CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

The rising demand for light weight alloys such as Aluminum, magnesium and copper in aircraft, missiles, electronics, nuclear, aerospace, and commercial fields has received significant attention in recent years due to their potential advantages of high strength, hardness, wear and corrosion resistance, dimensional stability, good ductility, machinability and formability (Murat Aydin 2012; Boguslawa et al 2011; Karthikeyan et al 2010 and Zhang et al 2004). Every single product made by these alloys must be designed and fabricated to perform a specific function in an efficient way to withstand certain operating conditions without failure during its entire useful life. To meet these stringent requirements, it is not only necessary to develop new materials but, equally important to identify the methods to fabricate them into useful engineering components. Among the many manufacturing methods, metal forming plays a major role in terms of improved mechanical and metallurgical properties.

Grain refinement is one of the techniques used to improve the mechanical properties of polycrystalline metals. In the 1990s Severe Plastic Deformation (SPD) processes such as Equal Channel Angular Pressing (ECAP), Accumulative Roll Bonding (ARB) and High Pressure Torsion (HPT) processes, have attracted the attention of researchers, because grain sizes of several hundred nanometers can be obtained using these processes.

Ultra Fine-Grain (UFG) metals produced by SPD processes show high strength consistent with the Hall-Petch relationship, and they also exhibit unusual mechanical properties compared to coarse-grained metals; for instance, a sudden decrease in uniform elongation, strain-rate sensitivity, flow stress, and significant improvement of low-temperature toughness. Twist Extrusion (TE) is a relatively new and attractive SPD technique in a group of metal forming processes, through which large strains are induced in the material in order to obtain grain refinement. The main objective of this research is to experimentally investigate the influence of various parameters, like extrusion load, temperature, and number of passes, on the mechanical and metallurgical properties, during the twist extrusion of AA 6xxx & AA 7xxx series alloys, and to suggest a suitable material with optimum mechanical properties. Before discussing the subject of this research in detail, it is essential to provide some background information, and a state-of-the-art review on the extrusion process technology.

1.2 BACKGROUND OF THE EXTRUSION PROCESS

Extrusion is a process that compresses the metal or plastic to flow through a suitably shaped die to form the product with reduced but constant cross section. The commercial exploitation of this process started early in the nineteenth century with the extrusion of lead pipes. Extrusion of steels became possible only after 1930 when extrusion chambers could be designed to withstand high temperature and pressure. The material is plastically deformed under the compression in the die cavity. Extrusion produces compressive and shear forces in the stock. The process can be carried out either hot or cold, depending on the ductility of the material. Because of the large forces required in extrusion, most metals are extruded hot to reduce the forces required, eliminate cold working effects and reduce the directional properties. However, cold extrusion is possible for many metals such as

Aluminum, magnesium and lead and its alloys and has become an important commercial process. These materials exhibit relatively low yield strength at hot working temperatures. Steels, stainless steels, nickel-based alloys and titanium are far more difficult to extrude. Their yield strengths are high and the metals tendency to weld with the wall of die. Further the confining chamber requires necessary conditions of temperature and pressure. The reaction of the extrusion billet with the container and die results in high compressive stresses that effectively reduce the cracking of materials during primary breakdown from the ingot. This is an important reason for the increased utilization of extrusion on the working of metals difficult to form, like stainless steel, nickel based alloys and other high temperature materials.

The variables influencing an extrusion process are: (i) the percentage of area reduction, (ii) the die geometry, (iii) the product geometry, (iv) the speed of extrusion, (v) the billet temperature, and (vi) lubrication. This process produces a wide variety of cross-sections that are hard to produce cost-effectively using other methods.

The main advantages of this process over other manufacturing processes are, its ability to create complex cross-sections even with the work materials that are brittle. Extrusions often minimize the need for secondary machining and also form finished parts with an excellent surface finish. The overall surface finish obtained by the extrusion process for steel is 3 μm; and for Aluminum and Magnesium it is 0.8 μm. Aluminum extrusions also find extensive use in automobiles, railway coaches and marine applications. The other applications of Aluminum extrusion include conveyors, aerospace products, architectural framing, circuit board, modern house hold fittings, medical equipment, vending machines, and cable products. Extrusion has many attracting features.

1. Many shapes can be produced in extrusion that is normally impossible by rolling such as one containing re-entrant angles or longitudinal holes.
2. No need for draft thereby ensuring saving in both metal and waste.
3. Less expensive die.
4. Conversion from one product to the other requires single die change which ensures small quantities can be produced accurately.
5. Compared to other deformation process single stage reduction can be possible.

The major limitation of this process is the requirement that the cross-section to be uniform for the entire length of the part.

1.3 TYPES OF EXTRUSION PROCESSES

According to the direction of the metal flow, the extrusion process can be classified as Direct (or) Forward extrusion, and Indirect (or) Backward extrusion. According to various techniques, it is classified as Cold extrusion, Warm extrusion, Hot extrusion, Impact extrusion and Hydrostatic extrusion.

1.3.1 Direct Extrusion

In the direct extrusion process, the billet is pushed through the die by ram pressure, and the direction of the metal flow is in the same direction as the ram travel. In this process, the billet slides relative to the walls of the container. Because of the relative motion between the heated billet and the container walls, the friction is severe and is reduced by using molten glass as a lubricant in case of steels at higher temperatures. The friction with container opposes forward motion of the billet. At lower temperatures, oils with graphite powder are used for lubrication. The schematic illustration of the direct extrusion process is shown in Figure 1.1.

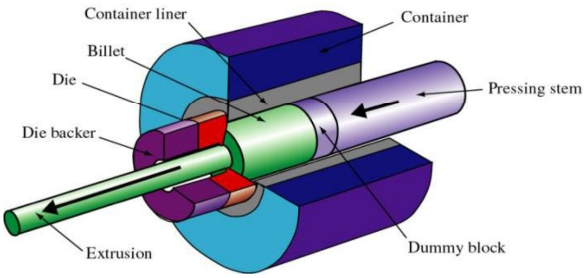


Figure 1.1 Schematic sketch of the Direct Extrusion Process

1.3.2 Indirect Extrusion

In the indirect extrusion the billet is stationary and the metal flows in the opposite direction of the ram. The billet chamber side wall friction is eliminated since there is no relative motion. The required force is lower. The added complexity of the indirect process such as applying force through hollow ram, extracting product through hollow and removing residual billet material at the end of the stroke serves to increase the operation and maintenance cost. It is more efficient since it reduces the friction losses considerably. The schematic illustration of the indirect extrusion process is shown in Figure 1.2.

