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Friction Bit Joining of 5754 Aluminum to DP980 Ultra-High Strength Steel: A Feasibility Study

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Strength Steel: A Feasibility Study

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ABSTRACT

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In this study, the dissimilar metals 5754 aluminum and DP980 ultra-high strength steel were joined using the friction bit joining (FBJ) process. The friction bits were made using one of three steels: 4140, 4340, or H13. Experiments were performed in lap shear, T-peel, and cross tension configurations, with the 0.070" thick 5754 aluminum alloy as the top layer through which the friction bit cut, and the 0.065" thick DP980 as the bottom layer to which the friction bit welded. All experiments were performed using a computer controlled welding machine that was purpose-built and provided by MegaStir Technologies.

Through a series of designed experiments (DOE), weld processing parameters were varied and controlled to determine which parameters had a significant effect on weld strength at a 95% confidence level. The parameters that were varied included spindle rotational speeds, Z-command depths, Z-velocity plunge rates, dwell times, and friction bit geometry. Maximum lap shear weld strengths were calculated to be 1425.4lbf and were to be obtained using a bit tip length at 0.175", tip diameter at 0.245", neck diameter at 0.198", cutting and welding z-velocities at 2.6"/min, cutting and welding RPMs at 550 and 2160 respectively, cutting and welding z-commands at -0.07" and -0.12" respectively, cooling dwell at 500 ms, and welding dwell at 1133.8 ms. These parameters were further refined to reduce the weld creation time to 1.66 seconds. These parameters also worked well in conjunction with an adhesive to form weld bonded samples. The uncured adhesive had no effect on the lap shear strengths of the samples.

Using the parameters described above, it was discovered that cross tension and T-peel samples suffered from shearing within the bit that caused the samples to break underneath the flange of the bit during testing. Visual inspection of sectioned welds indicated the presence of cracking and void zones within the bit.

Keywords: Britney Weickum, friction bit joining, FBJ, dissimilar metals, spot joining, DP980, aluminum, ultra high strength steel, friction welding

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1 INTRODUCTION

A new method of spot welding has been recently developed and characterized. This new method, called Friction Bit Joining (FBJ), is unique in that it uses a consumable bit to drill through the top layers of sheet metal, and then the bit's rotational speed is increased to friction join to the bottom sheet metal. A flange helps to keep the top layers of sheet metal compressed and joined with the bottom layer. Research into this new technology has been developing its use in joining steel, aluminum, and magnesium in both dissimilar and similar arrangements. The focus of this work is on joints made between steel and aluminum sheet metal.

1.1 Conventional Joining Methods

Joining dissimilar metals has long been a problem that cannot be easily solved using conventional joining methods because of the difference in melting points and mechanical properties between the materials. Direct resistance spot welding (RSW) cannot be effectively used because it relies on the materials fusing together. When there is a large difference in melting points, one material will melt long before the other material, so the materials experience difficulty in actually forming a solid joint. Also, when molten dissimilar metals do join, they form brittle compounds, creating welds with poor properties. Non-brittle welds are desirable because they allow for more elongation of the part without failure. Also, if the weld is strong and yet allows for elongation, it is less likely to be the point of failure and it is able to absorb more energy than a brittle weld.

Self-Piercing Riveting (SPR) can bypass this problem since it is a cold joining process, but it has limited uses, especially when joining ultra high strength steels (UHSS), since UHSS do not allow for very much formability, making it difficult to form the steel around the rivet. Also, the stronger the steel, the harder it is for SPR to penetrate and deform properly without the use of purpose-made dies.

Friction Stir Spot Welding (FSSW) has shown some promise in joining dissimilar metals, and it shares similarities with FBJ in that they both use friction to join the sheet metals. The difference between FSSW and FBJ is that FSSW uses a non-consumable bit that stirs the dissimilar metals together, whereas FBJ relies on a steel-to-steel friction bond formed between the consumable bit and the UHSS.

1.2 Problem Statement

The introduction of aluminum as a major component of automobiles has been slow, partly because of the difficulties of joining aluminum to steel. Aluminum frames and bodies are used by some specialty automotive companies, but it is expensive and relatively uncommon when compared with the norm of steel frames and bodies. However, the automotive industry is increasingly interested in using aluminum in order to reduce the overall weight of vehicles, and thereby improve their fuel efficiency. Also, with the development of UHSS, thinner, stronger steels can be used as a means of continuing to reduce the weight of the vehicle. As the automotive industry moves toward using thinner and lighter metals, a method of efficiently and effectively joining these materials needs to be developed to ensure quality welds and to further the integration of these materials in the design of vehicles.

1.3 Hypotheses

The following hypotheses will guide the direction of this research on the feasibility of the FBJ process in joining dissimilar metals. All of the following hypotheses refer to joints made between 5754 aluminum and DP980 and DP590 UHSS.

Hypothesis 1: The FBJ process is capable of producing aluminum to steel lap shear joints with strengths that are greater than joints produced using SPR as a comparison.

Hypothesis 2: The FBJ process is capable of producing high quality joints as evaluated through visual inspection and by statistical consistency over a large number of samples.

Hypothesis 3: The FBJ process is capable of producing joints with the cross tension and T-peel strengths equal to or greater than 50% of the lap shear strength.

Hypothesis 4: The FBJ process is capable of producing joints in less than 2 seconds.

1.4 Methodology

The materials experimentally joined were 0.065” thick DP980 steel, 0.065” thick DP590 steel, and 0.070” thick 5754 aluminum. The bit materials used were 4340 steel, 4140 steel, and H13 steel. Various heat treatments of the bit alloys were used in an attempt to find a hardness that allowed the bit to join while at the same time avoiding excessive shearing and deformation of the bit during welding.

The experiments were completed using a machine designed and constructed by MegaStir Technologies located in West Bountiful, Utah. Alterations have been made to the machine since its original development to increase its stiffness. At first, large bar clamps were placed to help stiffen the C-shaped frame and prevent it from flexing open during welding. This helped some, but the clamps loosened over time. Later, a welded frame was made and was bolted between the spindle and the anvil on the open part of the C-shape of the frame.

Lap shear, cross tension, and T-peel testing were used to evaluate joint strength and performance. Once parameters that created consistently strong welds were found, samples were visually inspected for defects. Comparison SPR samples were made using DP590 joined with the 5754 aluminum, and were provided by a General Motors (GM) research lab.

1.5 Delimitations and Assumptions

A design of experiments (DOE) approach was used to determine optimal parameters to maximize the strengths created using the FBJ process. Some of the samples from the DOE were cross-sectioned, mounted, and polished for visual inspection. Experiments were completed using 5754 aluminum joined to DP980 steel and DP590 steel. The materials used to make the bits for the joints were 4340, 4140, and H13 steel.

This research does not include the joining of magnesium to steel, magnesium to magnesium, aluminum to aluminum, nor steel to steel. Other bit materials were not tested. Comparison data were gleaned from literature reviews, previous research that had been done on 5754 aluminum with DP980 or DP590 steel, and SPR sample data obtained from GM.

1.6 Definitions of Terms

DP – Dual phase steel that has a ferrite and martensitic microstructure.

DP590 – A high strength dual phase steel with an ultimate tensile strength of 590 MPa.

DP980 – A high strength dual phase steel with an ultimate tensile strength of 980 MPa.

FBJ – Friction Bit Joining is a new joining technology that uses a consumable bit to spot join sheet metals by drilling through the top sheet and friction welding to the bottom sheet.

FSSW – Friction Stir Spot Welding is a solid-state welding process that uses a non-consumable tool to stir the metals to be joined together at a point.

HAZ – Heat Affected Zone is the area within a material that has changed properties due to welding or some other heat intensive processes.

IMC – Intermetallic Compound is formed when dissimilar metals diffuse together at a weld interface.

RSW – Resistance spot welding (RSW) is a fusion welding process that uses electrodes to clamp the sheet metals together and pass a current through them which produces the necessary welding heat.

SPR – Self-Piercing Riveting is a cold process that uses a die set to force a rivet into sheet metal without pre-drilling a hole.

UHSS – Ultra High Strength Steel. Steels that yield at 560 MPa or above are considered UHSS.

2 LITERATURE REVIEW

2.1 Introduction

Joining dissimilar metals has been a topic of interest as of late to academics and industrialists alike. There are several techniques that are currently being used in the automotive industry or that are in the process of being studied and applied to creating spot joints in dissimilar metals. SPR, RSW, FSSW, weldbonding, clinching, and FBJ will be discussed in this chapter.

2.2 Self-Piercing Riveting

SPR is a joining technique that is already successfully used in the automotive industry. Jaguar Cars uses rivets extensively in their aluminum body vehicles (Mortimer 2005). Self-Piercing Riveting is a cold process that uses a die set to force a rivet into sheet metal without pre-drilling a hole, as shown in Figure 1. Since SPR is a cold process, the difference in melting points does not affect the ability of sheet metals to be joined using SPR; it is versatile and can be used to join both similar and dissimilar metals. However, SPR performance is highly dependent on the ductility and elongation of the material it joins, since it must plastically deform these materials to create the joint (Abe, Kato and Mori 2006). As the strength of steel increases, its ductility and elongation decreases.

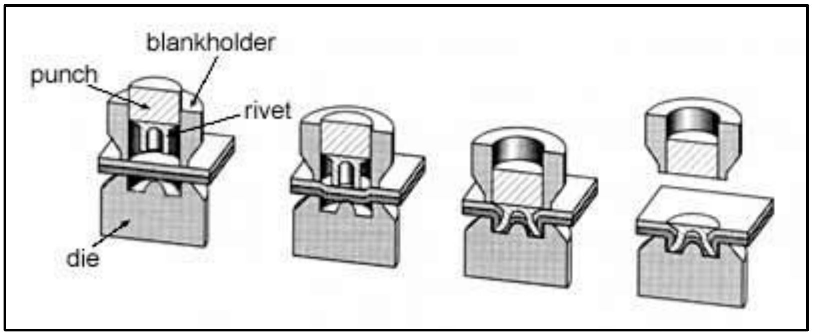

Figure 1: SPR Process and Die Set (TWI Ltd. 2009)

In the automotive industry, the focus is on using thinner, yet stronger, sheet material to reduce vehicle weight. Although it is possible to use SPR to join aluminum and steel, it is difficult to do so because of the difference in flow stress between the two materials (Abe, Kato and Mori 2006). Using conventional rivets and dies, Abe et al. have shown that SPR is capable of fully joining aluminum sheets with high tensile strength steel sheets below 590 MPa (Abe, Kato and Mori 2009). To be able to join ultra high tensile strength steels at 980 MPa, the die shape must be optimized in order to reduce defects caused by the high hardness and low ductility of the metal (Mori, et al. 2006). However, this process has a limited range of sheet thicknesses for which it is useful. Sheet thickness is important because defects occur with small total thickness, small thickness of the lower sheet, or large total thickness of the sheets (Abe, Kato and Mori 2006). In order to decrease overall vehicle weight, thinner and lighter materials are more desirable, but they are more difficult to join.

