Friction Stir Processing for Superplasticity and Other Applications

by

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Abstract

Friction stir welding is a recent welding technology that had expanding the capabilities of welding aluminum alloys. From this process, it was discovered that the microstructural properties of a metal could be altered with a single pass of the tool, and from this the area of friction stir processing can be expanded beyond welding.

While friction stir processing is a new field of research, many areas of study have been discovered including the area of friction stir superplasticity. Using the small grain size achieved by the process and the high grain boundary misorientation angle, it has been found that friction stir processing is capable of creating high strain rate superplasticity in aluminum alloys.

This study evaluates the technology of friction stir processing. In detail, the study examines the applications, competing technologies, intellectual property, and the start of the business aspects of the technology.

In summary, it was found that the main applications for the technology are in the automotive and aerospace industries. The largest competing technology generally uses a six-step process that does not allow for high strain rates and thick sections. Both of these can be achieved by friction stir processing. Key patents in the area were also examined. In the business evaluation it was determined that the technology would likely be applied first in the automotive industry and used by a major automotive manufacturer in order to reduce costs.

Overall, friction stir superplasticity appears to have a lot of potential for future superplasticity applications.

Thesis Supervisor: Thomas W. Eagar
Title: Thomas Lord Professor of Materials Engineering and Eng. Systems

Acknowledgements

First and foremost I would like to thank God for giving me the ability, will, and passion to study friction stir processing. I am so lucky to find an area to study that makes me happy.

My family also deserves a lot of thanks. They have been supportive and without them I probably would have not been in the situation to write this information. Mom and Andrea for pushing me to come here, Mom and Emma for taking me here, and Mom, Dad, Emma, Abby, and Andrea among other family members for being especially supportive and keeping me in good spirits.

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I became interested in friction stir welding while I was at NASA so I would like to thanks my co-workers there for showing me what they could do and getting me excited about the field.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The motivation for looking into friction stir processing and superplasticity came from its potential use in the aerospace industry. Friction stir welding is a relatively new and interesting field for aerospace applications. The purpose of this technology evaluation is to examine expanding this technology to other uses, specifically in the area of superplasticity where there could be a lot of aerospace applications.

In order to fully examine the aspect of friction stir superplasticity, the technologies that led to the applications are also discussed in detail. The topics that are emphasized are background technology, applications, competing technologies, intellectual property in the field, and the potential for business applications.

Chapter 2

Background

Recently, friction stir welding technology has been used for purposes other than welding in the form of friction stir processing (FSP). Current developments encompass a wide variety of metallurgical areas, especially in the area of friction stir superplasticity.

The technology for obtaining superplasticity by FSP has been created as a result of the technology for friction stir welding (FSW) and the concept of FSP. Figure 2.1 shows the technology hierarchy that led to the specific application.

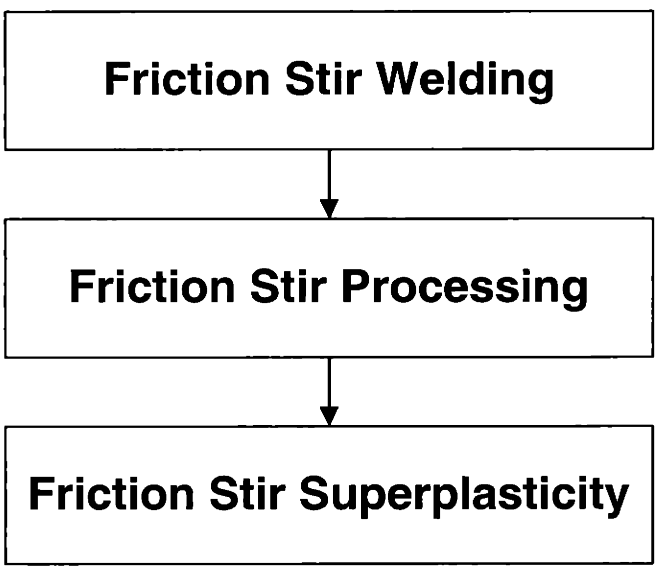

Figure 2.1. Hierarchy of technologies to achieve friction stir superplasticity.

In an attempt to fully describe the process of friction stir superplasticity, the processes of FSW and FSP will also be described in detail. Later the applications of the two processes will be discussed due to the fact that the same friction stir welding equipment is used to perform all these operations.

2.1 Friction Stir Welding

Welding technology underwent a major advancement in December 1991 when Wayne Thomas and his team at The Welding Institute (TWI) in England developed friction stir welding [1]. This new process opened the door for the welding of aluminum and other difficult to weld metals and revolutionized the quality of joints produced by welding. Research is being performed all over the world on FSW and is helping to perfect the process and increase its usefulness to industries everywhere.

2.1.1 The Process

In most FSW processes, two plates are set next to each other with the two pieces touching at the joint. These parts are then clamped in the machine that is used to do the welding. The work piece is then lowered and starts to spin while a constant force remains on the shoulder touching the workpiece. The work piece consists of a shoulder and a pin. The pin enters the materials while the shoulder remains on the top of the joint. The spinning and the close contact of the shoulder and pin assembly cause frictional heating and stirring of the metal, which forms the weld [2].

The resultant joint is a combination of the two pieces that are essentially mixed together. This joint has properties that are as good as if not better than the properties of the original metal. The process is a solid state welding process. The metal is not melted, but instead it is plasticized allowing it to be mixed. Since no melting occurs, the welding can be done in any position, making the process quite versatile, although it does require placing the workpiece in a fixture.

Figure 2-2 shows a schematic of friction stir welding. From the figure, it can be seen that a tool advances and rotates across the joint between two pieces of metal to create a weld.

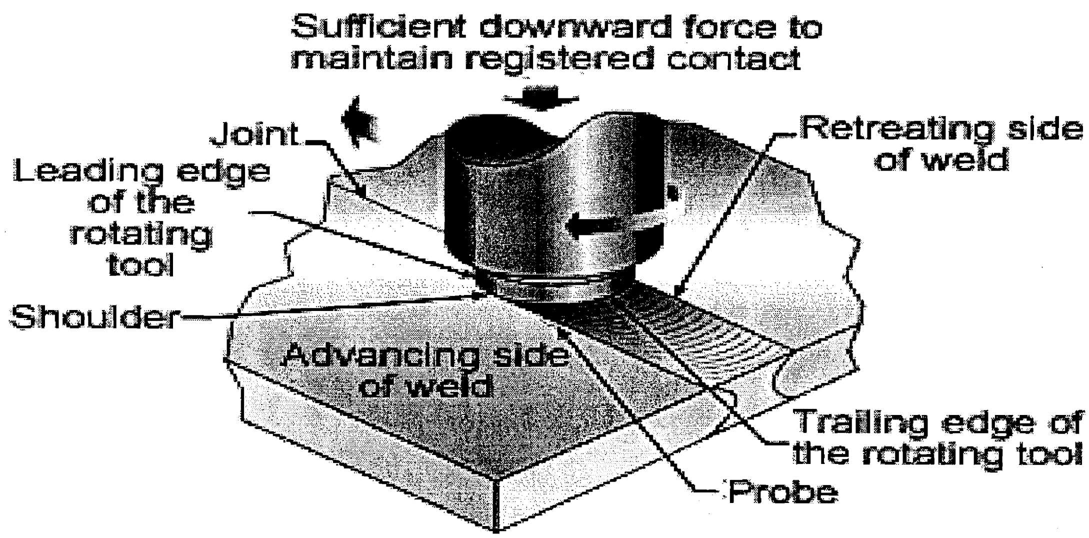

Figure 2-2. Schematic of the friction stir welding process (Source: http://www.mts.com/aesd/friction_stir.htm)

2.1.2 Equipment

There are an increasing number of companies that build and sell equipment for friction stir welding. The machines are built solely for the process. They range in size from large scale to portable demonstration models. Other pieces of machining equipment have also been modified with special tools to be able to perform this operation as well. The machines are quite versatile since the workpiece can be used for numerous alloys.