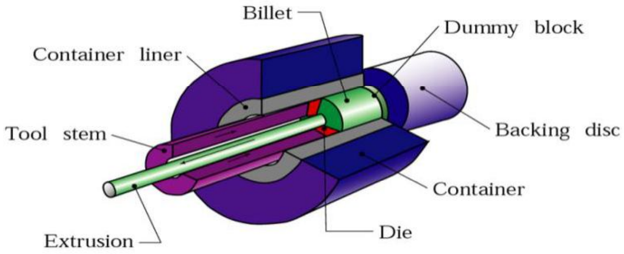


Figure 1.2 Schematic sketch of the Indirect Extrusion Process

1.3.3 Hot Extrusion

The Hot Extrusion process is generally performed at high temperatures, approximately 50 to 75 % of the melting point of the metal, which keeps the materials away from work hardening. In general, most of the hot extrusions are done using horizontal hydraulic presses ranging from 250 to 12,000 tons. The pressure range is 30 to 700 MPa. Depending on the type of material the appropriate lubrication is decided. Aluminum alloys are generally non-lubricated, while Steel, Titanium, and Copper alloys are typically lubricated (Semiation et al 2005). Glass powder is commonly used as a solid lubricant for higher temperature extrusions while graphite or palm oil for all the lower temperature extrusions.

1.3.4 Warm Extrusion

The Warm extrusion process is carried out above the room temperature, but below the material's re-crystallization temperature. Generally, the warm extrusion temperature ranges from 424 to 975 °C. Warm extrusion is generally recommended when it is desired to acquire a proper balance of all the requisite forces, final extrudate properties, and ductility. By using warm extrusion equipments, the extrusion ratio may become very high, but the best part is that it still produces high quality parts. The extrusion ratio can be defined as the initial cross-sectional area divided by the final extrusion's cross-sectional area.

1.3.5 Cold Extrusion

The Cold Extrusion process is carried out at room temperature or at marginally elevated temperature. A punch is used to apply pressure to the billet enclosed, partially or completely, in a stationary die. Cold extrusion is highly advantageous, as it withstands the stresses that are created by the extrusion process. The other advantages of cold extrusion include improved surface finish, good mechanical properties, good dimensional precision, high production rates and absence of oxide layers (Kalpakjain and Schmid 2003). The specific drawback of the process is higher loads, limited deformation, higher lubrication cost, and limited shape complexity. Copper and copper alloys, Aluminum and Aluminum alloys, carbon steels, alloy steels, and stainless steels can be cold extruded (Semiation et al 2005).

1.3.6 Impact Extrusion

Impact extrusion is a type of cold extrusion process which is similar to the indirect extrusion process. The properly lubricated billet is placed into a die cavity and then impacted with a single stroke by a punch. This forces the metal to flow back around the punch through a small clearance between the die and the punch. Impact extrusion is best suited for soft materials like lead, Aluminum or tin. This method is commonly used for producing very thin wall tubular sections made of non-ferrous alloys. The schematic illustration of the impact extrusion process is shown in Figure 1.3.

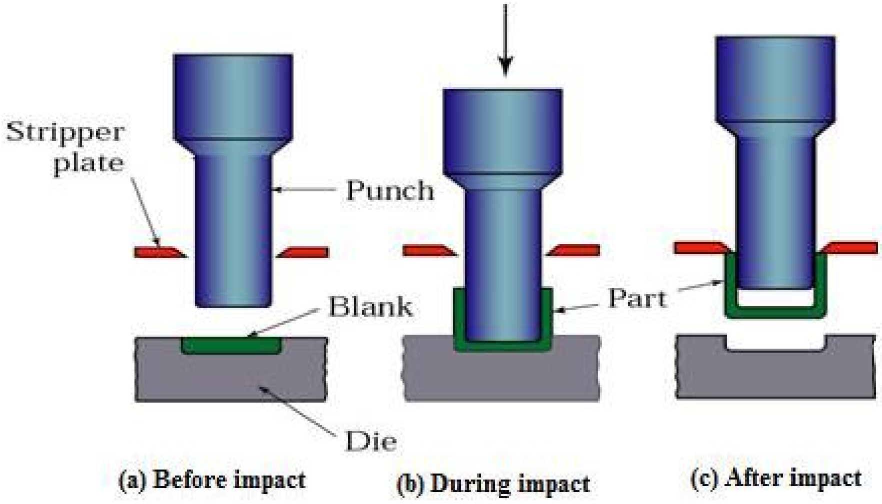


Figure 1.3(a-c) Schematic sketches of the Impact Extrusion process

1.3.7 Hydrostatic Extrusion

Hydrostatic Extrusion is usually performed at room temperature. The pressure required for the deformation of the work piece is supplied by means of a fluid surrounding the billet. Since the hydrostatic pressure increases the ductility of materials, a variety of high strength materials, including brittle ones can be successfully extruded by this method (Kalpakjain and Schmid 2003; Semiation et al 2005). In this process the friction between the container wall and the billet is eliminated; however, this process has limited applications due to the need for specialized equipment and tooling. Further it results in low production rate with higher set up time. The schematic illustration of hydrostatic extrusion process is shown in Figure 1.4.

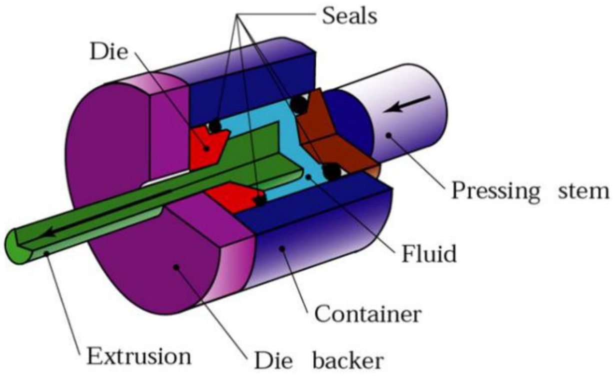


Figure 1.4 Schematic sketch of the Hydrostatic Extrusion Process

1.3.8 Extrusion Defects

The following are the defects that occur in the components produced by extrusion processes.

(a) Centre bursts – The centre burst is formed when the centre of the extrusion develops cracks or voids. These cracks are due to a state of hydrostatic tensile stress at the centreline in the deformation zone. (A similar situation that arise in the necked region in a tensile stress specimen)

(b) Piping – A flow pattern that draws the surface oxides and impurities to the center of the product. Such a pattern is often caused by high friction or cooling of the outer regions of the billet.