SPR has both advantages and limitations when compared to other process. Some of the advantages include the same cycle time as spot welding, little part distortion, and good tool life. Unlike spot welding, cycle time does not increase as the thickness of the sheets increases. Some limitations include the requirement for simultaneous access to both sides of the joint in order to create the joint, and the size of the riveting gun which restricts where the joints can be made (Barnes and Pashby 2000).

SPR compares with FBJ in many different aspects. With the FBJ process, the joint is made using heat instead of plastic deformation, so the ductility and elongation of the metal does not affect its ability to be joined. With SPR plastic deformation, there is a definite limit on how thin the sheet metal can be before the rivets break through the bottom sheet, or if it will work at all. But, with FBJ, the joint is made at or near the surface of the lower sheet, so it has the potential to join even thinner materials. Although SPR uses less power compared with resistance spot welding, it has the additional cost of rivets that makes it an expensive joining solution (Connolly 2007). This is a problem that is also faced by FBJ.

2.3 Resistance Spot Welding Using Transition Material

RSW is a fusion welding process that uses electrodes to clamp the sheet metals together and pass a current through them in order to create a weld nugget. The RSW process is shown in Figure 2.

Direct joining of aluminum and steel alloys is not recommended because the vastly different thermal and physical properties of the two metals creates brittle intermetallic compounds (IMCs) that significantly weaken the weld (Sun, et al. 2004). However, by using a transition material such as a hot or cold-rolled aluminum-clad steel sheet, experiments have shown that the thickness of the IMC layer can be reduced, which greatly increases the weld strength obtained (Oikawa, et al. 1999), (Sun, et al. 2004). Oikawa et al. found that an increase in welding current or welding time increases the thickness of the IMC layer within the transition material. They were able to produce lap shear samples with a tensile strength of approximately

3.0 kN, and U tension samples with a tensile strength of approximately 1.5 kN. These U tension samples are similar to the cross tension samples created using FBJ, which were hypothesized to also fail at 50% of the lap shear tensile strength.

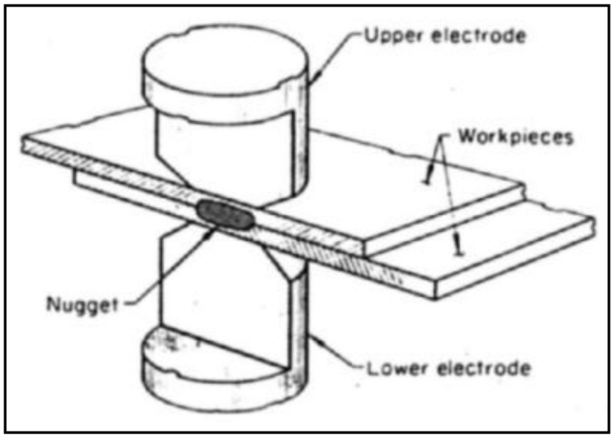

Figure 2: RSW Process (K 2008)

2.4 Friction Stir Spot Welding

FSSW is a solid-state joining process that uses frictional heat to soften the metals and a non-consumable bit to stir the metals together to create a joint. The FSSW process is shown in Figure 3.

A major concern of FSSW is the condition of the weld interface. In Tanaka et al.'s study of friction stir welded (FSW) mild steel to aluminum, it was found that brittle IMCs that make it difficult to fusion weld steel and aluminum also appear in FSW samples (Tanaka, Morishige and Hirata 2009). This is due to the metals diffusing as the friction heats the samples. Decreasing the thickness of the IMC exponentially increased the strength of the welds. Because of the IMC, however, they were unable to create any specimens that would fail in the aluminum base metal; the specimens always failed at the weld interface. Kimapong and Watanabe also reported difficulty in controlling weld quality as a result of IMCs at the weld interface (Kimapong and Watanabe 2005a), (Kimapong and Watanabe 2005b). They found that increased rotational speed, tool tilt angle, and pin diameter all increased the thickness of the IMC formed, thereby decreasing the strength of the joint.

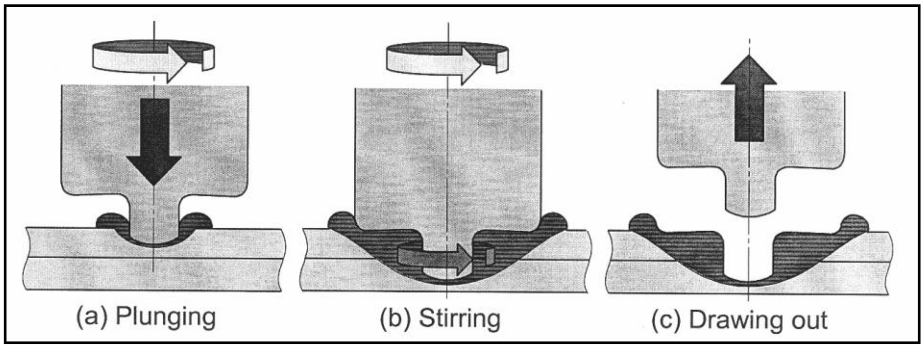

Figure 3: FSSW Process (Feng, et al. 2005)

Chen and Nakata performed an interesting study on the effect of the surface state of steel in a dissimilar joint (Chen and Nakata 2008). They compared dissimilar welds of AC4C cast aluminum alloy joined with three differently finished steel sheets (zinc-coated, brushed, and mirror finishes). Using the same welding parameters for all of the specimens, the tensile test results indicated that the surface finish of the steel had a significant effect on the strength of the joint. The zinc-coated steel joint performed the best with fracture loads of 5.02 kN or 97.7% of the steel sheet base metal fracture load, followed by the brushed finish joint at 3.25 kN, while the mirror finish joint split during tensile test preparation. FBJ would have less concern over the surface state of the steel sheet since it actually creates a friction weld between the similar steels of the bit and the steel sheet. However, it is still important that FBJ be able to perform at least as well as the zinc-coated steel joint created with FSSW.

2.5 Weldbonding

Adhesives can be used in conjunction with welding to create weldbonds. Adhesives easily join dissimilar metals and materials since they bond to the surface of the material. They can be used to increase the stiffness of structures, which means that it could be used on thinner materials to make them as stiff as thicker materials (Fellows, et al. 2008). According to Fellows, et al., it can even improve upon the stiffness of spot welds. Other advantages of adhesives include dampening properties to reduce vibration, and to seal joints against moisture and debris which aids in corrosion resistance (Barnes and Pashby 2000).

Pan et al. studied FSSW in conjunction with adhesives and found that spot friction weld-bonding was possible (Pan, et al. 2006). However, the difference in strength between the samples with uncured adhesive and the samples without any adhesive was between 1-1.5 kN, which seemed to indicate that FSSW was adversely affected by the presence of adhesive. However, when the adhesive was cured, the strength of the joint was over 7 kN. This study provided information on how to apply adhesives when creating a weldbonded sample, as well as performance baselines that can be compared with FBJ.

2.6 Clinching

Clinching is a cold joining process that clamps together several metal sheets by extruding them between a punch and a die as shown in Figure 4. Like FSSW, this process does not require any added material and thus does not add to the weight of the joint created. Clinching typically takes around one second to create a joint (Varis 2003).

According to Hamel et al., the final geometry of a clinched joint greatly influences its mechanical strength (Hamel, et al. 2000). In order to maximize strength, they used finite element modeling to analyze which clinching parameters influenced the final clinch geometry. Through their analysis, they discovered that the main factor that influenced the final joint geometry was the geometry of the tools. Other factors included the metal hardening of the sheets and the friction applied between surfaces in contact. The friction applied between the surfaces in contact is important because, like FSSW, the surface state of the materials to be joined has to be taken into consideration when creating joints.

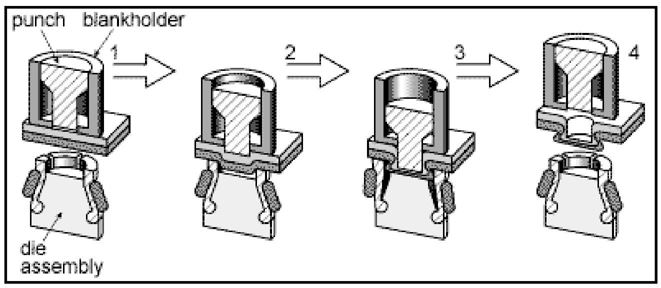

Figure 4: Clinching Process (TWI Ltd. 2004)

The ductility of the joining metals is an important factor in clinching. Because of the low ductility of high-strength steel, defects such as necking, cracking, or no interlocking tend to occur during the forming of the clinched joint (Lee, et al. 2010). Lee et al. found that these defects could be controlled by balancing the die radius and die depth so that the interlocking length and the neck thickness combination generated would create a strong joint.

A major drawback of clinching is that it requires high joining forces of up to 100 kN to deform the metals, which necessitates the use of heavy processing equipment (Schraft, Schmid and Breckweg 2003), (Lee, et al. 2010). The joining forces also have a negative impact on tool life. To counteract these shortcomings, Schraft et al. developed a new clinching process that superimposed the clinching with an orbital or radial movement of the punch. In doing so, they were able to reduce the joining forces by 50-70%. Clinched joints using this method had a shear tensile strength of approximately 4kN.

2.7 Friction Bit Joining

FBJ is a newly developing technology that uses a consumable bit to join sheet metals in a spot weld formation. The FBJ process overview is shown in Figure 5. The bit cuts through the top aluminum sheet metal, and then creates friction and joins to the bottom steel sheet. After a cooling period, the bit breaks off, leaving a flange that helps to hold the top sheet to the bottom sheet. By creating a friction weld between the similar steels of the friction bit and the UHSS sheet, FBJ avoids the creation of IMCs that weaken FSSW and RSW joints.

