

**ROLE OF FRICTION IN THE THERMAL DEVELOPMENT OF
ULTRASONICALLY CONSOLIDATED FOILS AND CONTINUOUS FIBER
REINFORCED METAL MATRIX COMPOSITE TAPE**

by

Stephen Koellhoffer

A thesis submitted to the Faculty of the University of Delaware in partial
fulfillment of the requirements for the degree of Master of Science in Mechanical
Engineering

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ABSTRACT

Ultrasonic consolidation (UC) is a low temperature bonding process which utilizes interfacial friction to promote bonding. Current research in the field of UC possesses a gap between theoretical predictions and actual processing temperatures; closing this gap allows for increased process control. This thesis seeks to develop and execute a model capable of predicting the thermal development during the UC of foils and continuous fiber reinforced metal matrix composite (MMC) tapes. To achieve this a thermal model has been developed that utilizes a frictional work flux term containing an experimentally determined, process dependent, friction coefficient, μ . Friction coefficients were found to vary between 0.1 and 0.8 depending on material pairing and process settings. When compared to infrared (IR) temperature measurements, a constant friction coefficient lead to model predictions of temperature accurate to 15% on average, whereas a process dependent friction coefficient had an average error of 7%. A process dependent friction coefficient provides more consistent results, and lower maximum errors (21% versus 52% for a constant μ), when a wide array of process settings may be employed. There are several applications for the model developed in this thesis such as targeting a specific temperature to allow thermally sensitive materials to be processed, or to retain a heat treated state, additionally, the simulated temperature profile could be used as an input to diffusion or mechanical models.

Chapter 1

INTRODUCTION

Ultrasonic metal welding (USMW) is not a new technology. In fact, it has been around since 1950 (Hazlett and Ambekar 1970). Initial applications included traditional metal seam and spot welds, dissimilar metal/non-metal bonding, and electronics wire bonding (Neppiras 1965). Presently there is an increased interest in the bonding of thin foils to form multi-layered metal and metal matrix composite (MMC) structures (White 2003). This particular application of USMW is referred to as ultrasonic consolidation (UC). With UC, layers of metallic films (foils or prepreg MMC tape) are built up on top of each other forming the desired shape; this is synonymous to the methodology used in automated tape placement (ATP) currently employed in the thermoplastic tape lamination industry in use by aerospace companies. Tierney and Gillespie (2006) investigated and modeled the in situ strength development of the thermoplastic ATP process. By building up thin successive layers and avoiding bulk heating, residual stresses from fabrication are reduced. In addition to the benefits shared with polymers, by keeping weld temperatures low, materials could be hardened and heat treated prior to processing. UC provides many advantages over traditional liquid processing methods typically employed in the manufacture of composites as discussed by Doumanidis and Gao (2004).

1.1 Ultrasonic Consolidation Process

Ultrasonic consolidation (UC) is a low temperature bonding process that can be used in the fabrication of metal and metal matrix composite (MMC) parts. The

low temperature nature of the processes is what makes UC attractive over liquid processing techniques. Weld temperatures are typically below 50% of the melt temperature and the dwell time at this temperature is very short (0.02 s to 0.72 s) allowing materials to retain much of their preprocessed crystallography. Upon inspection of the post weld interface there is often no indication of melting or recrystallization for low temperature welds; this has been observed by both Yang et al. (2009) and Clews (2009). However, Clews does state that microstructural changes could readily occur given the right combination of temperature and time. Such is likely the case for welds made by Mariani and Ghassemieh (2010). Mariani and Ghassemieh welded at speeds of 34.5 mm/s and high temperatures were predicted to be 50% to 80% of the melt temperature (330°C to 528°C). For these elevated temperature foil-foil welds some microstructural changes were visible as Mariani and Ghassemieh observed recrystallization in a thin layer (5 μm band) at the weld interface, between 100 μm foils, using electron backscatter diffraction. Largely retained crystallography and minimal residual stress buildups introduced by tape lamination may reduce or eliminate the need for costly post-processing heat treatments. Localized heating, versus bulk heating, also helps reduce processing costs by decreasing the amount of energy required during fabrication. Additionally, low temperature layered processing facilitates the use and placement of thermally sensitive materials (e.g. embedded sensors and fibers) that could be otherwise damaged or imprecisely placed using liquid processing. This has been demonstrated by various researchers. Cheng et al. (2007) successfully embedded nickel based thin film thermocouples into copper work pieces via UC. Siggard et al. (2006) consolidated USB-based sensors into aluminum. Kong et al. (2004b) embedded shape memory

alloy (SMA) fibers into aluminum to create adaptive structures for aerospace applications. After embedding SMA fibers, Kong and Soar built upon their previous work by using SiC (2005a) for structural applications and optical fibers (2005b) for data transport. With UC, it is also possible to weld a variety of dissimilar materials including: aluminum, brass, stainless steel, super alloys, SiC fiber, and MMC tape. Janaki Ram et al. (2007) were able to successfully consolidate many of these material combinations. Using optical and scanning electron microscopy bonds were qualitatively assessed for the presence voids. Janaki Ram et al. determined that the UC process is suitable for the fabrication of multi-material structures.

Figure 1.1 is a schematic of the key elements during UC of a tape bonded to a substrate.

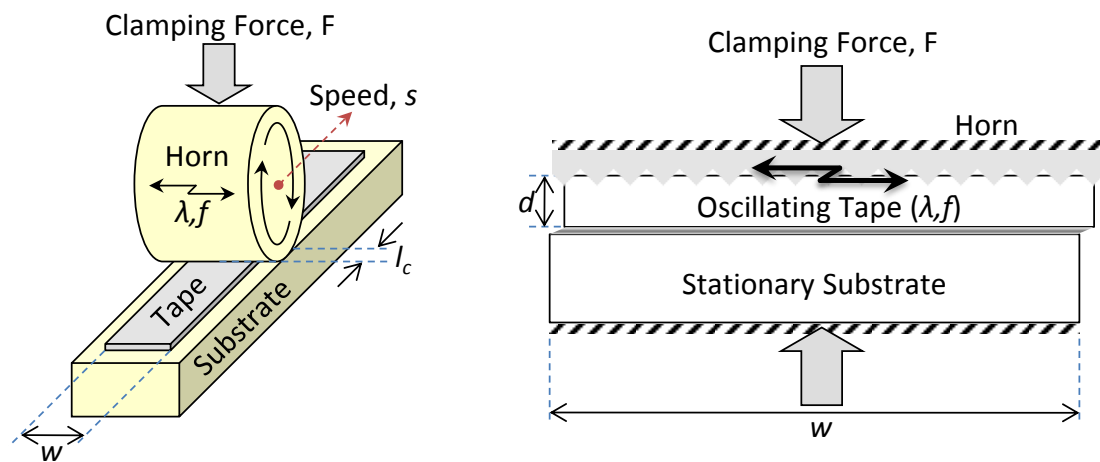


Figure 1.1 UC Schematic: left, isometric view of a tape being welded to a substrate; right, through-thickness cross section of tape and substrate. (Koellhoffer et al. 2011)

The cylindrical horn (also referred to as the sonotrode) applies a normal force, F , which brings the top tape in contact with the material to which it will be bonded. Sufficient force is required to ensure intimate contact at the interface. Processing time, t , is controlled by the contact length (the longitudinal distance over which force is applied), l_c , and linear weld speed (tangential speed at the horn's surface, determined via the horn's rotations per minute, RPM, and diameter, D), s . s and t are defined by equations 1.1 and 1.2.

$$s = \pi D \frac{RPM}{60} \quad \text{Eq. 1.1}$$

$$t = \frac{l_c}{s} \quad \text{Eq. 1.2}$$

The horn oscillates at a fixed frequency of 20 kHz, f , and peak-to-peak amplitude, λ . The number of oscillation cycles, N , a sample is subjected to for any given weld is determined by:

$$N = tf = \frac{fl_c}{s} \quad \text{Eq. 1.3}$$

The surface of the horn is knurled. This provides a firm grip between the horn and the upper surface of the tape thus preventing slip, and consequently aiding welding, at the tool-tape interface. Thereby relative motion occurs between the lower surface of the tape and the substrate surface resulting in frictional work. Friction causes abrasion of the contacting surfaces smoothing out irregularities, breakup and dispersion of surface oxides and asperities, and heat generation from dissipated frictional work; all of which promote bonding and welding. Additional details regarding the specifications of the welder used in this study as well as the materials processed will be given in chapter 3, **Equipment and Materials**.

The exact bonding mechanisms involved in UC are not well understood, characterized, or defined. It has been suggested that diffusion and plastic deformation aid in the bonding process as theorized by Neppiras (1965) and discussed by Hazlett and Ambekar (1970). Janaki Ram et al. (2007) attributed flow lines to plastic deformation which permitted the embedment of fibers during UC. Yang et al. (2009) has utilized various optical techniques (orientation imaging microscopy, OIM, and x-ray energy dispersive spectroscopy, EDS) that quantified the presence of plastic deformation and diffusion during UC. It is also known that the bonding mechanisms of ultrasonic welding are heat-assisted. Though not required, the application of additional heat (pre-heating) facilitates the welding process as reported by Neppiras (1965). Plastic deformation occurs from friction, the applied load, and thermal and acoustic softening. Acoustic softening is the reduction of the material's yield strength from vibratory loads. This can occur when a material is subjected to high frequency loads. Langenecker (1966) showed that the effects of ultrasonic exposure has much the same effect as elevated temperatures do on the yield strength through the comparison of stress vs. elongation plots at varying temperature and ultrasonic energy levels. In turn, this makes localized plastic deformation occur more readily which is required to bring mating surfaces together and fill the gaps between the mating surfaces. Gaps can be naturally occurring due to material variation or induced by embedding materials (e.g. fibers, sensors, etc.). While some material mixing may occur providing a mechanical bond from plastic flow, the experimentally measured concentration gradients obtained through EDS by Gunduz et al. (2005) and Mariani and Ghassemieh (2010) suggest diffusion occurs along the boundaries between materials producing superior atomic bonds. However, since surfaces must be in close

contact, the applied pressure and plastic deformation aid diffusion. The diffusion process is temperature dependent, as is yield strength, thus the processing temperature and contact time are important factors in the bonding process. The rate of diffusion relates to temperature exponentially according to the following Arrhenius equation (Askeland and Phulé 2003).

$$D = D_0 e^{-Q/RT} \quad \text{Eq. 1.4}$$

Where D is the diffusion coefficient representing the rate of diffusion, T is temperature, D_0 is the pre-exponential term equal to the rate of diffusion at very high temperatures ($\lim_{T \rightarrow \infty} D$), Q is the activation energy, and R is the gas constant.

Temperature increases are attributed to two sources: bulk plastic deformation, and interfacial friction. The latter being the focus of this thesis. It is assumed that slip occurs at the interface between materials being consolidated for the entire duration of the welding process, which promotes friction and deformation of material at the weld's interface. In this thesis, thermal contributions from deformation are neglected and only frictional contributions are accounted for in the development of the thermal model.

1.2 Friction

Friction is the resulting force that opposes motion between two contacting surfaces. Friction is a phenomenon present in virtually everything one does; be it in a constructive role or a destructive one. Friction necessitates the lubrication of moving parts that would otherwise wear, and provides the traction between people's feet and the ground. For ultrasonic welding friction provides heat and causes contacting surfaces to erode.