(c) Surface cracking – When the surface of an extrusion splits the surface cracking is formed. This is often caused by the improper extrusion temperature, friction, or too high a speed. It can also happen at lower temperatures, if the extruded product temporarily sticks to the die. The schematic sketch of the extrusion defects is shown in Figure 1.5.

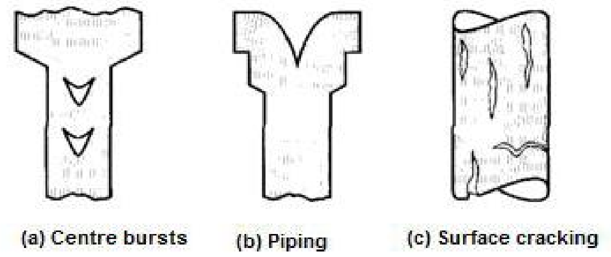

(a) Centre bursts (b) Piping (c) Surface cracking

Figure 1.5(a-c) Schematic sketches of the Extrusion Defects

1.4 SEVERE PLASTIC DEFORMATION

The rapid developments of nano technology have made an intense impact on the field of materials research. Grain size is an important microstructural factor affecting all the aspects of physical and mechanical behaviour and chemical and bio-chemical responses of polycrystalline metals. Control of grain size has long been recognized as a step towards the design and development of the materials with desired properties. SPD is one of the significant avenue for grain refinement. Metals with grain sizes smaller than

1μm have received much attention in the past decade. These materials have been classified as Ultra Fine grain (UFG) materials (grain sizes in the range of 100 to 1000-nm) and nano-materials (grain size <100-nm) depending on the grain size. The range of grain sizes developed by different materials is shown in Figure 1.6. There are two approaches for the synthesis of nanomaterials. These are known as "bottom up" and "top down" approaches. In the bottom up approach, atoms, molecules and even nanosize particles can be used for the creation of complex nanostructures. In the "top down" approach coarse-grained materials are refined into ultra-fine grained/nanostructured materials.

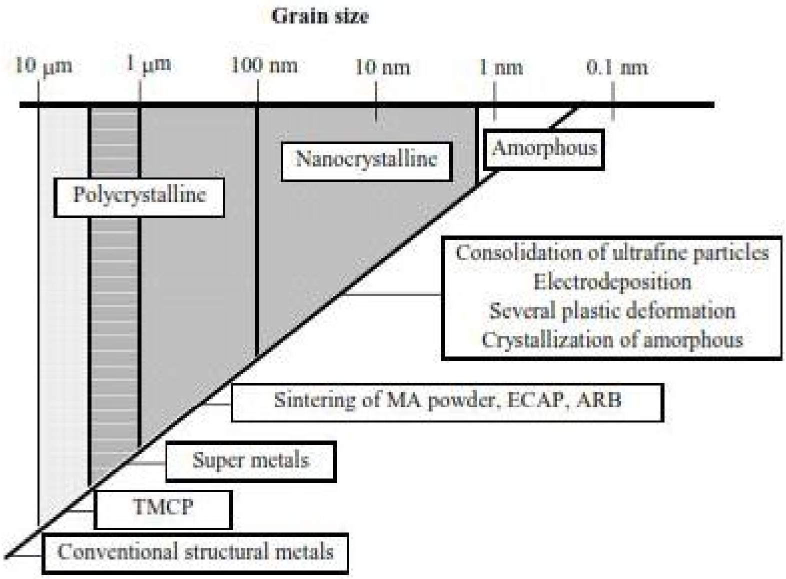


Figure 1.6 Grain size range developed by different materials

The severe plastic deformation (SPD) technique is one of the top down approaches, where extremely high strains are imposed at relatively low temperatures (Valiev & Aleksandrov (1999); Valiev et al 2000). SPD is a modified form of "intensive plastic deformation". The term severe plastic deformation was first introduced by Musalimove and Valiev in 1992. These techniques are quite popular due to their ability to produce considerable grain refinement in a fully dense, bulk- scale work pieces thus providing promising applications for structural and the related areas. The achievable grain size lie within sub micro meter and nano meter ranges. Another main feature of the SPD processes is that the external dimensions of the work piece remain unchanged. This allows for the repeated application of the process to accumulate larger strains. Microstructure refinement by SPD is based on a general trend for the formation and evolution of dislocation substructures consisting of cells and sub grains during large plastic strains common for all metals and alloys.

Materials processed by the SPD have shown superior mechanical properties such as high strength, excellent fatigue life, high toughness and low temperature super-plasticity. As the specific material properties are becoming stringent in the current developmental scenario, there is a continuing increase in the market for high-strength metals and alloys. These materials find applications in aerospace, automobile, transportation, food and chemical processing, electronics, and conventional defence industries. The market emphasis and exceptional material properties' requirements have led to a considerable interest in the development of ultra-fine grained/nanomaterials by severe plastic deformation.

1.5 METHODS OF SEVERE PLASTIC DEFORMATION

Several methods of SPD are available for refining the microstructure in order to achieve superior strength and other properties. The various SPD processes are shown in Figure 1.7. These techniques enjoy great popularity owing to their ability to produce considerable grain refinement in fully dense, bulk-scale work pieces, thus giving promise of structural applications. The achievable grain sizes lie within the sub micrometer (100–1000 nm) and nanometer (<100 nm) ranges. SPD processed materials with such grain sizes are generally referred to as nano SPD materials.