Miles et al. performed experiments using this process with both similar and dissimilar metals (Miles, et al. 2009). The experiments were done using UHSS DP980 joined to itself and DP980 joined with 5754 aluminum. Lap shear joints made between DP980 and 5754 aluminum averaged 6.3 kN, while cross tension samples of the same materials averaged 2.5 kN. These results were compared with SPR joints made between HSLA 350 and 5754 aluminum, and it was found that the FBJ process was able to create joints that support approximately 1 kN greater lap shear fracture load than the SPR joint.

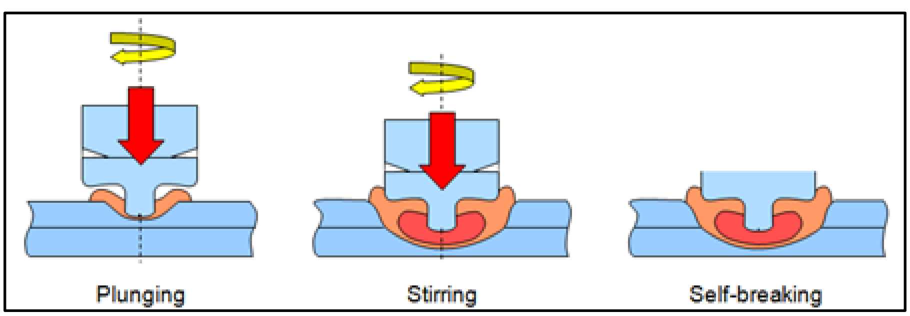

Figure 5: FBJ Process Overview (Miles, et al. November 5, 2009)

2.8 Summary

This literature review shows that extensive research and development has gone into finding solutions that will allow for the joining of dissimilar metals as applied in the automotive industry. Each method has its advantages and disadvantages. This research provides a baseline performance guide that the FBJ process will need to meet or exceed in order to determine feasibility of the FBJ process for use in automotive production.

3 RESEARCH METHODOLOGY

3.1 The Friction Bit Joining Machine

The machine engineered and built by MegaStir Technologies was specially made to meet the requirements of the FBJ process. It has servo motors that allow for precise control of the spindle rotation and speed. Another motor controls the Z-axis and is able to apply high loads during the weld cycle.

The machine has two sensors which allow for control and feedback during the welding cycle. A load cell sensor is located in the fixture plate and it is used to measure the load placed on the weld in the z-axis. A 20-lb. force is used to touch-off the bit on the sheet metal above this sensor in order to establish the machine zero due to the varying lengths of bits. During the welding cycle, this sensor graphs the load data in the computer program so that it can be analyzed further if desired. The maximum force for a given weld cycle is also recorded. The second sensor is a laser micrometer that is mounted on the spindle. This sensor sets the machine zero during the touch-off stage. During the weld cycle, this sensor monitors the spindle depth. The laser micrometer is used to control the depth of the spindle at each phase of the joining process. The maximum penetration depth is displayed on the computer read-out until it is reset or until an object crosses the laser beam.

3.1.1 Machine Controls

The machine has many different settings that can be controlled during the welding cycle. There are different phases available in the joining process that can be activated or deactivated according to what is needed. Each phase can have a different spindle RPM, z-velocity, z-depth, number of peck cycles, and dwell time.

Figure 6 illustrates the four phases of the FBJ process. The first phase of the welding process is used for drilling through the top sheet of aluminum. The second phase of the cycle is used for welding, and typically has a higher RPM. Also, there is a dwell time at the end of the second phase that allows the bit to continue spinning and create heat to make the friction joint without increasing the depth. The third phase of the process is a cooling period where the spindle stops rotating and the machine dwells for a specified time while the bit cools. The fourth phase of the welding cycle is used to shear the bit head off from the excess shank. The bit head creates the joint between the aluminum and steel. Eventually, a bit will be made that will consist of only the bit head portion, thereby eliminating this final shearing stage.

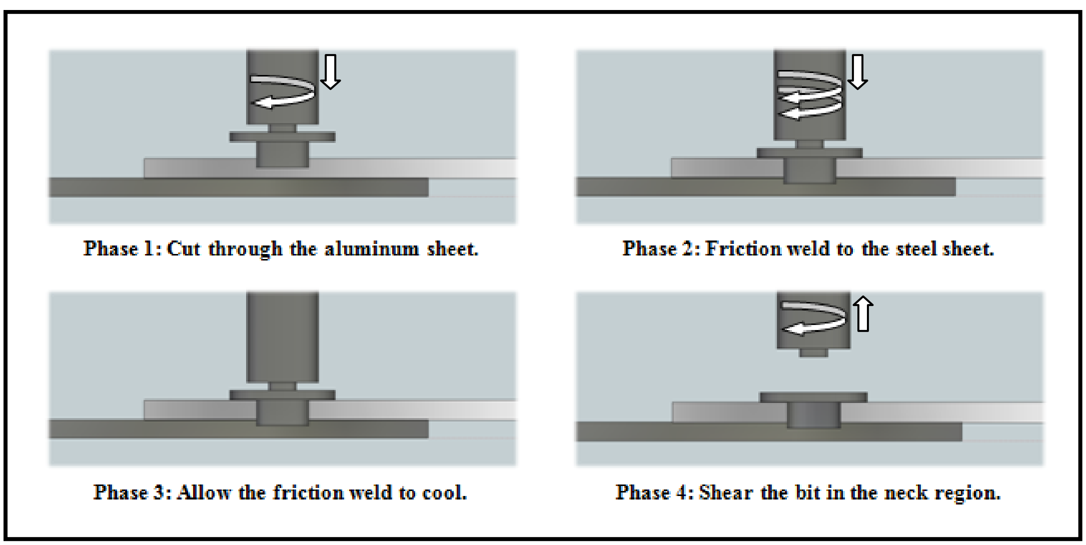

Figure 6: Friction Bit Joining Process

3.2 Bit Manufacturing and Materials

The joining bits were manufactured from 4140, 4340, or H13 steel rods. The 4140 and 4340 bits were machined from ⅜" diameter rod stock, and the H13 bits were machined from ½" diameter rod stock. The bit geometry was programmed and cut using an Okuma Space Turn LB300-M CNC lathe. Any residual burrs were removed by hand using either a file or pliers, and a flat was ground into the side of the shank using a grinder.

Two different joining bit tip geometries were used during experimentation. The first bit used consisted of two cutting faces milled into the end of the bit without any chip clearance fluting milled into the head, as shown in Figure 7. Also shown in Figure 7 is the second bit used, which was shaped more like a drill bit with two cutting faces and flutes milled into the tip for chip clearance. These bits will be referred to as non-fluted and fluted bits, respectively.

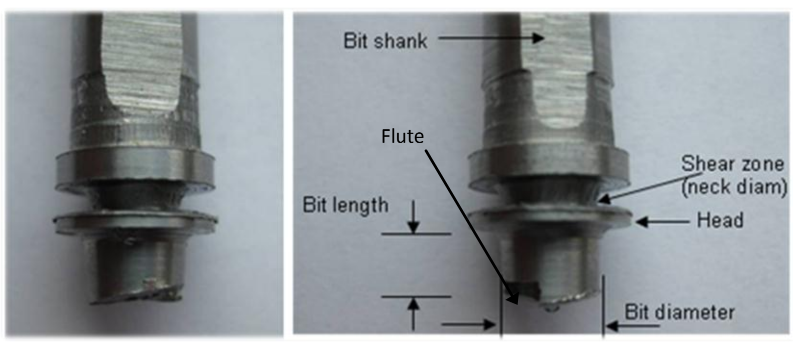

Figure 7: Non-Fluted and Fluted Bit Designs

3.3 Sheet Materials

The sheet metals used in this study include 0.065" thick DP980 steel sheet, 0.065" thick DP590 steel sheet, and 0.070" thick 5754 aluminum sheet. The aluminum was joined primarily to the DP980, but it was also joined to the DP590 in order to have a direct comparison with SPR, as prepared by GM.

DP980 and DP590 are dual-phase steels, meaning they have both a ferrite and martensitic microstructure. The ferrite matrix lends to formability, while the martensite increases the tensile strength. DP980 has an ultimate tensile strength of 980 MPa, while DP590 has an ultimate tensile strength of 590 MPa. According to a UK-based metals company, aluminum alloy 5754 consists of a mixture of manganese, iron, magnesium, silicon, and aluminum (Aalco Metals Ltd. 2011). With an ultimate tensile strength between 140-290 MPa depending on the temper, this particular alloy exhibits excellent corrosion resistance and weldability, and very good cold workability, making it an ideal candidate for use in vehicle bodies.

3.3.1 Specimen Preparation

Lap shear and T-peel samples were prepared using 1 inch by 4 inch rectangular coupons that were sheared to size. Lap shear samples were welded with one inch of overlap. T-peel samples were welded with the sheet metals stacked on top of each other, and then the sheets were bent into a T-shaped configuration so that one inch from the welded end remained unbent. Cross tension samples were prepared using 2 inch by 6 inch rectangular coupons that were sheared to size, and then drilled with two ¾" holes 4 inches apart. All coupons were used as-is without any surface cleaning or preparation since it was presumed that this was how the material would be used in an industrial setting. For the weldbonded samples, DOW Betamate 73305GB structural adhesive was applied as a Z bead as seen in Figure 8, and then the samples were welded together using the FBJ process. The adhesive was applied following the procedures listed in Pan et al.'s study on FSSW weldbonding (Pan, et al. 2006).

3.4 Testing Methods

Joint performance and quality were evaluated using several different testing methods. Lap shear, T-peel, and cross tension tests were used to evaluate the joint strength. Mounting and polishing of cross-sectioned samples was performed by MegaStir Technologies, and visual inspection of these samples provided qualitative measures of the joint properties. The purpose of visual inspection was to determine the presence of defects, which lead to poor joint quality and performance.

Figure 8: Adhesive Application for Weldbonded Specimens

3.4.1 Mechanical Testing

Lap shear, T-peel, and cross tension tensile testing were done using an Instron tensile testing machine. The lap shear samples were mounted in the jaws and shimmed to ensure that the load was pulling perpendicular to the weld axis, as seen in Figure 9. Purpose-made U-shaped jaws were bolted through the holes in the cross tension samples seen in Figure 10 to allow them to be pulled apart along the weld axis. T-peel samples, as seen in Figure 11, were bent in a fixture, and then pulled in the Instron machine without any shims. All samples were pulled at an extension rate of 0.4 inches per minute.

