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Development and Characterization of Friction Bit Joining: A New Solid State Spot Joining Technology Applied to Dissimilar Al/Steel Joints

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DEVELOPMENT AND CHARACTERIZATION OF FRICTION BIT JOINING: A NEW SOLID STATE SPOT JOINING TECHNOLOGY APPLIED TO DISSIMILAR AL/STEEL JOINTS

by

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ABSTRACT

DEVELOPMENT AND CHARACTERIZATION OF FRICTION BIT JOINING: A NEW SOLID STATE SPOT JOINING TECHNOLOGY APPLIED TO DISSIMILAR AL/STEEL JOINTS

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Friction bit joining (FBJ) is a new solid-state spot joining technology developed in cooperation between Brigham Young University of Provo Utah, and MegaStir Technologies of West Bountiful Utah. Although capable of joining several different material combinations, this research focuses on the application of FBJ to joining 5754 aluminum to DP 980 steel, two alloys commonly used in automotive applications. The thicknesses of the materials used were 0.070 inches (1.78 mm) and 0.065 inches (1.65 mm), respectively.

The FBJ process employs a consumable 4140 steel bit and is carried out on a purpose built research machine. In the first stage of the weld cycle the bit is used to drill through the aluminum top sheet to be joined. After this, spindle speed is increased so that

the bit tip effectively forms a friction weld to the steel bottom sheet. Momentary stoppage of the spindle facilitates weld cooling before the spindle is restarted, shearing the bit tip from the bit shank, and retracted. Incorporated into the bit tip geometry is a flange that securely holds the aluminum in place after joint formation is complete.

This research consists of several developmental steps since the technology only recently began to be formally studied. Initial joint strengths observed in lapshear tensile testing averaged only 978.5 pounds (4.35 kN), with a relatively high standard deviation for the data set. Final lapshear tensile test results were improved to an average of 1421.8 pounds (6.32 kN), with a significantly lower, and acceptable, standard deviation for the data set. Similar improvements were realized during the development work in cross tension tensile test results, as average strengths increased from 255.8 pounds (1.14 kN) to 566.3 pounds (2.52 kN). Improvements were also observed in the standard deviation values of cross tension data sets from initial evaluation to the final data set presented in this work.

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1 Introduction

1.1 Background

A new method of welding has been conceived and developed in the very recent past. The new process is called Friction Bit Joining (FBJ). This is a completely new concept in joining technology. The process is used to join sheet materials together in orientations similar to those seen in traditional spot welding applications.

The technology is capable of forming joints between 3 separate sheets in one operation, more conventional steel-to-steel joints between two sheets, and most importantly for this work, joints between aluminum and steel.

1.1.1 Conventional Spot Welding Technology

The most common form of spot welding is a technology known as resistance spot welding (RSW). This process is quite versatile and is used anywhere from metal furniture construction to automobile fabrication.

The RSW process involves clamping the pieces to be joined between two electrodes. The clamping force on the electrodes holds the work pieces to be joined while current is passed from one electrode, through the work pieces, to the second electrode. The resistance to the current flow generates enormous amounts of heat in the work pieces. The result is localized melting of the work pieces, which then allows fusion joining to take place. Multiple welds are carried out along a path appropriate for the fabrication application.

Strictly speaking, RSW is capable of joining dissimilar materials such as aluminum and steel. Very specialized welding parameters are required to achieve any level of bonding between aluminum and steel sheets. Although joints can be formed, they suffer from defects in the joint that cause them to perform poorly. (Takeda; et. al., 2007) The joints that are formed by this method are inferior, such that use in most real world applications is not considered feasible.

1.1.2 Friction Stir Spot Welding

Friction Stir Spot Welding (FSSW) is a technology that has developed out of traditional, liner, friction stir welding. It involves the use of a non-consumable tool that is used to plunge into two sheets at the point of desired joint formation. The friction generated, from rotational speed and high forces in the Z-direction, allows the metal to become malleable and stir together to form a joint. The machine operates in the z-axis direction only since spot welds, not linear ones, are being formed (Connolly, 2007).

This technology is capable of forming joints between two sheets of steel, or even between aluminum and steel. The key to successful joint formation between aluminum and steel using this technology is the fact that each respective base metal does not become molten during the process. Instead the frictional heat that is developed renders the metals soft and malleable, allowing them to be stirred together. The reduced heat input of friction stir spot welding reduces the formation of intermetallic compounds, the cause of poor joint quality when using RSW to join aluminum to steel. Intermetallics form when dissimilar metals interact while in the molten state, as is the case with RSW. Although the metals are not completely molten with the FSSW process, heat and dissimilar metal contact does still form some intermetallic compounds.

Despite this fact, FSSW is capable of forming joints between aluminum and steel of sufficient quality to allow their limited used in some production environments. Mazda is currently using FSSW to join selected aluminum body components to steel framework (Aluminum Now, 2005).

1.1.3 Self-Piercing Riveting

Self-Piercing Riveting (SPR) produces riveted joints without the need for first drilling a pilot hole. This allows for quick cycle times and does produce a quality joint. The formation of a joint entails driving a hardened cylindrical rivet through the materials to be joined. The base materials, along with the rivet itself, are deformed as they encounter a lower die that forces conical deformation of the rivet, locking the fastener in place. This technology is capable of forming aluminum-to-aluminum, steel-to-steel, and aluminum-to-steel joints. (Abe; et. al., 2006)

The nature of this process requires that immense forces be applied during the riveting process. This means that machines must be built which can handle the massive loads involved. This factor also imposes some limitations on the technology in terms of joining certain material combinations.

SPR is not currently used to join Ultra High Strength Steels (UHSS). The hardness of these steels makes them difficult to penetrate with the self-piercing rivet, and does not allow sufficient plastic deformation for proper joint formation. The use of SPR in any joints, fully or partially, consisting of UHSS is not documented in current research.

1.1.4 Friction Bit Joining

Friction Bit Joining (FBJ) is a unique process that utilizes a consumable bit to drill through the first layer to be joined after which rotational speed, and force in the z-axis, are increased such that the bit is degraded and becomes friction welded to the work pieces. FBJ is closely related to traditional stud friction welding in terms of its joining mechanism, but is capable of spot joining automotive grade sheet metals.

In the case of steel-to-steel joints the bit is designed so that bit material, top sheet material, and bottom sheet material are all stirred together to form a joint. When joining aluminum to steel using this process it is desirable to design a bit which minimizes disruption of the top aluminum material and only promotes the stirring together (joining) of the bit material (steel) and the steel bottom sheet. The aluminum top sheet is then held in place by a flange incorporated into the bit design. This approach acts to prevent the stirring in of aluminum with the steel, further minimizing the formation of intermetallic compounds. It is hoped that this approach will allow superior joint performance in aluminum-to-steel joints using FBJ, as compared to similar joints formed using FSSW or RSW.

1.1.5 Advantages of FBJ in Aluminum-to-steel Joints

Currently, FSSW is the only viable option for welding aluminum to steel in spot welded applications. Although FSSW does a satisfactory job of forming such joints, it is quite possible that FBJ will be capable of producing superior joints. This would allow for a reduction of overall weld quantities required for a given application, while also allowing for wider application possibilities through improved joint performance characteristics.

1.2 Problem Statement

Joining aluminum to steel has been a roadblock for many years in progressive automotive design. The lack of a viable method for joining these two materials has stifled heavy integration of aluminum into car body design. As it stands today, full aluminum bodies are only available on high-end vehicles where higher profit margins allow the use of more expensive manufacturing processes. Currently, aluminum bodied vehicles like those offered by Jaguar are joined using a combination of rivets and specialty adhesives (Mortimer, 2004). This is expensive and is only justified for these high-end luxury cars. Further integration of aluminum parts into lower-end production vehicles will require the introduction of a joining technology capable of efficiently, and inexpensively, joining aluminum and steel.

The use of aluminum in vehicle design is desired so that more fuel-efficient cars can be produced. Another way to lower the final weight of a finished vehicle is to use thinner steels, where steel must be used. This has led to the development of ultra high strength steels (UHSS). Because of the significant strength of these new steels, the thickness of body panels can be effectively reduced while still meeting necessary strength requirements. The result is a net reduction in vehicle weight. Since the automotive industry is moving in the direction of UHSS it stands to reason that any process capable of joining aluminum to steel ought to be able to do so in UHSS, in order to be considered robust enough for future use in the automotive industry.

1.2.1 Hypotheses

The following hypotheses will guide this research of the FBJ process. The proposed hypotheses give benchmarks in terms process performance requirements and final joint performance and appearance.

Hypothesis 1: The FBJ process is capable of producing joints in 5754 aluminum and DP 980 steel that perform in lap shear tests at an average of 1000 pounds or above over 10 consecutive samples, and perform in cross tension tests at an average of 500 pounds or above over 10 consecutive samples.

Hypothesis 2: The FBJ process is superior to the SPR process in terms of total operating loads required to form a joint. That is to say that FBJ requires significantly lower operating force, an average of 2500 pounds or less over 20 consecutive samples, to form a joint than does SPR.

Hypothesis 3: The FBJ process is capable of forming joints that have satisfactory surface finish for use in automotive applications. This means the joint must have minimal flash so that conventional coating techniques will wet all areas surrounding the joint to prevent any bare metal where corrosion may begin. This does not mean the joint has to be invisible, as it will generally be used only in inconspicuous areas.

1.3 Methodology

The following materials will be used for this experimental work. Materials to be joined will be 0.065” DP 980 steel and 0.070” 5754 aluminum. The bit material will be 4140 steel, with an annealed state hardness of 28 – 30 on the Rockwell C scale.

Experiments will be carried out on a purpose-built research machine constructed by MegaStir Technologies of West Bountiful, Utah.

Because this technology is brand new no best known parameters exist for the process. This will necessitate some initial informal experimentation to discover reasonably good parameters for use in later, more formal, experiments.

Lap shear and cross tension testing will be used extensively to evaluate joint performance. Some samples will be cross-sectioned, mounted, and polished for evaluation via microscopy.

1.4 Delimitations

This research will only focus on the joining of aluminum and steel using FBJ. Comparisons to technologies such as RSW and FSSW will be made via research results previously achieved by others. Furthermore, the only materials that will be joined during these experiments are DP 980 steel and 5754 aluminum.

This research will not explore or evaluate the use of FBJ to join multiple sheets (3 or more) of material, or the use of FBJ in conventional steel-to-steel joints.

1.5 Definition of Terms

DP – Dual phase steel that consists of two fractions, one martensite and one ferrite.

DP 980 – A dual phase steel with an ultimate strength of 980 MPa or 140 ksi. This steel consists of a 60% martensite fraction and a 40% ferrite fraction.

FBJ – Friction Bit Joining

FSW – Friction Stir Welding

FSSW – Friction Stir Spot Welding

FW – Friction Welding

RSW – Resistance Spot Welding

SPR – Self-Piercing Riveting

UHSS – Ultra High Strength Steel. Steels that have an ultimate tensile strength of 600 MPa or above are considered UHSS.

2 Literature Review

2.1 Introduction

The ability to join aluminum and steel has long been a difficult technical problem in many industries, especially the automotive sectors. There are a number of technologies available today that can form dissimilar metal joints, with varying degrees of final joint quality. Some of these technologies are used for linear joining while others are used to form joints in a spot-joined configuration.