The following seven companies are licensed to build and sell friction stir welding equipment by TWI, the owner of FSW intellectual property [1].

1. ESAB AB – Sweden
2. Friction Stir Welding Link Inc. – Menomonee, WI

3. GEMCOR – West Seneca, NY
4. General Tool Co. – Cincinati, OH
5. Hitachi Research Laboratory/Hitachi Ltd. – Japan
6. MTS Systems Corporation – Eden Praire, MN
7. Smart Technology Group Ltd. – West Yorkshire, UK

2.1.3 Weld Characteristics

The weld produced by FSW is unique. The grain size in the weld is extremely small and is usually many times smaller than the grains of the parent material. The weld is of higher quality than most welds. Since no material is added, there is less of a need to grind and machine the piece after welding. Little distortion is experienced during welding, further adding to the quality of the weld. The weld that results is stronger than any previous welding process for heat treated aluminum alloys [2]. The recrystallized area is called the weld nugget [1] The term nugget is used worldwide to describe the area that is plasticized and rejoined. The time to weld is relatively short making the process feasible for production applications.

2.1.4 Current Research

There are numerous areas of FSW that are being researched and the number of areas continues to expand. Some of the recent development areas are described below.

Process Modeling – Modeling of the process of FSW is an important area for researchers to completely understand FSW and its effects on materials that are being welded. As a result, numerous research topics have arisen in the area of modeling. For example, it has been found that there are two methods of metal flow in FSW. The two flow paths are the helical motion of the metal for a couple of rotations as it is pushed behind the tools and the extrusion of metal from the front to the back to fill in areas not filled in by the first method [3]. These two methods have been shown to produce two different property characteristics so a complete understanding of them and their relative proportions could greatly improve process control for FSW [3]. Deformation behavior is also being modeled based on tool rpm and plunge rates based on temperature responses. Various tooling materials are also being examined in this process to determine their heating effects [4]. Flow patterns, property tracking, and tool efficiency are also being modeled to help improve the effectiveness of FSW [5,6].

Process Modifications – Variations on the FSW process are being researched to improve the quality and understanding of the welds. TWI, the original inventors of the FSW process, invented a variation on the process, skew-stir™, which puts the tool on an axis and redesigns the probe to optimize the ratio of swept volume in the weld to the static volume of the workpieces [7]. Another area of research is on the forces used and the energy to cause the heating and welding of the metal [8].

NASA – At Marshall Space Flight Center (MSFC), FSW is continually being researched for specialty aerospace and large scale applications. FSW has been found to provide the best quality weld for the Space Shuttle External Tank. MSFC is also working on modeling the process and moving it into specialty areas like cryogenic tanks and the Space Shuttle Solid Rocket Booster structures. Work is being performed in all areas of FSW for a complete understanding for aerospace applications [9].

Crack Growth – Since FSW is increasingly being utilized in aerospace applications, the issue of cracking in the welds is continuing to be researched with fatigue cracking being one of the major issues currently being studied. It has been found that even low residual stresses from FSW can allow fatigue crack growth in the welds [10] and fatigue crack growth is the main issue in cracking [11]. More work needs to be performed to determine the fatigue life tolerances that must be included in designs.

Corrosion – Since FSW significantly changes the microstructure of the parent material in the weld, studies are being performed on the corrosion resistance of these joints. The types of corrosion being investigated include pitting and galvanic corrosion. Initial investigations show that pitting occurs in these alloys, but intergrangular corrosion was not a problem. Further work will include a more in depth look at the textures created by the weld and their effects on corrosion [12].

Tool Wear – Work in tool wear is being performed by comparing the wear rates of tools in various alloys to determine alloys that wear the tool more rapidly. It has been found that oxides contained in metal matrix composites significantly decrease the life of the tooling. The shape of the probe on the tooling also has an effect on tool life. Threaded probes have a higher wear rate then non-threaded probes due to greater surface area [13].

2.2 Friction Stir Processing

Friction stir processing (FSP) is a new research area derived from FSW technology that refines the grain structure of a material. It is a thermomechanical process of essentially lowering the probe and shoulder onto a plate or sheet of metal to alter the properties.

2.2.1 General Information

Friction stir processing is truly a novel method of altering the structure of a material. The most common use for FSP is grain refinement. Figure 2-3 shows a cross section of a piece of sheet to which FSP was performed. The micrograph on the lower left is the grain size of the parent material. The one of the lower right shows the grain size in the processed area. It can be easily seen that there is a significant decrease in the grain size of the material. Note that the micrograph on the right is also magnified 10X from the one on the left.

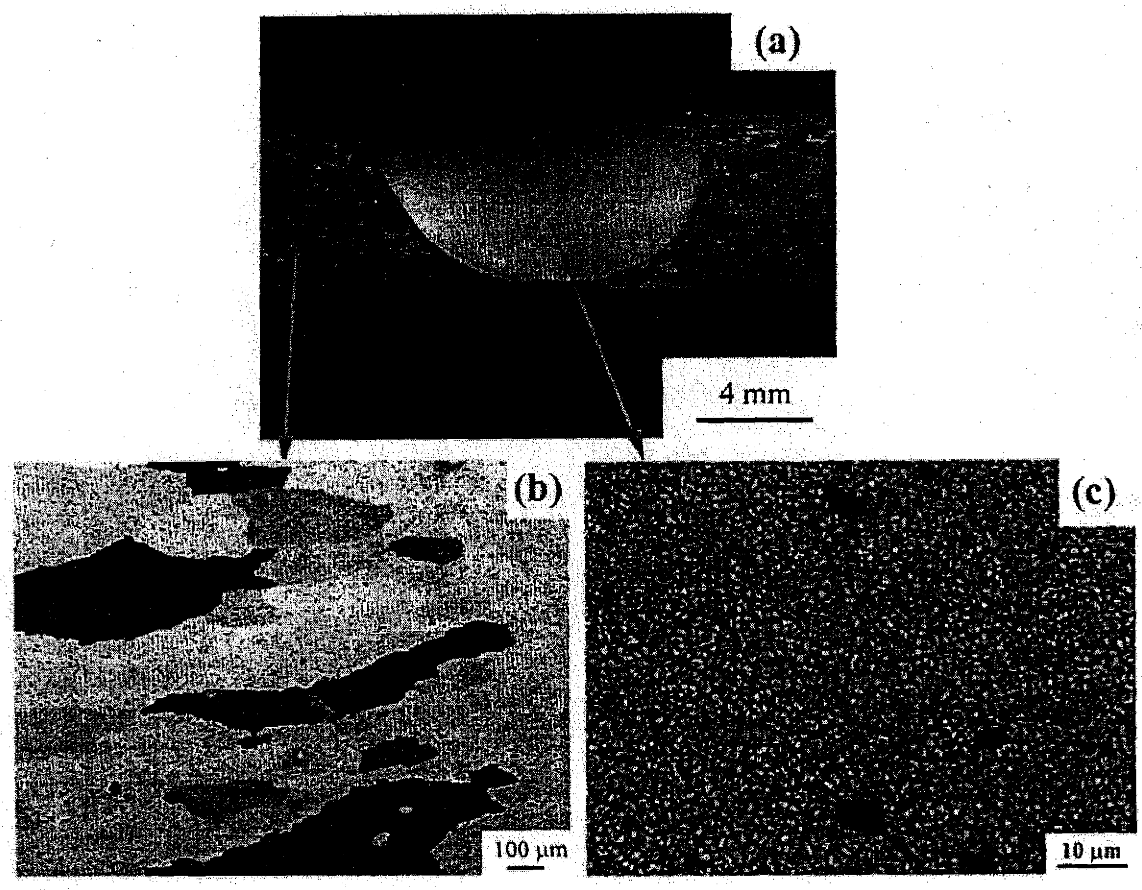

Figure 2-3. Example of grain refinement in area that has been friction stir processed (Source: UMR C-FSP [23]).