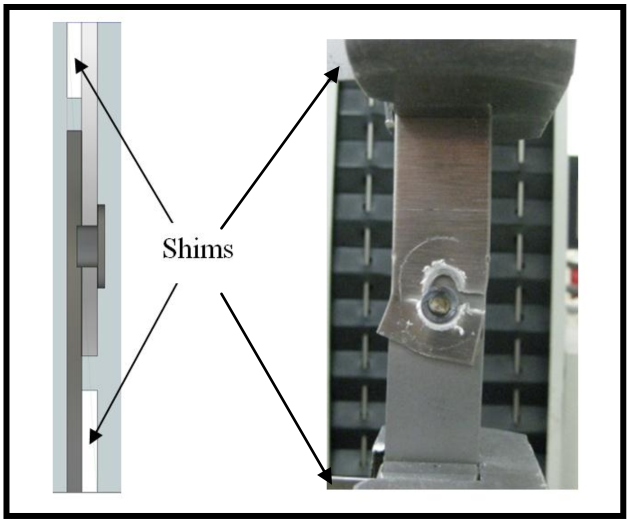

Figure 9: Lap Shear Testing Configuration

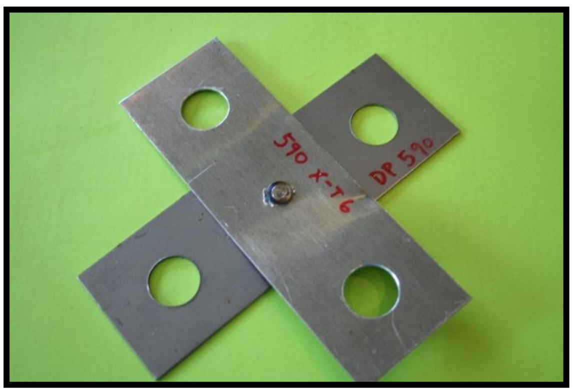

Figure 10: Cross Tension Testing Configuration

Figure 11: T-Peel Testing Configuration

3.4.2 Visual Inspection

Samples that were to be mounted and polished for visual inspection were sectioned using a Sodick Wire EDM. A Wire EDM was chosen for this process because it was a process that was least likely to change the appearance of the weld, and it would only remove a small portion of material when sectioning the sample. Mounting and polishing was performed by MegaStir Technologies. They took pictures of the samples so that they could be viewed and analyzed electronically.

3.5 Research Approach

Preliminary experimentation had already been performed in the previously mentioned study by Miles et al., so a more formal research approach was taken (Miles, et al. 2009). An initial bit design and welding process were in place, so this research expanded that initial study using a design of experiments (DOE) approach. The DOE was used to determine the statistical significance of the different welding factors, as well as to create an optimized equation to maximize the lap shear strength.

Another experimental approach for data collection was to make consecutive joints at a given set of parameters. This approach was used to test the reliability and repeatability of the joints. Averages, ranges, T-tests, and F-tests were used to analyze these data to test for significance. Data were analyzed using Microsoft® Excel 2007, Microsoft Corporation, Redmond, WA.

4 RESEARCH RESULTS AND ANALYSIS

4.1 Screening Design of Experiments

Friction bit joining is a newly developed process, but some previous experimentation has been performed. The results of this study focused on the effect of bit design and welding process parameters on weld strength in different configurations. A randomized 32 run 2^{10-5} fractional factorial design of experiments (DOE) with two replications was used to find the most significant factors affecting lap shear strength, which is a primary indicator of weld quality. A total of ten factors were studied during the screening DOE.

4.1.1 Bit Design and Geometry

The bit used for initial experimentation was 4340 steel with two cutting faces milled into the end of the bit, and did not have any chip clearance fluting milled into the tip, as shown in Figure 12. The initial geometry included a tip length of 0.205", tip diameter of 0.235", and neck diameter of 0.208". For the screening DOE, the tip length was varied by ±0.030", and the tip diameter and neck diameter were each varied by ±0.010" of the initial values.

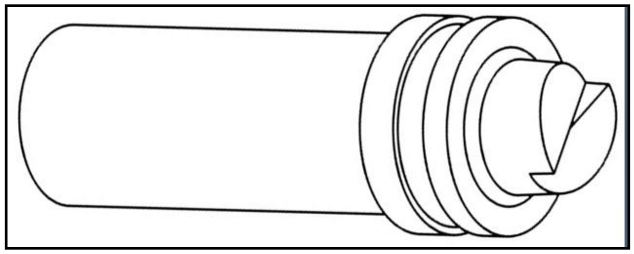

Figure 12: Initial Bit Design

4.1.2 Welding Parameters

The welding parameters included four stages: cutting, welding, cooling, and breaking. Table 1 lists the initial welding parameters used in each stage and indicates the parameters that were varied during experimentation. For the screening DOE, the cutting and welding RPM were varied by ±10%, cutting and welding Z-velocity by ±30%, welding Z-command by ±0.010", welding dwell by ±500ms, and cooling dwell was varied by +1500ms. The welding and cooling Z-command were set to be equal so that the bit would not move while it was cooling. All other values remained constant. The cutting Z-command was set to 0.005" deeper than the thickness of the aluminum sheet metal to ensure that the entire thickness of the aluminum was cut before the welding cycle began.

Table 1: Initial Welding Parameters with Shaded Parameters Varied

	Cutting	Welding	Cooling	Breaking
RPM	500	2400	0	800
Z-velocity (in/min)	2	2	0	10
Z-command (in)	-0.070	-0.120	-0.120	0.200
Peck Cycles	1	0	0	—
Dwell (ms)	0	1000	500	0

4.1.3 DOE Experiment and Results

Coding the high and low values of the variables using 1 and -1 respectively, a 32 run 2^{10-5} fractional factorial with two replications was performed, and each run was randomized. Table 3 shows the DOE setup and experimental results. The results of the screening DOE indicated that the factors that had a significant effect on the lap shear strength were tip length, welding dwell, and cooling dwell.

Using stepwise regression analysis techniques as shown in Table 2, tip length was shown to have a significant effect on lap shear strength at the 95% confidence level. Some two-factor interactions that included tip length were also shown to be significant, but because this experiment was a fractional factorial, those effects were confounded with other two-factor interactions. The other two-factor interactions all contained cooling dwell, so this factor was also chosen for further study. The final factor chosen for further study was the welding dwell.

Table 2: Stepwise Regression Summary Output

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.48326
R Square	0.23354
Adjusted R Square	0.19985
Standard Error	285.72721
Observations	96

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	2263651.26	565912.815	6.9318	0.0001
Residual	91	7429243.365	81640.037		
Total	95	9692894.625			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1162.0228	29.4389	39.4723	0.0000	1103.5460	1220.4996
X1	-124.0012	39.2583	-3.1586	0.0022	-201.9829	-46.0194
X1X2 = X9X10	66.2623	29.2116	2.2684	0.0257	8.2370	124.2876
X1X8 = X3X10	84.1776	21.4798	3.9189	0.0002	41.5107	126.8445
X1X9 = X2X10	-91.2926	29.7126	-3.0725	0.0028	-150.3130	-32.2723

Factors Tested
- X1 = Tip Length
- X2 = Tip Diameter
- X3 = Neck Diameter
- X4 = Cutting RPM
- X5 = Cutting Z-velocity
- X6 = Welding RPM
- X7 = Welding Z-velocity
- X8 = Welding Z-command
- X9 = Welding Dwell
- X10 = Cooling Dwell

Table 3: Screening DOE Coded Values and Results

Standard Run	Bit Length X_1	Cutter Diameter X_2	Neck Diameter X_3	Cut RPM X_4	Cut Z-Vel X_5	Weld RPM X_6	Weld Z-Vel X_7	Weld Z-Com X_8	Weld Dwell X_9	Cool Dwell X_{10}	Y_1	Y_2	Y_3	Yavg	Variance
	Factors										Shear Strength				
1	-1	-1	-1	-1	-1	1	1	1	1	1	1257	1523	1273	1351.0	22252
2	1	-1	-1	-1	-1	-1	-1	-1	-1	1	1165	1044	966	1058.3	10054
3	-1	1	-1	-1	-1	-1	-1	-1	1	-1	1290	1319	1475	1361.3	9900
4	1	1	-1	-1	-1	1	1	1	-1	-1	1303	1343	1378	1341.3	1408
5	-1	-1	1	-1	-1	-1	-1	1	-1	-1	1478	1582	708	1256.0	227932
6	1	-1	1	-1	-1	1	1	-1	1	-1	745	619	686	683.3	3974
7	-1	1	1	-1	-1	1	1	-1	-1	1	1540	1276	1524	1446.7	21909
8	1	1	1	-1	-1	-1	-1	1	1	1	1448	498	1346	1097.3	272001
9	-1	-1	-1	1	-1	-1	1	-1	-1	-1	1488	1322	1436	1415.3	7209
10	1	-1	-1	1	-1	1	-1	1	1	-1	1347	411	583	780.3	248229
11	-1	1	-1	1	-1	1	-1	1	-1	1	1039	1168	505	904.0	123561
12	1	1	-1	1	-1	-1	1	-1	1	1	1295	1223	1334	1284.0	3171
13	-1	-1	1	1	-1	1	-1	-1	1	1	1193	1532	1296	1340.3	30204
14	1	-1	1	1	-1	-1	1	1	-1	1	1333	1335	1245	1304.3	2641
15	-1	1	1	1	-1	-1	1	1	1	-1	1044	718	920	894.0	27076
16	1	1	1	1	-1	1	-1	-1	-1	-1	791	1492	1079	1120.7	124152
17	-1	-1	-1	-1	1	1	-1	-1	-1	-1	1547	1277	333	1052.3	406305
18	1	-1	-1	-1	1	-1	1	1	1	-1	1352	1232	1267	1283.7	3808
19	-1	1	-1	-1	1	-1	1	1	-1	1	1515	836	0	783.7	575860
20	1	1	-1	-1	1	1	-1	-1	1	1	1229	1355	923	1169.0	49356
21	-1	-1	1	-1	1	-1	1	-1	1	1	1562	1631	1169	1454.0	62109
22	1	-1	1	-1	1	1	-1	1	-1	1	1316	1307	1267	1296.7	680
23	-1	1	1	-1	1	1	-1	1	1	-1	1558	418	1416	1130.7	385961
24	1	1	1	-1	1	-1	1	-1	-1	-1	1256	1340	1365	1320.3	3260
25	-1	-1	-1	1	1	-1	-1	1	1	1	1272	1408	1336	1338.7	4629
26	1	-1	-1	1	1	1	1	-1	-1	1	1217	1289	1183	1229.7	2929
27	-1	1	-1	1	1	1	1	-1	1	-1	976	1349	1271	1198.7	38706
28	1	1	-1	1	1	-1	-1	1	-1	-1	1210	1163	1253	1208.7	2026
29	-1	-1	1	1	1	1	1	1	-1	-1	826	1401	598	941.7	171236
30	1	-1	1	1	1	-1	-1	-1	1	-1	708	963	1233	968.0	68925
31	-1	1	1	1	1	-1	-1	-1	-1	1	1239	1398	1301	1312.7	6422
32	1	1	1	1	1	1	1	1	1	1	1256	1379	1329	1321.3	3826

4.2 Full Factorial Design of Experiments

Using the three factors identified in the screening DOE, a randomized eleven run 2^3 factorial with center points DOE and two replications was completed in order to optimize the lap shear strength.

