TEMPERATURE MEASUREMENT METHOD OF FRICTION STIR WELDING USING ULTRASONIC TIME OF FLIGHT

By

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Thesis

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LIST OF NOMENCLATURE

Symbol

FSW Friction Stir Welding
TWI The Welding Institute
HAZ Heat Affected Zone
TMAZ Thermomechanically Affected Zone
US Ultrasonic
ρ Density
G Ultrasonic time of flight
T Temperature
ν Speed of sound
ξ Ultrasonic time of flight factor
f Frequency
λ Wavelength
D Piezoelectric crystal diameter
t Plate thickness
Z Acoustic Impedance
NZ Near Zone/ Fresnel Zone
k Beam spread constant
α Beam angle
θ Beam spread angle
E Strain/ Young’s modulus
ω Tool rotation rate (rpm)
PZT 5 Lead Zirconate Titanate
SDH Side drilled hole
RPM Rotations per Minute
IPM Inches per Minute
TOF Time of flight
CHAPTER I

INTRODUCTION

Since its invention in 1991 at The Welding Institute (TWI) of Cambridge, England (Thomas et al., 1991), the solid-state joining technique known as Friction Stir Welding (FSW) has gained great popularity and is being implemented in many industries. Applications of FSW include its use in the shipbuilding, aerospace, automotive, and even railway industry. Among the reasons that FSW has become so popular is that FSW is an energy efficient process that produces no fumes, arc flash, or spatter (Cook et. al, 2004), and it has the ability to join materials that are usually difficult to weld using fusion welding as well as minimizing the change in a material’s characteristic properties and dimensions.

FSW is most often used on low melting point alloys such as aluminum and also thinner materials (< 1 in.) but recent developments have seen FSW being used on both stronger alloys such as steel and thicker materials. Contrary to standard fusion welding, FSW does not use an arc, shielding gas or filler material for its process, but instead uses a non-consumable pin that rotates to join the materials or work pieces by utilizing the force and heat produced between the pin and material. As the tool is moved through the material, the material on the leading edge enters the plasticized region and is swept around to the back of the tool where the lagging material is left to form a solid joint (Midling et. al, 1996). This process of the tool traversing along the weld line in a plasticized tubular shaft of metal results in severe solid state deformation involving dynamic recrystallization of the base material (Ding 2008).

Ultrasonic pulse measurements have been widely used in non-destructive testing for decades (Yee 1985). Applications vary for inspection of welds, casting, forgings, and ingots to
airplane wings, turbines, and nuclear reactors. An early use of sonic waves was the qualitative testing done by railway workers testing the train wheels where they would hit the wheels with a hammer and listen for a distinctive sound produced if a train wheel was defective (usually having a lamination or crack). Similar test were also done on railway tracks with great success.

The first real use of ultrasound pulses was in the medical field where ultrasound pulses are used to examine the wombs of expecting mothers. Major advancements have then been made mostly in the medical field, such as 3D imaging, and it wasn’t until recently that the industrial field has caught up with the medical industry.

Since then, ultrasonic measurements has advanced from generally being used in flaw detection to applications in numerous other fields such as ultrasonic pyrometry in process control systems (Hoyle 1994). Other applications include non-destructive evaluation of material properties such as the Young’s Modulus and Shear Modulus as well as measurements of residual stresses in materials.

Due to the fact that the sound speed is a strong function of temperature in most materials, this study proposes the use of the change in the time of flight of the ultrasonic pulse to measure the temperature during friction stir welding.
CHAPTER II

LITERATURE REVIEW

According to Longhurst (2009), heating, plastic deformation and forging are the three phenomena that are experienced by the material during the FSW process. A non-consumable rotating tool, consisting of a probe and shoulder, is plunged into the materials to be joined and then traverses the joint line. Due to the friction and plastic deformation, heat is generated and as the temperature increases, plasticization of the material occurs and it is sheared at the front of the probe and it is rotated to the rear of the probe where under significant shoulder pressure it is forged together. Figure 1 illustrates the FSW process.

