{\psi}{2}\right) + \psi \quad (6)$$

where N is the number of passes; φ is the channel angle and ψ is the corner angle. Consequently, the extrusion stress or pressure as postulated by V.M. Segal, as sourced from [28] depicted in Equation 7 :

$$P_N = \frac{2}{\sqrt{3}} \sigma_O \cot\left(\frac{\varphi}{2}\right) \tag{7a}$$

For $\varphi = 90^o$, $P_N = \frac{2}{\sqrt{3}} \sigma_O$,

For $\varphi = 120^o$, $P_N = \frac{2}{3} \sigma_O$

The von Mises effective strain equation during extrusion using the ECAE method in terms of the effective strain as shown in Equation 7b:

$$\varepsilon_N = \frac{\gamma_N}{\sqrt{3}} \tag{7b}$$

where N = number of passes, γ = equivalent plastic shear strain, φ = angle between the channels (inner arc angle), ψ = outer arc angle, ε_N = effective strain, P = Plunger Pressure or Required Stress required to push the test material through the die, σ_O is the yield strength of the material under test. It is also worthy to note that the required pressure for deformation mostly depends on the ECAE angle and the yield strength of the material. Variations occur with the inclusion of ψ in the pressure formula. The assumption employed in the geometric analysis above does not include the effect of friction, strain hardening, strain-rate sensitivity, and strain distribution. Rather the analysis only includes; simple shear, frictionless die surface, uniform plastic flow on a plane, complete filling of the die channel by the billet using rigid perfectly plastic material (with no strain hardening behavior included). It is well known now that the process of ECAE was developed in the early 1970s by Segal in the Soviet Union as a metalworking process based on simple shear imposition by SPD method of a well-lubricated billet through two intersecting channels of the identical cross-section as shown in Fig. 2 above at a particular die inner and outer angles. The billet is pressed through the die consisting of two channels with identical cross-sections and intersecting at an angle, usually $60^o < \varphi < 135^o$. Often $\varphi = 90°$ [29]. Due to the identical cross-section of the channels, the dimensions of the billet remain unchanged, and the process can in principle be repeated any given number of times. Metals and metallic alloys process via ECAE have a vast range of applications in the automobile, manufacturing, and aerospace industries as large plastic deformation has been principally obtained by classical forming techniques like cold rolling wire drawing and extrusion particularly for the manufacture of automobile and air-craft spare parts and their components. The ECAE is also a well-known method for the production of bulk materials with an UFG structure where the homogeneity of the material flow, needed pressure and resulting strains strongly influence the process parameters [30].

2.0 Types of Severe Plastic Deformation Processes

Due to diverse research conducted so far on metals and metallic alloy using the ECAE process, most literature over decades has invented other conventional types of ECAE process through modification of existing designs or by creating a new ECAE rig design or by a combination of two or more ECAE processes. In ECAE, it is seen that as the billet crosses the shear plane, induced shear strain is also accompanied by a reduction in the cross-section [32]. With the increase in the number of passes, the thickness reduction is much more significant thereby reducing the practicability of multi-pass for the ECAE process. The simple shear (γ) per pass during ECAE is identified as sourced from the literature can be expressed as stated in Equation 8.

$$\gamma = 2\tan(90^{\circ} - {}^{\varphi}/_{2}) \tag{8}$$

where φ is the angle of drawing and the true plastic strain per pass is given by Equation 9.

$$\varepsilon = \frac{\sqrt{2}}{3}[(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_x)^2 + (\varepsilon_y)^2 + (\frac{3}{2}\gamma^2)]^{1/2} \approx \frac{\gamma}{\sqrt{3}}[1 + 2(^{\varepsilon_y}/_{\gamma})^2] \quad (9)$$

where ε is the equivalent strain while $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are the strain components along the x, y, and z axes respectively.

When $^{\varepsilon_y}/_{\gamma}$ the ratio is small or minimal, then the above expression is approximated as:

$$\varepsilon = \frac{\gamma}{\sqrt{3}} \quad (10)$$

The selection of the channel intersection angle is another prime decision in ECAD. It is seen that if the angle is too sharp, then cracks readily appear on the stretch surface. Excessive shearing may even result in the tearing of the specimen.

2.1 Equal Channel Angular Drawing (ECAD)

The proposed idea is to eliminate the problems associated with the compressive load during ECAE by pulling a billet through intersecting channels with the sole purpose of producing a potentially high plastic strain in a continuous way [31]. Over the years, literature has revealed that the process has two major advantages over the ECAE which include: the length of the specimen not limited by the bulk instabilities and the process can be conveniently incorporated as one of the intermediate steps in a continuous industrial process. Thus, ECAD offers two major advantages over ECAE: first, the length of the specimen is not limited by the buckling instabilities of the extruding ram, and secondly, it can be incorporated as one of the intermediate steps in a continuous industrial process shown in Fig 3.