2.2.2 Areas of Friction Stir Processing

Friction stir processing is a relatively new processing technique so all the areas of use are new and more are sure to come about shortly. The following are the areas of FSP that have been identified and are beginning to be researched: channeling, casting modification, microforming, powder processing, surfacing, and superplasticity.

2.2.2.1 Friction Stir Channeling

Channels are often used in plates of metal to allow for advanced cooling of components. While this is a common application, the formation of the channels is often quite difficult and requires intricate machining and casting processes or even a combination of numerous plates bound together to give the proper channeling. New FSP methods allow for easy addition of channels into plates of metal. The FSP method reduces the cost of the channels.

2.2.2.2 Friction Stir Casting Modification

FSP technology is starting to be used in casting applications. When a casting is made, there are often defects associated with the final product including porosity, dendritic microstructure, and non-uniform distribution of particles. FSP is now being investigated as a method of eliminating these defects [14].

FSP can be applied locally where the properties of a casting need to be improved. The stirring motion will remove porosity and disperse any particles in the area equally. The plastic deformation in the process refines the grain size. In areas where a casting experiences higher stresses or requires better properties, localized FSP can be performed to remove the cast structure [14].

It has been found that by using a high rotation rate and low transverse speeds, dispersoids in a metal will become uniformly dispersed. By using this process on a casting, both the yield strength and the ultimate tensile strength are increased [14].

2.2.2.3 Friction Stir Microforming

Microforming is using metal processes, FSP in this case, to make small compents or "microparts" that are less than 400 μm in size. These parts are formed by combining the concepts of FSP, superplasticity, and metallic glasses [15]. The University of Missouri – Rolla has filed a patent for this process and it is under development [16].

2.2.2.4 Friction Stir Powder Processing

FSP technologies are also being researched for use in powder metallurgy (P/M) processing. They are especially appealing as a joining method for these parts due to the fact that the FSW process is a solid state process. One good thing about FSW P/M parts is that there is no damage to the SiC particulates in the weld [17]. Berbon et al. [18] also found that FSP resulted in a homogeneous microstructure with increased ductility for a nanocomposite P/M alloy. This makes FSP a very valuable process for P/M materials. Good distribution of particles, homogenous microstructure, and outstanding weld or material properties can be obtained for FSP P/M parts.

2.2.2.5 Friction Stir Surfacing

In many applications, a material where the bulk is metal and the surface is a metal-matrix composite is desired. This combination allows the material to have good ductility and toughness while also having unique surface properties such as wear resistance. There has been a process developed to combat this problem called laser melt treatment (also known as laser processing or laser surface engineering). While this process does work, there are problems associated with the temperatures at which it is performed. Since the processing is in the liquid phase, it is carried out at high temperatures where there is reaction between the ceramic reinforcement and the metal matrix causing undesirable phases. With FSP, ceramic particles can be incorporated into the metal matrix uniformly at low temperatures and various depths. This accomplishes the needs of the metal-matrix surface composite while solving problems with high temperature interactions [19].

2.2.2.6 Friction Stir Superplasticity

The main focus of this study is the use of friction stir processing techniques to obtain superplastic properties in metals. The method of obtaining these properties and the ultrafine grain size has a patent pending and looks like a means of obtaining a fine grain size for superplasticity [16].

2.3 Friction Stir Superplasticity

When FSP is performed on a metal, the grains are refined allowing for the piece to be superplastically deformed.

2.3.1 Superplasticity

A material that exhibits superplasticity is capable of tensile elongation that is extremely large. The metal must have three key features in order to experience this elongation. The grain size must be extremely small, the temperature must be elevated, and there must be controlled rates of deformation. Specifically, the grain must be approximately 10 μm or less, the temperature must be about one-half the absolute melting point, and the strain rate must be less than 0.01 s^{-1}. Due to this combination of requirements very few alloys exhibit superplastic behavior. These alloys are mostly aluminum and titanium alloys [20]. While normal metals exhibit tensile elongations of about 10-30%, these superplastic alloys can exhibit elongations of over 100%. Some alloys can even be elongated as much as 2000 to 3000% [21].

Superplastic forming has developed commercially due to the fact that large complicated parts can be made out of a single piece and contain complex shapes and curves. Thus, deep and complicated shapes can be made in one-step operations. This reduces cost and production times for part formation. The only time disadvantage is that the forming rates are relatively slow to achieve high tensile elongation [21].

The precision in superplastic forming is excellent and there are rarely residual stresses in the part. Low forces are used to make the parts due to the fact that they are made at elevated temperatures. The resultant grain size is also fine and very uniform, good homogeneity [21].

2.3.2 Mechanism of Friction Stir Superplasticity

When a metal undergoes friction stir processing, the localized frictional heating and the intense plastic deformation refine the grains [22]. When the fine grains of the metal are plastically deformed, they experience grain boundary sliding which allows them to superplastically deform. This is how a superplastic microstructure is obtained.

At the Center for Friction Stir Processing (C-FSP) at the University of Missouri – Rolla (UMR), the percent elongation was measured for various strain rates for an Al-Zn-Mg-Sc alloy. To obtain the sample, a 6.5 mm thick monolithic plate was friction stir processed with a single pass and mini tensile specimens were machined out of the FSP region to a final thickness of ~0.5 mm. Figure 2-3 shows the elongations that were obtained at strain rates ranging from 3 x 10^{-3} to 1 x 10^{-1} s^{-1}. As is shown in the figure, 1792% elongation was shown in the alloy when it was strained at 3 x 10^{-2} s^{-1} [23].

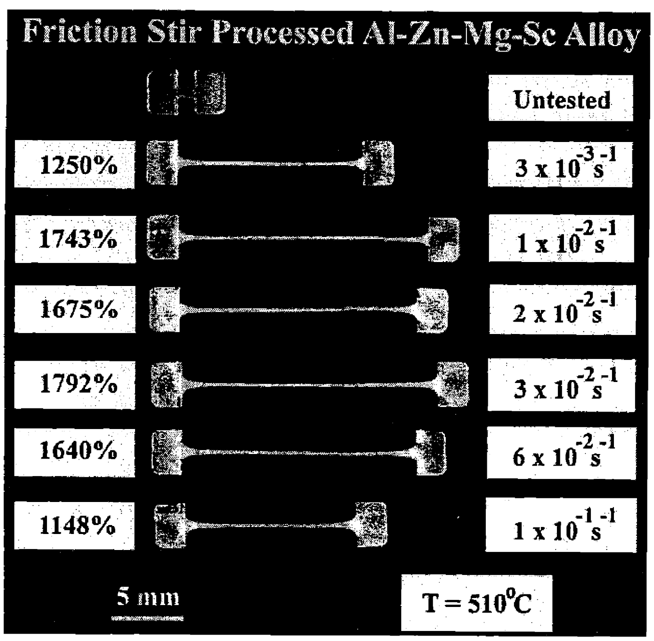

Figure 2-4. Percent elongations achieved by using various strain rates on Al-Zn-Mg-Sc alloys [23] (Source UMR F-CSP).

2.3.3 Effects of Grain Size and Misorientation Angle

The grain size is the most important factor in obtaining superplasticity in aluminum alloys and that is why FSP is an attractive process for acquiring this. It has been shown that the strain rate of a fine grained aluminum alloy can be given by [24, 25]:

$$\dot{\varepsilon} = 40\frac{D_0 E b}{kT}\exp\left(\frac{-84000}{RT}\right)\left(\frac{b}{d}\right)^2\left(\frac{\sigma-\sigma_0}{E}\right)^2 \qquad (1)$$

$\dot{\varepsilon}$ = strain rate
D_0 = pre-exponential constant for diffusivity
E = Young's modulus
b = Burger's vector
k = Boltzman's constant
T = absolute temperature
R = gas constant
d = grain size
σ = applied stress
σ_0 = threshold stress

From this equation, there are three relationships that can be inferred. The first is that when the grain size is decreased, the strain rate at a constant temperature increases. The second is that as the grain size decreases, the temperature at which superplastic deformation occurs decreases. The final relationship of importance is that as the grain size decreases, the flow stress decreases. The combination of these three relationships shows the importance of a small grain size for maximizing the superplastic potential of a metal.