![Figure 1, FSW diagram for typical butt weld configuration (Mishra 2005)](image)

Figure 1, FSW diagram for typical butt weld configuration (Mishra 2005)
Figure 2, Joint configuration for friction stir welding: a) square butt b) edge butt c) T joint butt d) lap joint e) multiple lap joint f) T lap joint g) fillet joint (Mishra 2005)

Figure 2 shows the typical joint configurations for FSW. The simplest being the square butt joint shown in Figure 2a. Square butt joints consist of two plates or sheet with the same thickness being placed on a backing plate and firmly clamped to prevent the abutting joint faces from being forced apart from the forces involved in FSW. The axial force is largest during the initial plunge of the tool, hence ensuring that the plates in this configuration do not separate is crucial. The rotating tool is plunged into the joint line until the shoulder comes in contact with the top of the plates. The tool is then traversed along the joint face producing a weld behind the rotating tool. As for the lap joint configuration shown in Figure 2d, two plates or sheets (plates and sheets need not be of same thicknesses) are placed on top of each other and clamped down to a backing plate. Similar to the butt joint configuration, a rotating tool is plunged into the top plate through to the bottom plate at the desired location and is then traversed along its desired weld direction, again causing a weld to form behind the rotating tool joining the two plates. In comparison to conventional fusion welding, FSW does not require any special preparation like
having beveled join prep for welding to commence. It is enough that the joining materials are clean and clamped down in order for FSW to be done.

**FSW Process Parameters**

Two of the important parameters for FSW are tool rotation rate ($\omega$, RPM) in clockwise or counterclockwise direction and tool traverse speed (in./min) along the joint line. The stirring and mixing of the material is a result of the tool rotation and the stirred material from the front to the back of the pin is moved by the translation of the tool. As intuition would suggest, higher tool rotation rates would result in higher temperatures being generated due to the higher friction heating and in turn results in more intense stirring and mixing of materials. Despite that, the parameter that most governs the heating is the frictional coupling of the tool surface with the work piece.

Additionally, another important process parameter is the angle of the spindle with respect to the work piece surface or it is sometime known as the tool tilt (refer Figure 3). Sometimes it is desired that there be a slight tilt of the spindle towards the trailing direction. This is to ensure that the shoulder of the tool holds the stirred material by the pin and moves material from the front of the pin towards the back as will be explain in the material flow section. The plunge depth of the pin into the material is also important in that too shallow of a plunge will result in the shoulder of the tool not being in contact with the surface of the material. This will lead to inefficient movement of the material from the front of the tool and can cause welds with inner channel or surface grooves. Too deep a plunge depth will in turn result in excessive flash and a significantly concave weld being produced.
The performing of preheating or cooling can also have an impact of some specific FSW processes especially for high melting point materials such as steel and titanium or high conductivity materials such as copper.

**Weld Zone Characteristics**

Without a standard for characterizing the weld zone, it would be hard for researchers to study FSW. Threadgill (2007) wrote a terminology paper in which the basic regions used to classify the weld zone including the advancing and retreating sides of the weld were defined and is shown in Figure 3. Additionally, the micro-structural classification for the cross-section of a friction stir welded joint was also defined.

![Figure 3, Diagram of Threadgill (2007) FSW tool terms](image)
The geometry in Figure 4 corresponds to either a butt weld or a bead-on-plate weld. The parent material is defined as the region that is far enough from the joint line that it is not affected by heat. The heat affected zone (HAZ) is the area that lies just outside the joint line and on a macro scale is not affected by plastic deformation upon basic inspection, but there may very well be on a micro scale according to Threadgill (2007). The area that is affected by both heat and plastic deformation caused by stirring is called the thermo-mechanically affected zone (TMAZ) and depending on the welded material, tool design, and the welding parameters can vary its shape, although usually its shape at a minimum encompasses the trapezoidal area defined by the tool shoulder diameter and the diameter of the bottom of the probe. In the TMAZ, its material may or may not be recrystallized with the recrystallized material being contained within the weld nugget. Despite there being some dispute among researchers over things such as the term nugget (Threadgill (2007) states it “lacks scientific pedigree”) and the dynamics of recrystallization in FSW, the classification of these different weld zone regions have not changed. Unnecessarily wordy, terms like “dynamically recrystallized zone” are among the other names for the nugget.
“Stirred zone” is another one of those which is not completely accurate because the TMAZ also includes stirred material (Threadgill, 2007). Many studies have been performed to study material flow and modes of recrystallization in FSW, and these will be discussed further in the following section.