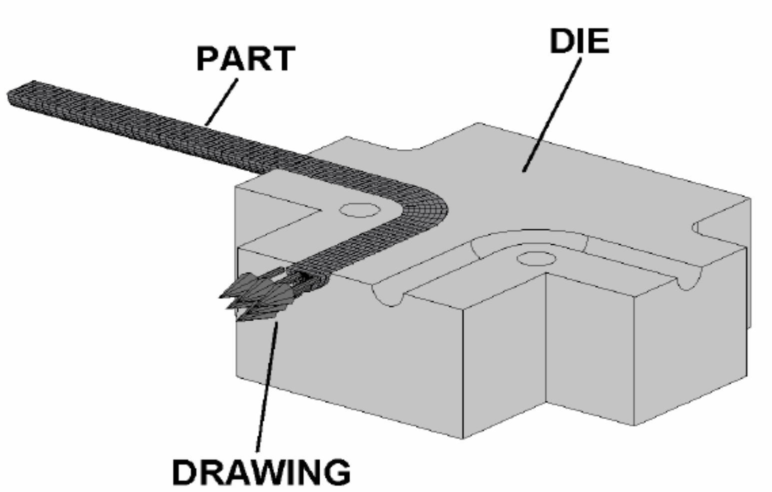

Figure 3: Schematics of Equal Channel Angular Drawing Process [31].

2.2 Accumulated Roll Bonding (ARB)

The major advantage of ARB over other SPD processes is continuous and fast fabrication [32]. It is primarily used for the straining of sheet metals. At this stage, excess grease is removed from two sheets of metals and their surface is cleaned with a wire brush. The brushed sheets are stacked together and heated up to a temperature below recrystallization temperature to enable a successful bonding between different layers and to increase the ductility of the processed materials [33]. Heated sheets are then rolled mostly with a conventional rolling facility to their half-thickness to generate an ultrafine structure so that a high strain is accumulated in the material [34-35]. Besides these advantages over other SPD processes, ARB has many significant drawbacks. Therefore, in sheet metals applications, the ARB technique has hardly been applied to the industrial scale. Also, the confinement of shear strain which is a vital ingredient for grain refinement in sheet metal works is quite noticeable on sheet metal surfaces.

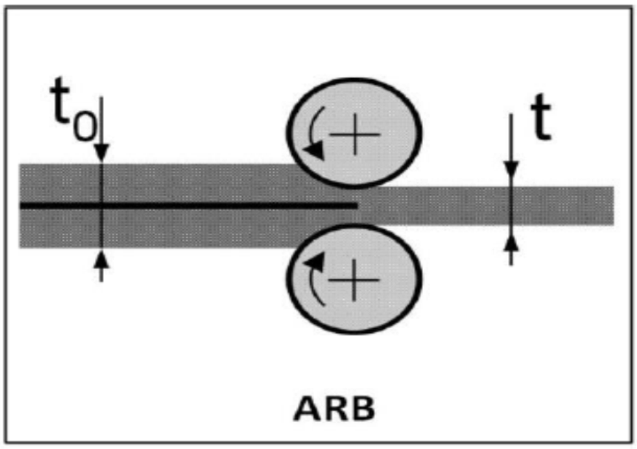

Figure 3: Schematics of Roll Bonding (ARB) process [36].

The thickness reduction by the ARB process in most literature is selected as 50% so that sheet material has the initial thickness after every forming cycle [36]. The final thickness of the strip (t), total reduction (t_r), where t_o is the initial thickness of the strip and equivalent von Mises strain (ε_{vm}) after cycles can be calculated using Equation 11.

$$\left.\begin{aligned} t &= \frac{t_o}{2^n} \\ r_t &= \frac{t_o - t}{t_o} = 1 - \frac{t}{t_o} = 1 - \frac{1}{2^n} \\ \varepsilon_{vM} &= \left\{\frac{2}{\sqrt{3}} In\left(\frac{1}{2}\right)\right\} X\, n = 0.08\, X\, n \end{aligned}\right\} \quad (11)$$

Due to the above mention constraint, the process may only be applicable in the fabrication of a wide variety of materials are commercially pure Aluminium and Aluminium-alloys, Titanium and Ti-alloys, Magnesium alloys, e.t.c.

2.4 C-Shaped Equal Channel Reciprocating Extrusion (CECRE)

The principle of the CECRE process is to introduce accumulated shear strain into the sample without changing its shape [32, 37] using die of inner and outer angles of 40^o and 120^o, respectively. The methods have been used in a few works to improve the mechanical properties of metallic alloys and composites such as Magnesium, Titanium, and Aluminum alloys) subjected under compressive loading as illustrated in Fig. 4. By using the CECRE method, the extruded specimen is under severe shearing deformation without any changes of its geometrical dimensions by a simple application of shear forces on both ends of the die. This newly devised SPD method called the CECRE process is used to refine the grains by finite element methods or under experimental conditions. Thus, it was recently discovered that the CECRE method does take advantage of Cyclic Extrusion Compression (CEC) and ECAE processes. The method also minimises the disadvantages of the significant differences between the mechanical and microstructural properties of the alloy as a resulting strain difference between the central and peripheral areas associated with CEC and ECAE processes [38].

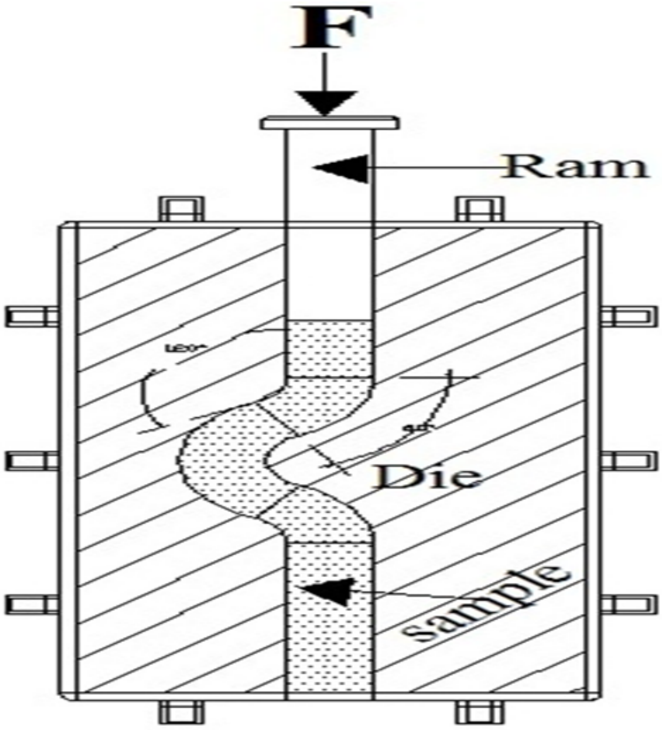

Figure 4: Schematics of the C-shape Equal Channel Reciprocating Extrusion (CECRE) Process [37].