Currently available joining methods will be discussed in this chapter such as resistance spot welding (RSW), friction stir welding (FSW), friction stir spot welding (FSSW), and self-piercing riveting (SPR). Also included in this discussion will be a process called Friction Welding (FW). Although the FW process is capable of joining aluminum and steel bar stock in a butt joint orientation, this is not the main reason for its inclusion in this review of literature. In fact, the geometry of the joining process does not even allow it to be used for spot joining sheet materials. It is included here mainly due to the fact that the process shares a key element in common with the Friction Bit Joining (FBJ) process. The similarities between FBJ and FW come in the ability to join steel to steel via a friction mechanism. FBJ utilizes a steel bit that penetrates an aluminum top layer and is ultimately friction welded to a steel bottom sheet to form an effective aluminum-to-steel joint. This steel bit-to-steel bottom sheet friction welded aspect of the process requires an overview of the traditional friction welding process in order to understand the mechanisms present in the technology currently under investigation.

Because the FBJ process is newly invented, there is no outside research available on this specific subject. The purpose of this thesis work is to develop, and characterize, the current capabilities of the FBJ process in the specific case of joining aluminum to steel, and to provide direction for future research efforts. Due to the fact that this research is pioneering in nature, the majority of the works cited will deal with competitive, or related, processes and their current capabilities.

2.2 Resistance Spot Welding

Resistance Spot Welding (RSW) is currently used almost exclusively for joining steel sheets to one another in automotive manufacturing. The process is relatively inexpensive to carry out and has the benefit of extremely short cycle times. RSW creates satisfactory welds in steel-to-steel joints and, less commonly, aluminum-to-aluminum joints.

Resistance spot welding is ideal for steel-to-steel joints as it forms quality joints quickly and cheaply. Very little electrode wear occurs while joining steel to steel. This reduces the expense associated with replacing welding electrodes. Although RSW is capable of joining aluminum to aluminum, the formation of this joint is more expensive than a similar steel-to-steel joint. The characteristic of steel that makes it easy to weld is its relatively high electrical resistance, as compared to aluminum (ASM Metals Reference Book, 1993). Electrical resistance is the means by which heat is generated as electricity is directed through the materials to be joined. Higher resistance means greater heat generation, assuming amperage stays the same. This basic consequence of Ohm’s law means that the heat needed to melt the steel is capable of being generated with lower amperage levels.

Aluminum materials are much better conductors of electricity, meaning they have lower electrical resistance. Aluminum is also a better conductor of heat than is steel (ASM Metals Reference, 1993). This means that while steel holds thermal energy near the weld site for melting to occur, aluminum quickly dissipates that heat making it more difficult for melting to proceed. Although aluminum does melt at a lower temperature than steel, the consequence of these combined facts is that resistance spot welding of aluminum-to-aluminum joints requires significantly greater electrical current than is required for steel-to-steel joints. The higher energy requirements for this type of joint make it more costly (Barnes; Pashby, 1998). In addition to this there is also significantly greater electrode wear when joining aluminum to aluminum. This electrode wear is the result of the higher current needed to form the joint. The high current, and resultant heat, causes alloying to occur between the molten aluminum base metal and the hot copper electrodes. This alloying accelerates electrode tip deterioration. Electrode wear adds to the cost of the process as electrodes must be dressed or replaced frequently throughout production runs (Spinella et. al. 2005). While joining steel electrode tips do not need to be dressed or replaced for at least 10,000 spot welds. This is compared to only 400-2000 spot welds in aluminum before tip dressing or replacement is required (Davies; Goodyer, 1991).

As 5754 aluminum alloy is one of the base metals used in this research it bears mentioning the performance of the RSW process while joining this material. This value can serve as a minimum baseline for the performance of the FBJ process while joining this aluminum alloy to a DP 980 steel sheet. With a weld nugget diameter of 0.250 inches (the same weld diameter found in FBJ joints for this study) resistance spot welded joints in 0.079” (2.0mm) 5754 aluminum sheet perform in lap shear tensile tests at an average of 955 pounds (Thornton; et. al., 1996). This value would suggest that the FBJ process should be capable of creating joints between 5754 aluminum and steel that perform in lap shear tensile tests at 955 pounds or above, with a similar weld nugget diameter, in order to be considered viable for industrial applications. Therefore, the benchmark of 1,000 pounds is used as a minimum value in this research, for the simplicity of round numbers.

The performance of the RSW process in conventional steel-to-steel welding also bears mentioning for a frame of reference regarding the technology and its capabilities in conventional steel-to-steel applications. A typical weld between two sheets of DP600 steel with a nugget diameter of 0.167 inches (4.26 mm) gives an ultimate tensile load in lap shear of 1,924 lbs. When weld nugget size is increased to 0.315 inches (8.0 mm) the ultimate tensile load rises significantly to 5,845 lbs (Marya; et. al., 2006).

RSW is capable of forming quality steel-to-steel joints, and aluminum-to-aluminum joints. Joining steels is quick and inexpensive, while joining aluminum is similarly quick, but does incur some additional costs. Joining aluminum to aluminum can also be a bit more difficult to achieve in terms of properly setting process variables (Cho; et. al., 2003).

Although resistance spot welding is considered a robust process when it comes to joining identical metals, the process falls short when it is applied to joining dissimilar metal materials. This is particularly true in the case of joining aluminum to steel. Strictly speaking, resistance spot welding of aluminum to steel is possible (Takeda; et. al., 2007). However, during fusion welding of aluminum and steel, brittle intermetallic compounds are formed that ultimately limit the effectiveness of the joint (Iwase; et. al., 2007; Ishida, 1987; Agudo; et. al., 2007; Takeda, 2007). These intermetallics are formed as a result of the two metals contacting one another while in their molten state, a reality that is encountered with any fusion welding process. A study performed by Wantanabe, et. al. in 2005 suggests that the thickness of the intermetallic layer increases as magnesium content is increased in the aluminum alloy being joined to the steel. This is of particular interest as the 5754 aluminum used in this study, a common automotive grade aluminum, contains 2.6 – 3.6 percent magnesium (Miles; et. al., 2004) Wantanabe's research would suggest that the relatively high magnesium content of the 5754 aluminum alloy make it particularly susceptible to brittle intermetallic formation during fusion welding. It was shown that intermetallic layer thicknesses increased as magnesium content in the aluminum increased. As a result of this the corresponding lap shear joint strengths decreased, due to the thicker intermetallic layer (Wantanabe; et. al. 2005).

Some efforts have been made to reduce the intimate contact between molten aluminum and steel during fusion welding by introducing an intermediate material to the joint. Such a layer is used because it is more compatible with the aluminum and steel materials for welding purposes, and acts as a barrier between the two base materials. When fusion welding is carried out using this type of technique the formation of brittle intermetallics is reduced as each molten base material is largely in contact with the more compatible intermediate material. Such techniques do yield improvements to joint strengths; however, the introduction of an intermediate layer does entail higher material costs and labor requirements (Sun; et. al., 2004; Fukui; et. al., 1997; Yasuyama; et. al., 1996). These types of solutions are less than ideal as they are more expensive to carry out and intermetallic compound formation can still be an issue.

The performance of these modified RSW processes varies depending on the base materials used and the type of insert material employed. In standard lap shear tensile tests values ranged from 427 to 697 pounds in one study, while being as high as 1,500 pounds in another study (Yasuyama; et. al., 1996; Sun; et. al., 2004). In the same two studies average cross tension numbers were found to vary between 304 and 348 pounds, with some values reaching as high as 1,079 pounds. These numbers are the result of static load testing. It should be noted that even the RSW/insert method that yields higher static load numbers, comparable to the self-piercing riveting process, falls short under dynamic loading (Sun; et. al., 2004). No resistance spot welding method is currently capable of forming joints between aluminum and steel that perform comparably to self-piercing riveting in terms of fatigue resistance. Although it is true that research into the use of RSW in joining aluminum to steel has generated significant progress towards satisfactory joint performance, too many shortcomings still exist. The remaining performance problems still present in resistance spot welded aluminum-to-steel joints necessitate the use of other joining methods to form joints between these two materials.

2.3 Friction Stir Welding

Friction Stir Welding (FSW) involves the utilization of a rotating tool that spins and plunges into two base materials to be joined. The resultant heat generated from friction, along with the rotational motion, facilitate the stirring together of material at the joint line. This stirring action effectively forms a metallurgical joint between the two specimens. FSW is most often carried out in a linear fashion for the formation of standard butt joints between two metal plates (Nicholas, 2003).

The friction stir welding method has been used to successfully join aluminum to steel. The resultant joint properties are much improved over any fusion welding techniques that have been used to attempt the joining of these two metals. FSW is more successful than other techniques in this regard, but it does still have some shortcomings. Although the majority of each joint is formed at temperatures low enough to prevent the formation of brittle intermetallic compounds, there is a particular area of the weld that gets quite a bit hotter. The interface between the tool shoulder and the metal substrate is the location of greatest heat generation. The increased heat in this area does allow the formation of some intermetallic compounds. These intermetallics ultimately serve as sites for crack initiation when the joint is placed under load. The result is performance that is better than previously possible, but still less than desired (Watanabe; et. al., 2006).

2.4 Friction Stir Spot Welding

Friction stir spot welding (FSSW) is a process that is based largely on traditional linear FSW, but adapted to spot joining. In this technique a similar tool is used that rotates while significant pressure is applied. In this case the joint formed is a lap joint as opposed to a butt joint. Additionally, there is no linear movement of the friction stir tool relative to the work pieces. Instead the weld is formed via plunging, followed by dwelling at depth for heat generation and stirring, then retraction from the work pieces (Connolly, 2007). The result is a spot weld between the two sheets of metal. This method has been used to successfully join aluminum to aluminum, steel to steel, and aluminum to steel (Connolly, 2007; Hovanski; et. al., 2007; Gendo; et. al., 2006). In the case of aluminum-to-steel joints the process is even capable of producing joints of sufficient quality for actual use in production applications (Gendo; et. al., 2006). Mazda has been using the FSSW process to join an aluminum trunk lid to steel hinges in its MX-5 sports car since the 2006 model (Aluminum Now, 2005).

A study by Tanaka; et. al. provides some performance data regarding FSSW joints between aluminum and steel. For the study a 6xxx series aluminum was used with a thickness of 0.039” (1.0mm). This was joined to a cold rolled carbon steel sheet with a thickness of 0.028” (0.7mm). The best resultant strength for the described joint was 809 lbs. (3.6 kN) in lap shear (Tanaka; et. al., 2006).

Although the process has been demonstrated to successfully join aluminum to steel, the joint strengths are not spectacular. This limits the processes applications to those that do not require high strength. A better performing technology for joining aluminum and steel is still desirable, especially for structural applications where strength is a top priority.

2.5 Self-Piercing Riveting

The self-piercing riveting (SPR) process is a non-welding method of joining sheet materials in a spot-joined orientation. The SPR process is capable of forming riveted joints between two sheets of metal without the need for a pre-drilled pilot hole. The sheets to be joined are pierced by the actual rivet fastener during the formation of the joint. The self-piercing nature of the process requires the use of a rivet that is harder than either of the base materials to be joined, along with significant amounts of force to carry out the joining process.

No heat, other than an insignificant amount from metal deformation, is generated during this joining process. This means that the metals are not fused together, but are fastened in a mechanical joint. Since the SPR joint is purely mechanical in nature, the process is capable of joining dissimilar metals.

In order to properly characterize the FBJ process and its capabilities it becomes important to benchmark it against competing technologies. In order to facilitate this process some performance values are included from current research regarding the SPR process.

Due to the fact that joints between aluminum and steel are somewhat rare, both in research and real applications, numbers regarding both aluminum-to-aluminum joints and aluminum to steel configurations are presented. The SPR process, when used to join 1, 2, and 3 millimeter thick coupons of aluminum to one another in different combinations yields lap shear values ranging from 563 pounds (2.51 kN) to 1358 pounds (6.04 kN) (Atzeni; et. al., 2005). Joints between 0.079" (2.0mm) 5282-O aluminum and 0.063" (1.6mm) DP600 steel yield values of 1461 lbs in lap shear and 1169 lbs in cross tension (Sun; Khaleel, 2005).