**Material Flow**

Arbegast et al. (2003) suggested that the FSW process can be modeled as a metalworking process in terms of five conventional metal working zones: (a) preheat, (b) initial deformation, (c) extrusion, (d) forging, and (e) post heat/cool down (Figure 5). It is theorized that the preheat zone; the zone in front of the pin, the rotation of the tool and an adiabatic heating caused by the deformation of the material causes the temperature to rise. The extent and heating rate of this zone is zone is governed mainly by the traverse speed of the tool as well as the thermal properties of the material. The initial deformation zone is formed when the material is heated above a critical temperature and when the magnitude of stress exceeds the critical flow stress of the material, this results in the flow of the material. The extrusion zone then receives the material that is forced down from the initial deformation zone whilst the material that is forced upwards move into the shoulder zone. Also in the extrusion zone, within a finite width, material will flow around the pin from the front to the rear of the tool. The zone where the material from the front of the tool is forced into the cavity left by the forward moving pin under hydrostatic pressure conditions is called the forging zone. In this zone, the tool shoulder applies a downward forging force to help constrain the material in this cavity. Behind that is the cool down zone. This is where the material cools under either passive force or forced cooling conditions.
Temperature Measurement Methods

Temperature measurements of the weld during FSW have previously been carried out (Mahoney et al. 1998) using various methods including infra-red imaging/ thermometers, embedded thermocouples in the parent metal as well as direct contact thermometers. These methods usually only measure the temperature of the surface of the metal or in the case of internal temperatures requires the drilling of holes (Tang et al. 1998), and the addition of foreign material into the weld. Using ultrasonic time of flight (TOF), it is possible to measure the average temperature of the weld as the weld is being made and also to possibly to measure the average temperature of the different zones as per Figure 5.

From Myers et al. (2012), the time of flight for a pulse through an isothermal, homogeneous medium is related to the average temperature between the ultrasonic transducers by the equation

\[ G_j = \frac{R_g}{V_0} \left(1 + \xi \theta_{ave} \right) \]
Where $R_{ij}$ is the distance traveled by the ultrasonic pulse, $v_0$ is speed of sound in the material at a reference temperature, $\xi$ is the ultrasonic time of flight factor which is material dependent, and $\theta_{ave}$ is the change in temperature from the reference temperature. The time of flight can thus be normalized to the initial state by

$$
\frac{G_{ij}}{G_0} = \frac{R_{ij}}{v_0} \left[ 1 + \xi \left( T_{ave} \mid \theta \right) \right] = 1 + \xi \left( T_{ave} \mid \theta \right)
$$

Where $G_0$ is the time of flight at some reference temperature. From this it is easy to see that the average temperature between two transducers becomes:

$$T_{ave} \mid = \frac{1}{\xi} \left( \frac{G_{ij}}{G_0} - 1 \right) + T_0$$

**Ultrasonic Fundamentals**

The principle behind ultrasonic examination is having an ultrasonic transducer that pulses ultrasonic waves into a material and the sound will either reflect off of boundaries like edges or the other side of the wall or off of discontinuities like cracks or lamination and the return pulse is then analyzed. An important factor in ultrasonic examination is having a layer of couplant between the test material and the transducer to eliminate the air barrier between the two. The layer of couplant is important because the difference in acoustic impedance of the Perspex shoe in the transducer and air, and of the test material and air is very high. Having a high difference in acoustic impedance means that more of the sound would be reflected back and less of it would be transmitted as can be calculated from the following equation

$$R = \frac{(Z_1 - Z_2)^2}{(Z_1 + Z_2)^2}$$

Where $Z = \rho v$
\[ R = \text{reflection coefficient} \]
\[ Z_{1,2} = \text{Acoustic impedance of material 1,2} \]
\[ \rho = \text{material density} \]
\[ v = \text{sound speed} \]

