CHAPTER 1

INTRODUCTION

The primitive man was continually on search of new materials to enhance the quality of his life. Initially, he explored the nature around him and started using naturally occurring metals and materials for his wants. When these materials did not possess enough strength or shape to satisfy his ever growing needs, his attention turned towards trying different manufacturing processes or synthesizing new materials such as alloys or composites. Alloys are the materials which are developed by adding small quantities of metallic or non metallic materials other than the primary element in order to improve the characteristics of existing materials. With the advent of automobiles and aircraft and the world becoming a global village, even these new classes of materials were unable to fully cater to his requirements. It then became imperative to refine the existing manufacturing processes in order to improve the strength, shape and formability of existing or synthesized materials.

1.1 NEED FOR THE STUDY

One way to improve the mechanical or technological properties such as formability of materials is by altering their grain structure. There are many ways to alter the grain structure of a material either during the stages of production such as rolling etc., or through heat /solution treatment such as normalizing, quenching, precipitation hardening etc.
Recently certain processes such as Friction Stir Process (FSP), Equal Channel Angular Pressing (ECAP), Accumulative Roll Bonding (ARB), Thermo Mechanical Treatment (TMT), High Pressure Torsion (HPT), and Multi-axial Alternative Forging (MAF) (Ma (2008)) are evolving to refine the grain structure of a material such that remarkable enhancement in mechanical properties and formability characteristics is present.

Out of these, friction stir processing is a prime technique which refines grain structure locally by a combination of heating, plasticization and stirring of material. Even though optimizing a particular property through locally modified microstructure is not innovative, the challenge is to identify practical ways of realizing the idea. FSP provides a solution to this challenge.

1.2 FRICTION STIR PROCESSING

Friction Stir Processing (FSP) is an emerging surface engineering technology based on the principles of Friction Stir Welding (FSW), a solid state joining process invented at The Welding Institute (TWI), UK in 1991. FSP locally refines microstructures and also eliminates inherent defects in the starting material, thus improving its strength, ductility, corrosion resistance, fatigue resistance, formability, and a host of other properties. It can also produce fine grains through the thickness to impart superplasticity. To friction stir process a location within a plate or sheet, a specially designed cylindrical tool is rotated and plunged into the selected area. The tool has a small diameter pin with a concentric larger diameter shoulder. The rotating pin contacts the surface and as it descends to the part, friction heats the surface. When the shoulder contacts the surface, it causes additional frictional heat and plasticizes a larger cylindrical column of metal around the inserted pin. The area to be processed and the tool are moved relative to each other such that the tool traverses, with overlapping passes, until the entire selected area is processed to a fine grain size and the material is transported from the leading
to the trailing face of the pin. As the processed zone cools without solidification due to absence of any liquid, it forms a defects constrained recrystallized fine grain microstructure.

1.2.1 Zones of Friction Stir Processing

The various zones of FSP are listed below.

a. Stir Zone (SZ) or Nugget zone
b. Thermomechanically affected Zone (TMAZ)
c. HeatAffected Zone (HAZ)
d. Unaffected or parent material.

Figure 1.1 shows the various zones of during friction stir processing of alloys.

Figure 1.1 Various zones of friction stir processing (Nandan et al (2008))

a) Stir /Nugget Zone

Stir Zone or Nugget zone is the processed zone which undergoes intense plastic deformation, mixing, and thermal exposure, resulting in significant microstructural changes. In general, the nugget zone is characterized by fine recrystallized grains with high-angle grain boundaries, a typical microstructure for superplasticity.
b) Thermomechanically Affected Zone (TMAZ)

Thermomechanically affected Zone (TMAZ) is the region surrounding the nugget zone. It is characterized by less heat generation compared to the nugget zone.

c) Heat Affected Zone (HAZ)

The zone next to TMAZ is the Heat Affected Zone (HAZ). There is a decrease in the hardness in this zone due to differences in the grain structure.

d) Unaffected or Parent Metal

The material remote from the processed area, which has not been deformed is termed as unaffected or parent metal. Although it may have experienced a thermal cycle from the process zone, it is not affected by the heat in terms of microstructure or mechanical properties.