Authors, Bowden and Tabor (1950), published a book detailing theoretical and experimental studies in an effort to advance the understanding of the mechanics and mechanisms involved in the friction and lubrication of solids. Their book reports that the classical expression quantifying friction, equation 1.5, dates back as far as Leonardo da Vinci, but most credit it to the work of Amontons and Coulomb. The law states that the force of sliding friction, F_{fr} , is proportional to its normal force, F_N . The constant of proportionality, μ , is interchangeably referred to as the coefficient of friction or the friction coefficient.

$$F_{fr} = \mu F_N \quad \text{Eq. 1.5}$$

While very convenient for calculations, this expression comes with a deceptively complex caveat; to accurately determine F_{fr} , the friction coefficient must be known. The coefficient of friction is not a material property, but rather an empirical representation of all factors influencing friction. This is due to the fact that despite thousands of years of study, no unified model or theory has been able to account for all of the intricacies involved with contacting surfaces in relative motion (Blau 2009). While you may find tables with typical μ values or ranges in the back of a textbook, they are only valid for *typical* contact scenarios. In Blau's book, much effort is spent listing factors that can affect the frictional behavior. Some parameters affecting friction include: contact geometry (macro and micro), material pairing, and ambient conditions. Therefore, when comparing friction coefficient trends and magnitudes from one friction test to another, unless the test is an exact copy, at best, only qualitative comparisons can be drawn.

For this study, rather than focusing on everything that may influence friction, the parameters that are variable and controllable will be investigated.

Specifically, the influence of material pairing, surface condition and welder control parameters (oscillation amplitude, applied load, and sonotrode rotational speed) will be assessed.

1.2.1 Friction Coefficient Trends

1.2.1.1 Kinetic Factors

Naidu and Raman investigated, experimentally, the influence of several parameters on the coefficient of friction for the fretting fatigue behavior of aluminum alloy (AA) 6061-T6 (2005). Parameters investigated by Naidu and Raman (contact pressure, max cyclic stress, and number of cycles) can be related to the input parameters involved in welding (clamping force, F_N , oscillation amplitude, λ , and weld speed, s). In their test a uniaxial tensile specimen was loaded into a hydraulic tester. A ring was then placed around the gauge length of the specimen. The ring consisted of a cylindrical load cell and AA6061-T6 fretting pads with attached strain gauges. This setup enabled control and monitoring of the normal force, frictional force, applied cyclic load, and number of cycles.

Clamping/normal force, F_N , is proportionally related to the applied pressure through the contact area, $l_c w$, so any influence pressure may have on the friction coefficient will be evident through variations in F_N .

The number of cycles, N , can be related to both weld time, t , and weld speed, s . For UC the number of cycles equals the frequency times the weld time, and is inversely proportional to the linear weld speed. Naidu and Raman's experiment was load controlled, so for the sake of comparison the applied cyclic load will be thought of as its proportional counterpart, slip displacement, or amplitude.

Stress is proportional to strain ($\sigma = E\varepsilon$), and strain is proportional to the change in gauge length ($\varepsilon = \Delta L/L$). When a fretting pad is applied to the elongating bar, interfacial slip, λ , will also be proportional to ΔL . Therefore, the induced slip displacement is proportional to applied cyclic stress. Thus variations in the friction coefficient as a function of cyclic stress can be similarly related to changes in λ . This approach is taken by Siddiq and Ghassemieh's (2008) in their UC study to determine μ as a function of weld amplitude, λ .

In summary, the correlation between Naidu and Raman's testing and UC welder parameters is as follows: F_N is proportional to contact pressure, λ is proportional to cyclic stress, and s is inversely proportional to N .

The pertinent trends from the Naidu and Raman study are shown in figures 1.2, 1.3, and 1.4. Qualitatively these trends consist of: decreasing μ for increased clamping force, increasing μ for increased slip amplitudes, and for high speeds (short times, small N) initially increasing μ approaching a stable value at lower speeds (longer times, large N). The stable value is achieved between approximately 700 and 1100 cycles for the loads tested in the study (50 MPa to 200 MPa). The friction coefficients for the entire study fell between 0.1 and 1.3 (Naidu and Raman, 2005).

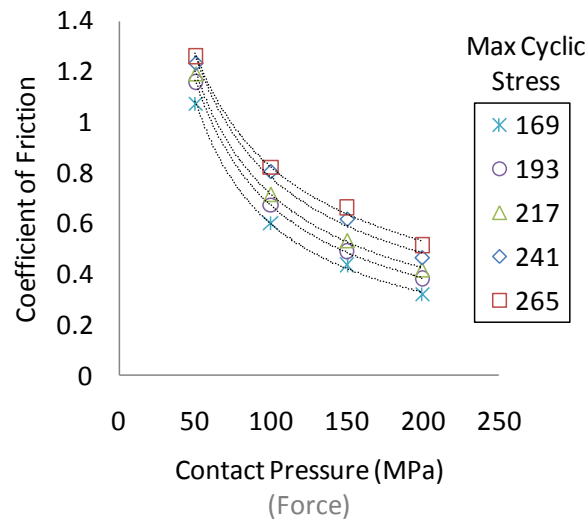


Figure 1.2 Friction coefficient vs. contact pressure during fretting fatigue testing (Naidu and Raman 2005). For UC force, not pressure, is specified, which is proportional to contact pressure.

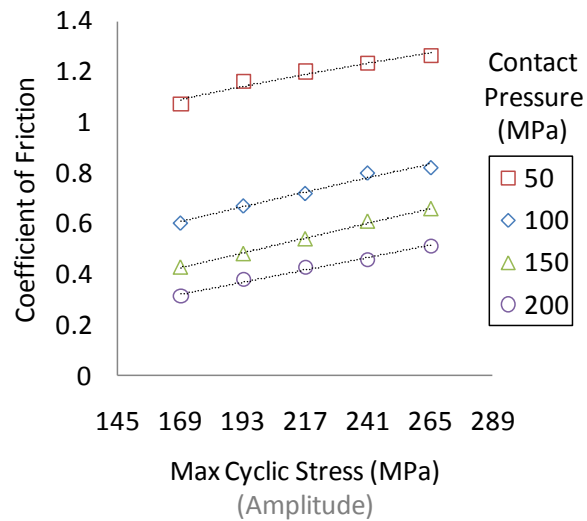


Figure 1.3 Friction coefficient vs. maximum applied cyclic stress during fretting fatigue testing (Naidu and Raman 2005). For UC amplitude, not stress, is specified, but stress is proportional to the induced slip amplitude.

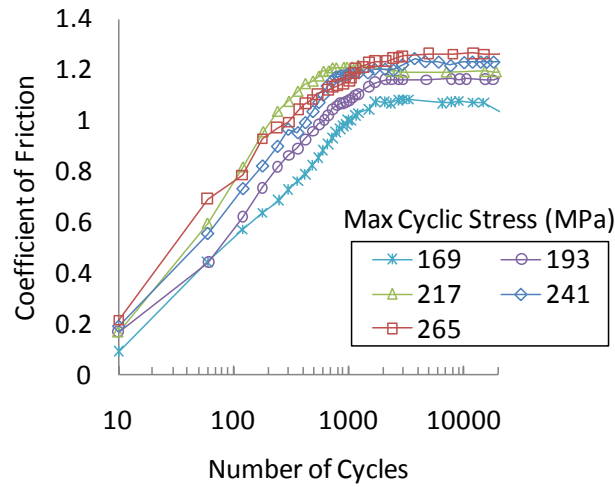


Figure 1.4 Friction coefficient vs. number of cycles during fretting fatigue testing (Naidu and Raman 2005). For UC the number of cycles equals the frequency times the weld time, and is inversely proportional to the linear weld speed.

As shown in figures 1.2, 1.3 and 1.4, the influence of λ , F , and s can be significant. As a result, a single valued constant friction coefficient, $\mu_{constant}$, may not be sufficiently accurate in predicting the heat generated during the process. Therefore, a coefficient of friction, μ_{RSM} , which depends on λ , F , and s , will also be investigated. This work will explore the dependence of μ on the welding machine set points and compare the error introduced due to use of a constant friction coefficient.

1.2.1.2 Thermal Influence

Temperature also influences the friction behavior between materials. In 2007, Zhang and Li submitted a conference paper detailing an earlier version of their numerical model of the UC process. Part of this work included investigating the influence of temperature on the sliding friction coefficient of self mated Al. In figure

1.5 the data from Zhang and Li's (2007) study on μ vs. T is presented for reference. For UC temperature is not a direct machine input, but rather an output parameter that will depend on the processing conditions, including: material properties, geometry, and welder processing parameter set points (F_N , s , and λ). Unlike Naidu and Raman's fretting fatigue test, UC is not isothermal. Therefore, care must be taken when assessing the influence of F_N , s , and λ on μ during UC.

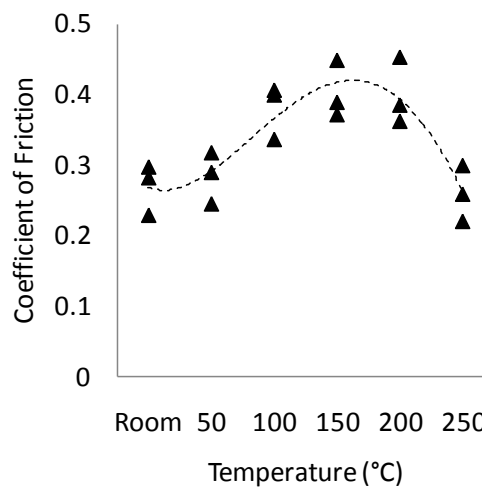


Figure 1.5 Friction coefficient vs. temperature during sliding (Zhang and Li 2007)

1.2.1.3 Material Factors

In addition to the parameters controlled by the welder, material pairing and variability are likely to cause deviations in the friction coefficient. The surface roughness of materials can differ from one batch to another, and even within a single batch. The friction coefficient's dependence on surface roughness can be seen in figure 1.6. Highest coefficients occur when surfaces are very smooth or very rough,

the former being due to large amounts of area in contact, and the later due to mechanical interlocking (Bhushan 1999).

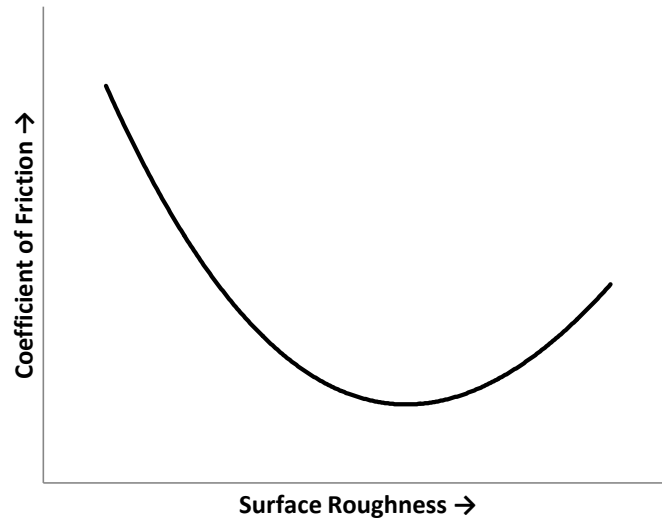


Figure 1.6 Qualitative representation of the dependence of the friction coefficient on the surface roughness of contacting surfaces (Bhushan 1999).

In addition to roughness, surface preparation techniques have been shown to affect the friction coefficient. Contamination, as small as one molecule thick, will greatly affect the amount of friction present (Bowden and Tabor 1950).

Uncontaminated, clean surfaces can exhibit much higher friction coefficients than surfaces with typical cleaning procedures. For aluminum, typical coefficients of friction may be around 0.5, while meticulously cleaned samples could reach values closer to 2.0 (Blau 2009). Rather than attempting to remove all sources of contamination (oils, gases, oxidation, foreign particles, etc.), consistency should be

employed in the preparation of samples. This will result in *typical* friction coefficients, which are ultimately more practical for engineering applications. By obtaining such values, equation 1.5 can then be used to model phenomenon such as thermal events.

1.2.2 Frictional Heating Models

The basis for frictional heating models is that the work done by friction is converted into heat. This is true for any nonconservative force. Some of the energy may be converted into other phenomena such as sound, but the majority becomes heat (Bowden and Tabor 1950). Once frictional work is determined, an energy balance can be performed to quantify the thermal development of contacting surfaces in relative motion. Such an approach has been applied theoretically to ultrasonic metal welding, and will be discussed in the next chapter.