Ultrasound can propagate in many ways through a material and depending on the way it propagates will determine how fast the speed of sound is for that particular material. The most common types used for ultrasonic examination are longitudinal (particle vibrations parallel to wave direction) and transverse (particle vibrations perpendicular to wave direction). The other different modes of propagation are surface – Rayleigh waves, plate Lamb waves and plate Love waves. Longitudinal waves travel the fastest in any particular medium. The sound speed for traverse waves are in general half of that of longitudinal waves while surface waves travel at about 9/10 the speed of traverse waves but only have a penetration depth of about one wavelength. For the purpose of this study, the change in the time of flight of traverse (shear) waves was measured and was correlated to the change in temperature.

There are various methods used to carry out ultrasonic examinations. The two most basic techniques and the ones that were used in this study are the pulse echo technique and the pitch catch technique. The pulse echo technique is the simplest form where a single or dual crystal ultrasonic transducer is used to transmit the ultrasonic pulse and the same transducer is used to receive. There’re many variations to the pitch catch method. The one used in this study is similar to that used to determine the transfer correction of materials as explained in the American Petroleum Institute Recommended Practice 2X (API RP 2X 2004) where two angle beam transducers are placed facing each other on the same surface and one transducer acts as the transmitter of the ultrasound while the other one acts as the receiver. Other examination
techniques include the tandem and through transmission techniques where both use the pitch

catch principle, to the more advanced methods like phased array ultrasonic which uses multi-
crystal transducers that have the capabilities of multiplexing and also the Time of Flight

Diffraction (TOFD) method.

Figure 6, The various ultrasonic examination methods
Construction of the Ultrasonic (US) Transducer

The active element in a US transducer is the component that generates the ultrasonic pulse. It is usually made of a piezoelectric element usually Lead Zirconate Titanate (PZT 5). Lead Zirconate Titanate is most commonly the crystal used due to its relatively high efficiency and relatively high critical temperature. It is mounted on a highly damped backing plate material (usually a Tungsten/Araldite composite) that functions as a damper to the piezoelectric element in order to reduce its “ringing time” and also to absorb the ultrasonic wave generated towards the back of the crystal. A Perspex wear shoe is then placed in front of the piezoelectric element and it is all encased in an Aluminum body with an electrical connector that has electrical leads connecting to the piezoelectric element. A schematic representation of a US angle beam transducer can be seen in Figure 7. In order to produce angled sound beams in the material, the piezoelectric crystal is mounted at an angle and the sound beam angle produced is determined by the index of refraction between the Perspex and material using Snell’s Law.

\[
\frac{\sin \alpha_1}{v_1} = \frac{\sin \alpha_2}{v_2}
\]

Where,

\(\alpha_1\) = incident angle in material 1
\(\alpha_2\) = incident angle in material 2
\(v_1\) = speed of sound in material 1
\(v_2\) = speed of sound in material 2
Figure 7, Schematic representation of an ultrasonic angle beam transducer

Important Characteristics of the Ultrasonic Transducer

There are a few characteristics of an angle beam ultrasonic transducer that need to be determined before any measurements are carried out in order to get more accurate results. These being the index point, beam angle ($\alpha$) and beam spread ($\theta$) of the transducers. The index point is the location on the transducer where the main beam of the ultrasonic sound exits the transducer and enters the material. The beam angle is the angle the main beam travels in the material and is measured from the normal of the entering surface. In the Near Zone/ Fresnel Zone the ultrasonic beam travels in a cylindrical shape in front of the transducer, but in the Far Zone/ Fraunhofer Zone, the beam is analogous to a flash light in that it has a main beam that spreads out in a conical shape with the energy of the sound falling off towards the edge of the cone. The length of the Near Zone and the beam spread angle can be calculated by:

$$NZ = \frac{D^2}{4\lambda} \quad \text{and} \quad \sin \theta = k \frac{\lambda}{D}$$
In these equations, \( D \) represents the diameter of the piezoelectric crystal, \( \lambda \) is the wavelength of the sound beam given by the equation \( \lambda = \frac{v}{f} \), where \( v \) is the speed of sound in the material and \( f \) is the center frequency of the transducer. The constant \( k \) in the beam spread equation is 1.22 for the theoretical null. 1.08 for the 20dB edge (10% of peak). 0.88 for the 10dB (32% of peak) edge and 0.7 for the 6dB (50% of peak) edge. A transducer’s beam spread is the angle between a determined edge in the cone to the other side of the same determined edge (e.g. 10% edge – 10% edge). For straight beam transducers it is easy to calculate the beam spread using the equation above, but due to the refraction that occurs in angle beam transducers, it is not as simple and the beam spread has to be determined physically as the calibration section explains. Figure 8 shows the basic characteristics of an ultrasonic transducer while Figure 9 shows a conceptual representation of the sound field emitted by a US transducer.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{ultrasound_transducer.png}
\caption{Basic characteristics of an ultrasonic transducer}
\end{figure}
Experimental Equipment

For this study, the Friction Stir Welding machine used is a converted 1940’s era Kearney and Trecker Model K Number 2 three axis milling machine. Three additional motors each for the traverse, lateral, and vertical movements of the table were retrofitted to the machine as well as a control system that controls all three motors in addition to the machine’s spindle speed. The control system consists of a National Instrument DAQ, model USB-6008 that is connected to a Dell Vostro 230 PC that runs Windows XP and has a C# in house written software with a Graphical User Interface (GUI). Until recently, the machine used a Kistler cutting force dynamometer mounted rigidly between the spindle head and the tool holder to measure forces and torques. It has now been replaced with a low cost custom system that is more robust to the harsh vibration and temperature environment of FSW (Gibson 2011). The system consists of Vishay Micro-Measurements general purpose strain gages model C2A-06-250LW-350 to measure the axial force and torques and transmit the data wirelessly via an XBee XB24-DKS development kit to the weld control PC. There is also a touch screen monitor mounted on the
milling machine that mirrors the weld control PC display and acts as a secondary control station for the FSW machine. The machine can be seen in Figure 10.

The ultrasonic equipment used was a couple of GB SS 70° 4MHz transducers connected to a Panametrics-NDT Model 5072PR pulser/receiver which in turn was connected to a Tektronix TDS2001C digital oscilloscope. All connections were done using RG174 coaxial cables.

Also for this study, the temperature measurement equipment used were K-type thermocouple wires and an Omega OMB-DAQ 56 board connected to a PC installed with Omega’s Personal DaqView software. Also, an Omega Model OS524E Handheld Infrared Thermometer was used as a secondary method of measuring temperatures. The oven used for the calibration was a Blue M Stabil-Therm Gravity Oven.

Figure 10, Vanderbilt University Welding Automation Lab (VUWAL) FSW Machine
Throughout the welding process, the Aluminum plate is clamped firmly to the anvil and using a custom built jig that can compensate for the variation in surface height and also the plunge depth, the US transducers are mounted (about 5mm) behind the FSW tool for the pitch catch set up (Figure 12) or in the case of the pulse echo set up, only one transducer is positioned next to the tool either on the advancing side or the retreating side so that it is aligned with the FSW tool’s pin (Refer Figure 13). Before starting the weld, the tool is first positioned over the desired starting point of the weld. Using the user input RPM, the spindle motor is then engaged and the table is raised so that the tool plunges into the material. Once the tool reaches the programmed plunge depth set by the user, the traverse motor then proceeds to move the table so that the tool will traverse along the weld line. As the tool reaches the set weld length, the table is then conversely lowered causing the tool to be raise out from the material. This particular welding process causes an ‘exit hole’ to be left behind by the tool’s pin as it exits the material as can be seen in Figure 14.
Figure 12, Graphical representation of the pitch-catch experimental set up

Figure 13, Graphical representation of the pulse echo experimental set up
Figure 14, The left side of the image presents the resulting "Exit Hole" effect when the tool is removed from the material. The right side of the image presents the result from plunging the tool into the material.
CHAPTER III

TEMPERATURE MEASUREMENTS USING ULTRASONIC TIME OF FLIGHT

Calibration

Determination of Index Point

Since each transducer is hand assembled, the index point of a transducer is an important characteristic to know in order to obtain accurate measurements of the ultrasonic sound path. There’re several ways to determine the index point of a transducer. The method that was used was using a V2/A4 calibration block made out of Al-7075 in accordance to BS 2704 with a 5mm diameter hole target.