4.2.1 Bit Geometry and Welding Parameters

The previous range for the factor levels was used for this DOE, with tip length at 0.205”±0.030”, welding dwell at 1000±500ms, and cooling dwell at 500+1500ms. The same overall bit design was used, with some modifications of the tip and neck diameters. The larger tip diameter of 0.245” was used during this DOE because it was decided that the greater surface area would most likely create a stronger weld. Many of the welds created did not break in the neck region as intended, but rather under the flange, creating a weld with no way to hold the aluminum in place. Because of this, the smaller neck diameter of 0.198” was used to try to encourage the bit to shear in the neck region. The welding parameters used in the DOE are listed in Table 4, with the shaded values being those that were varied. Faster Z-velocities were used to reduce the overall welding time, and the Z-commands were kept at the original values.

Table 4: Welding Parameters as Used in the Full Factorial DOE

	Cutting	Welding	Cooling	Breaking
RPM	550	2160	0	800
Z-velocity (in/min)	2.6	2.6	0	10
Z-command (in)	-0.070	-0.120	-0.120	0.200
Peck Cycles	1	0	0	—
Dwell (ms)	0	1000	500	0

4.2.2 DOE Experiment and Results

Coding the high and low values of the variables using 1 and -1 respectively, an eleven run 2^3 full factorial with center points was performed with two replications. Each run was randomized. Table 5 shows the DOE setup, analysis, and experimental results.

The results of the full factorial DOE indicated that none of the factors or their interactions had a significant effect on the lap shear strength at the 95% confidence level. Also, curvature was not significant. Tip length was approaching significance with a p-value of 0.058, but it would require approximately 97 additional runs before it would become significant. Tip length was found to have the greatest effect on the lap shear strength, with the shorter tip length creating a stronger weld.

Using stepwise regression analysis, only the tip length and the intercept were found to be significant enough to use in an optimized equation. The coefficient for the tip length is equal to the effect thereof divided by two. The intercept of the equation was found to be 1248.70 as reported in the regression analysis. Maximizing Equation 1 gives a strength of 1308.9 lbf when tip length is at the low factor level.

$$Strength = 1248.70 - 60.17X_1 \tag{4.1}$$

4.3 Full Factorial DOE: Stiffened Frame

During experimentation, it was noted that the depth recorded on the laser micrometer after each run was inconsistent with the depth that was input in the machine controller. Also, the frame of the machine was still seen to be flexing open during operation despite the use of clamps that were applied to the machine during prior research.

Table 5: Full Factorial DOE Coded Values, Analysis, and Results

	Factors			Interactions				Lap Shear Strength					
Run	**Tip Length X1**	**Cool Dwell X2**	**Weld Dwell X3**	**X1X2**	**X1X3**	**X2X3**	**X1X2X3**	**Y1**	**Y2**	**Y3**	**Mean**	**Range**	**Variance**
1	-1	-1	-1	1	1	1	-1	1420	1148	1288	1285.3	272	18501.3
2	1	-1	-1	-1	-1	1	1	1293	1278	1230	1267.0	63	1083.0
3	-1	1	-1	-1	1	-1	1	1401	1319	1225	1315.0	176	7756.0
4	1	1	-1	1	-1	-1	-1	1104	1226	1314	1214.7	210	11121.3
5	-1	-1	1	1	-1	-1	1	1030	1472	1460	1320.7	442	63401.3
6	1	-1	1	-1	1	-1	-1	1173	781	1308	1087.3	527	74936.3
7	-1	1	1	-1	-1	1	-1	1422	1235	1348	1335.0	187	8869.0
8	1	1	1	1	1	1	1	1141	1205	1271	1205.7	130	4225.3
9								918	1323	1097			
10	0	0	0	0	0	0	0	1306	1275	1228	1207.7	406	18089.75
11								1324	1140	1258			

Sumprod:	-481.33	110.00	-133.33	22.00	-244.00	155.33	186.00			S_p^2 =	21854.4	S_p =	147.832
Effect:	-120.33	27.50	-33.33	5.50	-61.00	38.83	46.50			$Runs_f$=	8	$Reps_f$ =	3
H_0:	Effect=0	H_A:	Effect≠0							n_f =	24	Se_E =	60.352
α =	0.05	df =	24							Run_c=	3	n_c =	9
$t_{effects}$ =	-1.994	0.456	-0.552	0.091	-1.011	0.643	0.770			C =	-46.17	H_0:	C = 0
p-value =	0.058	0.653	0.586	0.928	0.332	0.526	0.449			Se_C =	57.783	t_c =	-0.799
Significant:	**N**	**N**	**N**	**N**	**N**	**N**	**N**			t^*_{crit} =	2.064	pvalue=	0.4321
n_f^* =	97	1849	1259	46237	376	927	647				Curvature Significant:	No	

In an attempt to better control the machine and limit the variability of results, a reinforcing structure was built and installed on the machine to further stiffen the frame as shown in Figure 13. In order to determine the effect of stiffening the frame, an eleven run 2^3 full factorial with center points was performed using the same factors and factor levels as the previous experiment, and the results were compared.

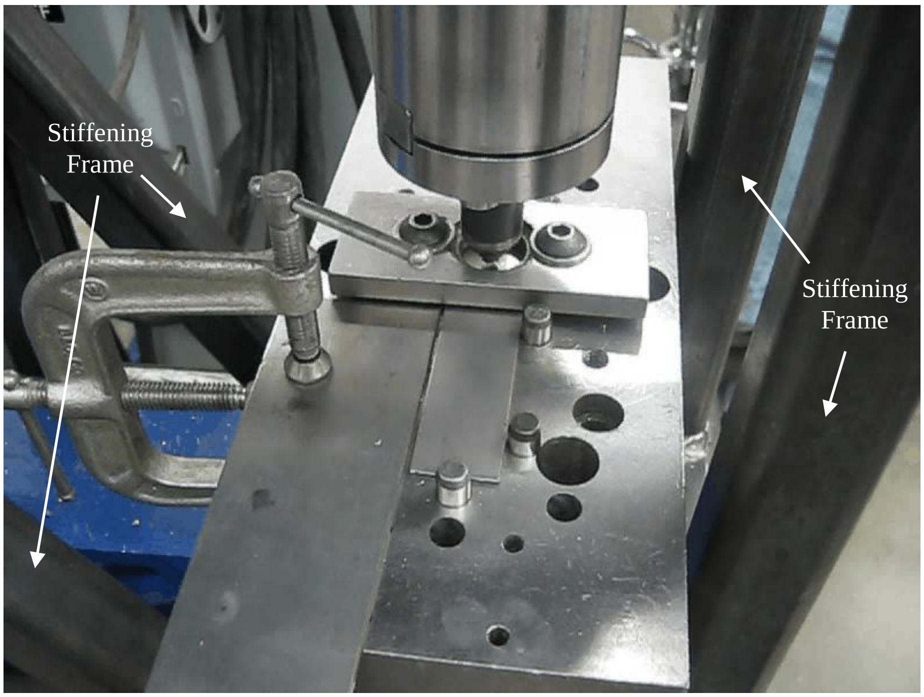

Figure 13: Friction Bit Joining Machine with Stiffening Frame

4.3.1 Bit Geometry and Welding Parameters

The previous factors and factor levels were used for this experiment, with tip length at 0.205" ±0.030", welding dwell at 1000 ±500ms, and cooling dwell at 500 +1500ms. The bit geometry and welding parameters from the full factorial DOE were also used in this experiment. In this way, the only difference between the two experiments is the implementation of the frame stiffener.

4.3.2 DOE Experiment and Results

Coding the high and low values of the variables using 1 and -1 respectively, an eleven run 2^3 full factorial with center points was performed with two replications. Each run was randomized. Table 6 shows the DOE setup, analysis, and experimental results.

The results of the full factorial DOE indicated that only the weld dwell time had a significant effect on the lap shear strength at the 95% confidence level with a p-value of 0.0004, with a longer welding dwell time creating a stronger weld. The interaction between tip length and weld dwell time was approaching significance with a p-value of 0.0669, but this is likely due to the high significance of weld dwell time. Also, curvature was significant, so a quadratic model of the data was required.