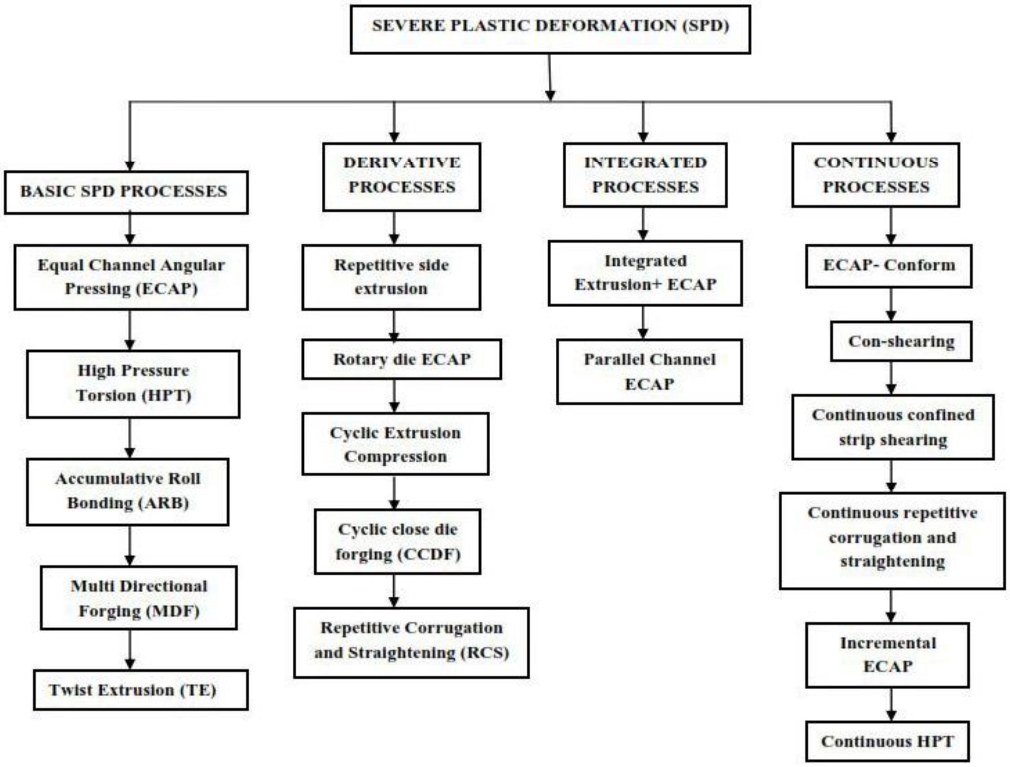


Figure 1.7 Flow chart of various SPD Processes

1.5.1 High Pressure Torsion

The High Pressure Torsion (HPT) technique is based on the use of the Bridgeman anvil-type device (Hebesberger et al (2005); Hafoka & Pippana 2007). This process involves a combination of high pressure and torsional strength. A disk-shaped sample is placed between a pair of anvils and the work is subjected to a high pressure of 2-5 GPa. The schematic sketch of the HPT process is shown in Figure 1.8. The rotation of one of the anvils forces the sample to deform by torsion. Up to five rotations of the anvil are usually enough to form a homogeneous microstructure with the grain size typically about 100 nm – 50 nm. The HPT is best suited for materials such as Aluminum, copper, nickel, and titanium and its alloys. The effective strain achieved by this process can be calculated from the Equation (1.1) (Estrin et al 2013).

$$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\frac{\pi r}{t} \tag{1.1}$$

where, r - distance from the axis
t - thickness of the sample
N - number of revolutions.

This method enables the preparation of disc-shaped samples with a diameter of upto 20 mm and thickness of about 0.2 mm.

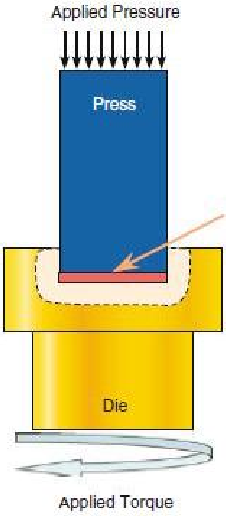


Figure 1.8 Schematic Sketch of the High Pressure Torsion Process

1.5.2 Accumulative Roll Bonding

In ARB, the rolled material is cut, stacked and rolled again. Therefore, the achieved strain is unlimited, because the repetition times are endless (Saito et al 1999). The schematic sketch of the ARB process is shown in Figure 1.9. The stacked sheets are bonded simultaneously during rolling. That is, ARB is not only a deformation process but also a roll-bonding process. The effective strain achieved by this process can be calculated from the Equation (1.2) (Estrin & Vinogradov 2013).

$$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\ln\frac{t_0}{t} \qquad (1.2)$$

Where, t_0 - initial thickness of the sample
t - thickness of the sample after rolling
N - number of passes.

To achieve good bonding, the degreasing and wire-brushing of the sheet surface are necessary before stacking. The sequence of rolling, cutting, brushing and stacking operation is repeated so that ultimately a large strain is accumulated in the sheet. Rolling at elevated temperature is advantageous for joinability and workability; though too high a temperature would cause recrystallization and cancel the accumulated strain. Therefore, the rolling (roll-bonding) in ARB is preferably carried out at ‘warm’ temperatures. Unlike conventional rolling, UFG structure formed in the course of repetitive rolling is not uniaxed but exhibit pan cake like grain irrespective of type of metal or alloy processed. ARB may be applied successfully for a wide range of materials such as commercial purity Aluminum, Al-Mg alloy and interstitial free steel. Further Al-Mg based laminated structure of composites can be made.

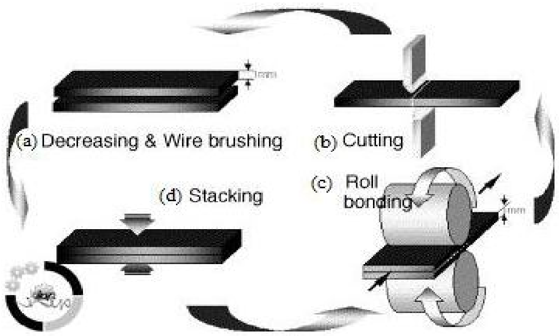
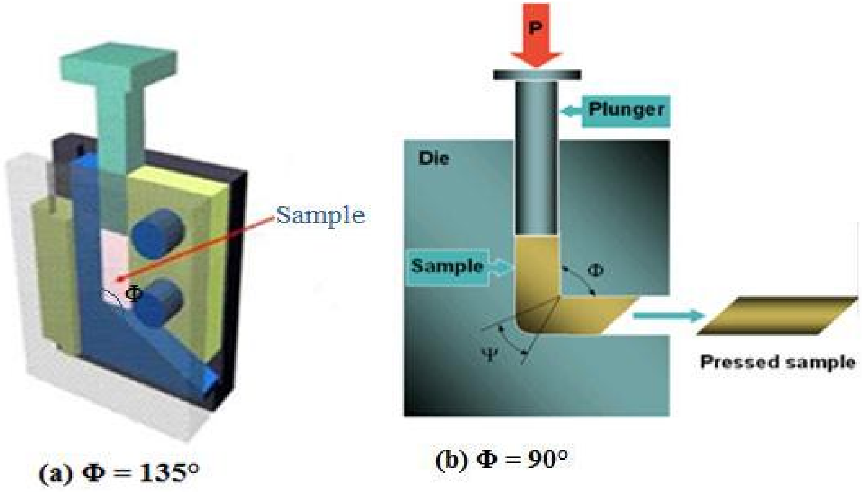


Figure 1.9(a-d) Schematic sketches of the Accumulative Roll Bonding process

1.5.3 Equal Channel Angular Pressing

This technique has originally been developed by Segal (1995). A billet of the test material is pressed through a die consisting of two channels with identical cross sections, intersecting at an angle Φ, usually 60° < Φ < 135° and often Φ =90°. Some dies have a rounded corner with angle ψ, others have ψ = 0 (Azushima et al 2008). The schematic sketch of the ECAP process is shown in Figure 1.10 (a and b).