2.4 Equal Channel Angular Swaging Extrusion (ECASE)

Oruganti, *et al*. [39] proposed a tool design guideline, another newly devised ECAE process known as ECASE where he conducted several numerical and experimental analyses using the said process on various metallic alloy materials. The ECASE method as a new SPD process is based upon the combination of conventional ECAP and the incremental bulk metal forming method of rotary swaging. During the ECASE process, two forming tools halved as shown in Fig. 5 with concentric arrangements around the workpiece were used to perform a high-frequency radial movement with short strokes due to oscillations motion. The contact time and relative movement between the tool and workpiece varied as the tool contours are building an eccentric channel.

2.5 Material Processing Using Equal Channel Angular Extrusion (ECAE)

The main advantage of the ECAE process compared with other forming processes is that multi-pass operations can be carried out without changing the cross-sectional shape. Thus, there is strain accumulation on the workpiece that can after undergoing different processing routes when rotated between different extrusion passes. Thus, the essential factors that influence deformation patterns in the extrusion process are the processing technique and the strain distribution of strain on the deformed material. Many studies of the ECAE process have been conducted experimentally so far, following the theoretical work by V. M. Segal. For this work, the required load and imposed strain were calculated by neglecting frictions at the die interface. Parshikov, *et al*. [40], gave a concise summary of what ECAE entails as a deformation and grain refinement process. The work involves a review of various articles of metals and alloy materials as various factors affecting the mechanical and microstructural properties such as temperature, die corner, and type of route was carefully reviewed using already postulated models and force equations as shown earlier to calculate the strains as stresses of such deformation process.

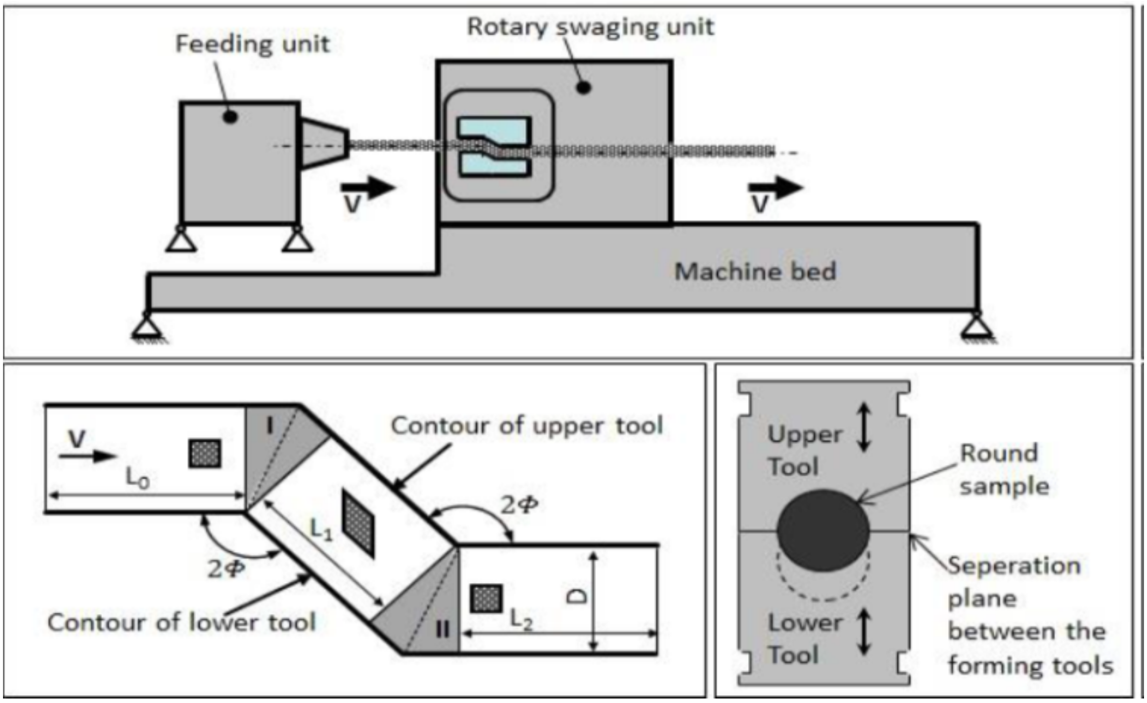

Figure 5: Schematic illustration of the rotary swaging machine (up), geometrical parameters of the tool system (down, left), and tool arrangement of ECASE process (down, right) [24, 39]

Perig, *et al*. [41] reveals in the World Congress on Engineering proceedings that deformation remains continuous at any particular point in a deforming body as the state of strain changes along the strain path. The ECAP is termed as very capable of producing the desired shape and sizes even as its mechanical and microstructural properties experience significant improvement due to variation in strain path direction during deformation. Due to widespread in the application of ECAE, different designs of similar processes have been revealed in the literature. Prados, *et al.* [42] introduced a new design for ECAE which was termed as an improvement over existing designs with additional attributes to process materials at high temperatures (up to 500 ^{o}C). The design was tested for different materials at different temperatures for the sole benefit of reducing the load and friction requirement and appropriate tooling.