The current performance achievable with the self-piercing rivet process has allowed it to be utilized in the manufacturing of all aluminum car bodies on high-end Jaguar vehicles (Mortimer, 2001; Mortimer, 2004). The joints formed for this application on the Jaguar are understood to be aluminum-to-aluminum joints, as opposed to aluminum-to-steel joints. Although the SPR process gains credibility as it is used in industry it should be noted that joints in the mentioned application are reinforced with industrial strength adhesives to aid in joint performance. Although the combination of SPR and adhesives produces a good joint, the high expense associated with the combined processes limits their use to high-end vehicles like the Jaguar, as opposed to typical production style automobiles.

The SPR process is capable of forming satisfactory aluminum-to-steel joints that are desired by many industries. However, the operating loads involved during a self-piercing rivet cycle can be quite significant. The loads involved in joining various aluminum-to-aluminum joints can range from 4496 pounds (19.99 kN) to 8992 pounds (39.99 kN) (Kim; et. al., 2006). These incredible loads require a heavy frame in order to handle the forces involved. This requirement can present difficulties when trying to design a versatile machine that will fit in multiple places for a variety of applications. The support required for the loads involved can increase machine size to a point where its use is only feasible to create joints in relatively simple and accessible locations. Although some smaller and more maneuverable machines are likely available, their decreased capacity may limit them in terms of the joints they can form.

Even though the SPR process is highly capable in terms of joint performance, the high operating loads make it less than ideal for several applications. A process capable of similar joint performance characteristics, while requiring lower operating loads, would be beneficial. Lower operating loads would allow the use of a less substantial machine, and should make the joining of aluminum to steel available for a larger variety of applications.

2.6 Friction Welding

Friction welding (FW) has been around for years and is a time-tested technology. It is commonly used for joining cylindrical shafts to one another for use in various applications (Murray, 1982). The solid-state nature of the welding process lends itself well to the joining of both similar and dissimilar metals (Shinoda; Kawata, 2004; Sahin; et. al., 1996; Fukumoto; et. al., 1999). Although the subject of this current research focuses on joining aluminum to steel, the relationship between FW and FBJ actually comes in the joining of steel to steel via a friction mechanism. FBJ, as will be explained further in Chapter 3, has an element in common with friction stud welding in terms of the actual welding steps that take place. In FBJ of aluminum to steel, for example, a steel bit drills through the aluminum top layer, but is then friction welded to the steel bottom sheet; just like a traditional friction stud weld. Since these technologies share some common traits, it is useful to understand how friction welding is carried out in traditional applications.

FW is performed on specialized machinery that has been designed for the process. In the case of joining two pieces of bar stock, one piece is held stationary in a rigid chuck while the other is mounted into a spindle, much like that found on a traditional lathe. It should be noted that it is common practice to machine the faces of the bar stock to be joined so that they interface in a precise manner during the welding step. Once the materials are setup, the machine is started and the spindle ramps up to speed. When the proper RPM is reached the two pieces are moved together under significant force. The rotation of the one piece against its stationary counterpart creates frictional heat that softens the base metal. The rotation facilitates the interaction of the two base metals so that an intimate metallurgical bond is formed under the heat of friction. Once the rotational phase of welding has been completed the spindle stops, after which additional pressure is applied in what is called a forging step (Murray, 1982). The forging step is used as a means of consolidating the weld and eliminating any voids that may have developed. It should be noted that some research has found that the forging step makes no difference in the final joint strength (Kimura; et. al., 2002). This becomes important for a process like FBJ where cycle times must be kept to a minimum. The elimination of a forging step, with no ill effects on joint strength, will certainly be beneficial to the process in terms of cycle time.

Friction stud welding is very similar to a traditional friction weld in the way the joint is formed. The difference is the geometry of the joint. In the case of a friction stud weld, a stud is joined to a flat surface. This is a common method that has been used to join studs to structural steel in preparation for encasement in concrete (Gilmour, 1974). If we were to take the aluminum top sheet out of the equation for the current FBJ research, friction stud welding is basically what we would be performing. An understanding of how friction welding is typically carried out will be beneficial as the FBJ process is further developed.

2.7 Summary

Of the several techniques available that are capable of spot joining aluminum and steel to some degree, only Friction Stir Spot Welding and Self-piercing Riveting provide satisfactory performance. Even though these processes are robust enough for use in limited applications, some of their shortcomings preclude them from further, more widespread, implementation.

FSSW is able to form joints between aluminum and steel, but the strengths of those joints are not very impressive. Granted, they are better than those achieved with methods such as RSW, but the process still leaves something to be desired. The SPR process produces excellent strengths in aluminum-to-steel joints. There is no doubt that SPR forms good joints. However, the significant loads required to carry out the SPR process may limit the applications for which it can be used. In addition, when a soft material like aluminum is joined to an UHSS like DP 980, then the SPR process is really no longer viable. This is due to the fact that such a high strength steel will be very difficult to form around the rivet during joint formation. There are currently no data available in the literature for SPR joints in steel above 600 MPa in strength.

Because of the shortcomings of current technologies for the spot joining of aluminum and steel, a better solution would be useful. It would be ideal if some process could perform at a level similar to SPR, in terms of joint strength, while being capable of operating at significantly lower loads during joint formation. It is proposed that FBJ will be able to meet these desired goals, and will thus be a viable and competitive process for spot joining aluminum and steel.

3 Research Methodology

3.1 FBJ Machine

The FBJ process requires the use of a machine capable of a wide range of spindle speeds, the ability to apply significant pressure in the Z-axis direction, and the capability of starting and stopping spindle rotation in a nearly instantaneous fashion. The use of servo motors for driving the spindle and moving the spindle along the Z-axis is warranted due to the unique capabilities of servo drive units, as opposed to traditional induction motors. Their use in an FBJ machine yields all the abilities outlined above.

The machine used for this research is a purpose built unit engineered and produced by MegaStir Technologies of West Bountiful, Utah. The machine is built around a large c-frame unit, ultimately to be mounted on an industrial robot once the technology is ready for implementation into manufacturing applications. A photograph of the FBJ machine is included in **Figure 3.1**.

Figure 3.1 – FBJ machine built by MegaStir Technologies

Attached to the lower arm of the c-frame is the fixture that is used to secure samples for the welding operation. Attached to the upper arm of the frame is the head unit of the machine. Directly attached to the frame is a set of steel ways that secure the moving portion of the head unit. A z-axis servo drive controls the movement of the head unit in the z-axis direction. A larger servo drive unit is secured directly to the movable portion of the head, which is responsible for driving the spindle of the machine.

Two sensors are present on the machine that provide critical data throughout the welding cycle. The first sensor is located within the fixture plate. This is a load cell that is used to detect load in the z-axis direction. This load cell is used during a touch off procedure in order to establish machine zero in the z direction. The sensor is also used to record the maximum z-force encountered during any given weld cycle. A laser micrometer is mounted near the bottom of the head unit. This sensor is used in conjunction with the load cell mentioned to establish a zero point in the z direction. After proper zeroing, the sensor monitors spindle depth during the weld cycle via multiple reads each second. This information is used in real time during the weld cycle to properly carry out the welding sequence.

3.1.1 Machine Controls

The FBJ machine utilizes PLC controls to run the unit during the course of a weld cycle. Although the load cell is required to properly zero the machine and gather peak load data, its input is not directly required for the actual execution of the weld cycle. The control software does allow one to run the machine in load control as opposed to depth control, in which case its input is used, but this research has only made use of the machine while in depth control mode, utilizing the laser micrometer during the weld cycle.

While running in depth control the laser micrometer is used to monitor spindle depth throughout the cycle. This input becomes critical when parameter changes are desired after achieving a specified depth. In fact, this is how the machine is programmed to change parameters throughout the several steps of the weld cycle.

In order to aid in explaining the machine controls I include a representation of the control matrix in **Table 3.1**.

Table 3.1 – Parameter variables and stages available for controlling the weld cycle

Weld Parameters						
Stage	1	2	3	4	5	6
RPM						
Z-Velocity (in/min)						
Z-Command (in)						
Peck Cycles						
Dwell (ms)						

As can be seen in the figure there are six available stages, with five adjustable parameters for each stage. For each stage of the cycle it is possible to specify spindle RPMs, z-velocity, z-depth, peck cycles (used during the drilling phase), and finally a dwell parameter that will be explained in a moment.

The RPM parameter is relatively self-explanatory as this defines the spindle speed in rotations per minute for the given stage. The z-velocity parameter controls the rate at which the machine moves in the z-direction for the given stage. The z-command parameter defines a final depth for the programmed stage. After reaching the programmed depth, provided no dwell command is entered, the machine will move to the next stage in the cycle. Peck cycles are used only during the drilling stage of the weld cycle. A peck is a temporary retraction of the bit from the samples in order to facilitate the removal of metal chips. Using this parameter one can specify the number of peck cycles before achieving the final depth defined for the stage.

The dwell parameter is useful when it is desired to continue with the programmed stage parameters for a period of time after achieving the specified depth for the stage. For instance, during the actual welding stage is it desirable to allow the bit to continue to spin for a moment after it has reached its final depth. This allows further generation of frictional heat to form the joint. In order to facilitate this, an appropriate dwell value would be entered for the welding stage of the cycle.

Table 3.2 shows an example of a functional welding cycle, which will be fully explained for the sake of clarity regarding the machine control parameters.

Table 3.2 – Example of a functional welding parameter set

Weld Parameters						
Stage	**1**	**2**	**3**	**4**	**5**	**6**
RPM	500	2400	0	800		
Z-Velocity (in/min)	2.0	2.0	0.0	10.0		
Z-Command (in)	-0.070	-0.110	-0.110	0.200		
Peck Cycles	1	0	0	0		
Dwell (ms)	0	1000	500	0		

The first stage of the welding cycle is used for drilling through the aluminum top sheet of the samples to be joined. As outlined in the above parameter matrix, the machine spindle will rotate at 500 RPM and plunge at a speed of 2.0 inches/min (50.8 mm/min). It will retract once for a single peck cycle before it reaches its final programmed depth of -0.070 inches (1.78 mm). Because no dwell is specified for the first stage, once reaching the programmed depth the machine will move to the second stage. In the second stage the spindle RPM will increase to 2400 RPM while the plunge rate is programmed to remain the same. These parameters will be maintained until a depth of -0.110 inches (2.79 mm) is achieved. At this point you will notice that stage 2 does have a dwell parameter specified. Once the programmed depth is achieved the spindle will continue to spin at the programmed 2400 RPM, at the specified depth of -0.110 inches (2.79 mm), for the duration specified by the dwell parameter. After reaching the programmed depth and satisfying the dwell period the machine then moves onto the third stage. In this stage spindle rotation is stopped and no spindle travel takes place. The dwell parameter for this stage allows the freshly formed weld to cool in preparation for the final step of the cycle. After stage 3 is complete the spindle is restarted at 800 RPM and retracts up to 0.200 inches (5.08 mm) at a rate of 10.0 inches/min (254 mm/min). This shears off the bit tip from the bit shank and completes the weld cycle.

3.1.2 Fixturing

As the FBJ process is in the development stages of research the fixturing solution designed for this work was largely manual in nature. For future implementation into manufacturing operations other, more automated, solutions will need to be engineered.

The fixture platform used for securing samples consists of a thick tool steel platform with several holes for fixture pins and several tapped holes for securing a clamping plate. A photo representation of this fixture is given in **Figure 3.2**.