To create an optimized equation for lap shear strength, the general equation for the strength of the weld as determined by the welding dwell time and the quadratic term was formed, and then Microsoft® Excel 2007 Solver was used to maximize the strength. The coefficient for the weld dwell time factor was the effect thereof divided by two. Regression analysis was used to replace the interaction with the smallest effect size with an X^2 term to account for the curvature found through experimentation. The factors that were not significant were also eliminated one at a time until only the weld dwell time and the quadratic term remained. The intercept of the equation was reported to be 1414.56. Maximizing Equation 2 gives a strength of 1425.4 lbf when the weld dwell is at a factor level of 0.268, which equates to 1133.8ms.

$$Strength = 1414.56 + 81.08X_3 - 151.56X^2 \tag{4.2}$$

Table 6: Replicated DOE after Stiffening the Frame of the Machine

Run	Factors Tip Length X1	Cool Dwell X2	Weld Dwell X3	Interactions X1X2	X1X3	X2X3	X1X2X3	Lap Shear Strength Y1	Y2	Y3	Mean	Range	Variance
1	-1	-1	-1	1	1	1	-1	1126	1046	1334	1168.7	288	22101.3
2	1	-1	-1	-1	-1	1	1	1132	1288	1201	1207.0	156	6111.0
3	-1	1	-1	-1	1	-1	1	1180	1285	1065	1176.7	220	12108.3
4	1	1	-1	1	-1	-1	-1	1218	1041	1267	1175.3	226	14134.3
5	-1	-1	1	1	-1	-1	1	1418	1501	1461	1460.0	83	1723.0
6	1	-1	1	-1	1	-1	-1	1403	1121	1218	1247.3	282	20526.3
7	-1	1	1	-1	-1	1	-1	1339	1415	1326	1360.0	89	2311.0
8	1	1	1	1	1	1	1	1365	1267	1295	1309.0	98	2548.0
9								1343	1445	1452			
10	0	0	0	0	0	0	0	1255	1546	1410	1414.6	291	7215.8
11								1409	1378	1493			

Sumprod:	-226.67	-62.00	648.67	122.00	-300.67	-14.67	201.33	S_p^2 =	9202.20	S_p =	95.93
Effect:	-56.67	-15.50	162.17	30.50	-75.17	-3.67	50.33	$Runs_f$=	8	$Reps_f$ =	3
H_0:	Effects=0	H_A:	Effects≠0					n_f =	24	Se_E =	39.162
α =	0.05	df =	24					$Runs_c$=	3	n_c =	9
$t_{effects}$ =	-1.447	-0.396	4.141	0.779	-1.919	-0.094	1.285	C =	151.56	H_0:	C = 0
p-value =	0.1608	0.6958	0.0004	0.4437	0.0669	0.9262	0.2110	Se_C =	37.495	t_c =	4.042
Significant:	**N**	**N**	**Y**	**N**	**N**	**N**	**N**	t^*_{crit} =	2.064	pvalue=	0.0005
									Curvature Significant:	Yes	

4.3.3 Additional DOE Analysis

To determine if stiffening the frame had an effect on the results of the experimentation, the first and second full factorial experiments were analyzed as a blocked experiment. The first experiment was determined to be in the first block with a factor level of -1, and the second stiffened frame experiment was used as the second block, which had a factor level of 1. If the blocked factor of stiffening the frame had no effect on the strength of the weld, then the effects of the interactions between the experimental factors and the blocked factor would be insignificant. Using a similar analysis as before, it was determined that stiffening the frame had no significant effect on the strength of the weld. However, an analysis of the variation showed that stiffening the frame did have a significant effect on reducing the variation of weld strength.

4.4 Bit Design and Material

After determining the optimum welding settings within the tested range, it was decided to experiment with different bit geometry and material combinations to find out if they would have a significant effect on the lap shear strength. Because of analytical mistakes made during experimentation, the optimal settings were thought to be different than was reported here. Thus, the following experiments were run at a tip length of 0.175", cooling dwell of 500 ms, and welding dwell of 1500 ms. The other settings remained the same as before with a tip diameter at 0.245", neck diameter at 0.198", cutting and welding z-velocities at 2.6"/min, cutting and welding RPMs at 550 and 2160 RPM respectively, and cutting and welding z-commands at -0.07" and -0.12" respectively.

The two bit geometries studied in this experiment were the non-fluted and the fluted designs as discussed in Chapter 3. Combined with both 4340 and 4140 steel, four different combinations of bit geometry and bit material were studied. To compare the combinations, ten runs of each bit were measured and recorded as shown in Table 7. These results were analyzed using F-tests and T-tests. F-tests were used to compare the variance in lap shear strength of the bit combinations, and T-tests were used to compare the average lap shear strengths.

First, the effect of the bit geometry was analyzed. When comparing the 4340 non-fluted and fluted bits, it was found that the fluted bits significantly reduced the variance in lap shear strength, but did not significantly increase the average lap shear strength. When comparing 4140 non-fluted and fluted bits, the fluted bits were marginally significant in both reducing the variance in lap shear strength and increasing the lap shear strength with p-values less than 0.08. This shows that the fluted bit geometry creates welds that are more consistent in strength. This is important for industry because reducing variation helps to improve quality and ensures that the product works as intended.

Next, the effect of the bit material was analyzed. Comparing the 4340 and 4140 non-fluted bits showed that there was no difference in either the variance of the two samples or the lap shear strength. Similarly, comparing 4340 and 4140 fluted bits provided further evidence that these bit materials do not affect the variance in lap shear strength. However, the difference in the average lap shear strength was found to be significant with a p-value of 0.013. Thus, the 4140 steel bit material has the potential to create a stronger weld.

Overall, the 4140 fluted bit design was found to create the strongest weld in lap shear with the least amount of variance. The average strength of the weld was 1320 lbf (5.87 kN), with a range of 177 lbf and a variance of 3855.

Table 7: Bit Geometry and Material Combinations

4340 - flat design		4340 - fluted design		4140 - flat design		4140 - fluted design	
Sample #	Lap Shear Strength (lbf)	Sample #	Lap Shear Strength (lbf)	Sample #	Lap Shear Strength (lbf)	Sample #	Lap Shear Strength (lbf)
1	1495	1	1096	1	1403	1	1268
2	1381	2	1255	2	1134	2	1284
3	985.8	3	1225	3	1251	3	1394
4	1220	4	1274	4	1284	4	1228
5	1339	5	1250	5	1256	5	1379
6	1057	6	1206	6	1253	6	1282
7	1225	7	1297	7	1365	7	1365
8	1232	8	1070	8	1052	8	1329
9	1148	9	1298	9	1216	9	1405
10	1182	10	1318	10	1283	10	1270
Average:	1226	Average:	1229	Average:	1250	Average:	1320
Range:	509	Range:	248	Range:	351	Range:	177
Variance:	22611	Variance:	7107	Variance:	10304	Variance:	3855

4.5 Weld Time Reduction

In order to be competitive with SPR, FBJ needed to not only match joint strength, but also to match joint creation speed. The welding time was calculated by dividing the displacement by the Z-velocity (in/min) and multiplying by 60 sec/min to find the welding time in seconds. At the welding parameters that were thought to be optimal as shown in Table 8, the welding time per joint was approximately 4.77 seconds. To be within the processing time range of SPR, it was decided that FBJ needed to be able to produce welds at 2.0 seconds or less.

Table 8: Final Weld Parameters from the Incorrectly Analyzed DOE

	Cutting	Welding	Cooling	Breaking
RPM	550	2160	0	800
Z-velocity (in/min)	2.6	2.6	0	10
Z-command (in)	-0.070	-0.120	-0.120	0.200
Peck Cycles	1	0	0	—
Dwell (ms)	0	1500	500	0

Using the welding parameters in Table 8 as a start point, the parameters were changed and tested until acceptable parameters were found that would create a joint in less than 2.0 seconds and still create a strong weld. Two main strategies were used to decrease the weld creation time: increasing the cutting and welding Z-velocity, and decreasing the welding dwell time. Because of the increase in cutting Z-velocity, the cutting RPM was also increased in order to ensure that the aluminum was being removed from the welding interface. Increasing the welding Z-velocity increases the friction heat generated, which somewhat counteracts the decrease in welding dwell. Another change that was made that decreased the welding time was to decrease the welding Z-command depth by 0.01in. The final parameters that were discovered are shown in Table 9. Using the same welding time calculation as above, it was found that at these new welding settings, welds could be created in 1.66 seconds, which nets a 65.2% welding cycle time reduction. These faster welding parameters were used for all subsequent experimentation.

Table 9: Parameters Used to Create Welds in Under 2.0 Seconds

	Cutting	Welding	Cooling	Breaking
RPM	1200	2160	0	800
Z-velocity (in/min)	10.0	10.0	0	10
Z-command (in)	-0.070	-0.110	-0.110	0.200
Peck Cycles	1	0	0	—
Dwell (ms)	0	500	500	0

Five consecutive runs of both the 4140 fluted and non-fluted bits were run at the 1.66 second welding time, as shown in Table 10. Compared with the 4140 fluted bit run at the 4.77 second weld time, both the 4140 fluted and the non-fluted bits run at the 1.66 second weld time were found to be significantly stronger. Although the fluted bit run at 1.66 seconds also had an increase in variation, it was decided that the fluted bit would be used for future experimentation because it had the higher average strength of 1462 lbf (6.50 kN) which would assumedly allow for a higher potential strength for future welds created.

Two samples of the 4140 fluted bits were also run at the 1.66 second welding parameters in DP590 to ensure that the parameters and bit choice would still work for that material choice. Both samples had lap shear strengths over 1500 lbf (6.67 kN). The first sample sheared at 1523 lbf (6.77 kN) and the second sheared at 1575 lbf (7.00 kN). Although not many DP590 samples were made, these results were promising.

Table 10: 4140 Fluted and Non-Fluted Bits at 1.66 Seconds

4140 fluted bit design at 1.66 seconds

Sample #	Lap Shear Strength (lbf)		
1	1294	Avg:	1462.4
2	1652	Range:	358
3	1441	Variance:	25371.3
4	1327		
5	1598		

4140 non-fluted bit design at 1.66 seconds

Sample #	Lap Shear Strength (lbf)		
1	1442	Avg:	1392.6
2	1509	Range:	198
3	1362	Variance:	6614.3
4	1311		
5	1339		

Leonid Lev of General Motors R&D and Planning was able to create some SPR samples with which to compare these results. Using a 6mm diameter Emhart Rucker rivet and 5754 aluminum and DP590 steel coupons, the SPR samples created had lap shear strengths ranging from 4690N to 5422N with the strength increasing as the rivet penetration depth increased. Five consecutive runs at the best rivet penetration depth averaged 5345N with a range of 405N. FBJ samples had an average strength 21.7% stronger than the SPR samples, with an average strength of 1462lbf (6505N). However the range for FBJ was 358lbf (1592N), which was almost four times that of SPR.

4.6 Weldbonding

The next experiment performed was to determine if it was possible to weldbond using the FBJ process. Using the parameters discovered in Table 9 and the 4140 fluted bit design with a tip length at 0.175", tip diameter at 0.245", and neck diameter at 0.198", five consecutive runs were performed on DP980. The DOW Betamate 73305GB structural adhesive was applied as a Z-bead, and then the samples were welded as usual.