Because of the widespread use of some alloys such as magnesium, aluminum, titanium, etc., it is essential to comprehend their mechanical and microstructural behaviour when exposed to different loading conditions, strain rate, and temperature. It is expedient to model the behaviour and later predict the behavioural characteristics for any of the proposed conditions [43]. Since ECAE is the most investigated and developed SPD process [44], the cross-section of the channels is the same, and the processed rods have theoretically the initial geometry based on strain concentration due to the repetitive pressing of material at a large strain. Thus, alloy specimens can be repetitively extruded and a huge cumulative strain applied without reducing the cross-section [45]. Investigating the textural and microstructure property of extruded metals and alloy have shown that ECAE processed materials do exhibit the formation of twin boundaries in the initial stage as the repetitive number of passes of ECAE plays a key role in releasing the shear strain imposed during plastic deformation. This may be due to the strongly orientated texture as observed in the specimen after several passes of ECAE via a specified extrusion route with a temperature as low as 500 ^{o}C.

The ECAE method as postulated by Rahul, [45] remains one of the most successful methods of severe plastic deformation used recently. It has great potentials of producing an UFG structure, uniform equiaxed structures and grain boundaries of predominant high-angle disorientation. The microstructural properties of material produced by the ECAE passes are due to a reduction in grain size as much as 0.6 microns after 6 passes of extrusion [47]. An ultrafine-grained structure can result in a lower friction coefficient and higher wear resistance [48]. This may be due to the reduction of the adhesion component of the friction coefficient. Table 1 depicts some of the materials that can be deformed using ECAE processes.

Table 1: Classification of various material been deformed using ECAE Processes [49]

S/N	Metals and Alloys	Powders	Others
1	Aluminum alloys	WC-Co	Polymers
2	Chromium	Ti-6Al-4V	Composites
3	Copper	Al8.5Ni10Y2.5La2.5	
4	Intermetallic	P-type Bi2Te3-Sb2Te3	
5	Iron and Steel		
6	Titanium		

3. Review Highlights on Severe Plastic Deformation as a Processing Technique

3.1 Modeling of Severe Plastic Deformation in Engineering Materials

There are two basic approaches to material, which are modeling and constitutive modelling. Material modelling implies the mathematical definition of the uniaxial flow behaviour for a specific material depending on the strain, strain rate, and temperature. By this initiative, the flow stress in metal works differs by mathematical definition for different materials. On the other hand, constitutive modelling involves the development of general equations for materials and defining the flow behaviour of the specific material by adjusting the model parameters using material test results. Major material models are summarised in Table 1.

The first three models in Table 1 predict the strain hardening of the material without taking the effect of strain rate and temperature into consideration. Extrusion parameters are ascertained based on the mechanical properties of such materials (i.e. yield strength) through tensile testing. The adaption of the flow stress curve on the tensile test result is then used to determine other extrusion parameters. All these three models are capable of modelling material behaviour, especially for low strain levels. However, for high plastic strain, the accuracy of the result generated by the models is quite doubtful. In high strained material processes, a model can be enhanced through the combination of material upsetting and tensile testing to define its parameters. By this method, first of all, the required material parameters are determined using tensile testing. Afterward, upsetting experiments are conducted with the same material. Material data derived from tensile testing is implemented in an FE simulation model of this particular upsetting test. By incremental variation of the parameters, upsetting force, or stress results obtained from FE simulation are adjusted to the ones from the upsetting test. Thus, the numerical results are then validated by the obtained experimental result.

Moreover, the last two models in Table 1 considers also the effect of strain rate and temperature. Both models predict the flow stress as a function of strain, strain rate, and temperature. The main advantage of the Johnson-Cook model over the power-law model is that it is implemented in nearly every Finite Element Software [50].

Table 1: Major material models depicting material property dependency on flow stress

Empirical Model	**Name**
$\sigma = \sigma_y + K\varepsilon^n$	Ludwik's expression
$\sigma = \sigma_y(1 + K\varepsilon)^n$	Swift expression
$\sigma = \sigma_y(1 - e^{-n\varepsilon})$	Voce's expression
$\sigma = \sigma_y(\frac{\varepsilon}{\varepsilon_0})^n\ (\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})^m\ (\frac{T}{T_0})^\tau$	Power Law Model
$\sigma = (A + B\varepsilon^n)\left(1 + CIn\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right).\left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right)$	Johnson-Cook Model

Sourced from: Gortan, [44]

3.2 Meshing and Mesh Generation in SPD Processed Materials

Meshing is the process that involves the creation of discretized geometrical patterns on the surface of a workpiece which can later be subjected to extrusion within the die channels. It is the uniform discretization of materials into nodal points and contours where required changes for extruded material properties can be noticed [51]. However, meshing of most alloys for pre-extrusion processes using SPD technique are more implementable, while considering the changes in the microstructure properties and textural characteristics of metallic alloys with little or no attention been paid to the elasticity property of the meshing material [52]. Furthermore, meshing provides a grid on extruded body super-imposed of the mesh on the workpiece at specified friction condition. The discrete geometry of mesh grid can either be triangular or rectangular in nature and this can also be noticed at the post-extrusion stage of SPD processes where grid elements and the nodal points can be observed on the extruded material. The grid elements and nodal points corresponds to the extruded material region while the nodal point implies the discrete lattice pattern in space with load parts on the extruded workpiece [53].