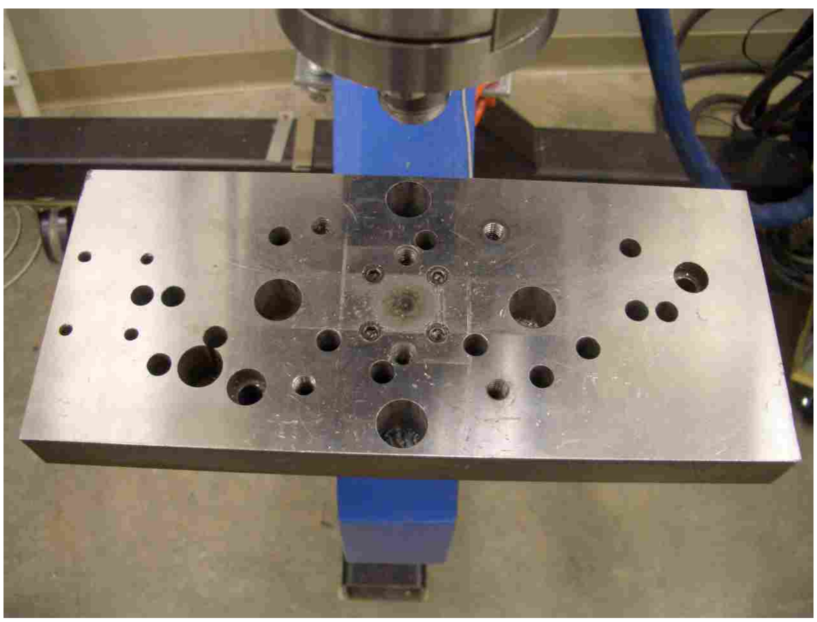

Figure 3.2 – Fixture platform used to secure samples for welding

The round anvil in the center of the fixture should be noted as the load cell for the machine is located directly below this feature. The anvil is machined such that it protrudes above the fixture surface by a few thousandths of an inch. This allows loads to be directly transferred to the underlying load cell accurately, without losing load through dispersion across the surface of the fixture.

The locating pins are used to ensure that the sample pieces are lined up properly, and that they remain parallel to one another during the weld cycle. Any rotation of the samples relative to one another during the weld cycle would result in a torque load on the joint during tension testing, a condition that would likely interfere with accurate physical testing.

Figure 3.3 shows a photo of a lap shear sample mounted in the fixture and ready for joining.

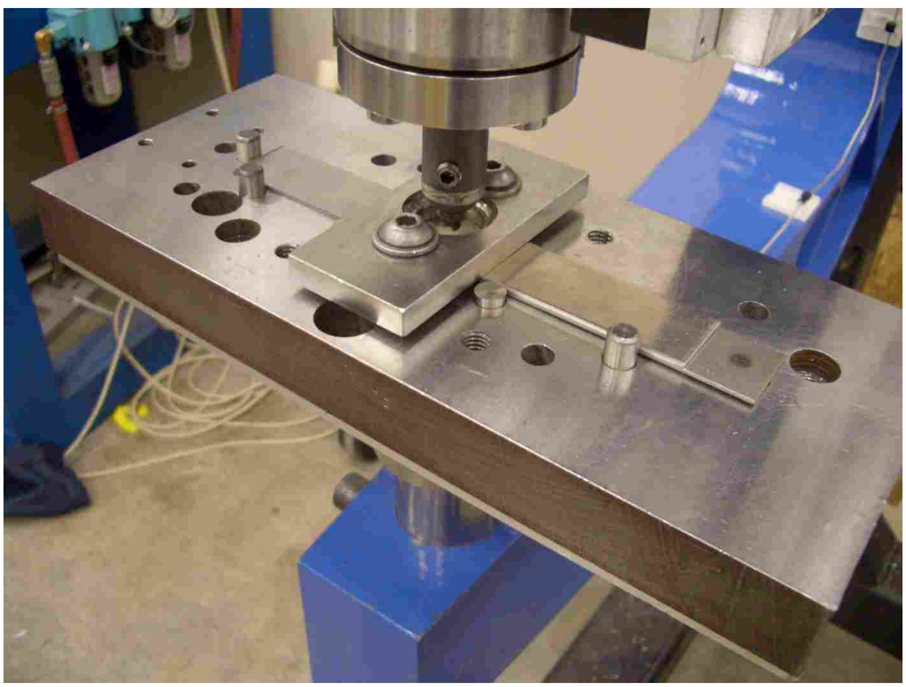

Figure 3.3 – Lap shear tensile specimens ready for welding

Notice the presence of a spacer coupon that is used to support the overhang of the upper aluminum coupon. The clamping plate is secured with two Allen head machine screws. The hole in the clamping plate allows access for the tool holder and bit to initiate contact with the samples for the joining process.

A slightly different fixturing setup is used to produce cross tension samples. An example of this setup is portrayed in **Figure 3.4**.

Figure 3.4 – Cross tension tensile specimens ready for welding

3.2 Bit Manufacturing

Bits are manufactured from 4140 stainless steel primarily using an Okuma Spaceturn LB300-M CNC lathe. In some cases other machinery has been used to achieve desired bit geometry. Among these is an Oliver Instrument Company Model 21 drill bit grinding machine which was used to impart a drill bit like tip to previously machined bits. Also used during the bit geometry development was a Darex E-90 end mill-sharpening unit. This unit was used to achieve an approximate bit tip geometry in a proof of concept fashion before investing time in programming the Okuma lathe to produce the specific design change. CNC machining programs are included, for reference, in the appendix of this document. **Figures 3.5**, **3.6** and **3.7** show photos of the machinery used for the production of the joining bits.

Figure 3.5 – Okuma Space Turn LB300-M

Figure 3.6 – Oliver Instrument Co. Model 21

Figure 3.7 – Darex E-90 Mill Sharpener

3.3 Materials

The materials used in this study are 0.065 inch (1.65 mm) thick DP 980 steel sheet, 0.070 inch (1.78 mm) thick 5754 aluminum sheet, and 3/8 inch (9.53 mm) 4140 steel bar stock. The DP 980 steel and 5754 aluminum sheet materials were used to produce specimens to be joined by the FBJ process. The 4140 steel bar stock was used to produce the joining bits used for the FBJ process.

5754 aluminum is an automotive grade material that is currently used for auto body structures, in limited quantities. DP 980 steel is not extensively used in current production vehicles. However, the ever-persistent push towards stronger and thinner steels has made this material a candidate for further incorporation into future automobiles in order to reduce overall vehicle weight. 4140 steel is an oil hardenable steel that is used in numerous applications. The steel is noted for is toughness and good fatigue strength. The steel is also easily machined in its annealed state. These properties make it an ideal choice for a bit material. Although the steel is a hardenable variety, the bits are machined, and used for welding, in their annealed state.

3.4 Specimen Preparation

Samples were prepared for this research by shearing coupons of each respective material (DP 980 steel and 5754 aluminum) to 1 inch by 4 inch size for lap shear testing, and 2 inch by 6 inch size for cross tension testing. The 2 inch by 6 inch coupons used for cross tension testing were then further processed by drilling locating holes in the coupons for proper fitment into the welding fixture. Lap shear coupons required no further processing after shearing to size.

The coupon surfaces to be welded together were degreased with methanol and allowed to dry before welding experiments took place.

3.5 Testing Methods

During this research a number of testing methods were used to evaluate joint performance and morphology. Lap shear and cross tension tensile tests were used to evaluate static joint strengths. Microscopy was used to evaluate the quality of the welds in a qualitative fashion by observing the cross sections of completed welds.

3.5.1 Mechanical Testing

Lap shear tensile testing and cross tension tensile testing are the main mechanical tests used during this research. All tensile testing was carried out at room temperature using an Instron tensile test frame, with model number 4204, and a ten kilo-Newton load cell.

Lap shear samples were mounted in the test jaws and shimmed using appropriate spacers to ensure loading perpendicular to the axis of the joint. Cross-tension samples were mounted using a purpose built fixture that allows the sample to be loaded parallel to the axis of the weld. Included with this fixture are square washers, which hold the sample coupons flat during the cross-tension test. Both tensile tests, lap shear and cross tension, are carried out at an extension rate of 0.4 inches per minute (10.16 mm/min).

Figures 3.8 and **3.9** show how the samples were mounted for the two tensile tests described.

Figure 3.8 – Lap shear tensile test

Figure 3.9 – Cross tension tensile test

3.5.2 Microscopy Evaluation

Microscopy evaluations were performed after selected development steps. These images were used to inspect for visual improvements in joint quality that corresponded to observed joint strength improvements. Microscopy images were also used to evaluate the joints for current flaws that could be eliminated through further development work. A good example was the observation of voids within the weld nugget that prompted specific changes to bit tip geometry in order to reduce gaps within the finished joint.

Completed joints were prepared for microscopy evaluation by cross sectioning them using a Sodick EPOC-300L wire EDM machine. After successful cross sectioning the tail of the sample was trimmed off using the same machine, yielding a specimen small enough to facilitate the mounting of the sample for polishing.

After successfully machining the sample in preparation for mounting, the specimen was sent to Russell Steel of MegaStir Technologies for actual mounting, polishing, and microscopy imaging. Many thanks go to him and MegaStir for their time and expertise. Resultant images were reviewed for joint quality and possible areas for improvement via development work.

3.6 Research Approach

Because this research is the first attempt to study FBJ in the application of aluminum-to-steel joints, a fair amount of time was spent experimenting with different weld parameter variables and bit design variables to improve the performance of the process. An initial bit design and set of parameters were arrived at through relatively informal experimentation. After somewhat respectable results were achieved, the initial set of parameters were noted and used as a starting place for this research. Formal data collection began at this point, and served as a baseline for further process development and improvement efforts.

3.6.1 Data Collection

Formal data sets consisted of twenty consecutive joints. Ten were produced for lap shear tensile testing, with the remaining being produced for cross tension tensile testing. Additional samples were produced as needed, with identical parameters, for use in microscopy analysis.

Averages and standard deviations were immediately calculated for these formal data sets. This helped in understanding current performance results in terms of average joint strengths and process consistency, or lack thereof.

After characterizing the performance of a given bit design and set of weld parameters efforts at improving the process took place. Using microscopy data, and some structured thinking, changes were proposed to increase joint strengths and decrease the standard deviation of future data sets. After experimentation with bit design and parameter adjustments resulted in joint strength improvement, another formal data set was collected in order to evaluate the further developed FBJ process for average strength and consistency. This technique was repeated several times until the average joint strengths became acceptably high, and standard deviations became acceptably low.

3.6.2 Statistical Analysis

Aside from the simple averages and standard deviation calculations performed throughout the course of the research, a t-test was also used to evaluate the several formal data sets. This test is used to determine whether the observed difference in data set means is attributable to special causation, such as the modification of process parameters, or if it is simply a result of chance alone. This test allows us to show whether real progress was made between data sets as the development of the FBJ process took place.

3.6.3 Hypotheses Accept or Reject Criteria

The first hypothesis that guides this research, regarding lap shear and cross tension tensile test results, will be accepted or rejected based on the average of ten samples for each tensile test type. If the averages of the groups meet or exceed the minimums put forth in the hypothesis, it will have failed to be rejected.

The second hypothesis, regarding maximum load requirements, will be accepted so long as the average maximum load is found to be 2500 pounds (11.12 kN) or less, across 20 consecutive samples. This is based on findings from literature that indicate SPR maximum loads range from 4000 to 8000 pounds (17.79 kN to 35.58 kN), depending on the material combination used.