The average lap shear strength of the five runs was 1443 lbf (6.41kN) as shown in Table 11. Unlike the FSSW weldbond study cited in the literature review, a t-test showed that there was no difference in strength between the FBJ uncured weldbonded samples and the non-adhesive samples. Also, Figure 14 and Figure 15 show sectioned samples that demonstrate how the frictional heat somewhat cured the adhesive, and this heat affected zone (HAZ) of the adhesives is localized around the welded bit. It also appears that the majority of the adhesive was forced out of the weld zone.

Table 11: Weldbonded 4140 Fluted Bits in DP980 at Fast Parameters

Sample #	Lap Shear Strength (lbf)		
1	1472	Avg:	1443.8
2	1422	Range:	82
3	1408	Variance:	1242.2
4	1427		
5	1490		

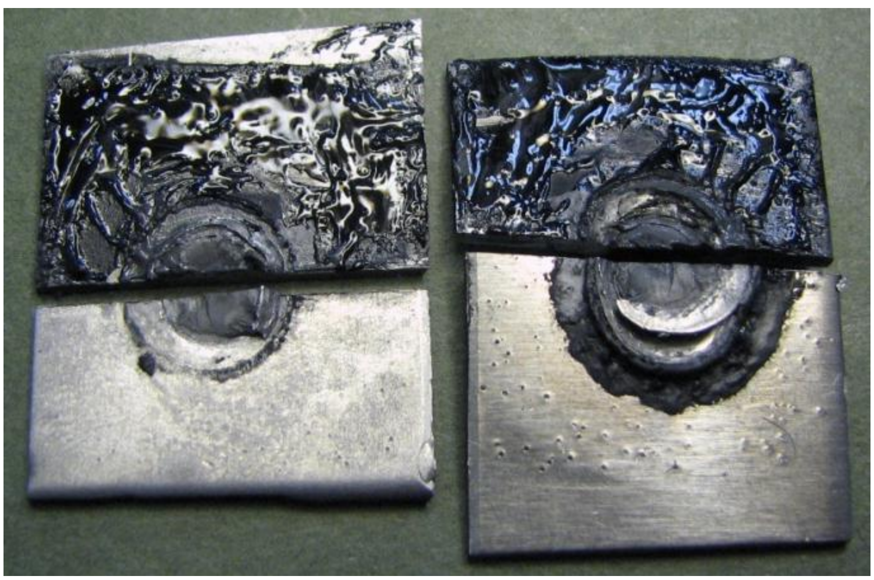

Figure 14: Weldbonded Shear Samples Showing the Cured Adhesive

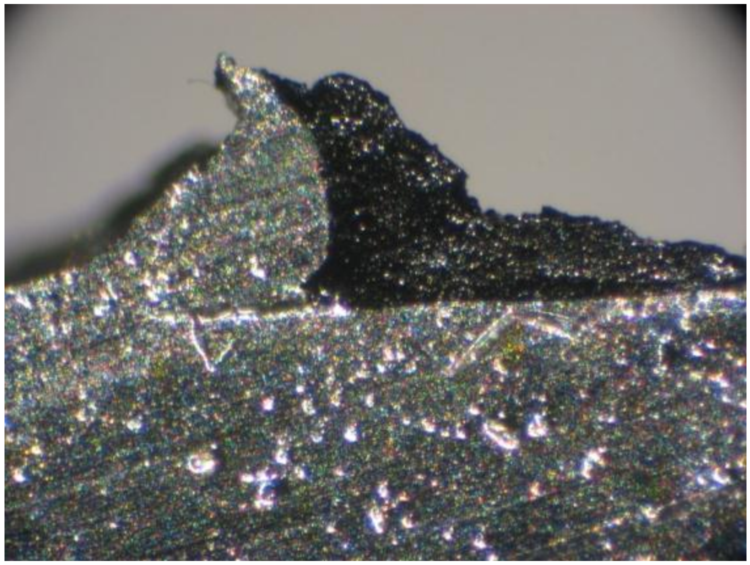

Figure 15: Sectioned Weldbonded Sample Showing the Adhesive HAZ around the Weld Zone

4.7 T-peel and Cross Tension

Once acceptable lap shear strengths were achieved, the next step was to determine if the same parameters would create welds in T-peel and cross tension configurations with strengths equal to or greater than 731 lbf, which is 50% of the average lap shear strength. Five samples of each configuration were run in DP980 and DP590. Extra samples were made when the bit head did not separate properly from the shank and thus had no flange to hold the top aluminum sheet securely to the steel sheet. This made for a total of 23 runs, with three of them being repeats.

Table 12 shows the strength of each sample. On average, none of configurations were able to produce welds equal to half the average lap shear strength. However, one DP590 cross tension sample did surpass this benchmark at a strength of 756 lbf (3.36kN), and two others within this category were over 42% of the average lap shear strength. None of the other samples exceeded 34% of the average lap shear strength.

Table 12: T-Peel and Cross Tension Tests in DP980 and DP590

DP980 T-Peel Run #	Strength(lbf)	Notes	
1	200.8	BB	
2	85.9	NF	
3	166.7	BB	
4	138.5	BB	
5	178	BB	
6	363.2	AL	
		Average	188.85
		Average without run 2	209.44

DP590 T-Peel Run #	Strength(lbf)	Notes	
1	27.7	NF	
2	180.9	BB	
3	199.5	BB	
4	223.1	BB	
5	218.3	BB	
6	215.8	BB	
		Average	177.55
		Average without run 1	207.52

DP980 Cross Tension Run #	Strength(lbf)	Notes	
1	478.1	BI	
2	564.8	BI	
3	494.8	BI	
4	413.2	BI	
5	484.8	BI	
		Average	487.14

DP590 Cross Tension Run #	Strength(lbf)	Notes	
1	654.2	BB	
2	489.1	BB	
3	307.7	NF	
4	756.2	BI	
5	619.9	BB	
6	295.3	BI	
		Average	520.4
		Average without run 3	562.94

Key:	
AL: Aluminum tear-out;	BB: Broke in the bit ;
BI: Broke at the interface;	NF: No flange

In addition to the strength of each sample, a note indicating how the joint failed is also included in Table 12. An example of the different failure modes is shown in Figure 16, with image a) showing aluminum tear-out, image b) showing breaking in the bit, image c) showing breaking at the interface, and image d) showing no flange. Both the T-peel and the cross tension samples suffered from shearing within the bit during welding. Only one sample pulled out of the aluminum, which is the preferred failure mode, while the majority of the samples broke in the bit. The samples that broke in the bit greatly resembled the samples that had no flange, leading to further experiments to discover what was happening in the bit during the welding process.

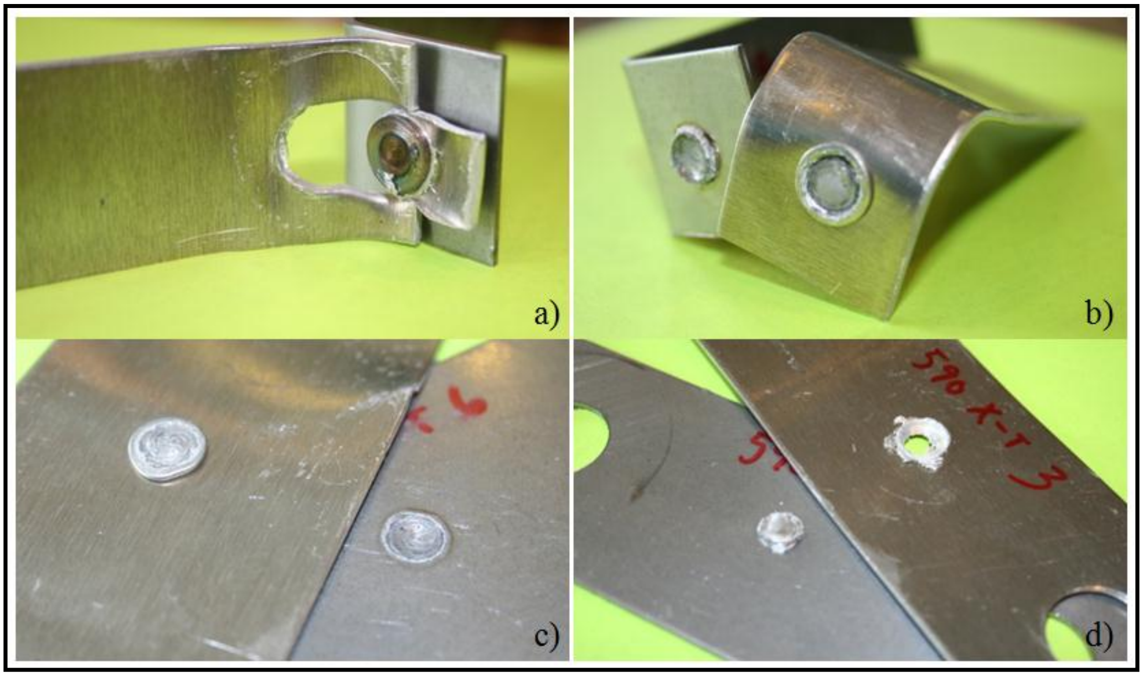

Figure 16: Failure Modes of Cross Tension and T-Peel Samples

4.8 Friction Bit Hardness and Depth Study

To gain understanding of why the samples were breaking in the bit, a preliminary depth analysis study was performed. This preliminary analysis was run at the 1.66 second welding parameters using the 4140 fluted bit design. However, the welding phase Z-command depth was varied from -0.105 to -0.120 in., incrementing by 0.005 in. A visual inspection of a cross-sectioned sample indicated the presence of an HAZ within the bit that was a slightly darker color than the rest of the bit. Two main defects were present within this HAZ: void zones and cracks. The cracks appeared to be a shearing of the bit during the welding phase when the bit would soften. The void zones appeared to form along these cracks, as well as along the edges of the bit where it deformed and folded upon itself. An example showing the presence of defects is shown in Figure 17. This shows that when a weld does not have a flange present, it is likely because the bit sheared during the welding phase and either did not rejoin with the flange, or it was weaker than the neck region and broke during the final phase of the FBJ process.