Placing the transducer facing the 25mm radius surface, the echo from the reflected surface is maximized. The position on the transducer that aligns with the marking on the V2 block is marked. This position is the index point of the transducer. The transducer is then flipped to face the 50mm radius surface and the procedure is repeated for the other side of the transducer. Usually the index point of both sides will coincide, but it is also not uncommon for them to vary slightly. This phenomenon is generally known as squint. Figure 15 shows a graphical representation of how the index point on a US transducer is determined.
Determination of Beam Angle and Beam Spread

Another important characteristic to know of an angle beam ultrasonic transducer is the angle the sound travels in the material to be tested. The transducers that were used were GB SS 70° 4MHz. The SS stands for Shear Wave which is the mode of propagation of the sound wave. 70° is the nominal angle the sound travels in carbon steel and 4MHz is the center frequency of the transducer. In order to determine the most accurate angle the sound would travel in Al 6061, a calibration block was made using the same sheet of Aluminum that will be welded with a 5mm diameter side drilled hole (SDH) placed at half the thickness depth (3.17mm). Also, it is important to note that with thinner materials (i.e. < 2” thick) the rolled direction of the plates will significantly affect the angle of the sound path and thus the distance traveled and also the time of flight. Due to the alignment of the grains in the rolled direction, an ultrasonic sound wave travelling in the rolled direction will be refracted more than a wave that is travelling traverse to the rolled direction. Therefore, it is important to know which direction the material was rolled (it is usually easy enough to determine visually) and to make the calibration block in accordance to
the way the experiment will be set up. In this case, the plate will be welded in the rolled direction and the transducers will be placed in the traverse direction.

Placing the transducer facing the SDH and using the first leg of the beam, the signal reflected from the SDH was maximized and the surface distance from the index point to the SDH was recorded. Next the transducer was moved forward till the signal reflected was reduced by 20dB (90% drop) and again the surface distance was recorded. A 20dB drop in the signal is equivalent to the 10% edge of the sound beam. The transducer was then moved backwards until the signal passed its maximized position and was again reduced by 20dB. These steps were repeated for the second and third leg of the beam. Figure 16 shows a graphical representation of the steps taken to determine that beam angle and the beam spread of a US transducer.
Figure 16, Graphical representation for calibration of ultrasonic beam angle and beam spread using the 20dB drop method
From Appendix A, it can be seen that an ultrasonic shear wave that travels in steel at a 70° angle travels at an angle about 65° in Aluminum 6061. This is consistent with the result obtained if the angle was calculated using Snell’s Law by taking the speed of sound of shear waves in steel as 3200 m/s and the speed of sound in Aluminum 6061 as 3150 m/s and also taking into account the manufacturing error of the transducers.

Once the beam angle is determined, the surface distance needed to get a double skip pitch catch setup can be calculated by:

$$SD = nd \tan \alpha$$

Where SD is the surface distance, n is the number of legs of the ultrasonic beam, d is the plate thickness and α is the calibrated beam angle. The surface distance is then checked manually by maximizing the signal from the transmitting transducer to the receiving transducer at the calculated distance.

![Graphical representation of set up for temperature calibration](image)

**Figure 17, Graphical representation of set up for temperature calibration**
Temperature Calibration

Using part of the jig that will hold the transducers in place during welding, the transducers were placed on a small Aluminum coupon and two thermocouples were placed on either ends of the Aluminum coupon. The set up was then placed inside a gravity oven and the temperature was slowly increased till around 70°C. The oven was then left to cool down without any external forces. The time of flight of the ultrasound was taken intermittently as the temperature was rising and also as it was cooling down. The calibration set up can be seen in Figure 18. For consistency, the TOF was taken as the positive maximum point of the received signal (Appendix B).