1.3 Relevant Literature

Current research in ultrasonic consolidation of metals can be divided into several primary categories: process capabilities, mechanical modeling and testing, and thermal modeling and testing. The following subsections are to serve as a brief overview of the most significant and relevant studies related to ultrasonic consolidation presented in this thesis.

1.3.1 Process Capabilities

The versatility of an ultrasonic welder is dependent on its design. The largest difference between welders is the type. Two types are seam welders and spot welders. The applications are quite different for these two welders. The sonotrode on a seam welder consists of a rotating oscillating head that can be used for continuous

welding of thin materials. Spot welders on the other hand use an oscillating tip that does not rotate. This is useful for joining both thick materials and small electrical components, but not continuous welds. Therefore, for tape placement applications and continuous processing of foils and metal prepregs, an ultrasonic seam welder (figure 1.1) is ideal. Most of the investigations mentioned in section 1.1 involving the embedment of materials (metal, ceramic, and optical fibers, and sensors) and consolidation of dissimilar metals utilize this style of welder (Siggard et al. 2006, Kong et al. 2004b, Kong and Soar 2005a and 2005b, and Janaki Ram et al. 2007). Commercial rapid prototyping systems utilizing UC also commonly employ a rolling horn to continuously deliver energy to deposited layers of thin foils (White 2003). As such this is the welder type in use at the University of Delaware and in this thesis.

1.3.2 Thermal/Mechanical Modeling and Testing

Works done cooperatively by Gao (2002) and Doumanidis (2004) detail mechanical analyses of ultrasonic welding for rapid prototyping applications. The welder used in these works was a spot welder with a 4 mm x 4mm square tip. Cylindrical and square horns have differing stress distributions along the weld length. A flat tipped horn will have highest stresses at the edge, while a cylindrical horn will have lowest stresses at the edge (nip point) and highest stress in the middle (directly under the cylinder). When welding, another difference is that a cylindrical horn can roll allowing for continuous welding, whereas a square tipped horn cannot. The focus of Gao (2002) and Doumanidis' (2004) work was the strain and friction coefficient development during welding. In their work, the surface strain is experimentally measured adjacent to the horn. Using the measured strain, elastic modulus, and applied force, a time dependent friction coefficient was determined and used for

subsequent simulations. Their results indicated that the friction coefficient increases during weld formation.

Siddiq and Ghassemieh of Sheffield University have developed a comprehensive thermomechanical model (2008 and 2009). The model is a synthesis of existing models and theory from thermal, mechanical, tribological, and ultrasonic studies applied concurrently to UC. The mechanical side of the model incorporates strain hardening, acoustic (ultrasonic) and thermal softening. The thermal side uses frictional work as the heat input. The friction coefficient is allowed to depend on pressure, amplitude, number of cycles and temperature. Validation of the thermal model is achieved through comparisons to UC investigations of others (Cheng and Li 2007) and temperature measurements adjacent to the weld.

A significant body of mechanics based work has been developed by researchers at Loughborough University. Their research began as an experimental investigation determining the processing window and feasibility of UC of thin Al foils and through basic mechanical testing (Kong et al. 2003; 2004a). After which a basic weld strength equation was formulated based on the debonding peel force and real, as opposed to apparent, bonded area (Kong et al. 2005). Concurrently, the embedment of various fiber types, including shape memory alloy metallic fibers, SiC ceramic fibers, and optical communication fibers at low, $< 5\%$, fiber volume fraction was completed (Kong et al. 2004b; Kong and Soar 2005a, 2005b; Li and Soar 2009a). Recently, the group's focus has been surface topography of the horn (Li and Soar 2009b) and the bond interface (Friel et al. 2010).

The Ohio State dissertation by Edgar de Vries' investigates the shear forces and temperatures at the weld interface during the spot welding of medium and

thick (0.6 mm – 3.0 mm) aluminum sheets (2004). The thermal model developed uses both friction and deformation heat inputs. This was done by defining discrete heating zones: one for deformation, and one for friction. The deformation zone consists of a small circle comparable to the horn's tip diameter, while the friction zone is a concentric ring surrounding the deformation zone, with a radius approximately twice as large. The zone sizes depend only on material thickness as per the de Vries model. An IR camera was utilized to capture processing temperatures. However, only general statements regarding correlations between the model predictions and experimental measurements are made. Conclusions regarding deformation thermal contributors were that elastic contributions are negligible and deformation effects occur only within a thin interfacial layer.

When measuring processing temperatures generally two approaches have been taken; A few researchers have utilized infrared imaging analysis to determine processing temperatures (Koellhoffer et al. 2011 and de Vries 2004), while others have used thermocouples. Early ultrasonic welding studies used the thermocouple approach for temperature measurement (Hazlett and Ambekar 1970). This is not surprising as the first industrial use IR camera was not produced until 1968, and throughout the 1970s such cameras were prohibitively expensive and weighed over 50 lbs (FLIR 2004). There are advantages and disadvantages of both IR camera and thermocouple measurement methods, for additional details see sections 3.3.1 and 3.3.2. Researchers from the University of Wisconsin fabricated their own thin film thermocouples (TFTC) possessing significantly faster response times than conventional thermocouples (Zhang et al. 2006). Like traditional thermocouples the spatial resolution of a TFTC is dependent upon the probe/junction area. TFTC

junction areas fabricated for Zhang et al.'s paper varied from $(0.001'')^2$ to $(0.003'')^2$ and were determined to have significantly improved response times over typical TCs without appreciable sensitivity loss. In 2007 the group published two more papers which utilized TFTCs to measure the thermal response of metals ultrasonically welded. Cheng and Li (2007) located singular and paired TFTCs as small as $(0.0004'')^2$ adjacent to (0.008" to 0.020" away) the weld area. The paired sensors were used to measure heat flux. Rather than placing sensors close to the weld, Cheng et al. (2007) embedded the TFTC directly into the weld coupon allowing for direct measurement of the transient weld temperature profile. Max weld temperatures recorded with TFTCs varied between 140°C and 200°C. Direct sensor embedment (be it TCs, optical fibers, etc.) provides the opportunity to fabricate smart structures capable of sensing and even adapting based on thermal and structural loads.

1.4 Summary

Ultrasonic consolidation is a low temperature bonding process capable of creating multilayered and mixed material structures. The ultrasonic consolidation process uses a normal force to hold surfaces to be bonded in contact with each other and a transverse oscillatory load to generate slip at the bond interface resulting in interfacial friction forces. Friction breaks up surface oxides and asperities, generates heat, and promotes bonding. Primary candidates for bonding mechanisms are diffusion and plastic deformation; both of which are aided by interfacial friction forces that can generate heat and smooth abraded surfaces promoting grain refinement. Frictional forces are characterized by the coefficient of friction which is susceptible to variability based on process settings (pressure, amplitude, and time). The investigations of relevant studies were presented in this chapter. The next chapter in

this thesis serves to detail the development of two thermal UC process models which utilize the friction coefficient.

1.5 Thesis Objective

The aforementioned works are a good knowledge base for researching the field of ultrasonics. Of particular interest to this study is the predictive modeling of welding temperatures. While some work has been done in this arena there exists a substantial gap between theoretical model predictions and measured weld temperatures. The work performed in this study serves to close this gap. A theoretical model will be developed and through the experimental determination of model parameters the weld temperature will be predicted. The accuracy of the model predictions will be validated with experimentally measured temperatures. These steps will provide a much needed accurate and clear connection between the theoretical and the experimental thermal side of ultrasonic consolidation.

Chapter 2

MODEL DEVELOPMENT

In this chapter the details of the development of two different thermal models, a transient two-dimensional (2D) finite element model and a lumped parameter model (that assumes that the temperature gradients within the material are negligible and hence the temperature only changes with time), are explained. The assumptions and simplifications applied to the aforementioned models are described. Consequently, the effect of the assumptions and limitations imposed on the results are discussed. While, this chapter focuses on the development of thermal models characterizing the UC process, mechanical aspects are also investigated to aid in better understanding of the overall process mechanics.

2.1 Process Physics

Free body diagrams provide a graphical representation of the loads present on a given system, in this case mechanical and thermal. For simplicity thermal and mechanical loads will be analyzed separately. Understanding and possessing the ability to predict the behavior of thermal loads associated with UC can aid in the investigation of future research into coupled systems.

2.1.1 Sample Deflections, Deformations, and Stresses

The mechanical loads present include the combination of a static normal force, F ; cyclic transverse displacement, λ ($\lambda/2$ to the right + $\lambda/2$ to the left); and interfacial friction opposing the direction of motion, $F_{friction}$. Figure 2.1 illustrates

the presence of these loads on the upper foil (or tape), with thickness, d . The shear deflection and slip displacement resulting from the applied load and foil (or tape) properties are γ and λ_{slip} , respectively.

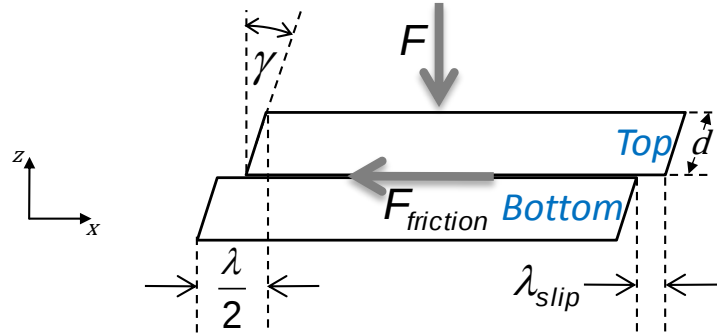


Figure 2.1 Diagram of mechanical loads acting on top foil, or tape, of thickness d , moving to the right. $\lambda/2$ is the applied amplitude in one direction. γ and λ_{slip} are the resulting deflection and displacement components, respectively, of the top foil or tape. Top and bottom foils, or tapes, are labeled for reference.

2.1.1.1 Normal Force

The normal force assists in several aspects of the UC process. Sufficient force is required to seat the knurled tool surface into the top foil and prevent slip at the tooling interface. Slip at the tool surface should be avoided so as to prevent material from welding to the sonotrode. Air gap closure leading to perfect contact between mating surfaces also relates to the applied normal force. This is particularly important for non-uniform surfaces. Without adequate clamping force, surfaces may only bond locally where contact points exist. The normal force will also affect the force of friction as indicated by equation 1.5.

2.1.1.2 Applied Displacement/Shear Load

Resolving the applied loads statically the shear stress, τ_{xy} , can be written as:

$$\tau_{xy} = \gamma G = \frac{F_{friction}}{wl_c} \quad \text{Eq. 2.1}$$

Where λ is the shear strain and G is the shear modulus. wl_c is the contact surface area and $F_{friction}$ is given by

$$F_{friction} = \mu F \quad \text{Eq. 2.2}$$

There is either slip or no-slip between samples. Figure 2.1 is indicative of a slip state. In general

$$\lambda_{applied} = \lambda_{slip} + \lambda_{def} = \frac{\lambda}{2} \quad \text{Eq. 2.3}$$

Where λ_{def} is the top foil or tape shear deflection (trigonometrically resolved as $\lambda_{def} = \gamma d$ for small γ). The shear strain of the top foil (see figure 2.1) is not necessarily equal to that of the bottom foil or the substrate. Clews' conclusions of increased softening of the upper foil due to higher levels of ultrasonic softening support the likelihood of varied strain levels based on proximity to the sonotrode (2009). A stiff or supported substrate would have a much smaller amount of deflection than the top foil, and is therefore assumed to be zero. Conversely, for foil-foil welds similar shear strains may be possible. Consider three possible conditions relating to the geometry of figure 2.1:

No-slip, $\lambda_{slip} = 0$; stiff bottom:	$\gamma \approx \lambda/2d$
No-slip, $\lambda_{slip} = 0$; similar bottom:	$\gamma \approx \lambda/4d$
Slip:	$\gamma = \frac{\mu F}{Gwl_c} \rightarrow \lambda_{def} \approx \frac{d\mu F}{Gwl_c} \ll \lambda$

A stiff bottom could consist of a hardened steel bottom foil, with an aluminum upper foil. A similar bottom would correspond to a scenario where the top and bottom (see figure 2.1) foil or tape are the same materials.