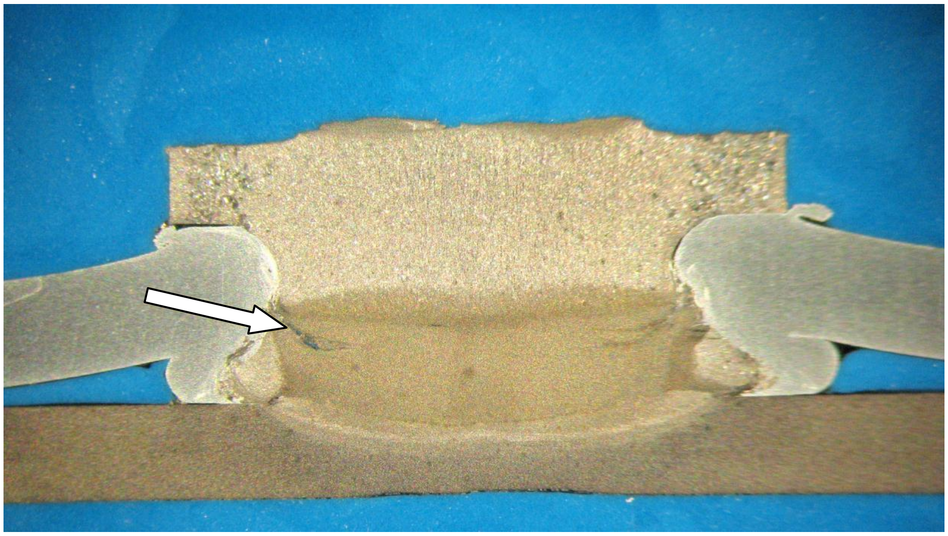

Figure 17: Depth Analysis Sample Run at -0.110" Welding Depth Showing Void and Cracks

In order to determine if the Rockwell C (R_c) hardness of the bit would affect the quality of the weld as determined through visual inspection, three groups of heat treated 4340 bits and one group of non-heat treated 4140 bits were compared at the same parameters of the preliminary depth analysis. The 4340 bits were all heat treated and hardened to approximately 54 R_c. One group of the 4340 bits was left untempered, while the other two groups were tempered to approximately 47 R_c and 37 R_c. The 4140 steel was used as received and had a hardness of approximately 33 R_c.

None of the samples mounted and polished were free from defects. No one particular heat treatment seemed to perform better than the others. It is possible that the heat generated during the welding process negates much of the heat treatment on the bits. Figure 18 includes some of the samples from the hardness analysis. Sample 10 was one of the worst samples, having a crack that extended the entire diameter of the bit, as well as a large void zone located on the crack. Samples 5, 7, and 9 also had cracks that extended the entire diameter of the bit, while samples 5, 9, and 16 appear to have trapped some aluminum within the bit material. As seen from these studies, neither heat treating the bit nor varying the welding depth seems to create a high quality weld.

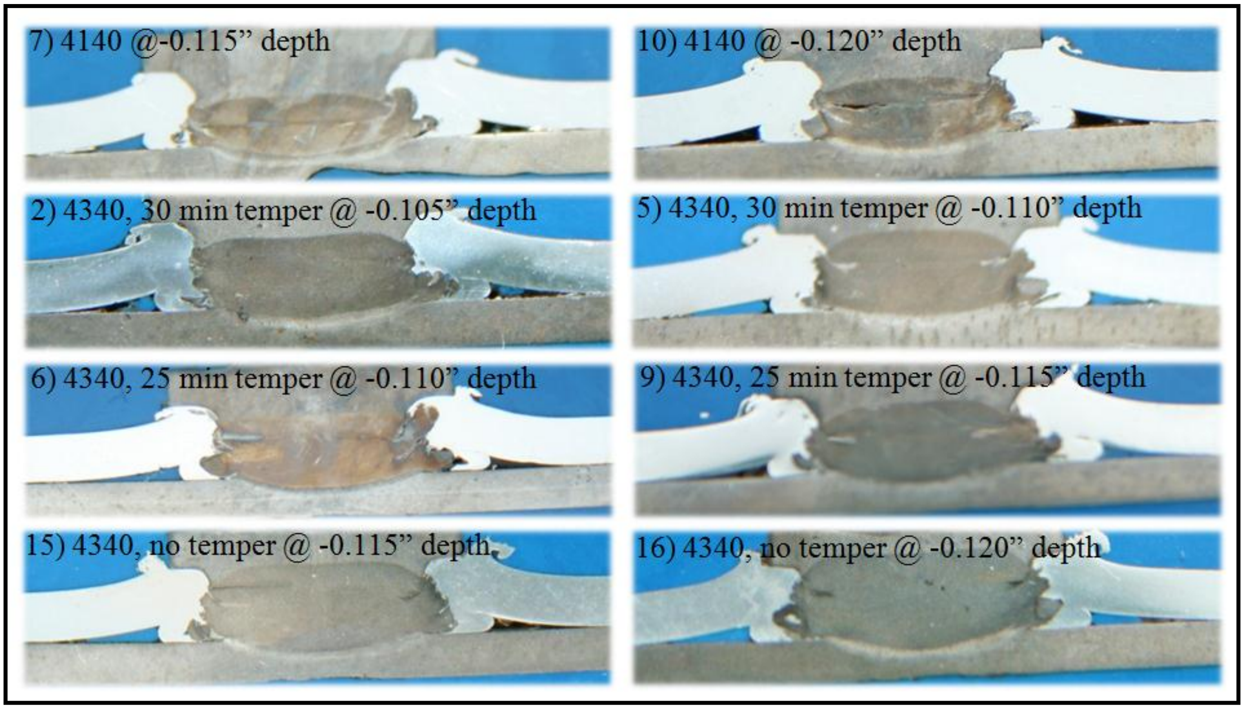

Figure 18: Samples from the FBJ Hardness and Depth Analysis

An additional depth analysis study was performed using H13 steel bits welded at the same parameters as above. However, none of the joints produced using H13 broke in the neck region, so they did not have a flange. It is likely that different welding parameters would have to be discovered for use with this bit material.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Through a series of designed experiments, optimal welding parameters were obtained to maximize the lap shear strength of aluminum alloy 5754 dissimilarly joined to DP980. Bit design and material were tested, and it was found that the 4140 fluted bit design outperformed the other bit design and material combinations tested, with an average lap shear strength of 1320lbf (5.87 kN) and a range of 177lbf (.79 kN). Using the 4140 fluted bit, the optimal welding parameters were further refined to reduce the welding time to 1.66 seconds, which created welds with an average lap shear strength of 1462lbf (6.50 kN). Running the 4140 fluted bit at the 1.66 second welding time parameters, it was determined that using an uncured adhesive to create a weldbond had no effect on the strength of the weld.

Although these welding parameters were strong in the lap shear welding configuration, it was discovered that defects within the weld caused the bits to break at low strengths in the cross tension and T-peel configurations. In DP980 the average T-peel and cross tension strengths were 209lbf (.93 kN) and 487lbf (2.16 kN) respectively. In DP590 the average T-peel and cross tension strengths were 207lbf (.92 kN) and 562lbf (2.5 kN) respectively.

5.2 Conclusions

In order to determine the feasibility of using the FBJ process to join 5754 aluminum to DP980 steel in a dissimilar joining configuration, the focus of this research was to optimize the strength of the weld while decreasing the welding time. Feasibility was defined as the ability to produce strong, quality welds at high speed as stated and tested through the following hypotheses.

Hypothesis 1: The FBJ process is capable of producing aluminum to steel lap shear joints with strengths that are greater than joints produced using SPR as a comparison.

- This hypothesis was not rejected.
- FBJ was able to create samples with an average strength 21.7% stronger than the SPR samples, averaging 1462 lbf (6.5 kN).

Hypothesis 2: The FBJ process is capable of producing high quality joints as evaluated through visual inspection and by statistical consistency over a large number of samples.

- This hypothesis was rejected.
- Cross sectioned samples indicated the presence of cracking and void zone defects within the bit material.
- Defects led to poor joint performance in the cross tension and T-peel configuration.
- Defects also caused the bit to break below the neck region during the final phase of the welding cycle, resulting in welds without flanges.

Hypothesis 3: The FBJ process is capable of producing joints with the cross tension and T-peel strengths equal to or greater than 50% of the lap shear strength.

- This hypothesis was rejected.

- No T-peel or cross tension sample group averaged 50% of the lap shear strength
- Only one sample had a tensile strength over 50% of the lap shear strength.
- These poor pulling strengths were likely due to the shearing within the bit that was seen in the cross sectioned samples.

Hypothesis 4: The FBJ process is capable of producing joints in less than 2 seconds.

- This hypothesis was not rejected.
- The total welding time was reduced from 4.77 seconds to 1.66 seconds.

At the current welding capabilities and bit design, the FBJ process is not a feasible alternative to joining dissimilar 5754 aluminum with DP980 steel. Although the samples were able to be created in under two seconds and performed better than SPR in a lap shear configuration, cross tension and T-peel joints suffered from poor quality within the weld. For FBJ to be feasible according to these hypotheses, progress on improving the weld quality would also have to improve the cross tension and T-peel strengths.

5.3 Recommendations

Although these experiments showed that FBJ is capable of creating dissimilar 5754 aluminum to DP980 steel joints, visual inspection of sectioned samples and sub-optimal cross tension and T-peel samples showed that there is still much room for improvement. Two main problems with the FBJ process that were observed during experimentation involved the FBJ machine and the friction bit. Resolving these problems would be beneficial for future research.

The first problem that was observed with the current welding process involved the welding machine itself. The purpose-made friction bit joining machine is essentially made up of a spindle and an anvil attached to a large C-frame. A laser micrometer is used to determine how far the bit will travel in the Z-axis direction. However, it was observed that a lack of machine rigidity was allowing the frame to flex open and twist laterally. This resulted in the actual bit depth being greater than the programmed depth, as well as possibly causing shearing within the bit during the welding cycle. Thus, the first recommendation is to develop a smaller, more rigid design for the welding frame, which would provide the following benefits:

- Eliminate welding frame flexing
- Eliminate lateral movement during the welding cycle
- Provide more accurate weld depth control

The second problem that was observed involved the friction bit design. The current bit design is simple and easy to manufacture, which makes it appropriate in an experimental setting. However, almost 3/4 of the bit is waste that does not become part of the welded joint. No process that was studied in the literature review had unused material after the joint creation. In order to be competitive with other processes, this waste needs to be eliminated. Thus, the other recommendation is to redesign the friction bit to only include the portion that is consumed in the welding process, which would provide the following benefits:

- Eliminate material waste
- Eliminate the cooling and shearing phases, further reducing weld cycle time

Developing new equipment and tooling according to these proposed recommendations would hopefully make the FBJ process more reliable, as well as increase its competitiveness with other joining processes. It is important to make these changes before continuing with more research since new welding parameters would likely be necessary to accommodate these modifications.

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