The third hypothesis deals with the somewhat qualitative aspect of joint appearance. This hypothesis will be accepted under only one of two circumstances. The first circumstance is that in which the joint does not exhibit any flash whatsoever around the flange of the bit tip, allowing complete paint coverage by default. The second circumstance is that minimal flash does occur, but it is not shaped such that it would prevent complete paint coverage while applying said paint at an angle 90^{o} to the surface of the joined sheets. Either of these two conditions must be exhibited in all 20 samples for the given data set. If any of the samples exhibit flash that would interfere with complete paint coverage then the hypothesis will be rejected.

4 Research Results and Discussion

4.1 Initial Bit Design and Parameters

As mentioned previously, the FBJ process is a new spot joining technology. As such, it was requisite to carry out informal experimentation with bit designs and parameter adjustments in order to gain some amount of success in joining aluminum to steel using the FBJ process. Through such experimentation an initial bit design and set of parameters was generated.

4.1.1 Initial Bit Design

Figure 4.1 shows a drawing of the bit design used at the start of this research. An understanding of the initial bit design features, and their purpose, will aid in the understanding of subsequent design changes made during the development work. It should be noted that the geometry specified in the drawing was created using the Okuma CNC lathe. Secondary processing, on the Oliver drill sharpener, was required after initial machining of the bit, to impart the required drill like cutting faces.

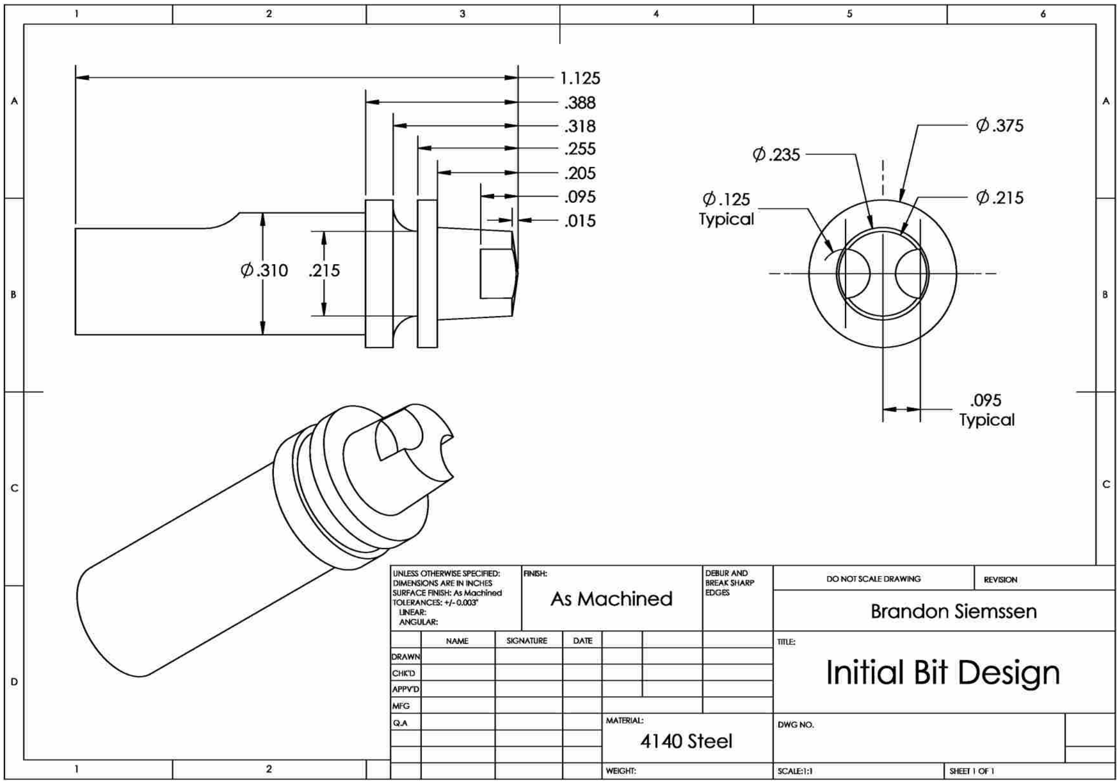

Figure 4.1 – CAD drawing of the initial bit design to be machined on the Okuma CNC lathe

The bit tip is designed to function something like a typical drill bit during the initial stage of the welding cycle. Cutting faces are present to cut the aluminum top sheet while flutes are provided to facilitate chip removal during the drilling stage. The bit tip geometry is ultimately destroyed during the welding stages of the cycle where actual joining takes place via the friction mechanism.

The majority of the metallurgical joining that takes place during the FBJ process occurs between the 4140 steel bit and the DP 980 steel bottom sheet. In order to aid in securing the aluminum top sheet in the finished joint a flange feature is included in the bit design. This flange is intended to contact the aluminum top sheet when the bit reaches final depth and provides assurance against pullout failure through the weaker aluminum material.

One last critical feature of the initial bit design is the inclusion of a shear zone between the bit tip, including the flange, and the bit shank. This zone was appropriately sized, through experimentation, such that it can withstand the torque placed on it during the drilling and welding stages of the joining cycle; yet, is also able to be sheared once the weld is formed and it is time for the spindle to retract.

The thicker upper flange present on the shank of the bit is present to act as a shoulder that rests against the bottom of the tool holder used for this research. The flat, which is ground on the shank of the bit, provides a landing area for the setscrew used to secure the bit within the tool holder. The flat area is required to prevent bit rotation within the tool holder during the welding cycle.

4.1.2 Initial Parameters

After the conception of an initial bit design, work began on the development of some starting welding parameters. Experimentation with the previously described bit yielded the parameters given in **Table 4.1**.

Table 4.1 – Initial parameter set used for data set one

Weld Parameters						
Stage	**1**	**2**	**3**	**4**	**5**	**6**
RPM	300	1000	1600	0	800	
Z-Velocity (in/min)	2.0	4.0	2.0	0.0	10.0	
Z-Command (in)	-0.090	-0.130	-0.155	-0.155	0.200	
Peck Cycles	1	0	0	0	0	
Dwell (ms)	0	0	1000	500	0	

4.1.3 Modifications to Welding Machine

It should be noted that during this initial development work something became apparent about the performance of this first generation FBJ machine. During weld cycles it was observed that the spindle would often deflect away from the center of the joint axis during the welding stages of the cycle. This presented difficulty, as it was clear that the integrity of the resultant joints were negatively affected.

Measurements were taken on the FBJ machine, using dial indicators during weld cycles, to determine where the flexure was occurring that allowed the observed spindle deflection to take place. It was determined that the majority of the deflection was occurring as the head unit was allowed to move within its mounting system. A series of rollers was being used to limit head movement in the x and y directions while still allowing travel in the z-direction. Upon discovery of the spindle deflection the roller system was replaced by MegaStir Technologies with a set of brass gibbs that now hold the head more securely within the mounting system. The gibbs system does produce more friction against movement in the z-direction; however, the servo drive motor for the z-axis has proven to be plenty powerful to drive the machine.

This design improvement significantly improved the performance of the machine. Only minimal spindle deflection was observed after the installation of the gibbs system. In an effort to add even more rigidity to the machine a set of inelegant bar clamps was added to the machine frame and tightened as much as possible by hand. This final modification improved the machines rigidity to a point where spindle deflection is no longer apparent to the eye. Photographic views of the machine modifications are included in **Figures 4.2** and **4.3**.

Figure 4.2 – Brass gibbs for rigidity

Figure 4.3 – Bar clamps mounted to frame

It should be noted that the brass gibbs system modification was installed before formal data collection began for this research. Furthermore, the bar clamps were also in place for all of the experiments included in this document.

4.2 Initial Data Set

With all of the informal development work complete, and the machine modifications finished, official data collection began for this research. The data collected for the initial bit design and parameter set are presented in **Tables 4.2** and **4.3**.

Table 4.2 – Lap shear tensile results from data set one

Sample	Z-force (lbs)	Lap Shear (lbs)
1	2960	851
2	2540	1389
3	2903	No Joint
4	3202	910
5	3067	1050
6	2068	No Joint
7	2766	921
8	3054	750
9	3586	No Joint
10	2512	No Joint
Average	2865.8	978.5
Std. Dev.		223.6

Table 4.3 – Cross tension tensile results from data set one

Sample	Z-force (lbs)	Cross Tension (lbs)
1	3324	57
2	3239	306
3	3452	244
4	3516	99
5	3524	386
6	3244	354
7	3211	196
8	3457	154
9	3200	629
10	3386	133
Average	3355.3	255.8
Std. Dev.		170.5

It is apparent that the initial combination of bit design and welding parameters leaves much to be desired in the area of joint strength performance and consistency. Although the initial data indicate that the process achieved an average lap shear joint strength of 978.5 pounds (4.35 kN) in completed joints, almost enough to meet the 1000-pound (4.44 kN) requirement, there were several joints that failed to form. Furthermore, the standard deviation among successfully formed lap shear joints was 223.6 pounds (0.99 kN). This indicates that the process was not capable of forming joints of consistent quality.

The cross tension results were better in terms of joint completion. All ten cross tension runs resulted in the successful formation of a finished joint. However, cross tension values were low with an average of 255.8 pounds (1.14 kN). The standard deviation of this data set was also unsatisfactory with a high value of 170.5 pounds (0.76 kN).

4.2.1 Failure Mode

It should also be noted that all joint fractures occurred in the interfacial failure mode. **Figures 4.4** and **4.5** show, diagrammatically and photographically, the failure mode of the tested joints.

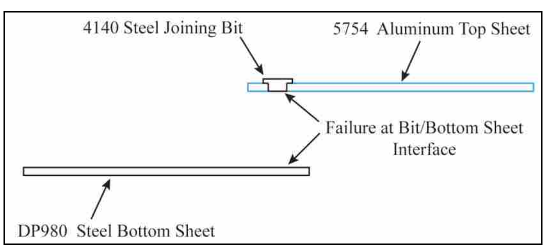

Figure 4.4 – Interfacial failure diagram

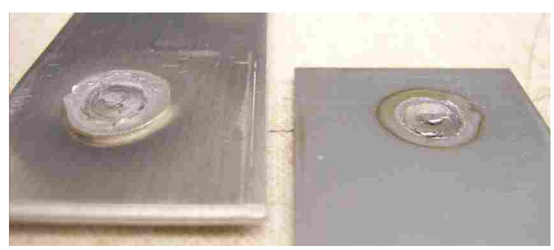

Figure 4.5 – Joint failure at interface

4.2.2 Microscopy Evaluation

Figure 4.6 shows a cross sectional view of the joint formed using this initial bit design and parameter set.

Figure 4.6 – Microscopy image of initial joint showing void at interface

Apparent in the morphology of the joint is the presence of a void at the interface of the joining bit and the steel bottom sheet. This incomplete joining at the interface accounts for the low joint strengths observed, especially in cross tension tensile testing. A priority for improving the joint strength performance of the FBJ process is the reduction of these observed voids in subsequent trials.

Although a great amount of the joint's strength does come from the steel to steel joining at the bit/bottom sheet interface it should be noted that metallurgical bonding is observed between the side areas of the bit material and the aluminum top sheet. Even though this bonding between bit and aluminum top sheet is not directly responsible for joint performance in lap shear tensile testing, or even cross tension testing due to the incorporated flange, it does help to stabilize the formed joint against torque forces. Without this metallurgical bond between the bit and aluminum the only resistance against rotational loading would be the mechanical lock provided by the flange of the bit tip.

4.3 Development for Data Set Two

Due to the voids present in the resultant joints of the first data set it was apparent that any changes made to the process should focus on improving the consolidation of the joint during the weld cycle.