The data in table 2.1 will be used for calculations correlating to a “typical weld.” This data is based on results and observations discussed in subsequent sections of this thesis. The method for determination of contact length, l_c , is detailed in section 4.3, and values for the friction coefficient, μ , are determined in section 4.5.

Table 2.1 Typical weld set points and properties

w (mm)	l_c (mm)	d (mm)	λ (μm)	F (N)	G (GPa)	μ
12.7	2.55	0.1	24	1739	26	0.4

For a no slip foil-foil weld the shear strain is taken as $\lambda/4d$. Using the values from table 2.1, and assuming linear elastic properties (Eq 2.1), this results in a shear stress of 1600 MPa. For pure slip, using equations 2.1 and 2.2, and table 2.1, the shear stress is 21 MPa. Therefore, it requires much less force to cause slip than resist it. However, even during *pure slip*, there will be some deflection. The shear deflection during slip, λ_{def} , is $(d\mu F)/(Gwl_c)$, or 0.08 μm , which is more than 2 orders of magnitude less than the applied amplitude. Therefore, only friction will be accounted for, without the inclusion of deformational phenomena, for modeling purposes in this thesis.

2.1.1.3 Horn Surface and Knurl Penetration

The horn must grip the sample without slipping during consolidation. This is achieved through a knurled or textured surface. A smoother tool surface will

likely decrease the occurrence of fiber damage, and may make subsequent easier due to a smoother post weld tape surface as compared to the resulting tape surface from coarse knurled tooling. However, if the sonotrode is not sufficiently rough, slip may occur at the tool-sample interface increasing the likelihood of tool sticking.

2.1.1.3.1 Brazing

Applying a braze layer may reduce the amount of potential fiber damage caused by the knurl on prepreg tapes. It may also facilitate consolidation by providing a more compliant surface. It is not known or clear as to how it will affect the strength of the weld and the bulk material. Brazed materials are not included in the scope of this work.

2.2 Sonotrode Oscillation Speed

The oscillatory speed is dependent on frequency, amplitude, and time. Modeling the oscillatory motion, A , as a sinusoidal wave (figure 2.2) results in equation 2.4. Peak amplitude has been defined as $\lambda/2$ so that the peak-to-peak (min-to-max) displacement is λ .

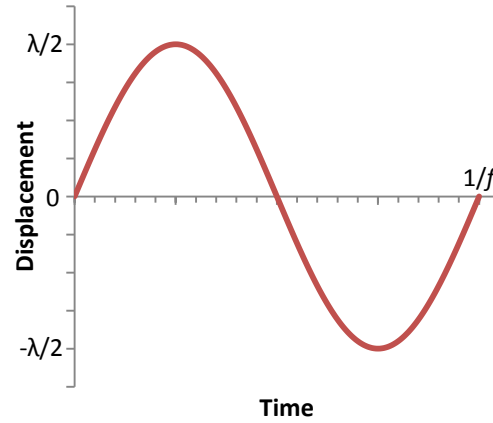


Figure 2.2 Oscillatory motion over one period

$$A = \frac{\lambda}{2} \sin 2\pi f t \quad \text{Eq. 2.4}$$

Differentiating A with respect to time, t , yields the velocity:

$$v = \pi f \lambda \cos 2\pi f t \quad \text{Eq. 2.5}$$

A time dependent velocity would substantially increase the analytic and numerical solution difficulty of any transient model involving speed. Considering typical welds are done at 20 kHz, measuring intra-period phenomena variations would require equipment with response times well under the 0.00005 second oscillation period. Due to the inability of readily available equipment to measure intra-period variations and the added computational complexity for modeling such phenomenon, average oscillation speed should be used. Since friction is a nonconservative force speed (not velocity) is appropriate. This would not apply to conservative forces, thus care should be taken when using velocity vs. speed for the determination of work done by a force

The average oscillatory speed is the average magnitude of the velocity. This is determined by integrating the absolute value of velocity over one period and multiplying it by the frequency. The resulting expression is:

$$\bar{v} = \left| \frac{d\Lambda}{dt} \right| = 2 \lambda f \quad \text{Eq. 2.6}$$

2.3 Heat Generation due to Deformation Work

Thermal contributions from deformation are negligible for several reasons; though, this is not immediately obvious. To assess the amount of heat generated by deformation the amount of plastic work needs to be determined. Plastic work per unit volume can be described by the product of the yield stress and the change in plastic strain developed. If the entire sample flowed plastically without slipping, and all plastic work was dissipated as heat, this could produce approximately five times the energy of the frictional contribution presented in this paper (see section 2.4 for heat generation flux derivation), assuming normal room temperature properties. However, numerous factors limit and diminish the ability for deformation to contribute significantly to the thermal development during UC of foils and tapes. Small temperature gradients through the material's thickness will cause a gradient of the yield stress. The weld's interface temperature will be the highest (either from localized plastic deformation and/or friction). Areas of highest temperature will have the lowest yield strength. By accounting for a small amount of thermal variation it is expected that only material near the interface will yield plastically. This has been confirmed experimentally. The entire bulk material does not flow plastically.

In a technical report promoting UC, White (2003) stated that plastic flow is confined to a thin interfacial layer 10 to 20 μm thick, which is at most 10% of the

sample's thickness. Their claim was based on grain boundary mapping of the cross section of a consolidated sample by means of electron backscatter diffraction analysis by Mariani and Ghassemieh (2010) in their microstructural investigation of ultrasonically consolidated aluminum foils. For the case of MMC tape in this study only the matrix will accumulate plastic strain as the brittle ceramic fiber reinforcement would break if yielded plastically. Thus the volume of material behaving plastically is further reduced via the fiber volume fraction. Inside the plastic zone, only 33% of the plastic work is expected to be converted into heat for UC aluminum (for non-UC plastic deformation typically 90% conversion is assumed). The remaining energy is stored in the material's microstructure.

This assumption is also used in Zhang and Li's (2009) dynamic thermal-mechanical model of the first 0.0025 seconds of an ultrasonic weld and is based upon the work by Hodowany (1997) and Ravichandran et al. (2002). Hodowany (1997) and Ravichandran et al. (2002) carried out experiments measuring the percentage of work dissipated as heat as a function of the plastic strain developed. As a consequence of the aforementioned factors present in UC the potential contribution of deformation is reduced from 458% of the frictional contribution to 6%.

Further reduction of the deformational heat contribution results from the decrease in material strength. As stated in Hibbeler's (2002) textbook, using a perfectly plastic material model, the stress level performing work will be limited by the materials yield strength. The experimental results shown in Langenecker's (1966) tensile testing indicated both elevated temperatures and the presence of ultrasonic energy significantly decreases the yield strength of Aluminum. For UC conditions similar to this study, the reduction in yield stress from mild heating (100°C) and

typical ultrasonic softening ($20,000 \text{ W/m}^2$) is on the order of 80% as indicated by Siddiq and Ghassemieh (2009) in their theoretical analysis investigating the thermal and acoustic softening exhibited during UC. Consequently, deformational contributions are reduced to approximately 1% (for MMC tape) of the frictional contribution using this simplified calculation. For 6061-T6 foils this increases to 7%, and for 3003-H18 it is 4% of the frictional contributions.

In 2009, Zhang and Li proposed a more detailed theoretical dynamic FEA simulation of the UC process which also supports the conclusion that deformational energy is negligible; after the 20th oscillatory cycle (0.001 s) the plastic heat generation rate saturated and contributed to only 0.3% (for 3003-H18, $\sigma_y=186 \text{ MPa}$) of any additional heat accumulated at the weld's interface. The back of the envelope calculation performed in this section assumes uniform stress across the width (vs. three dimensional) and does not allow slip; consequently, it is a very conservative, upper limit, approach to approximating the potential contribution of heat generated due to plastic deformation relative to frictional heating.

Since deformation is a negligible thermal contributor, the objective of this work is to explore the role of friction in increasing the interface temperature and its dependence on the machine variables such as speed, amplitude and applied force. The following sections will propose a model to relate temperature through energy balance to the friction coefficient. The value of the friction coefficient will be determined by conducting experiments under various speeds, applied forces and amplitudes on an ultrasonic welder and by matching the experimental temperatures measured with an IR camera with model predictions. Some of the challenges in this characterization technique will be outlined.

2.4 Heat Generation due to Frictional Work

Friction is a nonconservative force. Assuming all work done by friction is uniformly dissipated as heat, over the contact area, forms the basis of the friction model. This is a simplification of the parabolic pressure distribution (from the starting nip point, to centered under the horn, to the trailing nip point) being applied to the flat sample by the cylindrical horn. This simplification allows length-wise variations to be averaged. The rate at which work is done (i.e. power) is the product of the force of friction and the average oscillatory speed, $\bar{v}$. Dividing the friction power by the contact area, $w \cdot l_c$, defines the frictional heat flux. This frictional flux can be written as:

$$q''_{fr} = \frac{F_f \bar{v}}{w l_c} \quad \text{Eq. 2.7}$$

By combining equations 1.5, 2.6, and 2.7, with $F_N = F$, the horn applied clamping force, the frictional heat generation flux can be written as:

$$q''_{fr} = \frac{\mu F 2 \lambda f}{w l_c} \quad \text{Eq. 2.8}$$

2.5 Thermal Model

Two different models for predicting the processing temperature during UC will be employed in this work. Both utilize the same heat flux term based on frictional work as expressed by equation 2.8. However, the first model is analytic and spatially invariant, the other is a numerical finite element transient two-dimensional model. While the FE solution is more detailed and can account for spatial variations, it requires more time to obtain results than the analytical solution. Therefore, if sample properties allow (e.g. low Biot's number; high internal conduction, low convective

loss, h , and small sample size, l), the analytic approach may be more appealing in an environment where FEA software is not easily available.

2.5.1 Model Implementation

The energy balance applied to the region of interest will allow one to solve for the temperature field as a function of time and position. The friction is generated at the interface so it can be introduced as a flux boundary condition. Before we embark on solving the three dimensional time dependent problem, it may be worthwhile to check if one can simplify the problem to just time dependent by evaluating the Biot number. When the Biot number is much less than one, there is usually not much of temperature gradient in the domain of interest and one can use lumped parameter analysis and solve analytically for the temperature as a function of time. In Incropera and DeWitt's (2001) introductory heat transfer textbook the Biot number is defined as:

$$Bi = \frac{hl}{k} \quad \text{Eq. 2.9}$$

The Biot number is the ratio of convective losses to internal conduction. When materials are thin (small l) or highly conductive (large k), the internal temperature variation is small. Thus, for $Bi < 0.1$ (thermally thin) Incropera and DeWitt (2001) state that a material's internal temperature can usually be assumed to be spatially invariant making analytic temperature solutions possible. Conversely, thick samples with low conductivity and large convective losses will have spatially variant temperatures (thermally thick), which in turn are more involved to solve analytically. The Biot number is 0.07 for our welded foils and 0.13 for our MMC tape welded to an Al substrate. Both tape and foils have low Biot's numbers, but since foils and tapes

have high aspect numbers (i.e. the ratio of cross sectional length to thickness), the amount of thermal variation in both the thru thickness direction and across the width at the weld interface should be investigated. Using the finite element analysis approach detailed later, the following plots were generated illustrating the amount of temperature variation for a typical weld through the tape's/foils' thickness at the midplane, figure 2.3a, and across the width (from the sample's edge to the midplane) at the weld interface, figure 2.3b. The average interfacial temperature for the tape and foils is the same, 102 °C.