Reported works [37, 45, 54] have performed SPD technique on different alloys using different discretized elements and geometric sizes with variation in grain refinement properties at different alterations in physical properties of the extruded materials. Ogbezode, *et al*. [37] asserted that in order to actualise a better accuracy in computational analysis of tool wear between a workpiece and the die, both materials will require a finer mesh at the edges of the edges and workpiece been used. Thus, the research gap is that most mesh materials lack the requires elasticity property needed to withstand their easily breakage when subjected to high friction condition. Also, the mesh toughness property and ability drawn can also be an important factor that guarantees their capacity to withstand high friction. Mesh patterns to be used while subjecting metals/alloy to SPD must compensate for its inability to protect the metal matrix of such material. Otherwise, the unexpected breakage of a mesh during extrusion could make such extrudate to become more susceptible to the rigours of friction emaciating from the corners of the ECAE die.

3.3 Methods of Severe Plastic Deformation (SPD) Processes

To be able to compare SPD processes, first, the formulations of ECAE will be compared with other extrusion processes. For a better comparison with former studies, a Slip-Line Field (SLF) approach consisting of a single slip line that was used in first analytical investigations of ECAE can be adopted. As for other major SPD processes, the processing of different metallic materials is possible with ECAP, such as titanium, copper, aluminum, magnesium, and steel as well as their alloys [55]. The major merit of ECAP over other SPD techniques is the ability of the material samples to undergo easy adjustment in size and shape. With this method, materials samples of different geometries and sheet metals can be achieved using this approach. A round bar geometry was investigated in most literature as the following assumptions are made for the SLF or billet formulation which include:

i. The deformation has a plain strain.
ii. The deformation entails no formation dead metal zone.
iii. No application of backpressure into the samples.
iv. No clearance between the samples and the tool channel walls {i.e. the sample filled the channel walls.
v. The single tool system contains equal channel angles with two different deformation zones. The deformation follows the deformation extrusion routes as shown in Fig. 6.
vi. The sample's round geometry is shown by its rectangular equivalence with the same area of the cross-section.
vii. Constant friction was assumed to be constant all through the channels.
viii. The materials examined are considered as perfectly plastic regardless of strain hardening conditions within the plastic zone.
ix. The effect of temperature is minute. This can be curtailed by making small alterations on the materials yield strength based on different thermal calculations

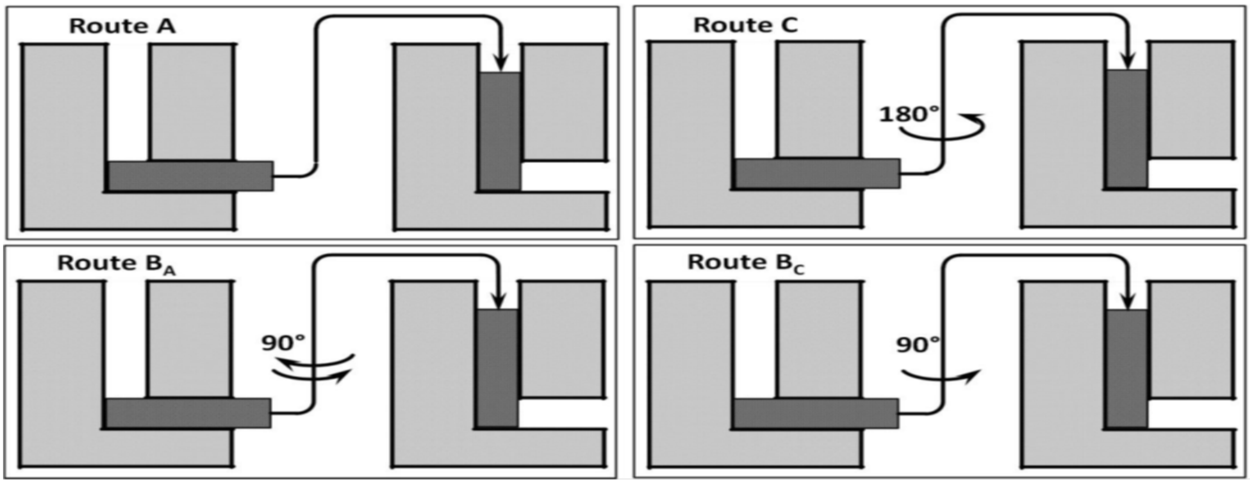

Figure 6: Major processing showing rotation schemes of the four ECAE routes [45]

The summary of the definition of deformation routes connotes the directions followed by the billet or test sample in an ECAE process as sourced from Adedokun, [6] and Rahul, [45] are stated as follows:
ROUTE A: 0^o, all passes; the billet is not rotated between successive passes.
ROUTE B or B_A: at a right angle (90^o) 270 ^{o}N odd, N even, the clockwise rotation of the billet at 90^o alternative to counterclockwise rotation.
ROUTE C: 180^o, all passes; the billet is rotated 180^o.
ROUTE D or B_C: 90^o, all passes; the billet is rotated 90^o clockwise.