4.3.1 Bit Development

The first bit used for this research was sharpened on an Oliver Instrument Company Model 21 drill bit-sharpening machine with a 120^{o} angle setting, resulting in a point angle of 120^{o} on the bit tip. Because the drilling taking place is performed for a very short time in a relatively soft material it was not absolutely necessary to have a the most efficient cutting geometry in place. With this in mind the bit tip point angle was changed from 120^{o} to 160^{o}. Although less ideal in terms of cutting performance, this effectively left more metal at the bit tip.

This was thought to be beneficial for two reasons. First, there is less void content in the bit tip geometry, as the bit was effectively made flatter at its tip. This will introduce fewer voids into the joint in the first place. Second, the bit tip now has additional metal material that can be stirred into the joint to fill in any voids that do result from the flutes still present on the bit. With this flatter bit tip geometry it was hoped that fewer voids would be present in the final joint, and that joint strength performance would improve accordingly.

4.3.2 Parameter Development

In addition to the geometry changes that were made to the joining bit, alterations were also made to the welding parameters in an effort to improve joint performance. **Table 4.4** shows the parameters used for the generation of data set number two.

Table 4.4 – Parameter set used for data set two

Weld Parameters						
Stage	**1**	**2**	**3**	**4**	**5**	**6**
RPM	500	1000	2400	0	800	
Z-Velocity (in/min)	2.0	4.0	2.0	0.0	10.0	
Z-Command (in)	-0.090	-0.120	-0.150	-0.150	0.200	
Peck Cycles	1	0	0	0	0	
Dwell (ms)	0	0	1000	500	0	

The most significant change to the parameters occurs in stage three. The RPM variable was increased from 1600 RPM to 2400 RPM. This change was made in an effort to introduce more frictional heat to the joint and to increase the stirring/consolidation of the softened bit material.

Through increased heat input it was hoped that joint formation would become more consistent. The joints that failed to form in the lap shear group from the first data set indicated that insufficient heat was present to consistently cause joint formation. Increasing the heat input should result in more reliable joint formation.

The increase in spindle speed during the welding stage of the cycle also provides more opportunity for weld consolidation. The increased stirring speed will provide more disruption at the weld interface, which should result in lower void content and increased joint strength.

A few smaller changes were also made to the welding parameters. The z-command in stage two, an intermediate step between drilling and welding, was reduced from -0.130" (-3.30 mm) to -0.120" (-3.05 mm). This effectively facilitates an earlier transition to the higher spindle speed of stage three by reducing the depth requirement for stage two. In addition, the final z-command depth in stages three and four was changed from -0.155" (-3.94 mm) to -0.150" (-3.81 mm). This small change was made since the bit length was changed slightly as a result of the point angle change made on the drill bit-grinding machine.

4.4 Data Set Two

Data collected after the described bit design and parameter changes are presented in **Tables 4.5** and **4.6**.

Table 4.5 – Lap shear tensile results from data set two

Sample	Z-force (lbs)	Lapshear (lbs)
1	2757	1572
2	3123	1435
3	2506	1223
4	2904	1357
5	2701	1457
6	2494	1576
7	2727	1265
8	2512	1432
9	2491	1586
10	2901	1213
Average	2711.6	1411.6
Std. Dev.		143.6

Table 4.6 – Cross tension tensile results from data set two

Sample	Z-force (lbs)	Cross Tension (lbs)
1	2221	434
2	2324	434
3	2072	566
4	2394	605
5	2654	388
6	2588	401
7	2374	636
8	2614	328
9	2308	396
10	2447	473
Average	2399.6	466.1
Std. Dev.		102.5

The results of data set number two show significant improvements over the initial data collected. To begin with, all 20 joints in the data set were formed successfully. This same result is also achieved in all subsequent data sets. The average lap shear tensile test result increased greatly to 1411.6 pounds (6.28 kN). This improvement in average lap shear performance was also accompanied by a welcome decrease in the standard deviation of the data set. The standard deviation of the lap shear data improved, by being reduced to 143.6 pounds (0.64 kN).

Cross tension tensile test results showed similarly impressive improvement. Average cross tension tensile strength increased to 466.1 pounds (2.07 kN), while the standard deviation for the set decreased to 102.5 pounds (0.46 kN).

Although the averages of the two tensile tests do show excellent improvement, and the standard deviations of the data have been lowered, there was still a need for improvement to the performance of the process. The lap shear average is satisfactory, yet the standard deviation of the lap shear data is still unacceptably high. The cross tension results need improvement, both in terms of joint strength improvement and decreasing the standard deviation of the experimental data.

4.4.1 Failure Mode

It should be noted that pullout failure through the aluminum top sheet is unlikely due to the relatively large reinforcing flange present in the joining bit geometry. It would be desirable to see pullout from the steel side where there is no reinforcement against pullout failure. However, even if pullout through the steel bottom sheet does not ultimately occur through further development, joint failure at some point along the bit material, instead of the bit/bottom sheet interface, would be beneficial. This type of failure would not look like a typical pullout failure observed in other spot joining processes, but would still, in fact, show joint failure at a point away from the joint interface.

This type of failure was actually observed in some of the joints for this data set. Although most failures did still occur at the weld interface, the presence of some non-interfacial joint failures is another indicator of the improvements that have been made to the FBJ process. **Figures 4.7** and **4.8** show diagrammatic and photographic examples of this failure mode.

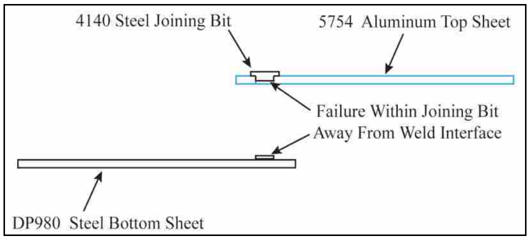

Figure 4.7 – Bit failure diagram

Figure 4.8 – Joint failure away from interface

4.5 Development for Data Set Three

Although significant improvements were realized in data set number two, the standard deviations of the data obtained were still unsatisfactory. Because voids within a joint provide crack initiation sites, and most failures were still occurring at the interface, it was assumed that sizable flaws were still present within the morphology of the joint. This would explain the still relatively high standard deviations of the data sets, as each joint formed would be different in terms of void size and location within the weld nugget.

4.5.1 Bit Development

Given the significant success provided by the previous change to the bit tip geometry another, more dramatic, design change was tried. The flutes present in the bit tip for chip clearing are an apparent source of voids that must be consolidated during the welding stages of the cycle. If these flutes could be eliminated then the amount of void consolidation required would be reduced significantly. The friction bit would function more like a traditional solid stud does in conventional stud friction welding. Because such a small amount of chip generation occurs during the drilling stage it was hypothesized that traditional chip clearing flutes were not actually necessary. With the need still in place to provide cutting faces at the bit tip, the following bit design was conceived. The bit design is represented in **Figure 4.9**.

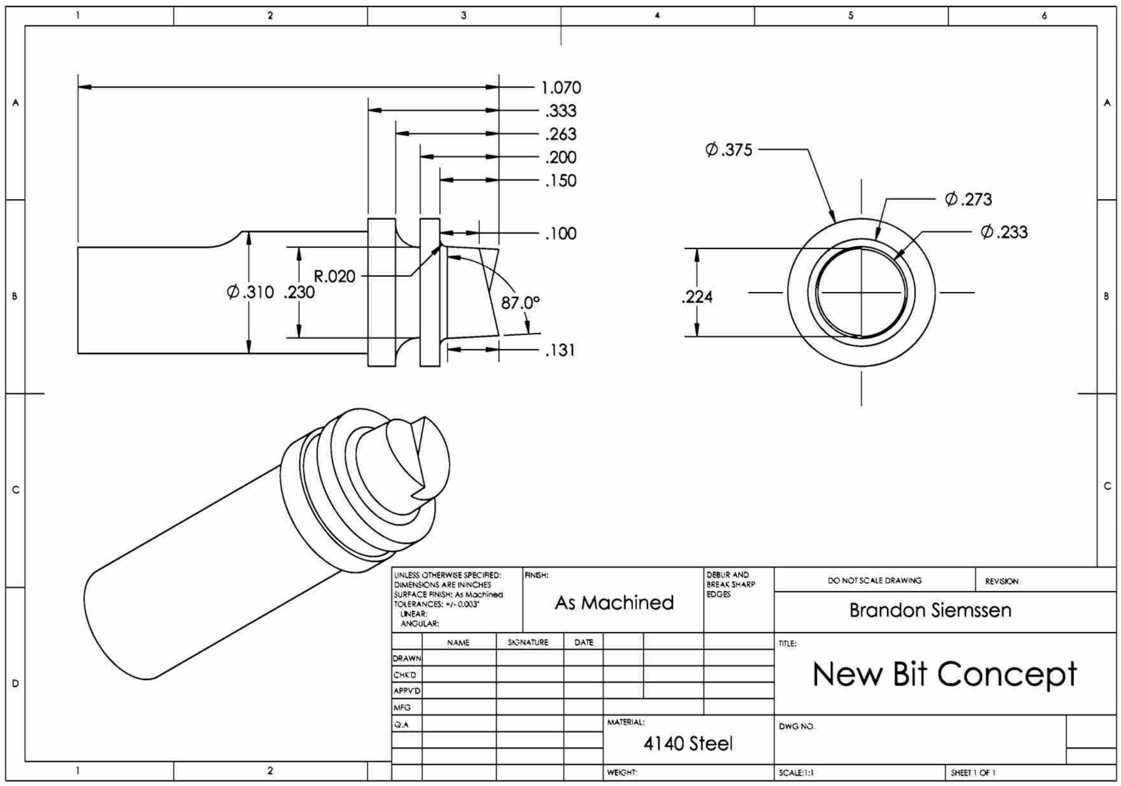

Figure 4.9 – CAD drawing of new bit tip concept

Because this design would require a significant amount of CNC programming it was desired to achieve an approximation of the bit tip design by some other means before investing the time writing new CNC code. In order to achieve this a Darex E-90 end mill sharpener was used, in a non-traditional manner, to generate the geometry. Although the end result was not an exact replication of the bit tip that had been designed, it was close enough to be used as a proof of concept. **Figure 4.10** shows a photo of the bit tip geometry achieved using the Darex machine.

Figure 4.10 – Darex sharpened bit tip

4.5.2 Parameter Development

The only changes to the weld cycle parameters for this third data set were made to account for the shortening of the bit tip length that occurred due to processing on the Darex machine. **Table 4.7** shows the modified parameters used for data set number three.

Table 4.7 – Parameter set used for data set three

Weld Parameters						
Stage	**1**	**2**	**3**	**4**	**5**	**6**
RPM	500	1000	2400	0	800	
Z-Velocity (in/min)	2.0	4.0	2.0	0.0	10.0	
Z-Command (in)	-0.090	-0.110	-0.130	-0.130	0.200	
Peck Cycles	1	0	0	0	0	
Dwell (ms)	0	0	1000	500	0	

As can be seen, parameter changes have been made to the z-command variables for stages two, three and four. These modified values allow the flange of the bit tip to engage the aluminum top sheet in a manner similar to previous trials that had used a longer bit tip.

4.6 Data Set Three

Data collected after the described bit design and parameter changes are presented in **Tables 4.8** and **4.9**.

Table 4.8 – Lap shear tensile results from data set three

Sample	Z-force (lbs)	Lapshear (lbs)
1	3543	1610
2	3728	1255
3	3370	1539
4	3903	1029
5	3890	1116
6	3367	1424
7	3109	1667
8	4133	1112
9	4106	1458
10	3731	1616
Average	3688	1382.6
Std. Dev.		236.8

Table 4.9 – Cross tension tensile results from data set three

Sample	Z-force (lbs)	Cross Tension (lbs)
1	3403	391
2	3463	520
3	3124	511
4	2694	497
5	3015	440
6	3433	514
7	4071	503
8	3998	279
9	3534	417
10	3825	605
Average	3456	467.7
Std. Dev.		89.8

This data set does not show very significant improvements in terms of cross tension tensile test performance and, in fact, indicates decreased performance in lap shear tensile testing.