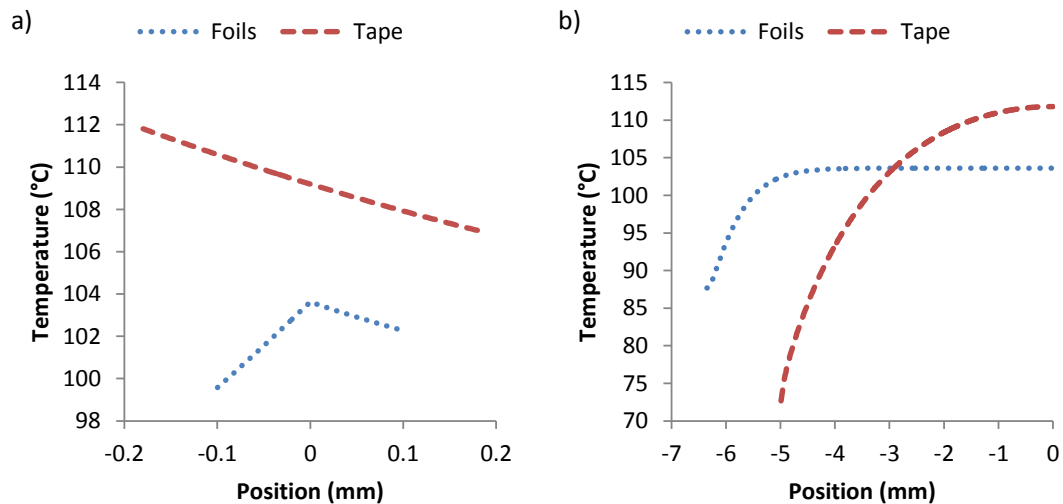


Figure 2.3 FE results for temperature variation for a typical weld: a) through the tape's/foils' thickness at the midplane, b) across the width (from the sample's edge to the midplane) at the weld interface. Note scale differences for temperature and position for each plot. (Koellhoffer et al. 2011)

In the thickness direction both foils and tapes show little variation in temperature. The coefficient of variation (CV) is 1% for foils and MMC tapes.

Hence, temperatures across the foil or tape surface will be representative of temperatures along the weld interface. Refer to Appendix C for a quantitative comparison of simulated surface and interfacial temperatures which the experimentally measured surface temperatures.

While temperature variation through the thickness is small, across the width larger variations are observed. The CV across the width is 3% for foils and 10% for tape. Therefore, the foils used in this study will be considered thermally thin, whereas the MMC tapes are thermally thick. Thus, the solution approach will differ depending on the materials being consolidated. Foil temperatures will be solved using lumped parameter analysis, while tape temperatures will be predicted with a commercial FEA software package, COMSOL Multiphysics (2008).

2.5.2 Analytic Solution – Lumped Parameter Analysis (LPA)

Since the temperature of welded foils does not vary spatially, temperature in the foil changes only with time. The first step is to perform an energy balance over the control volume of interest, the foil contact area and thickness. Any energy put into the control volume that is not dissipated into the surroundings is stored as described by equation 2.10.

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{stored} = \rho C_p V \frac{dT}{dt} \quad \text{Eq. 2.10}$$

Figure 2.4 illustrates the control volume for two identical foils being welded together. Thermal losses into the air, horn, and supporting anvil (flat knurled surface that secures the lower foil preventing slip during UC) are noted with outward arrows. The center shaded area represents the friction heat flux, q''_{fr} , which is the heat input into the control volume.

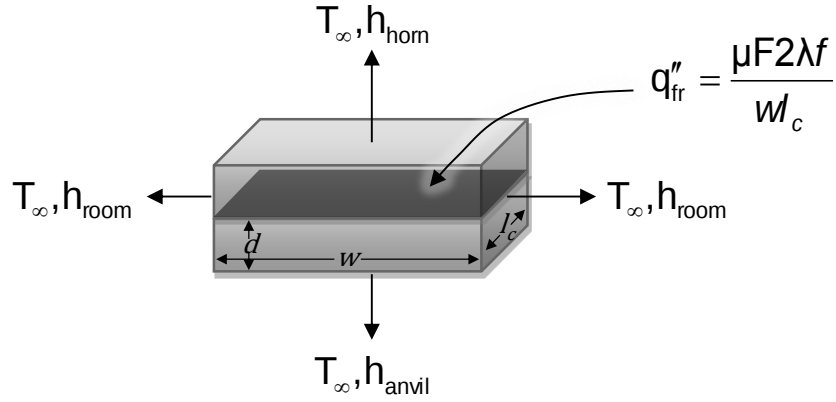


Figure 2.4 Foil-Foil control volume and thermal boundary conditions.
(Koellhoffer et al. 2011)

Using equation 2.10 in conjunction with the thermal loads from figure 2.4 the following equation is obtained:

$$\rho C_p V \frac{dT}{dt} = \dot{E}_{in} - \dot{E}_{out} = q''_{fr} \cdot w l_c - (h_{room} 4 d l_c + h_{horn} w l_c + h_{anvil} w l_c)(T - T_{\infty}) \quad \text{Eq. 2.11}$$

By assuming μ and the convection coefficients are independent of temperature and time, equation 2.11, which is a first order ODE, can be integrated to yield

$$T = T_{\infty} + \frac{\mu F 2 \lambda f}{H} \left(1 - e^{-\frac{H}{\rho C_p V} t} \right) \quad \text{Eq. 2.12}$$

Here the volume, V ; time, t ; and equivalent convective losses, H ; are given by:

$$V = 2 d w l_c \quad \text{Eq. 2.13}$$

$$t = \frac{l_c}{s} \quad \text{Eq. 2.14}$$

$$H = (h_{room} 4 d l_c + h_{horn} w l_c + h_{anvil} w l_c) \quad \text{Eq. 2.15}$$

respectively.

While losses to air, h_{room} , can be prescribed based on typical metal-to-still air values, h_{horn} and h_{anvil} cannot be predetermined. Thus, H is found

empirically through inverse modeling using a two-dimensional FEA model and equation 2.17. This allows conductive losses to be effectively converted into a convective loss term. The resulting values for H are between $3.2 \frac{W}{K}$ and $3.9 \frac{W}{K}$ depending on the total weld time. Details for determining H will be shown in section 2.5.4. Since convective coefficients were assumed to be independent of time during integration, solutions from equation 2.12 at times other than $t = l_c/s$ will be slightly off. For the purpose of this study this is inconsequential since the temperature at the end of the weld is what will be predicted and measured.

2.5.3 Numerical Solution - Finite Element Analysis

An FEA analysis does not provide the level of insight of an analytic solution, but fewer assumptions are required, complicated geometries can be modeled, and graphical representations of results can be easily obtained. It will be the only approach applied to the MMC tape as the Biot's number is larger than 0.1 and it was shown that there is spatial variation in the temperature field, (figure 2.3b). Figures 2.5, 2.6, and 2.7 are three variations of through-thickness two-dimensional UC FEA models. For all models, mesh refinement was performed to assure proper convergence. All weld energy is applied at the interface between materials being bonded via the frictional heat generation flux, q''_{fr} (see equation 2.8).

Figure 2.5 is the largest model dimensionally. There are five objects present in this model. From top to bottom these include: the lower half of the horn, the tape (barely visible), the substrate, and two steel riser blocks. This large scale model provides a good visual of the actual welder geometry, but many of the model elements are very far from the weld interface and do not heat up over the duration of a weld. This excessively large model results in wasted computational resources. The

reduced scale half-symmetry improves upon the large scale model by taking advantage of symmetry conditions and by only modeling a region in close proximity to the weld. The boundaries of the model that were cut from the large scale are indicated by the long dashed lines marked T_∞ . The heat flux near the T_∞ boundaries is zero, therefore the solution within the domain of the reduced scale model is unaffected by the abridged geometry.