The second most important factor in being able to superplastically form a part is the grain boundary misorientation angle. High angle grain misorientation is important for superplastic deformation to occur. In fact, low angle grain boundaries do not contribute to superplasticity [26].

Chapter 3

Applications

If a machine is purchased to perform friction stir processing for superplasticity, the equipment will still be quite versatile and be able to perform FSW and other types of FSP. For this reason, all these applications will be discussed in this section.

3.1 Friction Stir Welding Applications

Heat treated aluminum was once thought of as a difficult metal to weld due to inability to match base metal strength in the weld heat affected zone (HAZ), but it is the most widely used application for FSW. This allows for even more applications of this important engineering material. Not only is aluminum lightweight, but a joint that is made by friction stir welding is also lightweight. FSP, like all fusion welding process requires no additional fluxes or fillers so the weld has the same weight as if there were no joint there at all. This means that in transportation applications where weight reductions are necessary, the container used can be lightweight reducing cost or increasing carrying capacity. The weight reduction is a result of a weld HAZ with 100% joint efficiency as opposed to the traditional 50% efficiency. This can be seen in the external tank of NASA's space shuttle. FSW is now used on the orange tank that carries fuel as the shuttle rises above the atmosphere. This has allowed for a major cost reduction in the space program. Over a five-year period, it has been calculated that NASA will save $1 million on the tank processing due to cost reduction of creating the welds and cost avoidance of weld repairs [27].

Other areas of transportation are also benefiting from the lightweight welds produced by FSW. The process is now being used in airplanes, trains, marine uses, and trucks. All of these areas strive to reduce weight in order to minimize fuel consumption. These applications are also taking advantage of another key feature of FSW – the fact that it is a machine process. Since the weld is created entirely by a machine, the weld is very consistent and there are few situations where rework is needed [2].

3.2 Friction Stir Processing Applications

Friction stir channeling has potential for application because of the hole it creates in a solid piece of metal. This could be easily used for cooling plates where cooling fluids need to be run through the plates because additional cooling is needed. One such application would be the cooling slabs underneath the space shuttle. Currently dies for injection molding have holes that are drilled though them for cooling purposes. These holes are limited to straight lines since they are drilled in. Using friction stir channeling for these holes would increase the effectiveness of the cooling tubes in the dies. Aside from machining, holes can be put in a structure if it is layered with the holes designed in, but the method of friction stir channeling would be a much cheaper and more accurate method of creating the holes.

Castings inherently have microstructutal flaws due to their cooling pattern. Three cooling zones are formed in casting: the chill zone, the columnar zone, and the equiaxed zone. While the chill zone and the equiaxed zone have equiaxed grains with isotropic properties, the columnar zone has anisotropic grains. Friction stir casting modification can be applied in areas that require stronger, isotropic grains. This would allow for a cast engine to have better properties at the parts where it is bolted to the car body, a point that often causes casting problems. There are many other types of casting that would greatly benefit from a cheap method of strengthening just the areas that require strengthening.

With friction stir powder processing and surface modification, parts could easily be made to have different properties on the surface or in specific areas. This could be useful in adding a protective alloying element on the surface of a part. It also helps achieve more even mixing of powders.

The fine grain size acquired by FSP is a key feature for friction stir superplasticity. Applications that utilize the superplastic properties that can be made are discussed in the following section.

3.3 Applications for Friction Stir Superplasticity

There are various industries that could benefit from cheap superplastic capabilities. The two areas that seem to have the most potential for the near future are the aerospace and automotive industries. Other areas that could benefit include rail, architecture, and sports equipment. These areas are described below.

3.3.1 Aerospace Applications

Superplastic parts are already being used in a wide variety of commercial aerospace applications. These parts can be found on various aircraft including the Lear Jet 45, Boeing 777, F22, and F117A [28]. SuperformUSA has identified numerous application they feel could benefit from superplastic forming using their processing, but these parts could also be superplastically made using friction stir processing once the problems with using the process on various geometries are overcome. Table 3-1 lists these applications [28].

Table 3-1. Aerospace parts that could benefit from superplastic forming [28].

- Landing gear doors
- Wing tips/winglets
- Engine nacelles
- Air intakes
- Fairings
- Interior furnishings
- Avionics enclosures
- Equipment boxes
- Lighting enclosures
- Door skins
- Stiffening panels
- Special equipment skins

Friction stir superplasticity has numerous advantages for aerospace applications including the ones found in Table 3-1. There is no springback as a result of the processing of the superplastic part. This means that parts will keep the shape they were formed in and will have better tolerances for assembly. Friction stir processed parts will also have small residual stresses. This is advantageous because there will be no additional problems in the applications for failures as a result of stresses already in the joint. Weight in the parts will also be reduced. The removal of joints in the parts will permit a weight reduction that is very valuable in aerospace applications as well as reducing the number of pieces to create these parts. This single piece approach also greatly enhances the aesthetic properties and finish of the parts while eliminating scrap. Another advantage friction stir processing has for parts that are superplastically formed is that the complexity of the part can be greatly increased. While other superplastic forming methods also have many of these advantages, the key advantage of friction stir processing for superplasticity is its ability to do these things in a simple, cheap, and one step process as opposed to other types of superplastic forming that are expensive, requiring multiple processing steps to obtain the superplasticity.

3.3.2 Automotive Applications

Another industry that will have an increasing market for superplastically formed parts is the automotive industry. The automotive industry is large and is always working to make improvements to its products while finding costs saving since savings are quickly expanded when the number of vehicles produced is considered.

There are currently a few specialty-type vehicles using superplastically formed parts. These cars are all high end vehicles where cost is not as much of a factor. Vehicles using superplastically formed parts include Panoz Esperante, Aston Martin V12 Vanquish, Bentley S2, Morgan Aero 8, Bugatti EB110 [28].

These high-end vehicles are currently taking advantage of some of the qualities that superplastically formed parts have, including the freedom of design of custom parts with complex, smooth shapes. The cost associated with these parts will decrease once methods of friction stir processing are on the market and the number of parts that can be produced will also be increased due to the high strain rate allowed for parts by friction stir superplasticity. Any superplastic part has the advantage of no strain hardening for exceptional fit and the ability to make parts using fewer pieces [28].

3.3.3 Other Applications

While aerospace and automotive markets look like they have a lot of potential for friction stir processed superplastic parts, there are a wide variety of markets that should be considered. These areas include rail, architecture, visual art, sports equipment, biomedical implants [28]. Currently rail parts on both the interior and exterior of European trains and subways are using superplastically formed parts [28]. Architectural uses include decorative panels and single pieces that make a smoother, more modern look for the interiors of buildings. Visual art uses could be the formation of hollow sculptures or pieces that are intricate, metal, and lightweight. Sports equipment and biomedical implants both require that a part be intricate without rough edges. Friction stir superplasticity can be used to obtain these features for prosthetics and metal equipment.

3.3.4 Applications Currently Being Researched

There are numerous specific applications that are being researched for use with friction stir superplasticity. Some of these applications that have recently been looked for FSP improvements into are described below.

Thick Section Superplasticity. Mahoney et al. [29] used friction stir processing to obtain superplasticity in an aluminum alloy with both a high strain rate and a thick section. Sections thicker than 25 mm have exhibited superplastic properties and the limits of thickness have not been reached [30]. Such combination of properties is difficult to achieve in aluminum alloys. One reason for this is that friction stir processing affects the entire thickness of the sheet to obtain a uniform, fine grain size which is difficult using thermomechanical processing.

High Production Volume. Currently superplastic forming in used in a wide variety of aerospace applications to produce complex parts from sheet metal. The problem with the use of superplastic forming is that it can only be done for low volume production due to the amount of time is takes to form a part. Friction stir processing allows for fine grains to be obtained in the material which results in higher strain rate and lower processing temperatures. The high strain rates are what is desired for high production volume of superplastic parts. This can be obtained by friction stir processing thus opening the door for greater commercial availability of parts that are superplastically formed [26].