The cross tension tensile test average remains virtually identical in this data set with a value of 467.7 pounds (2.08 kN). The standard deviation of the cross tension data is slightly improved and falls to 89.8 pounds (0.40 kN). The average lap shear performance has a small decrease to 1382.6 pounds (6.15 kN) while the standard deviation for the set is markedly worse at 236.8 pounds (1.05 kN).

The results of this data set were somewhat disappointing, as they did not represent any major progress. However, the results of this significant bit tip geometry change did not result in any significant decrease in performance either. The reasoning behind the elimination of the flutes in the bit tip still seemed like the right track in terms of improving the process. With this in mind the next development steps were carried out.

4.7 Development for Data Set Four

The development for this data set focused on producing a bit that was closer to the bit design conceptualized for data set three. In addition to this, parameter changes were made with the hope of reducing maximum z-forces encountered during the weld cycle.

4.7.1 Bit Development

Since the Darex sharpening machine used previously was not designed to impart the geometry it had been asked to for this research, the bits were not by any means perfect before they were used. Instead of clearly defined cutting faces, due to the restrictions of the machine, the bits had a completely flat spot across the middle of the tip. It is likely that this inefficient geometry caused tracking problems during the drilling phase of the weld cycle that ultimately affected the quality of the final joint. With these shortcomings apparent, the production of a better bit tip was pursued.

The CNC programming required to produce the net shape geometry initially intended was carried out and the bits were manufactured. Another benefit of this design is the fact that these bits were completely produced, in one operation, on the Okuma CNC lathe without the need for secondary processing. This is advantageous, as this will reduce the manufacturing costs for mass-produced joining bits significantly.

It should also be noted that the shear zone diameter was increased by 0.015" (0.381 mm). This change was needed because bit shearing was occurring early, during the welding stage of the program, instead of at the intended time. The altered geometry of the bit tip apparently produced a greater torque during the weld cycle than previously encountered. A simple diameter increase at the shear zone allowed the joining bit to perform as intended.

Figure 4.11 shows a photo of the final bit geometry used for data set number four.

Figure 4.11 – Final bit geometry

4.7.2 Parameter Development

A significant difference between data set number two and data set number three is the observed maximum z-force during the weld cycle. The averages generated in data set three are roughly 1000 pounds (4.45 kN) greater than those observed in data set two, and fall around the 3500-pound (15.57 kN) mark. This is likely due the elimination of the flutes in the bit tip geometry. These flutes not only had provided a route for chip evacuation, but also provided room for bit collapse to take place. With a more solid bit tip, and similar weld parameters, it is not surprising that the result is greater maximum z-forces. Because maximum load is a concern for any solid state joining process it becomes important to make efforts at reducing these observed values.

In order to achieve a reduction in maximum z-force it is necessary to make a few changes to the welding parameters. Maximum bit penetration can be reduced in an effort to reduce maximum z-force. Along with this, a reduction in penetration speed will also facilitate the lowering of maximum z-force values. With these considerations in mind the following parameters were generated, represented in **Table 4.10**.

Table 4.10 – Parameter set used for data set four

Weld Parameters						
Stage	1	2	3	4	5	6
RPM	500	2400	0	800		
Z-Velocity (in/min)	2.0	2.0	0.0	10.0		
Z-Command (in)	-0.070	-0.110	-0.110	0.200		
Peck Cycles	1	0	0	0		
Dwell (ms)	0	1000	500	0		

The most significant change to this set of parameters is the elimination of what was formally stage two. This intermediate step previously took place at 1000 RPM with a plunge rate of 4.0 inches/min (101.6 mm/min). It was felt that the minimal spindle speed, combined with a higher plunge rate, was effectively pushing a bit, that hadn't been sufficiently heated, unnecessarily fast into the samples to be joined. This set of conditions was a major contributor to the maximum z-forces observed.

The other changes made to the welding parameters were made to the z-command variable of stages one, two and three. The stage one z-command was reduced to -0.070" (1.79 mm) so that drilling took place to a lesser depth. The z-command for stages two and three was reduced to -0.110" (2.79 mm), resulting in less bit tip penetration overall.

Although these changes were made to reduce overall bit penetration, they were also required as the final bit tip produced using the Okuma CNC lathe was even shorter than the bit tip used for data set three.

4.8 Data Set Four

After producing a bit that exhibited the exact geometry desired and modifying the welding parameters to reduce maximum z-force, data set four was collected. **Tables 4.11** and **4.12** show the results of data set four.

Table 4.11 – Lap shear tensile results from data set four

Sample	Z-force (lbs)	Lapshear (lbs)
1	2205	1403
2	1327	1501
3	1517	1489
4	1320	1420
5	1639	1360
6	2354	1468
7	1220	1370
8	1511	1322
9	1389	1412
10	987	1473
Average	1546.9	1421.8
Std. Dev.		60.1

Table 4.12 – Cross tension tensile results from data set four

Sample	Z-force (lbs)	Cross Tension (lbs)
1	1645	709
2	1613	507
3	1288	571
4	1340	702
5	1516	659
6	1825	477
7	1570	559
8	1144	558
9	1554	412
10	1436	509
Average	1493.1	566.3
Std. Dev.		97.8

This data demonstrates appreciable improvements in the FBJ process. The lap shear tensile test average is improved, even over that observed in data set two, with a value of 1421.8 pounds (6.32 kN). Even more important than this increase in average strength is the significant reduction in the standard deviation for the data set. The standard deviation of the lap shear values in this data set is reduced to 60.1 pounds (0.27 kN). This lap shear data indicates that the process performs well enough, and consistent enough, for serious consideration in industrial applications.

Cross tension tensile strengths are significantly improved in data set four as the average rose to 566.3 pounds (2.52 kN). Although it was desired to see a reduction, similar to that observed in the lap shear data, of the standard deviation in the cross tension results for data set number four, the average value achieved lies between those observed in data sets two and three at 97.8 pounds (0.44 kN). The average cross tension tensile strength is adequate, but the standard deviation of the set is higher than desired.

The maximum observed z-force was successfully reduced by a significant amount. If the average is taken across all twenty samples in the data set then the average maximum load for the process is calculated to be 1520 pounds (6.76 kN). This average is roughly 2000 pounds (8.90 kN) less than that observed in data set number three. The highest maximum load encountered during the twenty trials was 2354 pounds (10.47 kN), while the minimum was 987 pounds (4.39 kN). Although this range is quite wide, the majority of the maximum load values recorded were grouped around the average maximum load for the set.

4.8.1 Failure Mode

Several failure modes were observed among the samples produced for data set number four. Approximately half of the samples did still fail via interfacial fracture. However, the remainder failed in one of three ways. The most abundant failure mode occurred as the bit material fractured a small distance away from the weld interface. This type of failure mode was first noted in data set number two. Of the twenty samples produced for the data set three of them failed in the aluminum top sheet. In this failure mode necking, and finally cracking, occurred in the aluminum top sheet between a coupon edge and the hole generated by the joining bit. A photo showing an example of this failure mode is included in **Figure 4.12**. The final failure mode observed occurred in only one of the samples for the data set. This mode of failure occurred via pullout from the steel bottom coupon. A photo showing this failure is included in **Figure 4.13**.

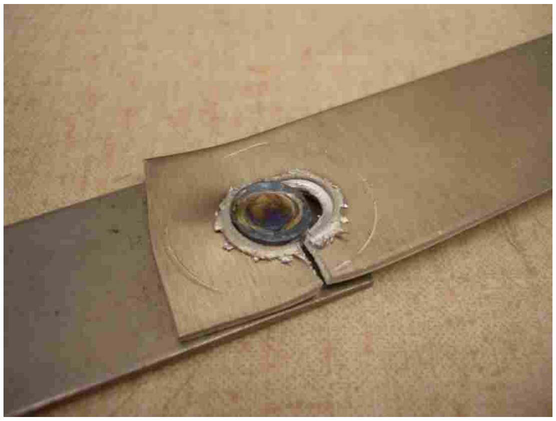

Figure 4.12 – Aluminum tear failure

Figure 4.13 – Steel pullout failure

4.8.2 Weld Cycle Time

Because the bit design and parameter set used for data set number four provide the best FBJ joint performance in this study, it bears mentioning weld cycle time in reference to this data set. Although most weld parameter sets used in this study do yield cycle times that are quite close to one another, small differences can make a large impact on production when thousands of weld cycles are carried out each day.

Cycle time for data set four, measured from bit contact with the aluminum top sheet to bit retraction, is six seconds per weld. Although the cycle time is longer than other technologies, the ability to join aluminum to steel with the demonstrated joint performance, and low load requirements, will make this technology ideal for many industrial applications.

4.8.3 Microscopy Evaluation

Figure 4.14 shows the cross sectional microscopy image of a joint formed using conditions identical to those used for data set number four.

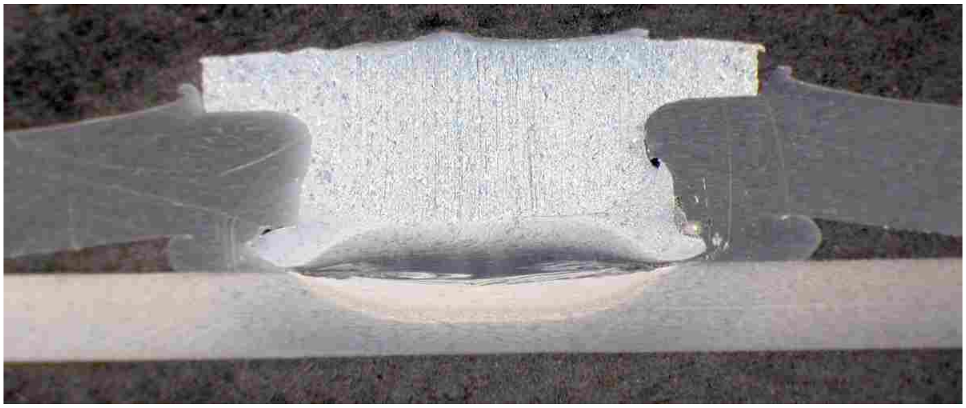

Figure 4.14 – Microscopy image from data set four parameters/bit design

Although difficult to see in this particular image, some void content is still present in the final joints, even though tensile strength performances have been significantly improved. This suggests that even further performance increases could be realized by further development work to completely eliminate any voids within the joint.

Such improvements may not seem completely needed given the demonstrated lap shear tensile strength performance; however, the cross tension tensile performance of the FBJ joints could stand to be improved. Although cross tension strength is currently satisfactory, it would be beneficial if further improvements could reduce the standard deviation observed in subsequent cross tension data sets.

4.9 Statistical Analysis

The final step in this research is to ensure that true improvement has been demonstrated as a result of the development work performed. In order to show this to be the case a simple t-test was used. Testing was carried out at both the 95% and 99% confidence level. All but the first lap shear data set contained 10 completed samples. This is important for the degrees of freedom calculations. The following **Tables 4.13** and **4.14** show the results of the described analysis.