1.2.2 Advancing and Retreating Sides

The side of the welding tool where surface motion (attained due to spinning) is in the same direction as the travel direction is referred to as the advancing side. The opposite side, where surface motion opposes the travel direction, is referred to as the retreating side. Figure 1.2 shows a typical friction stir processing setup.
1.2.3 Advantages of Friction Stir Processing

- Friction stir processing (FSP) provides the ability to thermomechanically process on selective locations of the surface of the material.
- The grain size can be varied in the desired area of the metal with less heat affected zone. The work metal as a whole is not affected by the process.
- FSP provides for recrystallization in the metal and this process is preferred for producing grain sizes of less than one micron.
- Friction between the tool and the work metal surface generates heat permitting the process to be carried out at varying depths.
- Enhances formability and improves the strength and ductility of work material.
- It imparts the behavior of superplasticity.
- Increases resistance to corrosion and fatigue.
1.2.4 Limitations of Friction Stir Processing

- If suitable values of the process parameters are not selected during FSP, it may develop certain process defects such as tunnel defects, pinholes, voids etc due to poor material flow and consolidation.

- Friction Stir Process can be performed on metals, plates and sheets only up to a depth of 50 mm.

- It is a local machining process; a large processed region cannot be obtained in a single pass.

1.3 SUPERPLASTIC FORMING

Superplastic forming is a metalworking process for forming the sheet metal. It works upon the principle of superplasticity, which means that a material can elongate beyond 100 percent of its original size and produce essentially neck-free elongations in metallic materials when deformed in tension. Higher ductility is also encountered in superplastic alloys during torsion and compression. Superplastic forming requires two components: a superplastic alloy as well as a special, high temperature, relatively low strain rate forming process. During the forming process the metal gets plastically deformed into the desired shape as the stress crosses the elastic limit. The superplastic alloy must possess ultra-fine, equiaxed and stable grains of size approximately between 10 and 20 μm. Superplastic deformation is a function of applied pressure, temperature and strain rate. The forming temperature is greater than 0.5 \( T_m \), where \( T_m \) is the melting temperature of the material in absolute units at a very low strain rate. Superplastic forming is carried out close to isothermal condition with a controlled strain rate. The optimum strain rate varies with the type of material, but is usually very low, in the order of \( 10^{-5} \) s\(^{-1}\) to \( 10^{-2} \) s\(^{-1}\). Aluminum and titanium based superplastic alloys are
widely used for producing complex shapes for aerospace and defense equipments, automobile parts and other engineering applications.

The constitutive equation of superplastic forming is given by

\[ \sigma = K \dot{\varepsilon}^m \]  \hspace{1cm} (1.1)

where \( K \) is the material constant, \( \dot{\varepsilon} \) is the strain rate and ‘m’ is the strain rate sensitivity index of the material which is defined as

\[ m = \frac{\dot{\sigma} \ln \sigma}{\dot{\varepsilon} \ln \dot{\varepsilon}} \]  \hspace{1cm} (1.2)

Figure 1.3 shows a typical superplastic forming setup.

**Figure 1.3 A setup for Superplastic Forming**

1.3.1 **Conditions for Possessing Superplasticity**

In conventional view, the following conditions are to be satisfied for possessing superplasticity.
i. The average grain size $(d)$ should not exceed some critical value $(d_c)$, which is about 10-15 μm.

ii. The temperature of deformation $(T)$ should be greater than $(0.4–0.5)\ T_m$, where $T_m$ is the melting point on the absolute scale.

iii. Superplasticity is present only within a range of strain-rates, usually approximately $10^{-5}\ \text{s}^{-1}$ to $10^{-1}\ \text{s}^{-1}$.

iv. The optimal strain-rate interval in a uni-axial tensile test is conventionally defined by the empirical condition $n>0.3$.