Multi-sheet Structures. Another use of FSP related to superplasticity involves the combination of diffusion bonding and superplastic forming. While this process combination is currently being used in titanium alloys, it is difficult to do with aluminum because of the oxidation layer that prevents good bonding. The area that is being researched is using a friction stir processing technique on the superplastic aluminum alloy to give it the multi-sheet superplastic properties [31].

3.4 Commercial Potential for Applications

Friction stir processed superplastic parts have the advantage in that they are high performance, low cost, and have a high production rate. Once the issues with parameters and processing controls are solved, FSP will be easily integrated into the commercial market.

The automotive market looks the most promising for initial implementation. This is due to the fact that superplastic materials are already desired in the industry, but strain rates are not yet what they need to be for high production volume. FSP will allow for this by making the parts capable of high strain rate superplasticity because of the advantage of high grain boundary misorientation angle added to the fine grain size achieved by other methods.

The aerospace market looks like it will quickly follow the automotive market in implementing FSP technology for superplastic parts. It is estimated that in the US, about 2300 commercial aircraft will be produced in 2003 [32]. This is not including the number of military aircraft that will be produced. More on the commercial potential of the process will be discussed later in chapter 6 in the business evaluation.

Chapter 4

Competing Technologies

4.1 Welding Technologies

There are many welding technologies that are well established and currently in use for a wide range of alloys. The welding market that FSW addresses is the market for welding of aluminum alloys. There are numerous welding processes that are used to weld aluminum. These processes include laser beam welding, gas metal arc welding (GMAW), and resistance spot welding among other techniques. FSW has advantages over these traditional processes because of the fact that it is a solid state process that produces an ultrafine grain structure without the need for an inert atmosphere.

A technology that FSW is currently replacing in a lot of applications is riveting. When materials are riveted, two sheets are overlapped and a plug is placed between matching holes in the sheets. The process allows for joining of aluminum sheets without the problems associated with welding aluminum. FSW is replacing this method due to the fact that a joint can now be produced at a low cost that has properties that are almost identical to the parent materials [33]. The process is also useful in the reduction of weight in the structure since two sheets can be joined with no overlap and no addition of materials.

4.2 Friction Stir Processing – Competing Technologies

Friction stir processing is still in the research phase of its development. As a result of this technology being new, it is currently not in the market as a commercial production process. However, there are a few areas where FSP is showing a lot of potential and may be able to expand into other markets.

4.2.1 Grain Refinement

One of the main goals of FSP is to obtain ultra-fine grain size. There are other methods that are currently used to create bulk ultrafine grained materials. These processes include powder processing, electrodeposition, and severe plastic deformation processing [23]. These methods are discussed below.

Powder Metallurgy – In the process of powder metallurgy (P/M), metal powder is formed into a desired shape and heat treated to give the desired properties. The combining of powder to create the bulk material gives the final product a fine grain size.

Electrodeposition – With electrodeposition, the method of material deposited on the surface allows for small grains to form. The term electroforming is used when the process is used to create the entire part rather than the surface.

Severe Plastic Deformation Processing – Severe plastic deformation (SePD) processing involves the refinement of grains in bulk material by causing large amount of plastic deformation to the material. Deformation can be performed by one of various methods including equal channel angular extrusion (ECAE), torsional deformation under pressure, multiaxial (or abc) forging, accumulative roll bonding, and multipass coin forge [23].

The method of grain refinement in SePD is from the fragmentation of the grains due to the fact that they have low grain boundary misorientaion angles that are converted into high angle misorientation angles. The severity of the deformation determines the amount of refinement. Large amounts of deformation can be performed and as a result, extrememely small grain can be acquired. The problem with SePD lies in the fact that most of the processes use small workpieces and this cannot be scaled to production size parts [26].

ECAE has the most potential for being scaled up to manufacturing size so it will be examined further. To obtain a grain size that is fine enough with high angle misorientation in the grain boundaries, six to eight passes must be performed. One pass will result in fine grains, but the high angle grain boundary misorientaion is not present. Low angle grain boundary misorientation does not contribute to superplasticity so low numbers of passes are not effective in obtaining the desired effect. This increases the cost of production by this method.

4.2.2 Other areas of FSP

In the previously described specific FSP areas, there are competing technologies as well. The technology that has the most obvious competition is friction stir channeling. As previously mentioned, the competing technologies at this point are machining and multilayer structures. Advantages of the FSP channeling process over machining include the ability to make channels that are curved, channels in contoured pieces, and channels inside the bulk of a material. Advantages of using FSP channeling over multilayer structures for interior channels include the accuracy of the channel and use in contoured materials. Cost savings are also present with the FSP method since no precion layering and bonding is required.

4.3 Friction Stir Superplasticity

Superplastic alloys are used in numerous applications in many industries so there is already a wide variety of established technologies and processes that will compete with the FSP method of superplasticity. Some of the grain refinement techniques of FSP will also be discussed in this section as the fine grain size is a key factor in superplastic alloys.

4.3.1 Competing Processes

Some methods of thermomechanical processing, powder metallurgy, and equal channel angular pressing are currently used to make superplastic parts, but none are capable of high production rates required to truly commercialize the use of the superplastic parts. These processes are discussed below and compared to friction stir superplasticity.

4.3.1.1 Thermomechanical Processes

There are several methods that use traditional thermomechanical processing (TMP) for superplasticity in parts, but they usually contain six steps and have very slow forming rates. There are two conventional methods used for superplastic materials using TMP. In the first, a fine grain size is achieved by statically recystallizing the microstructure. In the second process, a material is warm rolled and unrecrystallized prior to the superplastic deformation causing the fine grain size to be achieved during deformation [34].

Figure 4.1 shows a typical six-step TMP method used to obtain superplastic properties. The specific alloy for which this process was used is a superplastic 8090 aluminum alloy [35]. Note that the time axis is not to scale. Steps like homogenization take approximately 16 hours and steps like overaging take approximately 24 hours [34, 35].

There are other variations on this process. Brown describes one such technique in the patent "Method of producing aluminum alloys having superplastic properties" [36]. Figure 4.2 illustrates this method showing the processing temperature versus time. As is shown in the figure, the aluminum must undergo numerous processing steps in order to obtain superplastic properties. The six steps required in this process are much greater than the simple step used in the FSP method. The forming rates of the aluminum processed by this method are also slow at about 10^{-4} to 10^{-3} s^{-1} and limited to sheets that are less than 2.5 mm thick [23,36].