(a) Φ = 135°

(b) Φ = 90°

Figure 1.10(a-b) Schematic sketches of the Equal Channel Angular Pressing process

In the vicinity of the plane of intersection of these channels, the material undergoes severe plastic deformation, which is mainly of a simple shear strain upon passing the billets between two channels, the cross sectional dimensions of the billet remains unchanged, thereby permitting repetitive pressing causing the accumulation of large strain. The ECAP process can be applied for wide range of materials such as Ti, Cu, Cu-Al, Cu-Zn, Al-Mg-Sc and Al-Mg-Si alloys (Estrin & Vinogradov 2013). The effective strain achieved by this process can be calculated from the Equation (1.3).

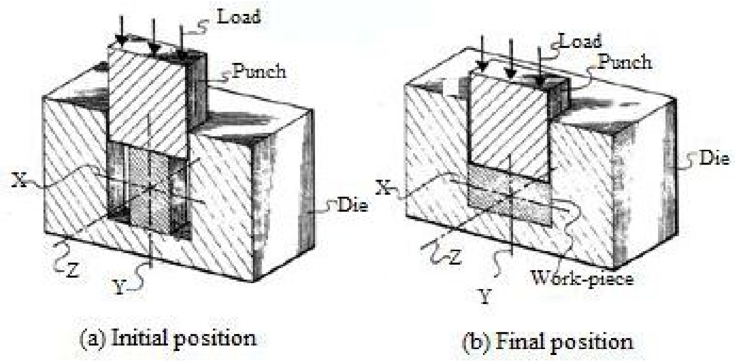
$$\varepsilon_{eff} = N \frac{2}{\sqrt{3}} Cot(\Phi) \tag{1.3}$$

where, N – Number of ECAP passes

Φ - Channel intersecting angle

1.5.4 Multi-Directional Forging (MDF)

Multi-Axial Compression/Forging, also known as Multi-directional forging (MDF), was proposed in the first half of the 1990s as a technique for micro structural refinement. Multi-Axial Compressions/Forgings involves the deformation of a rectangular cross section samples through a series of compressions, so that the initial dimensions of the billet are retained. The loading direction is changed through 90º between successive compressions (Cherukuri 2004). A schematic sketch of the one step multiple forging is shown in Figure 1.11(a and b).



(a) Initial position (b) Final position

Figure 1.11(a-b) Schematic sketches of the Multi Directional Forging Process

Multi-Axial Compression/Forging is effective in producing a fine grain structure, but the drawback of this process is the non-uniform strain distribution along the billet cross-section. However, this non-uniformity can be eliminated by very good lubrication of the billet, and through a large number of compression/forgings steps. The effective strain achieved by this process can be calculated from Equation (1.4).

$$\varepsilon_{eff} = N\frac{2}{\sqrt{3}}\ln\frac{a}{b} \tag{1.4}$$

where, *a*-width of the sample*;* *b*-breadth of the sample and *N* – number of processing steps. Since MDF is commonly performed in the temperature interval of 0.1–0.5T_m, where T_m is the melting temperature, grain refinement during MDF is usually associated with dynamic recrystallization. The homogeneity of the strain produced by MDF is lower than for ECAP or HPT. However, the method can be used for microstructural refinement in rather brittle materials, owing to higher temperatures and the low specific loads on tooling involved. Furthermore, MDF was demonstrated to be a potential technique for manufacturing large-size billets with microcrystalline (UFG) structures which was successfully applied to a wide range of materials.

1.5.5 Repetitive Corrugation and Straightening

In the RCS process, a workpiece is repetitively corrugated and straightened without significantly changing the cross-section geometry (Huang et al 2001). The schematic sketch of the RCS process is shown in Figure 1.12. Continuous repetitive corrugation and straightening have been conducted by strip drawing through toothed rolls (corrugation) and plain rolls (straightening) sets. The effective strain achieved by this process can be calculated from Equation (1.5).

$$\varepsilon_{eff} = N\frac{4}{\sqrt{3}}\ln\frac{r+t}{r+0.5t} \tag{1.5}$$

where, N - number of cycles

t - thickness of the work piece

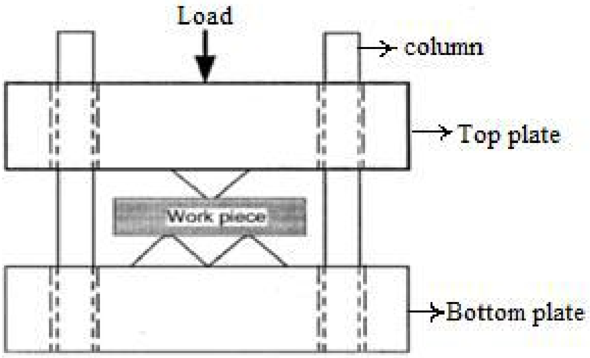


Figure 1.12 **Schematic sketch of Repetitive Corrugation and Straightening process**

1.5.6 Con-shearing Process

The con-shearing process is a continuous pure shear deformation process. During the process, the sheet material is guided to an equal channel die by a large centre roll, small satellite rolls, and guide shoe, as shown in Figure 1.13. The material undergoes pure shear deformation as it passes through the equal channel die. Since the die has equal channels, the thickness of the sheet is not changed, which allows multiple passes to accumulate more strain in the material (Lee et al 2002).