The main advantage of ECAE over other conventional extrusion is that the cross-section of the processed billet is the same as the initial one. The process is termed as repeatable; hence by subjecting the billet to multiple extrusions, heavy plastic strains can be achieved. Also, by rotating the billet (±n 90°) between subsequent passes, different shear planes can be introduced thus activating different slip systems. There are four different primary routes (A, BA, BC, and C) (Fig. 6) based on distinct sequences of the shear plane for multipass processing. This enables one to develop different microstructures and textures [53]. In Route A, the billet orientation is the same for all passes. In this case, the shear deformation adds strain in the same direction resulting in a lamellar grain structure.

For route BA, and route BC, after each pass the billet is rotated 90° in the alternate or same direction about the extrusion axis. The route BA result involves a material deformed alternatively in two directions, in orthogonal forms with a developed distorted fibrous structure. The route BC restores the original element shape after every two passes and leads to an array of ultrafine equiaxed grain boundaries having high angles of misorientation [54]. In the case of Route C, the billet is rotated through 180° after each extrusion, keeping the shear plane constant but the shear direction is reversed between the two passes. This results in an equiaxed grain structure after each even number of passes.

However; since the shear deformation occurs in the same plane (Fig. 7), the developed microstructure of materials differs from one another (i.e. non-isotropic). However, a more equal dimensioned grain structure is produced in route BC than route C due to alternate changes in slip planes during extrusion after every four consecutive passes. The die designs as depicted earlier from the works of literature have shown the main objectives of several die designs are to minimise the friction of the sample with the die walls. A normal diet is composed of two parts, which are the movable (i.e. top die) and the other part is the fixed one (i.e. Bottom die) with the punch which contains the sample.

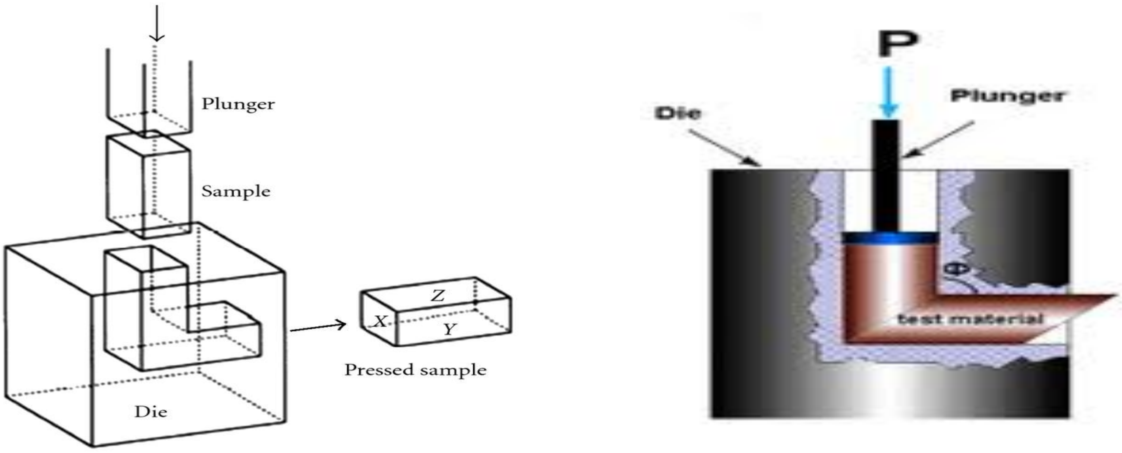

Figure 7: Illustration of ECAE Die with Plunger and Test Material [56]

The experimental realisation is shown in Fig. 7 above. The lower part of the fixed die has a small platform that is equal to the cross-sectional area of the specimen. The sample turns on the die surface during extrusion. This is placed between two cross-sectional dies with a plunger by the three lateral sides. Only one side of the sample is in contact with the bottom die. After an extrusion process, the top die can be split and the specimen can be removed. Another new sample can be also used to eject the first sample depending on the experimental conditions been employed.

3.4 Microstructural Evolution During SPD Process

The microstructural evolutions of metals and alloys subjected to low and medium plastic deformation have been discussed severally [57]. The outcome of their studies is a model describing severely the deformed metals with high to moderate stacking fault energy and grain subdivision which takes place by the formation of cell blocks separated by arrays of geometrical dislocations. Besides, some regions are dislocation-free but relatively bounded by low free-angle within the cells. The more severe the deformation, the narrower the cell blocks become and continue until the cell boundaries transform into high angle boundaries. This pattern has been often observed in ECAP of deformed metals and alloys and characterised by the formation of very small grain microstructures. Fig. 8 shows the optical micrograph of the ECAP copper as obtained at 6 passes [58]. The microstructure and the grain size of copper after undergoing deformation were reported to be reduced thereby formed a homogeneous grain size as compared with the as-received sample. The grain refinement of the ECAE copper was also revealed to be attributed to the process of deformation adopted. The average grain size of about 0.75 µm after six passes of processing was measured [59].

In another experiment conducted on the deformation of aluminium 6061 (AA 6061) via ECAP treatment, few grains were observed which is about 2.6 multiplied by the grain sizes obtained for the as-received sample. A free grains deformation was observed in the as-received sample due to the annealing process. An average grain size with a standard deviation of 76±42µm was calculated from their observation. Equiaxed structures with coarse grains were reported to be homogeneously distributed in both the normal and the extrusion direction. From their result, elongated lamellar morphologies were observed in the ECAP treated samples in the shear direction. It was also reported that the induced plastic strain led to grain refinement [60].