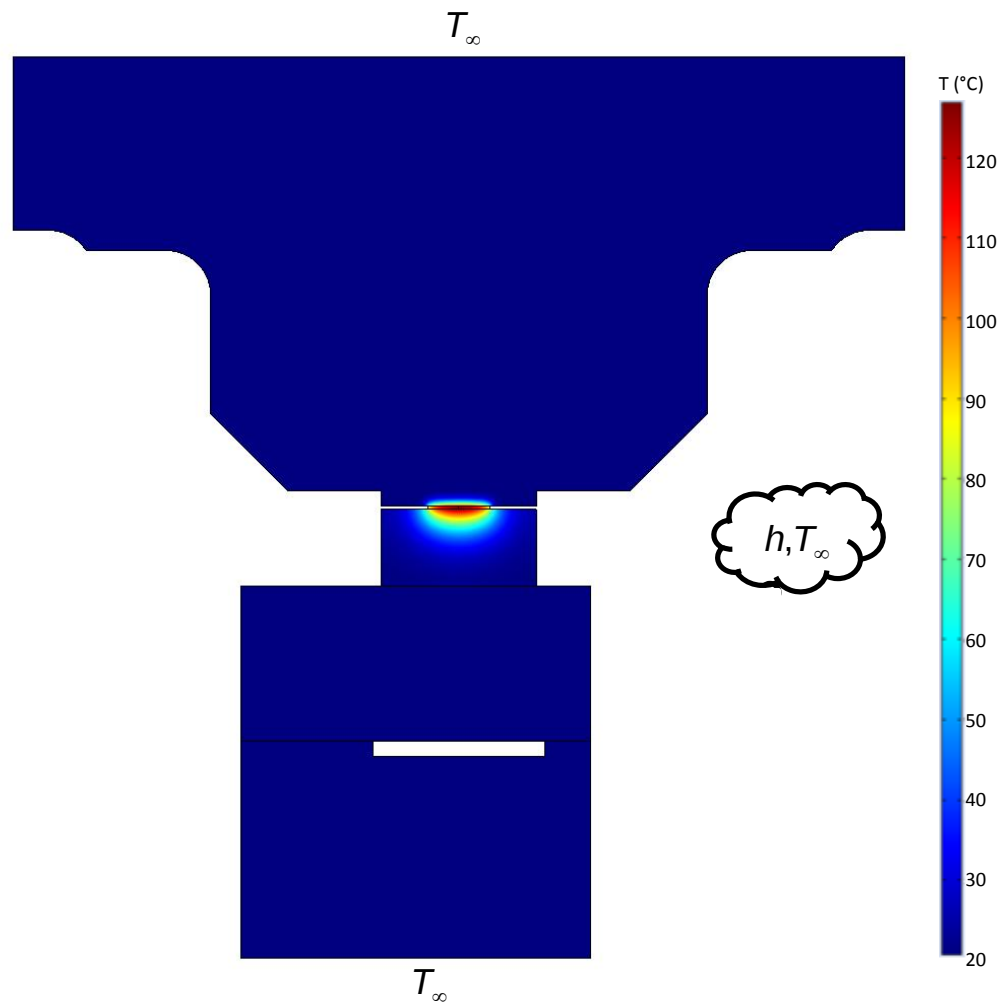


Figure 2.5 Large scale FEA model for typical tape-substrate weld

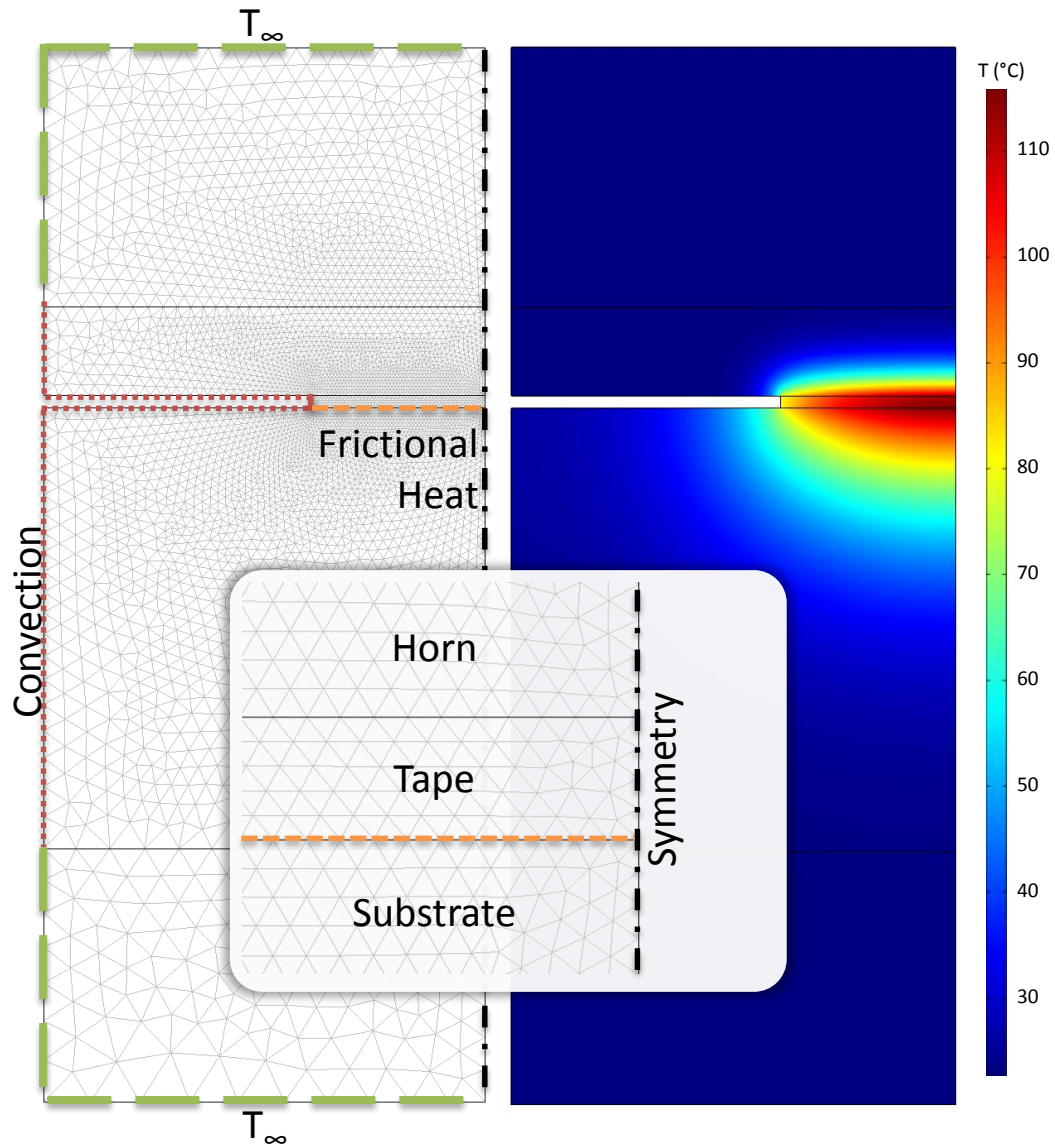


Figure 2.6 Reduced scale half-symmetry FEA model for typical tape-substrate weld with close up view of horn-tape-substrate interfaces. Left image shows mesh and boundary conditions. Right image shows typical temperature distribution.

Figure 2.7 shows the through-thickness two-dimensional FEA model for a foil-foil weld. The substrate and risers are replaced with the lower foil and an anvil.

While the LPA foil model provides a lot of information regarding weld development, a two-dimensional model is needed to determine the convective loss model parameter, H . Otherwise the tape-substrate and foil-foil models are the same. The initial temperature is taken as ambient temperature, T_{∞} . Due to the confined space between the horn and substrate/anvil a low convective loss was assumed, $h = 5 \frac{W}{m^2K}$, and applied on the boundaries exposed to air. With any of the abovementioned models one can solve for temperature as a function of time in the entire domain.

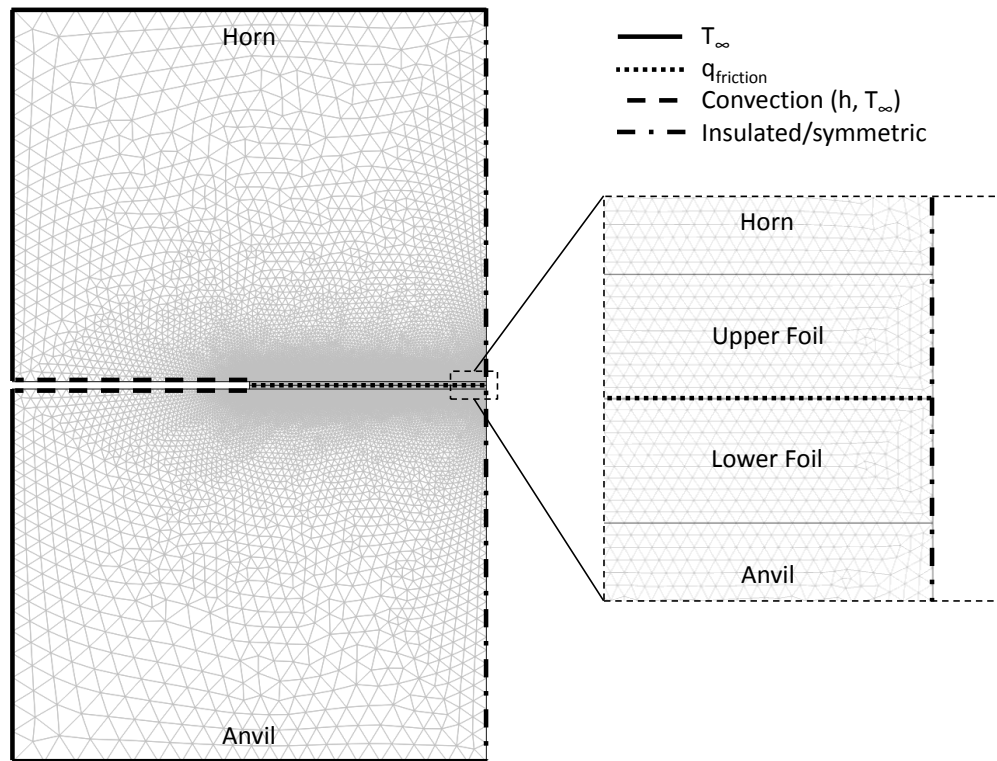


Figure 2.7 FEA half-symmetry foil-foil model. (Koellhoffer et al. 2011)

2.5.3.1 Uniform Heating

The majority of welds that will be investigated heat uniformly; that is q''_{fr} is constant across the weld interface. However, uniformly applied heat should not be expected to produce a uniform temperature profile across the width of a sample. The tool surfaces (horn, anvil, and substrate) are wider than the sample to be welded; therefore conductive losses into the tool surfaces will be larger towards the edge of a sample due to the increased thermal mass (sink). This will result in lower temperatures at the edge of a sample. Convective losses to air will also enhance this phenomenon. Equating conductive and convective losses near an exposed interface for aluminum, at $100\text{ }^{\circ}\text{C}$ in a $20\text{ }^{\circ}\text{C}$ room with a convection coefficient of $5\text{ W/m}^2\text{K}$, results in a temperature gradient of only $2\text{ }^{\circ}\text{C/m}$. The temperature gradients in the width direction near the sample edge shown in figure 2.3b are much larger than this (on the order of $10^3\text{ }^{\circ}\text{C/m}$). This would indicate conduction losses into the tooling are the primary reason for variations in the temperature profile. However, it is also possible for heat flux to be non-uniform due to imperfect contact between the mating surfaces.

2.5.3.2 Non-Uniform Heating

If the material being consolidated is not flat and sufficient force is not applied to permit gap closure at the weld interface thermal development will occur non-uniformly. To model such a condition one must know statistically how the processing pressure or temperature field varies, or model the welding process thermo-mechanically taking into account the initial samples geometry and temperature dependent elastic properties. Without interfacial gap closure between the mating surfaces bond strength cannot be maximized, therefore for optimal bond strength

processing conditions should be picked to achieve closure of the gaps. If material and/or processing condition limitations make uniform heating unfeasible, equation 2.8 can be applied non-uniformly. See Appendix A for details regarding the application of a non-uniform frictional heat generation flux.

2.5.3.2.1 Pressure Distribution

The pressure distribution between materials can be obtained using pressure sensitive film. This is most easily done without the presence of ultrasonic energy so the pressure film is not destroyed. By processing the samples without an applied transverse load the pressure profile generated could then be used directly in the applied heat flux equation. However, the pressure film will not accurately represent the contact mechanics since the addition of ultrasonics will change the surface profile through abrasion as well as the mechanical response through the addition of thermal and acoustic softening (Langenecker 1966). Consequently, this approach would have only limited success.

2.5.3.2.2 Initial Geometry

Using the geometry of a sample as a model input can be obtained through microscopy. Optical techniques that look directly at portions of a samples cross section are destructive since they require cutting the sample. Thus are only applicable if the cross section does not vary, or varies predictably. Alternatively, measuring surface topography could be used to quantify a sample's geometric profile nondestructively. Modern scanning white-light interferometers (SWLI) are capable of large fields of view (up to 14 mm) and could perform such a task. Monitoring the

topography in situ could also be used in a feedback control loop to continuously vary machine processing parameters to account for material variability.

2.5.4 Convective Loss Term Determination

The LPA solution assumes convective losses at the anvil and sonotrode interfaces. In reality it is a conductive loss from tooling contact. In order to accurately convert heat losses to the tooling into a simple convection coefficient an FEA model of the foils will be employed.

The heat flux terms for conduction and convection are as follows:

$$q''_{conduction} = k \frac{dT}{dy} \quad \text{Eq. 2.16}$$

$$q''_{convection} = h(T - T_{\infty}) \quad \text{Eq. 2.17}$$

By setting equation 2.16 equal to equation 2.17 the local convection coefficient, h , accounting for conductive losses can be determined, equation 2.18.

$$h = \frac{dT}{dy} \frac{k}{(T - T_{\infty})} \quad \text{Eq. 2.18}$$

Using the FEA model to solve for the temperature field h can be determined for any combination of welder parameters at any time. Figure 2.8 shows the variation of h at both the sonotrode and anvil interfaces as a function of time for two different combinations of welder parameters. From figure 2.8 it is clear that the only process parameter that affects h is time.

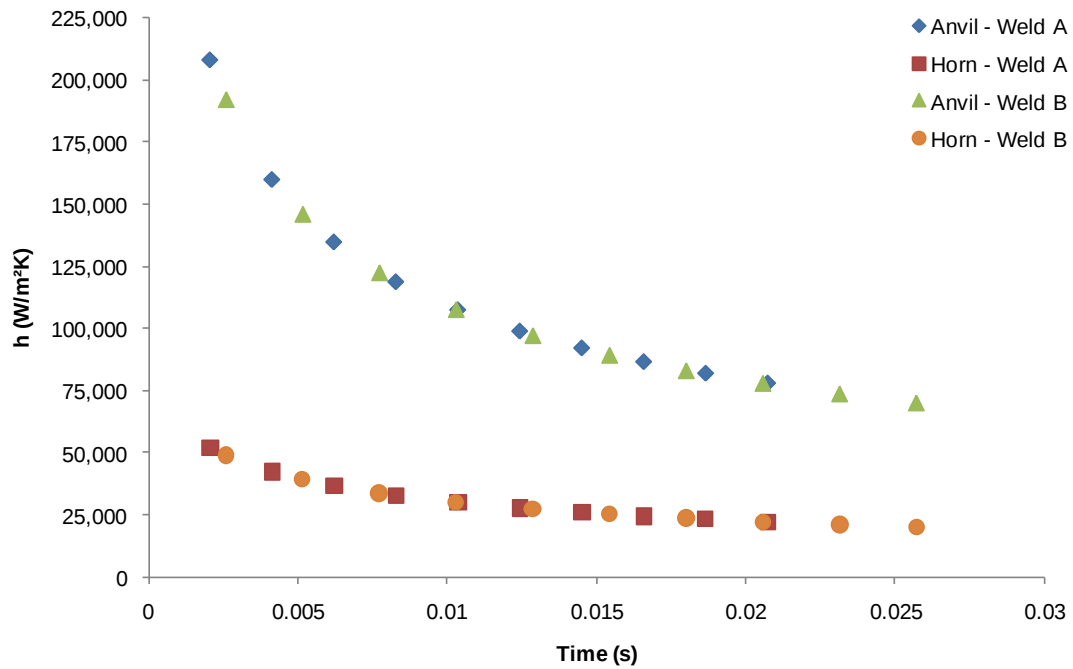


Figure 2.8 Effective heat transfer coefficient vs. time

When deriving the LPA solution in section 2.5.2 it was assumed H , the global convective loss term, was not a function of time, however, this is not the case. To account for this simplification the LPA temperature, T , in equation 2.12 is set equal to the foil's temperature solved for via the FEA model. By using the same combination of welder parameters in the LPA and FEA models H can be solved for as a function of its only dependent variable, total weld time. Thus, when performing experiments at a finite number of weld times determining H for each weld time provides one with a fast way to determine the final processing temperature without the need to run an FEA simulation every time the force or amplitude is adjusted.