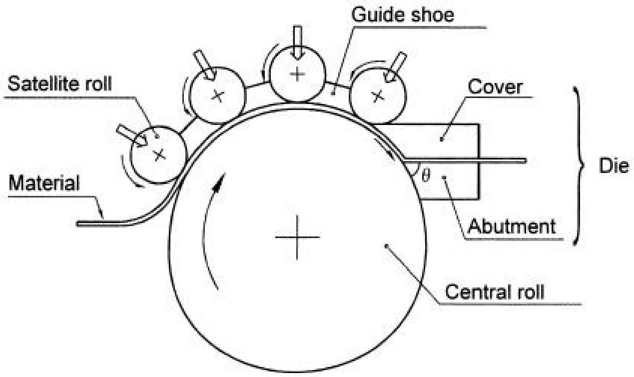


Figure 1.13 Schematic sketch of the Repetitive Con-shearing Process

1.5.7 Twist Extrusion

Twist extrusion process (TE) is a severe plastic deformation process which was first invented in 1999 by Y.Y.Beygelzimer of Donetsk Physicotechnical institute, Ukraine. The basic principle of this process is to press out a prismatic specimen through a die with a profile consisting of two prism sections separated by a twist section. The effective minimum and maximum strain achieved by this process can be calculated from the Equations (1.6 and 1.7) respectively.

$$\varepsilon_{eff}^{\min} \approx 0.4 + 0.1 \tan \beta \tag{1.6}$$

$$\varepsilon_{eff}^{\max} \approx N \frac{2}{\sqrt{3}} \tan \beta \tag{1.7}$$

Where, β - Twist line slope angle

N - Number of passes

This process uses extensive hydrostatic pressure to impose very high strain on bulk solids, producing exceptional grain refinement without introducing any significant change in the overall dimensions of the sample. As the specimen is processed, it undergoes severe plastic deformation while maintaining its original cross section (Beygelzimer et al 2006; Akbari Mousavi et al 2008) The schematic sketch of twist extrusion process is shown in Figure 1.14.

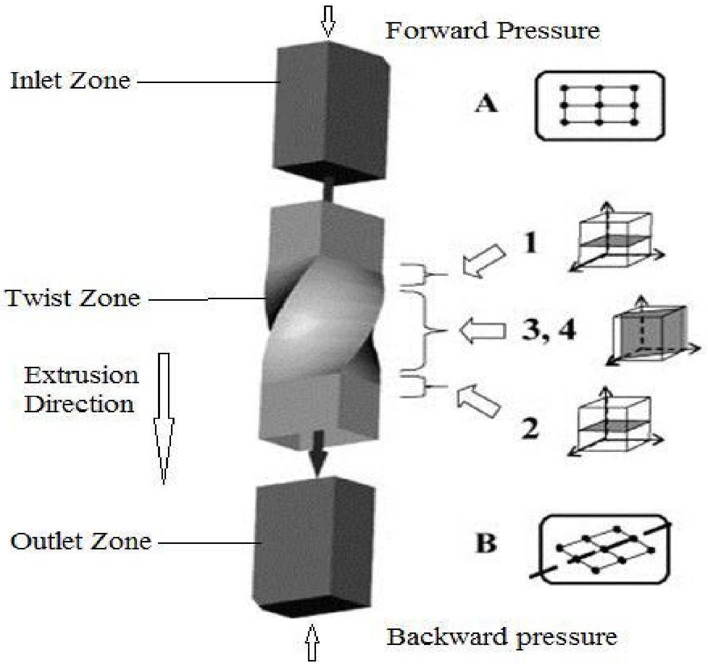


Figure 1.14 Schematic sketch of Twist Extrusion Process

1.6 IMPORTANCE OF TWIST EXTRUSION

The high strength and good ductility in several bulk ultra-fine grained metals produced by severe plastic deformation have received special interest (Valiev 2000). Several articles recently reported that the UFG materials maintain both high strength and adequate ductility. The grain refinement by SPD can lead to a unique combination of strength and ductility in metallic materials. Such superior mechanical properties are highly desirable in the development of advanced structural materials for the next generation. However, the achievement of these properties is associated with further treatment, to create a specific microstructure that is responsible for improving the ductility of the material.

During the last two decades SPD has emerged as a widely known procedure for the grain refinement of metals and alloys into sub-micrometer or even nanometer range. The synthesis of UFG materials by SPD refers to various experimental procedures of metal forming that may be used to impose very high strains on materials leading to exceptional grain refinement. High deformation at comparatively low homologous temperatures, is an efficient method of production of ultra-fine grained solid materials. Among the mentioned methods for the production of bulk UFG materials with an equiaxed microstructure and high angle grain boundary misorientation, ECAE and TE are promising ones for commercial and industrial use. A simple shear stress state is the most effective mode in obtaining ultra fine grained (UFG) materials, and it is the predominant mode in both the latter methods. Twist extrusion is one of the severe plastic deformation processes which has been successfully employed for the extrusion of copper (Beygelzimer et al 2009), titanium (Akbari Mousavi et al 2008 and Stolyarov et al 2005) and Aluminum (Orlov et al 2009; Zendehdel & Hassani 2012) to produce long, straight semi-finished products in the form of solids and hollow cross sections with various complexities.

In comparison with ECAE, TE provides some benefits, such as the ability to extrude hollow parts and rectangular cross-sections. In addition, it is possible to produce more isotropic and homogeneous deformation, by turning the samples through 90° in each consecutive deformation or alternatively, make use of consecutive clockwise–anticlockwise–clockwise twists. This feature is very important for electronic and magnetic materials. Therefore, the present work has been undertaken to develop fine grained Aluminum alloys by twist extrusion process and to examine the microstructure and mechanical properties of the twist extruded samples. TE can be applied for a wide range of materials such as Cu, Ti alloys, commercial purity Aluminum, Al-Mg alloys, Al-Mg-Si alloys, and Al-Mg-Zn alloys.

Aluminum alloys with ultra-fine structure serve as basic, initial semi-products. Their development uses technologies for the achievement of nano-structural materials. The achievement of an ultra-fine grained structure in the initial material leads to a substantial increase in plasticity, and makes it possible to form materials in conditions of super-plastic state. The tool geometry, number of passes through the matrix, obtained deformation magnitude and strain rate, process temperature and lubrication conditions play important role to achieve required structure.

1.6.1 Features of Twist Extrusion

- The size of the terminating distorted areas of the specimen, that is, the head and rear parts, of the billet, is much smaller under TE than under ECAE, which is especially important when doing repeated runs.
- TE can handle profile billets including those with an axial channel.
- TE can easily be installed on any standard extrusion equipment, by replacing a standard reduction die with a twist die.
- TE (unlike ECAE) does not change the direction of a billet's movement, which allows TE to be easily embedded into existing industrial lines (Yan Beygelzimer et al 2006).

1.6.2 Benefits of Twist Extrusion

There are currently three main benefits of Twist Extrusion:

- Obtaining ultra-fined grained crystalline and nano-crystalline structures in bulk specimens.

- Increasing the plasticity of secondary non-ferrous metals and alloys, which allows one to significantly broaden the range of production.
- Obtaining bulk specimens by consolidating porous materials which allows one to create substantially different, new compositions with unique characteristics (Beygelzimer et al 2006),

1.6.3 Applications of Twist Extrusion

- Aerospace-Engine components (blades, discs, rings and engine cases)
- Airframe components (tail sections, landing gear, wing supports and fasteners)
- Automotive applications- Clamps in locking devices, fasteners in racing bikes.
- Medical devices-joint replacement (hip balls and sockets), surgical instruments, wheel chairs etc.
- Sports products - Weight-sensitive products, such as high-performance mountain bicycles, tennis rackets.
- Food and Chemical industries-Heat exchangers, tanks, process vessels etc.