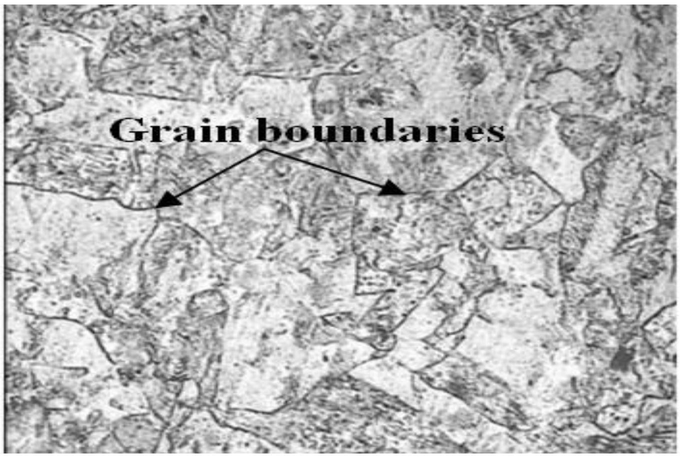

Figure 8: Optical microscope images of the ECAE copper obtained at 6 passes [16, 60]

Grain refinement by SPD implies that there is the creation of new high-angle grain boundaries. This can be accomplished by three mechanisms. The first is the elongation of existing grains during plastic deformation, causing an increase in the high angle boundary area. The second is the creation of high angle boundaries by grain subdivision mechanisms and the third is an elongated grain that can be split up by a localization phenomenon such as a shear band [61].

Moreover, the homogeneity of the specimen microstructure produces by the ECAP process is highly sensitive to the technological approach that was used in the process based on the following factors such as friction condition, die dimensions and rate of deformation Without a doubt, these factors influence the microstructure and finally the properties of ultra-fine grain material [62]. Therefore, analysis of the result as shown in Fig. 8 further explains the need why ECAE remains a discontinuous process with some limitations in its up-scaling potential. Besides, a useful material with a homogenous microstructure without cracks is produced as the specimen material is passed through the shear zone receives the desired deformation and grain refinement [49, 63]. This may be because the ECAP of deformed metals and alloys exhibit a very small grain size and subsequently their tensile strength is remarkably improved.

4. Overview of ECAE as Typical SPD Method

The ECAP technique can be initiated by pressing a three-dimensional specimen through a die channel of a uniform cross-sectional area with an angle of intersection. The billet experiences simple shear deformation at the intersection without any swift change in the cross-sectional area. This is because the die does not allow for lateral expansion. This implies that billet specimens do undergo pressing in subsequent forms along the rotational axis during each successive passes. The theoretical strain that can be induced on the specimen using an inner die angle of 90^{o} along the shear place will no doubt impose an equivalent shear strain of 1.15 on the material specimen using Equation 2. The premise used in this ECAE analysis includes a die friction-free surface, a constant plastic flow, no air space between the die channel and the workpiece, and no strain hardening tendencies included (i.e. material is rigid and perfectly plastic). With these assumptions, Equation 2 does not take into account the effect of friction, strain hardening, strain distribution, and deformation gradient, providing a homogeneous value of strain in the whole workpiece. During ECAP, significant grain refinement occurs together with dislocation strengthening, resulting in a significant enhancement in the strength of the alloys [64]. It is worthy of note that, the hardness (Vickers) incurred during the ECAE process by billets is mainly dependent on the strain imposed on the material [65]. This implies that the Vickers hardness of an ECAE processed material is a function of the strain path along channel length at where the shear strain is been imposed on the material, irrespective of the conditions of deformation. The difference between the states of strain at two points in the strain path is called finite strain if the interval between the two points is finite [66]. Thus, if the interval is infinitely small, then the strain path is known as an incremental strain.

In most SPD processes, (except high-pressure torsion), the deformation is applied with repetitive changes in the strain path. Especially in ECAE, several processing routes are available. The implications of the sample distortion have been described in detail. Fig. 9 represents the interactions of subsequent shear deformations in the first and second ECAE passes. A cubic element in the initial billet is elongated into a rhombohedra shape during the first ECAE pass. The elongation is visible in the XY plane. The first shear plane is active as indicated in Fig. 9(a). When the second passage through the die is carried out without rotation (route A), a further elongation in-plane XY occurs. A second shear plane, perpendicular to the first (when φ = 90°) is now active as shown in Fig. 9(b). In further passes, the 1st and 2nd shear planes are alternating active and further elongation occurs in each pass. Application of route C as depicted in Fig. 9(c), deformation always occurs along the same shear plane but alternating in the shear direction. The shape of an initial cubic element is restored after each 2N passes. Where "N" is an integer.

The [α] parameter as used by Venkatraman, *et al.* [57], Ramesh, *et al.* [67] as also introduced by Schmitt do quantitatively express the change of strain path from one pass to another as shown in Equation 12 as follows;

$$\alpha = \frac{\varepsilon_p \, . \, \dot{\varepsilon}}{\|\varepsilon_p\| . \|\dot{\varepsilon}\|} \qquad (12)$$

Where ε_p *and* $\dot{\varepsilon}$ are the strain rate tensors of the consecutive passes.

For the most drastic "orthogonal" change in strain path, $\alpha = 0$. For the monotonous strain, $\alpha = 0$ and strain reversal $\alpha = -1$. The ECAE die angle, α is majorly determined by the Route A passes. Route B is nearly orthogonal and has a relation: $-0.5 < \alpha < -0.25$, while in all cases, route C corresponds to strain reversal. In route B from the shear deformation, the cubic volume element is elongated in each orthogonal plane after the 2nd pass. For route B_A, the distortion will increase after each pass, but for route B_C the restoration of the cubic element is observed after each 4N passes. In both routes B_A and B_C, shear occurred on the shear planes intersecting at 120°. For a die angle of 90°, it was reported that route B is more efficient than A and C. For a die with φ = 120°, routes A and B are nearly as effective but C is less effective (see Fig. 9). Ductility loss appears to be a customary occurrence in some of the materials and this can be attributed to the non-equilibrium state of the grain boundaries such as the boundary sliding and the grain rotation [68].