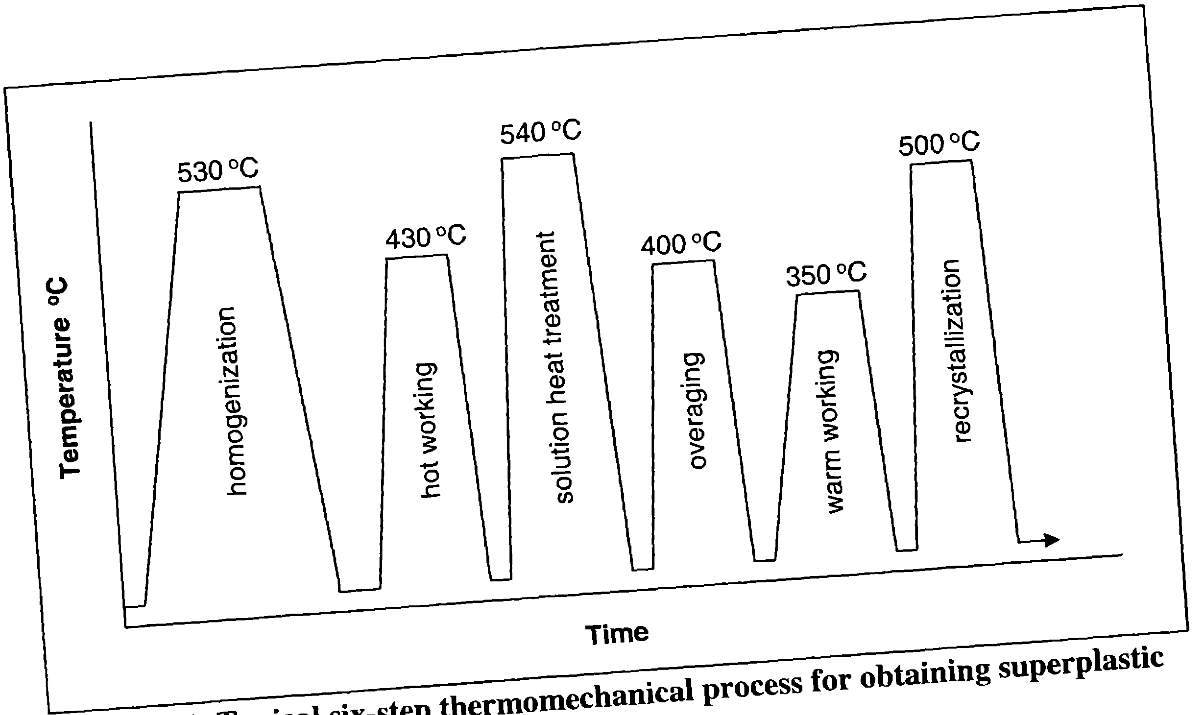

Figure 4-1. Typical six-step thermomechanical process for obtaining superplastic properties.

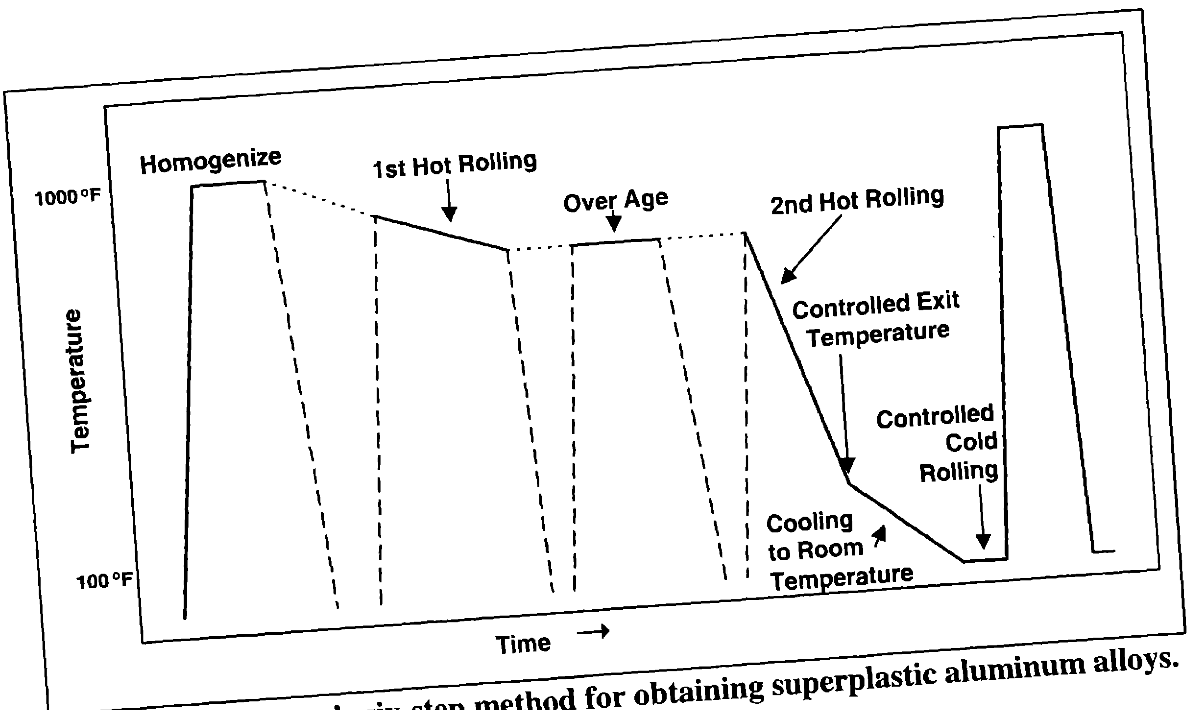

Figure 4-2. . Brown's six-step method for obtaining superplastic aluminum alloys.

Note that figures 4-1 and 4-2 and drawn in different formats to reflect interpretations found in literature.

Friction stir superplasticity exhibits some obvious advantages over these types of TMP. The whole process is cheaper and faster due to the fact the only one step is involved. High strain rates (10^{-2} to 10^{-1} s^{-1}) can also be achieved with the grain refinement effects of FSP as well as greater ductility (up to 1600%). The FSP method also has an advantage in that thicker sections can be used which increases the number of products that can be formed superplastically. The temperatures used are also lower due to the fact that heat treatments are not required and low temperature superplasticity can be achieved [23].

4.3.1.2 Powder Processing

As previously mentioned, powder processing is a method of achieving bulk ultrafine grained materials. The process is performed by taking metal powder, putting it into a desired shape, and heat treating it to join the powder together. While the process is an excellent method of tailoring an alloy and obtaining a wide variety of shapes, the metal powder is expensive and this prevents P/M from being used on a large scale production process.

4.3.1.3 Equal Channel Angular Pressing

Equal channel angular pressing (ECAP) is a method of severe deformation processing. By performing this process, an ultrafine grained metal can be achieved. ECAP consists of pushing a piece of metal through an L-shaped channel in a die causing shear deformation and producing a piece of material with the same dimensions. Repeating the process numerous times can produce large strains [37]. The rotation angle and direction the part is turned in each straining step. Figure 4-3 illustrates the ECAP process.

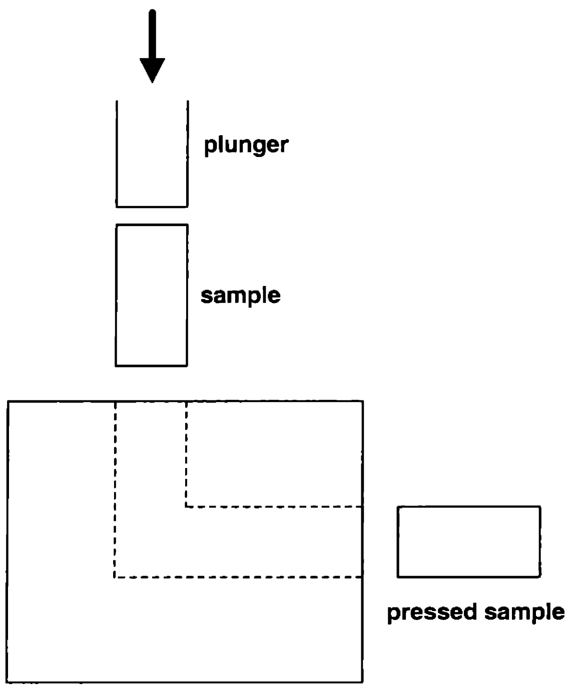

Figure 4-3. Process of equal channel angular pressing [37].

As with ECAE, to perform this process at production rates, the process must be repeated numerous times. While the process is capable of creating fine grain size for superplasticity, using the FSP method has many advantages over this process.

4.3.2 Mechanism of Superplasticity

The mechanism in FSP superplastic alloys is grain boundary sliding [23]. This mechanism is the same for any fine grained material that is superplastically deformed [25]. Thus most the competing technologies will deform with the same mechanism because they contain ultra-fine grains. The only processing method that will differ in the deformation mechanism is thermomechanical processing.

4.3.3 Comparison

All of the described processes have their advantages and the three competing technologies for friction stir superplasticity already have a specific market. The advantages and disadvantages of using FSP to obtain superplasticity are described below.