1.3.2 Advantages of Superplastic Forming

The advantages of superplastic forming are

- It can form large and complex work pieces in one operation.
- The finished product has excellent precision and a fine surface finish.
- It also does not suffer from spring back or residual stresses.
- Products can also be made larger to eliminate assemblies or reduce weight, which is critical in aerospace applications.
- Forming pressures are drastically reduced; in some cases it provides cheaper process of making novel or more lightweight components.
- Considerable cost savings may be possible on extremely close tolerance components, which reduce machining costs and the processes.
- Maximum utilization of the material with minimum wastage.
1.3.3  **Limitations of Superplastic Forming**

- The main disadvantage is its slow forming rate.
- Conventional SPF requires cycle times from two minutes to two hours; therefore it is used for lower volume products.

1.4  **OBJECTIVES AND SCOPE**

The significant contribution is grain refinement in a particular aluminum alloy through this process. Since grain refinement is vital in altering the mechanical and formability characteristics of a particular material there is a wide scope in carrying out a detailed study on effects of the friction stir process parameters. Achieving superplasticity on friction stir processed alloys is also a new and unexplored area.

Accordingly the following areas are focused and the objectives formulated.

- To find the influences of various friction stir process parameters such as tool feed and tool rotational speed on cast aluminum Al 2285, A319, A356 and A413 alloys.
- To find the influences of axial force, tool rotational speed and tool feed on wrought aluminum AA6063-T6 alloy.
- To monitor the output parameters such as yield strength, tensile strength, microhardness, ductility and microstructure of the processed specimens.
- To predict the mechanical properties of friction stir processed AA6063-T6 aluminum alloy through a regression analysis using the commercially available software Statistical Package for Social Science (SPSS).
To study the effect of first mode of metal transfer on the mechanical properties of the processed specimens.

To assess the possibility of superplastic forming of friction stir processed cast aluminum A319 alloys and wrought aluminum AA6063 alloys.

To develop a theoretical and numerical model to predict the formability, thickness distribution and forming time of the aluminum alloys formed through superplastic forming by finite element method and validating the results.

1.5 ORGANIZATION OF THE THESIS

This thesis is organized as follows. Chapter 2 provides a literature review on the need for friction stir processing in aluminum alloys. In addition it also gives the work carried out in friction stir processing so far in improving the mechanical properties of different alloys and also in inducing superplasticity. The influence of first mode of metal transfer on mechanical properties is also reviewed.

Chapter 3 presents the experimental setup for friction stir processing and superplastic forming. The various standards used in the preparation of room and elevated temperature tensile specimens are given. The extraction locations of specimens for tensile, hardness and superplastic forming are also given.

Chapter 4 provides the aspects of the theoretical and finite element modeling in superplastic forming of friction stir processed aluminum alloys. The principles of the theoretical model and its modeling aspects using Matlab and Abaqus are described in this chapter.
Chapter 5 gives the results and discussion in detail. The influences of process parameters and the first mode of metal transfer on various mechanical properties, during friction stir processing are provided. Investigations on superplastic forming of friction stir processed alloys are also provided here. The regression models developed to predict the effects of process parameters and the first mode of metal transfer on the mechanical properties of friction stir processed alloys are also dealt with in this chapter.

Conclusions and scope for future research are presented in Chapter 6.

Figure 1.4 shows the methodology adopted in for the study. The methodology was framed based on the identified objectives.
To study the behavior of ALUMINUM ALLOYS
Al 2285, A319, A356, A413 and AA6063-T6 on Friction Stir Processing

Parameters varied - Axial force, Tool feed, Tool rotational speed

Mechanical characterization  
- Evaluation of Yield strength, Ultimate tensile strength, Ductility, Microhardness
  - Regression Analysis and First mode of metal transfer analysis

Microstructural analysis  
- Optical and Scanning electron microscope micrographs
  - Second phase particle analysis

Superplastic forming behavior  
- Evaluation of Formability, Thickness distribution, Forming time
  - Development of a 2D sectional model using Abaqus and a Numerical model using Matlab
  - Experimental validation of the model

Results and Discussions

Conclusions

Figure 1.4 Methodology adopted in this study
1.6 SUMMARY

- In this section an outline of friction stir processing along with its advantages and limitations is provided.

- An overview of superplastic forming and its governing equation is stated. The advantages and limitations of superplastic forming are also listed out.

- The objectives of the work are defined.

- The methodology adopted to achieve the objectives in the course of investigation is shown using a flow chart.