It is interesting to note that despite the pulse-echo set up having a surface distance half of that of the pitch-catch set up, the beam path length (the distance the ultrasonic wave travels) is the same as that of the pitch-catch since the ultrasound has to travel to and back to the edge between the shoulder and the pin of the FSW tool. Hence the TOF for both set ups will be the same and only one set up was done for the temperature calibration. In the case of the pulse-echo set up, the reference TOF was taken by aiming the transducer to a 2mm milled notch reflector on the calibration block. Results from the calibration can be found in Appendix C.
Experimental

The material to be welded is Aluminum 6061 T6. It is a precipitation hardening aluminum alloy, containing magnesium and silicon as its major alloying elements. For simplicity and initial experimentation, only a process FSW will be done and monitored.

Each welding sample consisted of a piece of 10 in x 36 in x 0.25 in Al 6061 plate rigidly clamped to a steel anvil. See Figure 19 for the geometry of the weld. For each weld, the FSW tool was rotated in a clockwise direction. The FSW tool for this experiment was a tapered shoulder tool having a shoulder diameter of 1.0 in and a pin diameter of 0.26 in and a pin length of 0.18 in. A graphical representation of the tool used can be seen in Figure 18. The advantage of having a tapered shoulder tool is the ability to control the width of the weld as to not interfere with the US transducers placed behind the tool.

The material was prepped by cleaning the surface of any debris and scale by wiping it with an Acetone solution. Experiments were done in the Vanderbilt University Welding Automation Lab (VUWAL) to see if it was possible to measure the temperature of the weld during the FSW process and to compare the results with those using thermocouples and infrared thermometers. A total of four set ups were done for this experiment. The first being the pitch catch set up with the US transducers mounted in the jig behind the tool measuring the temperature of weld that was just made. The second and third being the pulse echo set up with a US transducer on the advancing and retreating side respectively. The fourth set up is a process weld with thermocouples placed close to the FSW tool at 1.5 in intervals on both the advancing and retreating sides of the weld as well as having an infrared thermometer taking the temperature of the weld right behind the tool.
Each sample weld was performed at 1000 RPM spindle speed and 5 IPM traverse rate with a penetration of 0.205 in below the surface of the top plate and a weld length of 3 in at $0^\circ$ tilt angle. These parameters were chosen from the fact Mishra (et al. 2005) reported that the maximum temperature increases with increasing tool rotation rate at a constant tool traverse speed and decreases with increasing traverse speed at a constant tool rotation rate. It was also reported that the maximum temperature during FSW increases with increasing the ratio of tool rotation rate/traverse speed hence a low rotation rate and high traverse speed was selected in order to obtain a lower temperature as a starting point. The weld process involves lowering the
rotating tool into the material at 0.10 inches per minute until the proper plunge depth is achieved. The tool then remains at that location for 5 sec, followed by the tool traversing through the material until it reaches the set weld length.

Before each weld, couplant was placed on the sample along the path the transducers would take and a reference TOF was taken for the initial temperature of the sample. During welding, couplant was constantly sprayed onto the sample to ensure there wouldn’t be any loss of coupling which in turn would result in a loss of the US signal. Due to the high temperatures that will be reached during FSW, the couplant chosen for this experiment was commercial motor oil. The use of commercial high temperature ultrasonic couplant was tested but the high temperatures caused the couplant to evaporate and smoke.
Result and Discussion

It was found that during the TOF and temperature calibration, the US pulse signal received decreased in intensity with an increase in temperature. The decrease was approximately 20dB/50°C or about 2dB (10%) every 5°C. This was compensated for by increasing the gain on the pulser/receiver. It was also noted that with the increase in temperature, the shape of the US pulse would change and at times it was harder to find a positive maximum. It is theorized that both of these are due to the PZT 5 losing its piezoelectric characteristics at temperatures higher than its recommended operating temperature.

During the experimental part of this study, it was found that the FSW machine’s motors, mainly the vertical motor and the spindle motor when it was driving the FSW tool caused significant interference to the US instrumentation system. The interference was magnified when the gain was increased to compensate for the increase in temperature as per the temperature calibration, leading to the saturation of the oscilloscope and a total loss of the US signal. It was also observed that the pitch catch set up was more forgiving when it came to the interference, but both set ups experienced a loss in the US signal even before the tool started traversing the weld (i.e. during the plunge routine) making it difficult to get any meaningful data.