The components processed by twist extrusion process are shown in Figure 1.15.

(a) Machine component (b) Automobile component

(c) Electrical component

Figure 1.15(a-c) Components processed by Twist Extrusion Process

1.7 LIMITATIONS OF SPD METHODS

Strength and ductility are the key mechanical properties of any material, but these properties typically have opposing characteristics. The materials processed by SPD methods may be strong but rarely ductile. The experimental investigation on UFG materials, processed by severe plastic deformation indicates, that they possess very high hardness and strength, but their ductility, particularly uniform elongation in tension has been rather low (Koch, 2003). A similar tendency is well known for metals, subjected to heavy straining by other processes such as rolling or drawing. The UFG materials processed via SPD have no capability to sustain a sufficiently high rate of strain hardening, and start necking soon after yielding which is a major short-coming of UFG materials. These drawbacks could be a barrier in bringing bulk UFG materials from the laboratory to the market.

1.8 ALUMINUM ALLOYS AND THEIR IMPORTANCE

The development of materials and processes is progressively more challenging and demanding. Many research innovations produced new materials or existing materials in different forms, which paves the way for new possibilities of applications and products. In 1808 Sir Humphrey Davy, the British electrochemist, established the existence of aluminum, and it was not until 17 years later, that the Danish scientist Oersted produced the first tiny pellet of the metal. In 1845 the German scientist Wohler, discovered the specific gravity of aluminum and also discovered that it was easy to shape, stable in air, and could easily be melted. Experiments in production techniques enabled Henri Saint-Clair Deville to display a solid bar of the metal at the Paris Exhibition in 1855. But it cost him a fortune to produce, making Aluminum more precious than gold, silver or platinum at that time. Napoleon III became enthusiastic about the possibilities of this new material, mainly for military purposes, and sponsored Deville in his efforts to find a low-cost method of production, so that it could be made and used in large quantities.

Aluminum alloys are used in advanced automotive applications, as their combination of high strength and light weight reduction improves the performance of the vehicle, due to rolling resistance and energy of acceleration, thus reducing the fuel consumption. In addition to these properties, Aluminum alloys possess an excellent strength to weight ratio, corrosion resistance, improved wear resistance, superior fracture toughness, and good thermal conductivity etc., which make them attractive for aerospace industries.

It is necessary to differentiate between wrought and cast alloys. Both these alloy types are subdivided into those alloys that are solution heat treatable and those that are not. Wrought alloys are generally used for further fabrication, for example, rolling, forging, extrusion, and drawing. Cast alloys are used in casting and have favourable flow characteristics. The most important elements that are added to Aluminum, are bismuth (Bi), boron (B), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), manganese (Mn), nickel (Ni), silicon (Si), titanium (Ti), zinc (Zn), and zirconium (Zr). Magnesium is the most frequent addition to Aluminum. In some alloys, two or more elements are used in combination (e.g., magnesium together with silicon or manganese).

Table 1.1 illustrates the Aluminum Association alloy designation system for wrought and cast alloys. The Wrought Alloy Designation System considers the 4-digit wrought Aluminum alloy identification system. The first digit (Xxxx) indicates the principal alloying element, which has been added to the Aluminum alloy, and is often used to describe the Aluminum alloy series, i.e., 1000 series, 2000 series, up to 8000 series.

The 1XXX series is the group with minimum purities of 99.00% and more. The last two of the four digits indicate the minimum percentage of Aluminum. For example, 1060 indicates the Aluminum purity of 99.60%. The second digit indicates modifications in the impurity limits or alloying elements. If the second digit is zero it indicates unalloyed Aluminum having natural impurity limits; integers 1-9 indicated special control of one or more individual impurities or alloying elements. For example, 1145 indicates Aluminum of 99.45% minimum purity, with the second digit 1 indicating special control of Iron and Silicon.

In the 2XXX to 8XXX groups, the last two of the four digits have no special significance, but serve only to identify the different alloys in the group. The second digit indicates alloy modifications; if it is zero it indicates the original alloy. National variations consisting of minor changes in the chemical composition of a standard alloy are accepted in the international system and are identified by a suffix letter after the numerical designation, e.g. 6101A. Experimental alloys are indicated by the prefix X, eg. X2030.

Table 1.1 The Aluminum Association alloy designation system (ASM Metals Hand book 1991)

The Aluminum Association alloy designation system			
Wrought Alloys	**Series**	**Cast Alloys**	**Series**
Al (99.00% minimum or greater)	1XXX	Al (99.00% minimum or greater)	1XX.X
	Alloys grouped by major alloying elements		
Cu	2XXX	Cu	2XX.X
Mn	3XXX	Si + Cu or Mg	3XX.X
Si	4XXX	Si	4XX.X
Mg	5XXX	Mg	5XX.X
Mg and Si	6XXX	Zn	7XX.X
Zn	7XXX	Sn	8XX.X
Other elements	8XXX	Other elements	9XX.X
Unused Series	9XXX	Unused Series	6XX.X

The physical properties exhibited by Aluminum alloys are significantly influenced by the treatment of the sample. A standardized system has been developed to designate these treatments as follows.

‘F’ - As Fabricated - No special control has been performed to the heat treatment or strain hardening after the shaping process, such as casting, hot working, or cold working.

‘O’ -Annealed - This is the lowest strength, highest ductility temper

‘H’ - Strain Hardened - (applied to wrought products only) Used for products that have been strengthened by strain hardening, with or without subsequent heat treatment. The designation is followed by two or more numbers.

‘W' - Solution Heat Treated - This is seldom encountered because it is an unstable temper that applies only to alloys that spontaneously age at ambient temperature after heat treatment.

‘T’ - Solution Heat Treated - Used for products that have been strengthened by heat treatment, with or without subsequent strain hardening. The designation is followed by one or more numbers.