Table 4.13 – Summary of lap shear t-test results

Test Between	Data Set 1 & 2	Data Set 2 & 3	Data Set 3 & 4	Data Set 1 & 4
Degrees of Freedom	14	18	18	14
t value at 95%	1.761	1.734	1.734	1.761
t value at 99%	2.624	2.552	2.552	2.624
Absolute z value	4.248	0.331	0.057	4.754
Sig. Diff at 95%	Yes	No	No	Yes
Sig. Diff at 99%	Yes	No	No	Yes

Table 4.14 – Summary of cross tension t-test results

Test Between	Data Set 1 & 2	Data Set 2 & 3	Data Set 3 & 4	Data Set 1 & 4
Degrees of Freedom	18	18	18	18
t value at 95%	1.734	1.734	1.734	1.734
t value at 99%	2.552	2.552	2.552	2.552
Absolute z value	3.343	0.037	2.348	4.995
Sig. Diff at 95%	Yes	No	Yes	Yes
Sig. Diff at 99%	Yes	No	No	Yes

From the results we see that significant differences were achieved between data sets one and two, and data sets one and four, for both lap shear and cross tension results. No significant difference was demonstrated between data sets two and three for either lap shear or cross tension results. In the case of data sets three and four a significant difference was demonstrated in the cross tension results, but not in the lap shear numbers.

The differences between data sets one and two, and the overall difference demonstrated between data sets one and four are quite impressive. It should be noted that both of these cases showed significant differences at the 99% confidence level.

The lack of a significant difference showing between data sets two and three is disappointing, but is nonetheless interesting considering the bit design change between these two data sets was the most significant in the entire study. Again, it was felt that the lack of performance increase was due to substandard bit production as opposed to the pursuit of an improper design change.

The results between data set three and data set four deserve discussion, as this was the only case where no significant difference was shown for one test type, but a significant difference was shown for another test type. As mentioned earlier, the lap shear data did not demonstrate a significant difference, while the cross tension data does demonstrate a considerable change. This result suggests that cross tension tensile strength is more sensitive to void content within the weld than is lap shear tensile strength. As the final bit design and parameter set produced a joint with lesser void content than previous trials, the cross tension strength was significantly affected for the better, while the lap shear strength stayed virtually the same.

Overall, it has been successfully demonstrated that significant development, and improvements, have been made to the FBJ process. From the initial successes to the more consistent and robust joint performances observed later in the study, FBJ has been developed to a point where its consideration for industrial applications is now warranted.

5 Conclusions

5.1 Summary of Work

Throughout the course of this research the Friction Bit Joining (FBJ) process has been successfully developed from a new joining concept, to a functional joining process with respectable performance results. Through successive developmental steps the lap shear tensile test results were improved from an initial average of 978.5 pounds (4.35 kN), with a high standard deviation of 223.6 pounds (0.99 kN), to a peak average of 1421.8 pounds (6.32 kN) with an acceptable standard deviation of 60.1 pounds (0.27 kN). Similar improvements were demonstrated in cross tension tensile test results. The initial average of 255.8 pounds (1.14 kN), with a standard deviation of 170.5 pounds (0.76 kN), was improved to an average of 566.3 pounds (2.52 kN) with a standard deviation of 97.8 pounds (0.44 kN). These improvements in static tensile tests were accompanied by microscopy evaluations showing visual improvements in weld quality, specifically the reduction of voids at the weld interface.

5.2 Conclusions

The intent of this research has been to develop the newly conceived FBJ process, and characterize its capabilities in joining 5754 aluminum to DP 980 Steel. It was proposed that the FBJ process could be developed to a point that it would become a welcome alternative to currently available technologies for joining aluminum and steel such as Self-Piercing Riveting (SPR), Spot Friction Welding (SFW), and highly modified Resistance Spot Welding (RSW) techniques.

Through this research the FBJ joining process has been developed to a point that its use in industry has become a possibility. The hypotheses that have guided this research are concluded as follows:

Hypothesis 1: The FBJ process is capable of producing joints in 5754 aluminum and DP 980 steel that perform in lap shear tests at an average of 1000 pounds or above in 10 consecutive samples, and perform in cross tension tests at an average of 500 pounds or above in 10 consecutive samples has failed to be rejected because the FBJ process has produced joints between 5754 aluminum and DP 980 steel with an average lap shear tensile strength of 1421.8 pounds (6.32 kN) across 10 consecutive samples, and an average cross tension tensile strength of 566.3 pounds (2.52 kN) across 10 consecutive samples.

Hypothesis 2: The FBJ process is superior to the SPR process in terms of total operating loads required to form a joint. That is to say that FBJ requires significantly lower operating force, an average of 2500 pounds or less across 20 samples, to form a joint than does SPR. This hypothesis has failed to be rejected because the FBJ process has been shown to operate at an average maximum load of 1520 pounds (6.76 kN) across 20 consecutive samples.

Hypothesis 3: The FBJ process is capable of forming joints that have satisfactory surface finish for use in automotive applications. This means the joint must have minimal flash so that conventional coating techniques will wet all areas surrounding the joint to prevent any bare metal where corrosion may begin. This does not mean the joint has to be invisible, as it will generally be used only in inconspicuous areas. This hypothesis is rejected because the FBJ process currently produces small amounts of flash in over half of the joints formed that will interfere with complete paint coverage. Although the flash is easily removed, this constitutes a secondary operation that is not acceptable for high production environments.

5.3 Recommendations

Although the lap shear and cross tension tensile strengths demonstrated in this research are respectable, there is still room for improvement. Specifically, the cross tension tensile strength average is currently only performing at 39.8 percent of the lap shear average. Conventional spot joining technologies usually perform in cross tension at 50 percent, or more, of the lap shear average. The current cross tension performance of FBJ, in relation to current lap shear performance, indicates further improvement needs to take place. Increases in FBJ cross tension joint strengths should be possible through further development efforts to eliminate voids within the weld nugget. A probable, and even more important, consequence of such joint morphology improvements would be a further reduction of the standard deviation of subsequent data sets.

Regarding the subject of standard deviation, it bears mentioning the issue of machine consistency. There were several times during this research that the machine was suspected of performing somewhat inconsistently. This was apparent as some bit tip flanges would occasionally be buried visibly deeper into the aluminum top sheet than were others. Samples made during a run that was overtly abnormal were thrown out so as to eliminate the effects of the apparent machine aberration. Abnormal runs were detected by monitoring the final depth recorded on the machine. Any run that penetrated significantly deeper than the running average was thrown out due to this special causation. Although these readily apparent abnormal runs were successfully dealt with, it is possible that smaller variations in the machine cycle are causing variable joint strength results. From this research it is clear that void content within the weld nugget is a major cause of variation, however, machine consistency should also be investigated and improved in order to further reduce the standard deviation of future data sets.

There are a number of testing and analysis methods that might be employed which were outside of the scope of this study. The use of these other methods will yield new perspectives on the current state of FBJ technology. With the insights gained from a wider battery of testing and analysis methods, future researchers may be even better guided in their improvement efforts. The following are recommended for future research and data collection.

- Dynamic fatigue testing
- Joint microhardness profile development
- Development of even less aggressive cutting faces on the bit tip to further reduce void content within the weld

- Further weld parameter and bit design adjustments to eliminate flash generation
- Design of Experiments to better understand the effect of individual weld parameters on final joint strength along with any possible two-factor interactions. This should focus first on just the drilling and welding stage while experimenting with spindle RPM, plunge rate, plunge depth, and dwell variables.
- Experimentation with incremental bit hardening in an effort to make a small cut into the steel bottom sheet before bit degradation begins. This could improve joint strengths by providing greater surface area at the weld interface and may even improve tracking during the welding stage of the cycle.

Much remains to be learned about the FBJ process and its ultimate performance capabilities. Although the process is currently performing in a respectable manner, it is felt that additional research efforts will generate further advances in FBJ technology.

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APPENDICES

Appendix 1: Initial Bit Design CNC Program

```
DEF WORK
PS LC,[-15,0],[15,05]
END
DRAW
G00 X20 Z20 (MARCH 16 07 SHEAR GROOVE)
G50 S2500
X.45 Z.1 S1000 T010101 M03 M42 M08
G96 S400
G85 NLAP1 D.05 F.006 U.015 W.006
NLAP1 G81
G00 X0
G01 Z0 G42 F.003
X.215 Z-.015
G76 X.235 Z-.205 L.015
X.375
Z-.40
X.3125 Z-.450
Z-1.25
X.375
G40 X.45
G80
G00 Z.1
G96 S450
G87 NLAP1
G00 Z.1
G97 S1000
X20 Z20
X.45 Z-.45 S1000 T040404 M03 M08
G97 S1000
G73 X.308 Z-.50 K.1 D.5 L.5 F.003
G00 Z.1M9
G97 S1000
X20 Z20
X.50 Z-.290 S1000 T030303 M03 M08
G97 S1000
G73 X.193 Z-.290 K0 D.03 L.06 F.002
```

```
G00 Z.1M9
G00 X20 Z20 M05
M110
M15
G94 X.65 Z.3 T1111 SB=2000 M13 M08
X.40Z.05
G190 X.190 Z-.095 C0 K.040 D.05 W.015 E5.0 F2.0 M211 M213
C180
G180
G00 X20 Z20 M12 M146
G95 M109
G97 S1000 M03
G00 X20 Z20
X.45 Z-1.25 S1000 T080808 M03 M08
G97 S1200
G01 X.25 F.003
G00 X.314
Z-1.20
G01 X.25 Z-1.25
X0
G00 X.45
X20 Z20
M02
```

Appendix 2: Final Bit Design CNC Program

```
DEF WORK
PS LC,[-15,0],[15,05]
END
DRAW
G00 X20 Z20 (JAN 22 SHEAR GROOVE + MILLED TIP)
G50 S2500
X.40 Z.1 S1000 T010101 M03 M42 M08 (TOOL 1)
G96 S400
G85 NLAP1 D.05 F.005 U.015 W.004 (ROUGH CUT)
NLAP1 G81 (DEFINE PROFILE)
G00 X0
G01 Z0 G42 F.003
X.215
G76 X.235 Z-.205 L.020
X.375
Z-.42
X.3125 Z-.520
Z-1.25
X.375
G40 X.40
G80
G00 Z.1
G96 S450
G87 NLAP1 (FINISH CUT)
G00 Z.1
G97 S1000
X20 Z20
X.45 Z-.47 S1000 T040404 M03 M08 (TOOL CHANGE - 1/8 INCH SQUARE
GROOVE)
G97 S1000
G73 X.308 Z-.52 K.1 D.5 L.5 F.003
G00 Z.1M9
G97 S1000
X20 Z20
X.50 Z-.290 S1000 T030303 M03 M08 (TOOL CHANGE - 1/16 MODIFIED
GROOVE)
```

```
G97 S1000
G73 X.208 Z-.290 K0 D.03 L.06 F.002
G00 Z.1
N500 G00 X20 Z20 M05
M110  (C-AXIS JOINT)
M146 M15 (C-AXIS UNCLAMP)
G00 X0.800 C297.7556 T0606 SB=1200 (FIRST START POINT - TOOL CHANGE -
3/8 END MILL)
G94 Z-0.120 M13 (GO TO START DEPTH)
G101 C62.2444 Z0 F6.50 (RUN CYCLE)
G00 X0.800 C117.7556 (GO TO SECOND START POINT)
G94 Z-0.120         (GO TO START DEPTH)
G101 C242.2444 Z0 F6.50 (RUN CYCLE)
G00 X20 Z20 M12 M146
G95 M109 (FEED IN/REV - CANCEL M110)
G97 S1000 M03
G00 X20 Z20 (HOME)
X.45 Z-1.25 S1000 T080808 M03 M08 (TOOL CHANGE - PARTING TOOL)
G97 S1200
G01 X.25 F.003  (BEGIN PART OFF)
G00 X.314       (REPOSITION)
Z-1.20          (REPOSITION)
G01 X.25 Z-1.25 (CUT ANGLE)
X0              (FINISH PART OFF)
G00 X.45
X20 Z20
M02
```