It is thought that the interference is less due to the mechanical vibration of the FSW system and more to the electromagnetic interference of the motors. Attempts were made to isolate the US transducer electrically from the FSW machine by using nylon screws and washers and also not grounding the oscilloscope and pulser/receiver. There were improvements in the signal, but not enough for clear data acquisition.

A next step would be to electrically/magnetically shield the motors on the FSW machine by constructing a Faraday cage around it. It is possible that most of the interference would be
eliminated if not suppressed by doing so. Another step that could be done once the interference is suppressed is to apply post processing signal filtering to minimize the interference even more.

Additionally, replacing the transducer could also possibly solve the interference problem. Among the properties of a transducer that can be controlled and that may have an effect are:

1. Operating frequency
2. Active element – instead of using PZT 5, possibly changing to a transmitting transducer that uses Barium Titanate could improve the signal generation since Barium Titanate is known to be the best US emitter. Also switching to a receiving transducer that uses Lithium Sulphate may or may not improve signal reception since Lithium Sulphate is known to be the best US receiver, and it may pick up even more noise and interference. By changing the active element, it may be possible to operate the transducers at a lower gain setting and thus a reduction in the exposure to the interference.
3. Operating temperature - In addition, using a transducer that could withstand higher temperatures could reduce the amount of loss of piezoelectric characteristics.
4. Type – The use of non-contact electromagnetic acoustic transducer (EMAT) probes that are less susceptible to the high temperatures that would affect the piezoelectric crystal. Hence less gain would needed to be added to maintain the amplitude of the receive signal at a certain level. Using EMAT probes would also do away with the use for couplants and the problems that are associated with it.
CHAPTER IV

FUTURE WORK

Temperature Measurements in FSW Butt Weld, FSW Spot Weld and FSW Lap Welds

A continuation from this work would be to ultrasonically measure the temperatures in actual FSW Butt Welds, FSW Spot Welds and also FSW Lap Welds. The challenge in them would be in trying to overcome the limitations of the ultrasonic beam. In the joining of thin plates, it may not be possible for shear wave angle beam examination to be carried out. A possibility would be to use Surface waves or Plate waves propagating throughout the plates in exchange. In the case of FSW lap welding, the joint configuration could provide some complications on how the US beam would propagate. Possibly a variation of the set up proposed in this paper could allow for the examination of lap welds. In addition, instead of having a separate system to measure the temperature, having the temperature reading integrated into the current system would open up possibilities for temperature control research to be conducted.

Measurement of Stresses during FSW

It has been shown that ultrasonic waves can be used to measure the residual stresses in a material with great success (Santos 2000). It thus proposed that using similar set ups as those used in this paper, the stresses during welding can be measured. Comparisons can then be made to those of previous models such as the ones by Nunes et, al. (2001) and also to the torque measurements obtained from the FSW machine.
CHAPTER V

CONCLUSIONS

The results of the temperature calibration showed that there is a strong correlation between the change in the time of flight of the ultrasonic waves and that change in temperature of the sample. From the initial experimentation done, it can be said that the use of ultrasonic TOF to measure the temperature of welds during the process of FSW is a very promising method that could replace the use of more commonly used methods such as thermocouples and infrared pyrometry. The use of ultrasonic TOF also has the advantage of measuring temperatures of the weld without the need to drill holes and embedding foreign material into the sample which could affect the weld process and lead to inaccuracies. Also, the potential of using ultrasonic to measure the stresses during the process of FSW at desired areas make ultrasonic a system that could be integrated into current system and could possibly be used for temperature and stress control research.
REFERENCES


Appendix A, Angle beam and beam spread calibration results
Appendix B, Sample ultrasonic signal obtained

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Appendix C, TOF-Temperature Calibration results
Appendix D, 3D representation in Pro-E of the pitch catch set up used. A) Profile view B) Side view C) Plan view D) Front view
Appendix E, 3D representation in Pro-E of the pulse echo setup used. A) Profile view B) Side view C) Front view D) Plan view