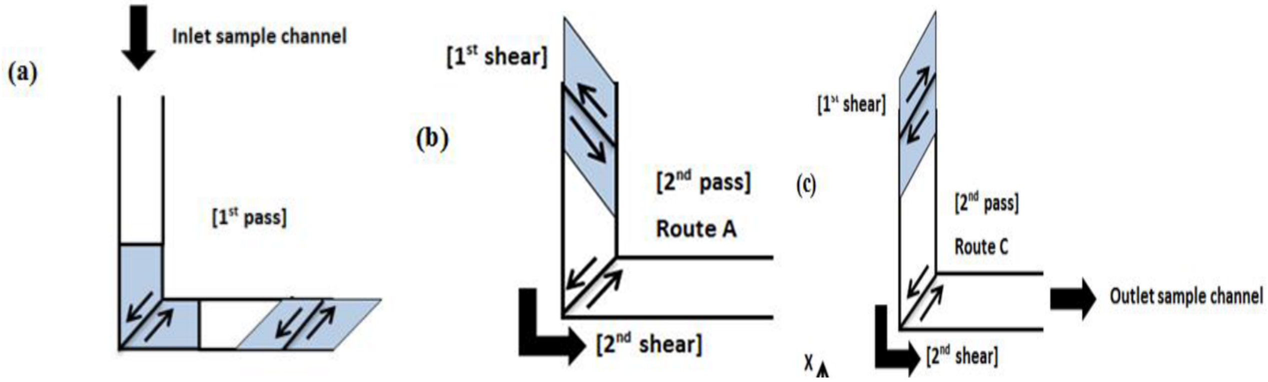

Figure 9: Interactions of consequent shear deformations in the first and second ECAE pass [16, 69].

A variety of materials is available for dies and tooling, each having its characteristics, applications, advantages, and limitations [69]. When selecting materials for the equipment, mechanical properties such as strength, toughness, machinability, ductility, elasticity, fatigue, and hardness should be taken into cognizance [70]. The cost and the availability of processed materials are also required for optimum output [71].

5.0 Concluding Remarks

Cubic element in the initial billet of material is forced through a die with two channels at a specific angle. The extruded sample through the outlet possessed new mechanical properties. ECAE routes have proved to produce ultrafine-grained bulk samples in a fully dense condition without changing the cross-sectional dimensions of the samples. Grain refinement by severe plastic deformation initiates the formation of new high-angle grain boundaries. Several changes in the grain sizes of the ECAE sample are dependent on the number of passes the sample is subjected to. During ECAE, significant grain refinement occurs together with dislocation strengthening and resulted in a significant enhancement in the strength of the deformed alloys.

In the foregoing review on processing of alloy and composite materials using extrusion, a severe Plastic Deformation (SPD) technique, the following conclusions can be drawn:

1. The Equal Channel Angular Extrusion (ECAE) process has been used over the years to improve the mechanical and microstructural properties of various alloy and composites metal matrix composites. The foregoing may be attributed to a well reported significant occurrence of superplastic flow in materials after ECAE processing of materials.
2. Nano-grained materials of grain size less than 1μm have been produced with the use of ECAE. Reported works showed that refinement occurred from 500 μm to 0.6 μm after four passes through a 90° die for an Al-1%Mg alloy during the extrusion process. This indicated that the SPD techniques remain a viable way of improving the microstructural properties of engineering materials.

3. In ECAE processed materials, microstructure of equiaxed grains separated by high angle boundaries is a prerequisite for achieving high tensile ductility.
4. Mechanical properties of ECAE processed samples may also depend on factors such as strain rate and temperature as the case with other processes. Strength (UTS and YS) and ductility usually increase with the first couple of passes. However, there is paucity of information on the use of Hopkinson pressure bar method to test the plastic deformation characteristics of ECAE processed materials.
5. An increase in extrusion temperature resulted in the development of equiaxed-like grains in aluminium-based alloys such as AA5052. Therefore, a severe plastic deformation process gives a better way of improving the mechanical and microstructural properties of most engineering materials without altering the geometry of such material.

6. Suggestions for Future Research Directions

Although laudable efforts on the choice of severe plastic deformation technique for enhancing properties of most alloy-based materials has been made, its cost implication as a processing technique attracts enormous concern among material scientists and engineers. Thus, numerical simulations could be used as an alternative to experimentation because of their cost-effectiveness. Therefore, further research works in this regard are suggested as follows:

- It is suggested that 3D technology should be used in this kind of work to minimise the project cost implication.
- For educational advancement and better appreciation of the 3D numerical simulation, tool wear analysis should be done on the billet materials under consideration in order to achieve homogenous stress-strain distribution on the workpiece.
- Stress-strain agglomeration commonly situated at the Die corner angle in SPD techniques which normally led to material wear should be properly addressed using multiple-stage extrusion processes at reasonable lubrication conditions.
- It is also suggested that while performing the SPD technique experiment, reasonable lubrication of the extrusion Die shear plane and Metal Matrix Composites (MMC) should be encouraged in order to avoid any form of damage or fracture on the material.

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Conflict of Interest: The authors declare that they have no conflict of interest

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