Using the aforementioned method of determining H, figure 2.9 illustrates the variation in H as a function of the weld time over the range of processing times used in this study to consolidate foil-foil welds.

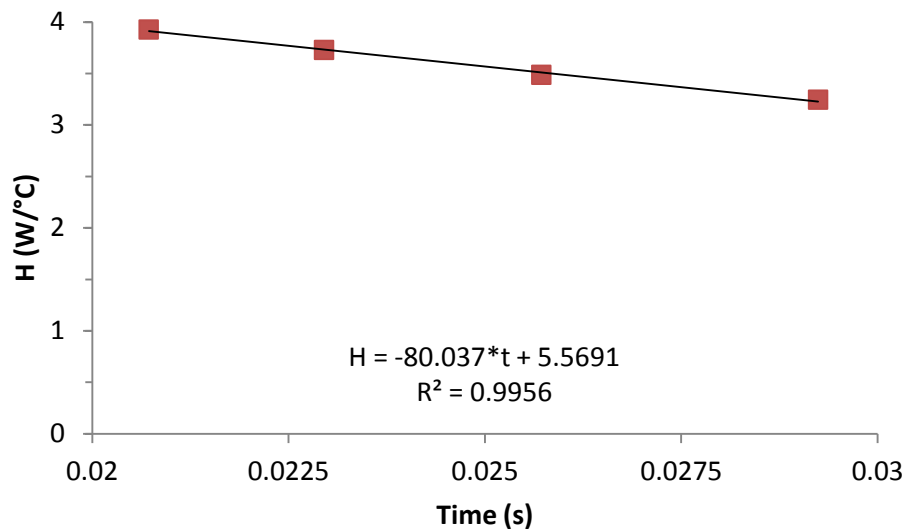


Figure 2.9 Convective loss term, H, as a function of weld time

2.6 Sample Resonance

When applying cyclic loads it is important to consider the system's harmonic response. Constructive or destructive interference may be encountered as the lower foil or substrate reacts to the applied ultrasonic loading. This has the potential to manifest as varied thermal states along the sample length during UC. To investigate harmonic phenomena three studies will be performed

1. FEA solution of mode shapes and eigenfrequencies
2. Effect of substrate width on weld energy oscillations
3. Weld energy oscillations of additional weld pairings

Details and results of these studies can be found in section 4.1.

2.7 Summary

In this chapter the model development was presented. A free body diagram was used to assess deflections during consolidation, which indicated interfacial slip would occur during the weld process. Mechanical work is used as the heat input for modeling processing temperatures. Deformation was determined not to be a significant thermal contributor. As such, only friction is considered in this thesis for thermal modeling.

Internal temperatures were shown to vary for MMC tapes. This necessitates a transient two-dimensional solution approach for tape welds. This is not the case for foils. Internal temperatures do not vary significantly for foils, thereby permitting the use of a lumped parameter model. With the use of an ultrasonic welder and temperature measurement equipment, both models can be validated. The measurement and welding equipment, as well as the materials processed, are presented in the next chapter.

Chapter 3

EQUIPMENT AND MATERIALS

For ultrasonically welding and experimentally measuring in situ temperatures an infrared camera and a customized ultrasonic welder were extensively utilized. The infrared camera is used to measure temperature profile along the nip point between the horn and sample during the consolidation process. The ultrasonic welder is used to consolidate an MMC tape or metallic foil to a metal substrate or another foil. Aluminum was the metal of choice in this work due to its high specific strength and availability in both fiber-reinforced and unreinforced states.

3.1 Ultrasonic Metal Welder

The welds were made with a modified seam welder purchased from AmTech. See figure 3.1 for a schematic of the welder. The knurled Ti-6Al-4V horn has a diameter of 146 mm, and can rotate at speeds up to 150 RPMs resulting in weld speeds up to 1200 mm/s, (equation 1.1). The prescribed amplitude of oscillation, λ , and fixed frequency, f , are regulated using feedback control built into the welder. The frequency used, 20 kHz, is, as reported by Neppiras' (1965) based on his investigation of the physical mechanisms involved in ultrasonic welding, typical of ultrasonic welding. The clamping force, F , is controlled with a pressure regulated pneumatic cylinder. The available parameter ranges for the welder are quite broad. This allows for greater flexibility and understanding of current and future welding geometries and material pairings.

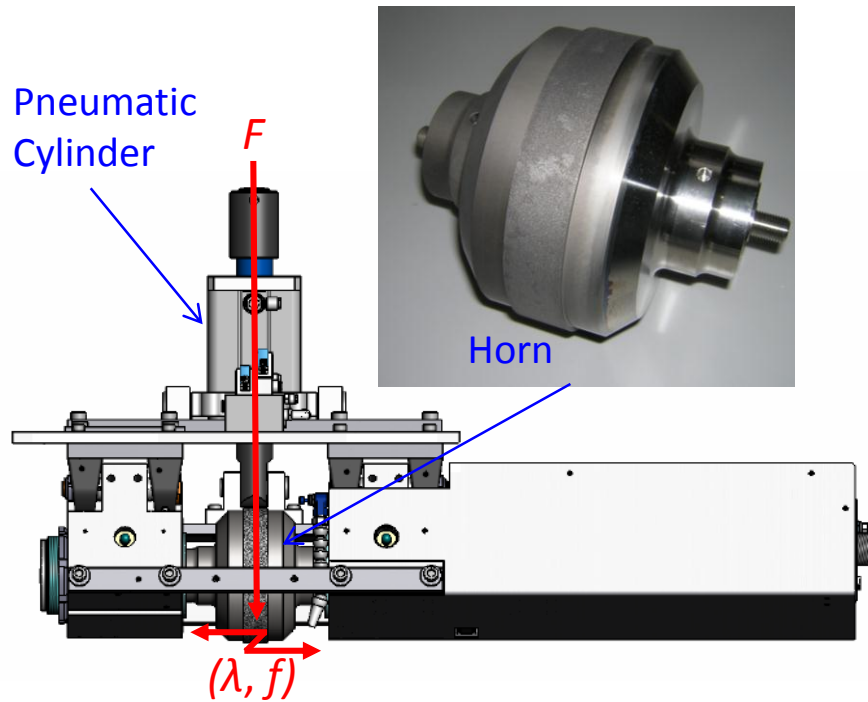


Figure 3.1 Ultrasonic welder schematic

Depending on materials consolidated (foil-foil vs. tape-substrate) contact lengths, l_c , varied (see table 3.1). From Askeland and Phulé's (2003) material science and engineering textbook it can be gathered that this is because the matrix metal in the MMC tape is pure Al, which has a yield strength 8 to 16 times lower than the foils, 17 MPa to 34 MPa vs. 276 MPa. A lower yield strength means that a larger amount of contact area is needed to support the same load. Additional detail regarding the contact length and the procedure for determining l_c will be discussed further in the experimental section 4.3.

Table 3.1 Material properties. (Koellhoffer et al. 2011)

	Material	l_c (mm)	w (mm)	d (mm)	C_p (J/kg·K)	k (W/m·K)	ρ (kg/m ³)
Foil	Al 6061-T6	2.55	12.7	0.1	896	167	2700
Substrate	Al 6061-T6	7.22	25.4	12.7	896	167	2700
Tape	Al/Al ₂ O ₃ (57% FVF)	7.22	10	0.36	802	81	3388

3.1.1 Calibration and Parameter Ranges

Force, pressure, and amplitude must all be calibrated to provide a quantitative means of modeling and testing the UC process. The following sections detail the process used to calibrate the three welder parameters. A summary of the welder parameter ranges is shown in table 3.2.

Table 3.2 Weld parameter ranges. (Koellhoffer et al. 2011)

	Available Parameter Range
Amplitude (μm)	6 to 45
Force (N)	300 to 5500
Speed (mm/s)	0 to 1200

3.1.1.1 Clamping Force

To determine the correlation between the regulator's air pressure set point and clamping force a load cell was placed between the sonotrode and anvil. Air pressure was increased incrementally to generate a calibration curve. See figure 3.2 for the data. Without the use of counterweights the minimum force possible at 0 psi is 67 lbf (297 N), the weight of the horn assembly. The max pressure the welder was rated at is 90 psi, or 1230 lbf (5490 N).

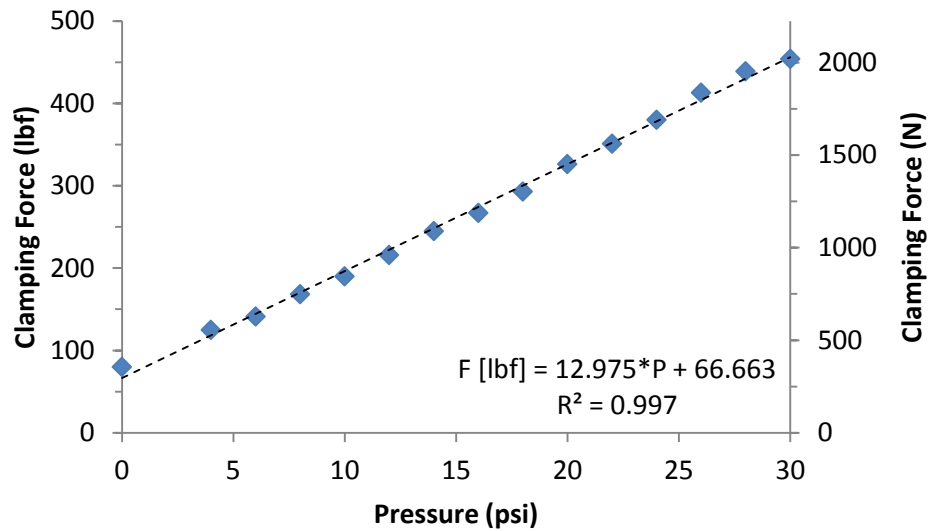


Figure 3.2 Sonotrode Load Calibration

3.1.1.2 Speed

Rotational speed was determined by marking the horn and visually counting the number of revolutions completed in approximately 1 minute. A stop watch was used to capture the exact test time for each set point. The set point is controlled by specifying a percentage of power applied to the motor. Set points ranged from the lowest power setting that could overcome the horn's static inertia up to 99% power. Two different motors were used in testing: a low speed motor, and a high speed motor. Figure 3.3 is a plot of the calibration experiment shown only over the 0% to 40% power range. Values out of this range were not practical in the lab setting. Linear speed was obtained by multiplying the measured rotations per second by the horns circumference.