Selective superplasticity is a new area that will become available with this process increasing the control of properties in a material. This will allow superplastic regions to be adjacent to non-superplastic region on the same sheet of metal. Since FSP can be used on curved sheets, superplasticity can also be achieved in contoured sheets. The combination of all these features enables numerous new technologies in the area of superplastic forming, such as superplastic forging. FSP creates an ideal grain structure with small size and high angle grain boundary misorientation. This allows it to be feasible in most other superplasticity applications.

Not only is friction stir superplasticity versatile for existing uses of superplasticity, it also makes a new type of superplastic forming possible for aluminum alloys – thick section superplasticity. This is important because until this point there has been no method for thick section superplasticity. New possibilities for parts arise with thicker sections.

Thus, the general advantages that friction stir superplasticity possesses are the fast processing time and the low cost. The fast processing time is due to the fact that only one step is required to obtain superplastic properties. The low cost is due to the fact that FSP is a one step process and parts can be selectively grain refined using a machine that does not require heating the metal before processing.

Along with the advantages of friction stir superplasticity come the disadvantages. The method of using FSP is performed a strip at a time with current equipment. If a large piece is superplastically deformed it could end up being cheaper and less expensive to perform the thermomechanical processing method. The exact mechanism of grain refinement is currently unknown and difficult to model. This also means that determining the best parameters to perform FSP must be learned before the part is created. This allows for items with high production rates to use this method, but more work needs to be done before it's financially feasible to use the process on niche and specialty parts.

Chapter 5

Intellectual Property

5.1 Friction Stir Welding IP

The original patent for FSW, "Friction Stir Butt Welding" is held by Thomas and his group at TWI [38]. The process was patented in 1991 in Great Britain and 1995 in the United States. There are two base patents that cover the process.

The first patent covers "a method of joining workpieces defining a joint region. It comprises causing a probe [or pin] of material harder than the workpiece material to enter the joint region and [this probe plunges into] opposed portions of the workpieces on either side of the joint region while causing relative cyclic movement between the probe and the workpieces. Frictional heat is generated to cause the opposed portions to take up the plasticised condition. The probe is removed and the plasticised portions allowed to solidify and join the workpieces together" [1,38].

A second patent covers "an improved method of friction stir welding [that] is based on enhanced flow of plasticised material both perpendicularly and vertically to the longitudinal extension of the adjacent assembled members by exposing the created plasticised material to a perpendicular pressure along the surface of the members and causing simultaneous material flow along the probe pin in the vertical direction allowing the plasticised material to solidify behind the probe. A non-consumable probe is provided comprising a concave bottom part with an interchangeable pin having surface of threaded configuration and in a preferred embodiment comprising two or more laterally protruding blades" [1,39].

Since the development of this process a lot of work has occurred in the area and numerous patents have been applied for. Table 5-1 shows a list of the number of U.S. patents held by researchers in the area of FSW [1].

Table 5-1. List of number of FSW patents and patent applications by company.

Name of Company	Number of Patents
Hitachi	69
Boeing	27
Showa Al Corp.	6
Lockheed Martin Corp.	4
NASA	4
BAE	3
Brigham Young University	3
ESAB	3
General Electric Co.	2
GKSS	2
Honda Giken Kogyo Kabushiki Kaisha	2
Mazda Motor Corporation	2
Nissan Motor Co Ltd	2
Tokai Rubber Industries Ltd., Showa Al Corp.	2
TWI	2
Alcoa	1
BOC Group	1
Cocks	1
Dana Corporation	1
Fokker Aerostructures BV	1
Ford Global Technologies Inc.	1
General Tool Company	1
The Lead Sheet Association	1
MCE	1
MTS Systems Corp.	1
Murray, M.	1
Siemans AG	1
Tower Auto	1

These patents are all in the area of FSW. While an attempt was made to find all related patents and some patent applications, there may be some missing from this list. These patents were found to be the most relevant to the process and its variations. When looking at the number of patents filed globally, it is interesting to find that the most process modification and improvement patents have been filed in Japan.

The companies listed above in section 2.1.2 all have Machine Licensing Agreements with TWI to build and sell FSW equipment. This license also allows the purchaser of the equipment to practice FSW for the life of the equipment as opposed to an annual process site license [40].

5.2 Friction Stir Processing IP

The collection of researchers working in the area of FSP is small as most work is being focused on FSW. There are a few organizations that are investigating the potential of FSP. These organizations include Rockwell Scientific, University of Missouri, Brigham Young University, Air Force Research Lab, Superform-USA, Boeing, and NIAIST (Japan).

The University of Missouri has filed for three patents in the area of friction stir processing. The three patents have been filed in the areas of superplasticity, channeling, and microforming. The applications for channeling and microforming were not available, but the patent application for superplasticity was found at the US Patent and Trademark Office website [41,42].

The patent application on superplasticity covers a "method for producing a shaped metallic component comprising: friction stirring at least a segment of a single piece of bulk metal to impart superplasticity thereto and thereby yield a single superplastic metal blank from said single piece of bulk metal: and deforming the superplastic metal blank to yield a shaped metallic component from said superplastic metal blank" [42].

There are thirty claims associated with the application covering FSP of the metal for superplasticity for a wide range of thicknesses both uniform and uneven. They cover variations on pieces of bulk materials that are and are not made superplastic. Various grain sizes and flow stresses are covered as well [42]. If all claims on the patent are accepted, then anyone using the FSP technology for superplastic forming will have to do so in agreement with the patent's licensing terms.

The only other patent that could be found relating to friction stir processing is Boeing's patent, "Friction stir grain refinement of structural members." This patent covers "a method for selectively improving the strength, toughness and fatigue resistance of a structural member in a region of high operational stress including the steps of casting the structural member in a preselected configuration" [43].

While this patent is related to friction stir processing technology, it does not interfere with the technology of the friction stir superplasticity that is the main subject of this investigation. Nor does it interfere with any of the topics discussed in this study. All the claims are related to friction stir processing and structural members.

Chapter 6

Business Evaluation

This chapter discusses where friction stir superplasticity will find it's way into the business world, some of the challenges it will face, and the prospects for creating a business with the technology.

6.1 New Technology in the Current and New Markets

Taking a new technology and integrating it into an existing market is both challenging and exciting. The new technology can offer a lot of potential, but companies aren't always willing to change their current process for one that only has claims of being a superior technology. The key to getting companies to start using a process is to prove that it works. Unfortunately, this is difficult for a person or a group of people who have a new technology, but no trusting customer base to which they can prove the worthiness of their technology.

Friction stir superplasticity has this same problem. The process has excellent claims to being the best option for superplastic aluminum alloys, but there needs to be proof before companies start using the process to create their parts.

So where would this technology be most useful and have the best chance of entering into a market to gain the needed acceptance and recognition? Figure 6-1 shows a diagram of technologies and companies and their pattern of integration and disintegration [44].

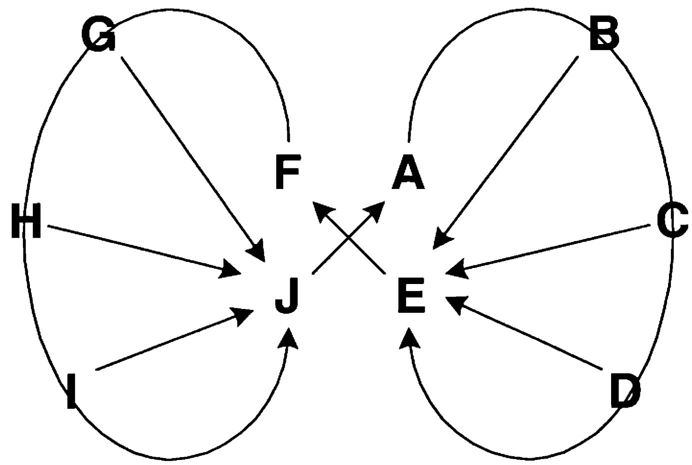

Figure 6-1. Vertical and horizontal industry trends and pressures.

The following letters correspond to the letters in the above figure and show their meanings in the context of business trends for the graph.