1.8.1 Aluminum Alloys in Extrusion and Severe Plastic Deformation

Despite being an old bulk deformation process, extrusion is an active area of research around the world. Based on a report from the European Aluminum association, the demand for Aluminum products dramatically increased from the year 2000. The extrusion fabrication process is usually the most economical way to make parts that have a most constant cross section, because the extrusion process puts the metal where it is needed resulting in a very strong part with relatively low weight. The AA6xxx (Al-Mg-Si) series have the biggest share of aluminum extrusion market. Magnesium in aluminum increases tensile strength, improves resistance to corrosion, improves strain hardening and enhances material strength by solid solution strengthening. Adding copper to aluminum increases material strength and hardness and also makes it heat treatable. More than 80% of Aluminum alloys employed worldwide in the manufacture of extruded sections belong to the 6XXX series (Al-Marahleh 2006). The reason is that this group of alloys has an attractive combination of properties for both manufacturing and application. They have medium strength, are heat treatable, and have good formability, machinability and weldability.

The majority of the investigators' work in the recent years has been related to developing new processes, new materials, and advanced numerical process simulation techniques. One of the most active topics today is related to the development of new SPD processes such as Equal channel angular pressing, Accumulative roll bonding, Repetitive corrugation and straightening, Twist extrusion etc. Aluminum is one of the materials which dominates in all these SPD investigations. Dmitry Orlov et al (2009), Akbari Mousavi et al (2010), Beygelzimer et al (2011), Ranjbar Bahadori et al (2011), Seyed Ali et al (2011), Zendehdel et al (2012), Ali Khosravifard et al (2012) have performed investigations on the twist extrusion process of several Aluminum alloys, and a lot of investigations have also been carried out on other SPD techniques on Aluminum alloys (Herba et al 2004; Pardis et al 2009; Mohammad Jahedi et al 2010 & 2011, Amir Hassani et al 2012, etc). From the literature studies it is very clear that the properties of Aluminum such as low density, recyclability, ductility and formability have attracted researchers to bring out new products for a variety of industrial and automotive applications.

1.8.2 Application of 6xxx and 7xxx Series Aluminum Alloys

Aluminum has long been known as one of the lightest structural materials, although in its pure form it provides minimal strength. In the early 1900s it was found that by alloying Aluminum with small amounts (<5%) of other elements, the strength could be drastically increased, while keeping the material relatively light. Modern strength increases in Aluminum are also obtained by work hardening and precipitation hardening, combined with mechanical and thermal treatments. Several different Aluminum alloy series have since been created, each providing unique characteristics.

The two highest strength series used for the present investigation are the 6xxx and 7xxx Aluminum alloys. The 6xxx group of Aluminum alloys contains magnesium and silicon as the major alloying elements and the 7xxx group of alloys contains zinc as its primary alloying elements. Due to this high strength to weight ratio in the 6xxx and 7xxx series Aluminum alloys, they have many advantages in the automotive and aerospace industries which demand high performance materials. Among the extruded products within the Al–Mg–Si system, AA6061-T6 and AA6082-T6 alloys are regarded as high strength alloys which are widely used for the construction of aircraft structures, such as wings and fuselages, yacht construction including small utility boats in ship building industries, automobile parts like wheel spacers, foodstuffs and beverages in packaging industries and the bushings used in vibration control in the automotive industry (Ahmad et al 2011; Lakshmi Narayanan et al 2009; Yucel Birol 2006 and Zhang et al 2004). Typically, an aircraft's wing box structure consists of a 7xxx series alloy upper wing skin. Specifically, the Aluminum alloy of interest for these applications is the high strength AA7075-T6 alloy. This is one of the most common alloys used in aircraft structures in the aerospace industry today (Azimzadegan et al 2010 and Puchi-kabrera et al 2011).

1.9 RESPONSE SURFACE METHOD (RSM)

The Design of Experiment technique (DOE) is a branch of statistics which provides the researcher with methods for selecting the independent variable values, at which a limited number of experiments will be conducted. The various experimental design methods create certain combinations of experiments (analysis) in which the independent variables are prescribed at specific values or levels. The results of these planned experiments are applied to investigate the sensitivity of some dependent quantity, identified as the response, to the independent variables. The statistical tools used to model the sensitivity in the observed data include the regression analysis, and analysis of variance (ANOVA) (Montgomery 2006).

The collective use of the DOE techniques, regression analysis, and ANOVA is termed as response surface methodology (RSM).The primary objective of this research is to apply the statistical methods in RSM to analyze and model computer data, which contain numerical noise. The first approach, and the primary focus of this research, was to employ traditional response surface modelling techniques which use polynomial functions computed by the method of least squares to model trends in the observed data. It is worthy to note that the polynomial models have a smoothing effect on the experimental error (i.e., uncertainty or noise) in the observed data. A traditional RSM does not use interpolating functions because such modelling methods replicate the experimental error in the observed data.

1.10 THE LAYOUT OF THE THESIS

Chapter 1 – Introduction: The introductory chapter 1 of the thesis outlines the theoretical explanation on extrusion processes; severe plastic deformation processes and twist extrusion process with definitions, material parameters, classification, methods, their advantages, limitations, applications etc.

Chapter 2 – Literature Review : Chapter 2 explains the extent of research work carried out by the researchers in the past on severe plastic deformation and twist extrusion of various materials, and also indicates the research gap which has to be considered for investigations. It explains the need, scope, and objectives of the present research work etc.

Chapter 3 – Materials and Methods: Chapter 3 explains the material properties of the die and work material, the die design, the experimental setup, and the machine specifications, and explains the experimental procedure to study and investigate the twist extrusion process parameters, such as extrusion load, temperature and number of passes on the mechanical and metallurgical aspects. The mechanical aspects that are investigated based on the hardness distribution, yield strength and tensile strength and the metallurgical aspects that are investigated based on the microstructural, microhardness and grain size of twist extruded components of AA6061-T6, AA6082-T6 and AA7075-T6 Aluminum alloys.

Chapter 4 – Optimization Technique and Mathematical Modelling: The most extensive applications of RSM are in the particular situations, where several input variables potentially influence some performance measure or quality characteristic of the process variables. Chapter 4 discusses the design of experiments and performance evaluation of the TE process. Based on DEFORM 3D software, finite element models are developed in order to predict the effective stress and effective strain variations on the twist extruded samples. The results of the simulation are validated with the experimental values.

Chapter 5 – Results and Discussion: Chapter 5 presents the overall results that have been obtained through the experiments, optimization methods for finding the optimal values, the finite element method results of simulation and corrosion studies completed in this study. Further expansion of the data gathered in this thesis through a discussion of the results was compared with the full-scale results obtained by other researchers.

Chapter 6 – Conclusion: Chapter 6 summarizes the conclusions drawn from this research, on the Twist Extrusion of AA6061-T6, AA6082-T6 and AA7075-T6 Aluminum alloys, and offers some recommendations so as to improve the methodology in future research.