A – Modular product, horizontal industry
B – Technical advances
C – Supplier market power
D – Proprietary system profitability
E – Pressure to integrate
F – Integral product, vertical industry
G – Niche competitors
H – High dimensional complexity
I – Organizational rigidities
J – Pressure to disintegrate

Friction stir superplasticity would enter into this scheme on the right hand side of the loop, the horizontal industry, due to the fact that is one part of a process of creating a larger product.

Another characteristic of friction stir superplasticity is the new markets for superplasticity that could become available. As previously discussed, it was previously unheard of to use thick section superplasticity on aluminum alloys. Now new products can be created using the new capabilities. A wider variety of parts will also be superplastically formed due to the high strain rate and production speeds now capable.

The effect of market penetration and new technologies is demonstrated in Figure 6-2. This figure has been used in various forms by different companies and individuals to show where a current company stands and where a company is looking to expand and compete. [44].

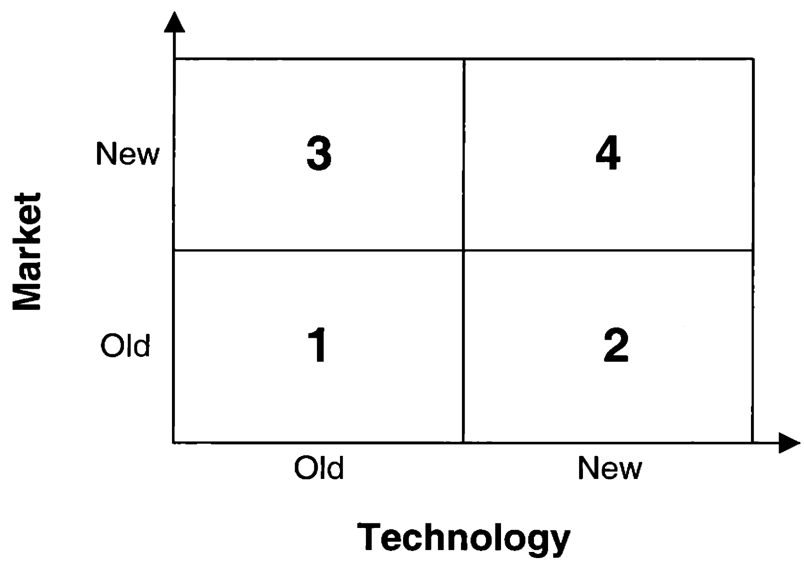

Figure 6-2. Business positions in the current and new technology and market regimes.

Current companies have a strong hold in the current technology and current market area as shown in area 1 of Figure 6-2. A new company would have difficulty establishing business in this area due to the fact that current companies are established and usually have a good customer base. The obvious area that friction stir superplasticity would penetrate first would be the area of the current market with a new technology, area 2. This is the area where many start-up companies begin and are able to succeed. Many parts that are superplastically formed could benefit from the new technology making it a direct competitor to companies who use the more traditional forms of obtaining superplasticity.

Area 3 is interesting in that it is usually utilized by companies with established business trying to expand by increasing their market. This presents competition for other companies mostly in the current technology area. This area, however, does not relate much to the issues of a new technology so it will not be discussed further.

Friction stir superplasticity has the potential to move into area 4 of Figure 6-2 after getting a firm hold in area 2. This means that once the new technology has infiltrated the current market, it will be able to expand into new markets. This area seems like it would be the most exciting for a new company to move into and very financially profitable if it works, but it is also a dangerous area to be in. Taking a new technology and trying to create a new market for it is difficult. Markets are very unpredictable because they are based on people. A company must have a strong hold in area 2 along with a knowledge of market trends to move into area 4.

6.2 Starting a Business with this Technology

If a company wished to use this technology to start a company there are numerous things that must be taken into account. The basic costs include the costs of blanks to use in the machine, the cost of a friction stir processing machine, the cost of a location to perform these operations, labor, intellectual property rights, and other considerations that can be costly for businesses. The amount of profit must then be calculated by looking at the market, determining the market infiltration, and the amount of profit that can be achieved by meeting these market demands. Other companies in similar areas must also be closely examined to determine exactly what the competition is and how they will be replaced with the new technology.

As previously mentioned, the automotive market will be easier for a company to enter then the aerospace market even though aerospace parts have a greater value. The automotive market it always looking for ways to reduce costs of parts and there is a high volume of automobiles produced annually. The aerospace industry is a little more reluctant to try new things when there are new processes because their tolerances are higher.

For most existing markets to use a new technology and for venture capitalists to fund the developing companies, an increase in value of ten times must be shown. The following section shows the value proposition for a company that wishes to start up a friction stir processing business.

6.3 Value of Technology

If this technology were examined in the sense that a business would be starting up next year to use the process of friction stir processing and making a profit, it seems like it would be a difficult task to perform.

Since the automotive market was looked at as being easier to move into, it will be examined. Each year there are approximately 6 million passenger cars produced in the United States [45]. Recently, there have been approximately 7 million light trucks produced in addition to those vehicles [46] making the total number of light vehicles produced in the United States about 13 million. Let's say a start up company is going to produce a part that, to be on the safe side, replaces a single part in each car. It can normally be assumed that in the first year, a new company can acquire 0.0001% [44] of the market. This would translate to roughly 1,300 vehicles. While this is a good estimate for a consumer market where consumers are selecting a new product, this may not be the best assumption for the automotive industry.

It can be assumed that it is likely that a larger company would select the part for one line of its cars or trucks. This could potentially be a large number of parts required. There is also the chance that only the smallest producer of vehicles is willing to take the chance, but that would mean less than 1000 parts required because the smallest US light vehicle manufacture, Freightliner, produces less than 1000 trucks per year [46]. In order for a company to take a chance making improved parts for a production process that is so well developed, they would have to have some sort of agreement with the companies to be willing to take the chance. If a company could convince an automotive manufacturer to support the entire company, it is more likely that the large manufacturer would be more likely to try the new idea and technology on its own. This means that the most promising way for a company to make money is to get good intellectual property rights that they can sell to a manufacturer for use in automobiles.

Ideally, this would expand into the aerospace industry as well. This market is much smaller and as a result is harder to get into. It is estimated that 2300 commercial aircraft will be produced in 2003. Due to this fact, it will be easier to follow with aerospace applications once the automotive industry has proven the benefits of the technology.

A problem that this technology faces is that it is not fully developed. It is difficult to speculate how long it will take for the exact grain refinement mechanism to be determined. Once this is achieved, it should be possible for parameters to be programmed into the machine for a specific alloy and thickness to achieve a specific grain size range. This is in the initial steps of research and it may take awhile before exact process control is acquired. This means that a company would not be able to form in the near future.

Due to the difficult market in this area, it would be better for a company to have a strong hold on intellectual property and sell those rights then it would be for them to sell actual parts to a company. While friction stir superplasticity will soon be able to solve specific superplasticity problems, this technology doesn't look like it will be commercialized in the near future for more generic processes.

Another option would be for a small company or even an indiviual to gain a lot of experience in the area and then when the process is developed further they would have the first superplastic parts out on the market and start a company in that way.

Chapter 7

Conclusions

This study has shown that friction stir processing is a competitive new technology and will be useful in expanding the uses and market for superplastically formed parts. While other technologies take multiple processing steps and require slow strain rates, using friction stir processing takes a single step to make pieces capable of high strain rates and thick sections. Applications for the technology include the aerospace industry and the automotive industry.

Through the technology evaluation performed in this study, it was found that using friction stir processing in the aerospace market would be preceded by its use in the automotive industry. Even within the automotive industry, it would be difficult for a company to just make the parts; it would be easier for them to take advantage of intellectual property rights.

Before this technology is ready for commercialization, a number of factors still need to be overcome. Processing parameters for various alloys and thicknesses should be fully calculated for the machine to be the most useful. To do this, a full understanding of the process of grain refinement must be achieved and parameters should be determined to refine the grains to specific size ranges. This area still requires further research

Overall, friction stir processing for superplasticity is an interesting technology and should be watched in the future as it grows into a common manufacturing process.

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