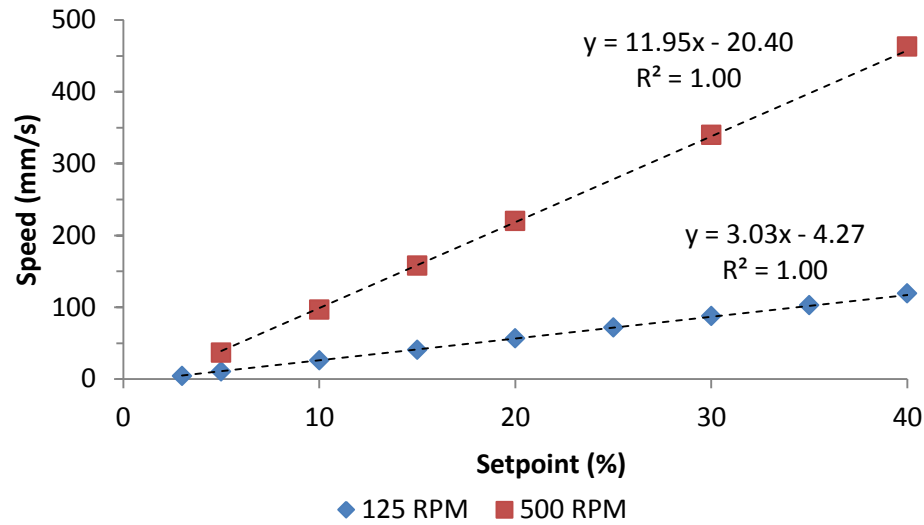


Figure 3.3 Motor Speed Calibration

3.1.1.3 Amplitude

Amplitudes for two of the six boosters were calibrated using a laser displacement sensor by AmTech, the welder's manufacturer. The laser's beam was focused on the outermost edge of the horn, and the horn was allowed to oscillate while the peak-to-peak amplitude was recorded. The amplitudes of the remaining four boosters can be interpolated from the data of the two tested boosters. The welds performed in this study used only the ultra-high gain, 1.9:1, booster. Amplitude is controlled by varying the amount of power based on a percentage scale 0% to 99%, where 0% corresponds to half power, and 99%, full power. For the ultra-high gain booster amplitudes were found to vary linearly from 22.9 μm to 44.9 μm for 0% to 99%, respectively. See Appendix E for AmTech's experimental data and specific booster ranges.

3.1.2 Frequency

The welder operates at 20 kHz placing it at the lowest end of the ultrasonic spectrum frequency spectrum. This frequency was specifically chosen for its applicability to the consolidation and processing of aluminum (Neppiras 1965). However, it is important to recognize the potential for harmonic interference incited by any modal response ensuing from a cyclically applied load. Samples most likely to experience appreciable constructive and/or destructive interference would be those without sufficient lateral support or stiffness. In this study substrates will have material welded to them. For ease of sample fabrication the substrate was supported by two bolts creating two pinned boundary conditions. The ramifications of this setup will be investigated in section 4.1.

3.1.3 Weld Procedure – Foils, Tapes, Substrates

Two different weld setups were used in this study, one for consolidating foils and tapes to each other, the other for welding tapes or foils to a substrate. In both cases, the tape or foil to be ultrasonically consolidated is taped down. This prevents movement from occurring when the sonotrode initially clamps down on the sample and begins rolling prior to the application of ultrasonics, thus greatly decreasing the likelihood of sample misalignment. When welding two foils to each other alignment is very important since any lateral movement would result in a change in contact area, thus affecting the bond characteristics. For substrate welding this is less of an issue because the substrates are wider than the samples being welded, thus a little bit of misalignment will not cause the contact area to change. Taping samples in place is adequate for short (~6 inches) welds performed at *reasonable* energy levels (e.g. 24 μm amplitude and 2000 N clamping force) in a lab setting, but would not suffice in a

commercial production environment. For large scale production careful placement of long samples will be necessary. The use of an alignment head and material dispenser would be required.

Applied amplitudes above 24 μm are likely to cause misalignment of unsupported foils (i.e. only held in place with tape). The top image in figure 3.4 is an example of a misaligned sample. The overlapping area darkens as the contact area between foils shrinks indicating a change in the processing conditions. The bottom picture in figure 3.4 is an example of a weld performed in which the energy level was too high. This occurred because the same energy levels used for 6061-T6 foils ($\lambda \approx 24$ μm , $F \approx 1200$ N, 51 mm/s feed rate) was too much for a soft, pure aluminum, foil. Destruction of 6061-T6 foils typically occurred when amplitudes were increase beyond 28 μm .



Figure 3.4 Misaligned sample (top) and sample welded at too high an energy level (bottom)

3.2 Microscopy

To determine shape and surface properties, microscopy was employed. Two microscopy devices were used to characterize samples. An optical light microscope was used to capture a cross sectional image of MetPreg tape. A scanning white light interferometer (SWLI) was used to look at pre-UC sample surface roughness, ultrasonically abraded interfacial surfaces and knurl indentation. SWLI differs from a typical light microscope in that it utilizes a piezoelectric transducer to move a sample in the direction of topographical interest. Intensity images are recorded and then subsequently processed in the spatial frequency domain generating a topographical image of the sample (Groot and Deck 1993).

3.3 Temperature Measurement

Two methods of temperature measurement were investigated in this study: thermal imaging utilizing an infrared camera and contact measurements were taken with a thermocouple.

3.3.1 Thermocouple - Uses and Limitations

Typical k-type thermocouples lack the spatial and temporal resolution to measure UC processing temperatures. Thermocouple placement also proves challenging. Putting the thermocouple between layers being consolidated risks thermocouple damage and may affect the welding process. An attempt to embed a thermocouple close to the weld interface was done by micro milling a notch into the center of a substrate. The notch was just large enough to contain the thermocouple probe. The probe was insulated and glued in place with an electrical epoxy. Figure 3.5 shows the completed sample. However, upon testing the probe only registered very low temperatures. This did not agree with values obtained by other researchers or the infrared measurements discussed later. Several factors prevent typical thermocouples from measuring UC temperatures accurately. The wire is round so, only a small amount is exposed at the surface. The substrate is aluminum, so heat dissipates rapidly. The glue needed (non-conductive) to ensure temperature is measured at the probe tip and likely reduces the temporal response of the thermocouple.

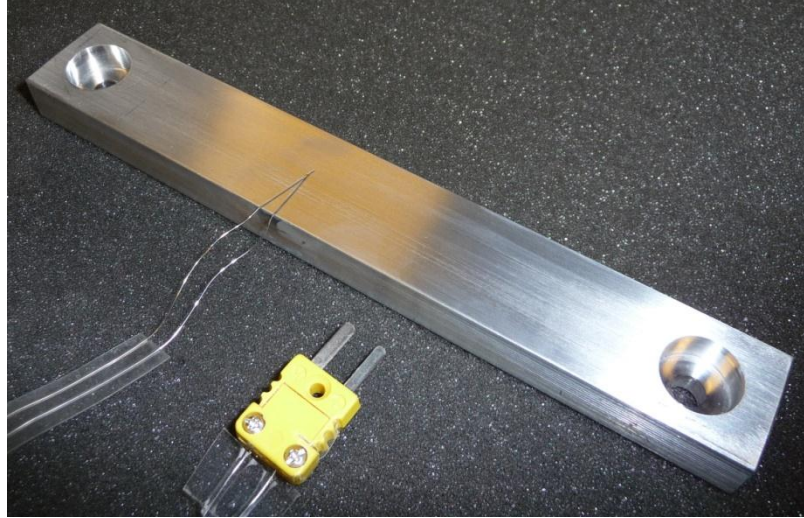


Figure 3.5 Thermocouple embedded in substrate

Thermocouples and thin film thermocouples/thermopiles are good indicators of temperature near the weld interface. Based on a temperature rise, one can back calculate the energy dissipated during consolidation (Cheng and Li 2007). In this study a thermocouple was used for two tasks: emissivity calibration and to ensure the welder had returned to ambient temperatures prior to welding the next sample. A preheated (or cooled) tool surface would cause variations in processing temperatures, so the thermocouple acted as an indicator to prevent bias and ensure the model boundary conditions are accurate.

3.3.2 Infrared (IR) Camera

To measure the processing temperature of foils and tapes a FLIR Thermovision Alert, model 194, infrared (IR) camera was used. This is possible because heat given off by objects can be seen in the IR spectrum. The amount heat radiated off an object is determined by its emissivity. Emissivity values range from 0

to 1. An emissivity of 0 corresponds to an object that emits no radiation, whereas an emissivity of 1 corresponds to a perfect emitter (i.e. a *black body*). Room temperature emissivities of metals typically range from 0.1 to 0.7. The exact emissivity of a sample will depend on several factors. Factors relevant to this study include surface finish, temperature, and viewing angle (Incropera and DeWitt 2001). Figure 3.6 shows a summary of the thermally imaging process; note the welding direction, overlaid IR image, temperature contours acquired (across the tape width), and camera positioning. The camera recorded in real time during the welding process. Each temperature contour captured corresponds to the temperature profile of the nip point from a single camera frame. The temperature profiles were acquired just as welding completed at the three different sample locations indicated in figure 3.6.

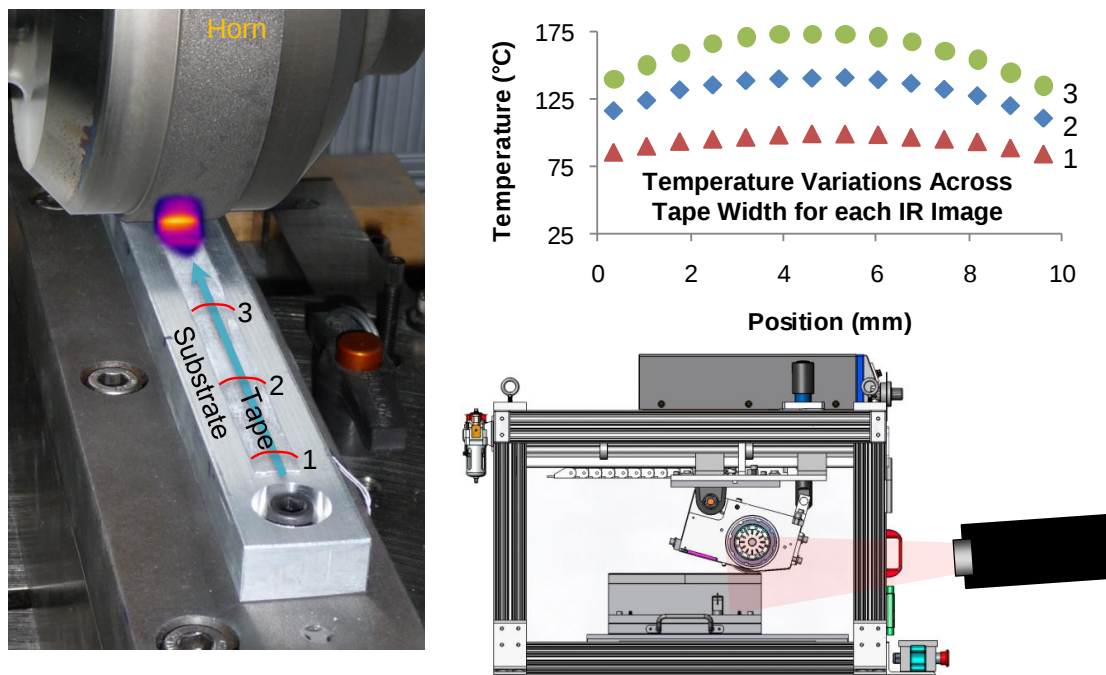


Figure 3.6 IR camera positioning and acquired data. (Koellhoffer et al. 2011)

3.3.2.1 Setup

The amount of heat emitted by an object as perceived by an IR camera depends on a materials emissivity as well as the surrounding environment. If the object is surrounded by reflective and/or absorbent materials this will alter the amount of energy directed at the camera lens. Therefore, variation in surroundings and camera positioning should be kept to a minimum during emissivity calibration and subsequent experimentation. In order to minimize measurement variability, all experiments in this study use the same camera viewing angle and distance. The camera was positioned directly in front of the welder at a fixed distance and angle so as to capture sample temperatures immediately following weld completion. The camera's area of focus was the nip point between the horn and the sample to be welded. Figure 3.7 illustrates the positioning of the camera relative to the center (longitudinally) of the specimen to be viewed. Temperature dependent emissivities were calibrated using the same surrounding geometries and camera positioning on a hotplate. When doing so, the horn was removed from the welder and placed on the hot plate with the sample.

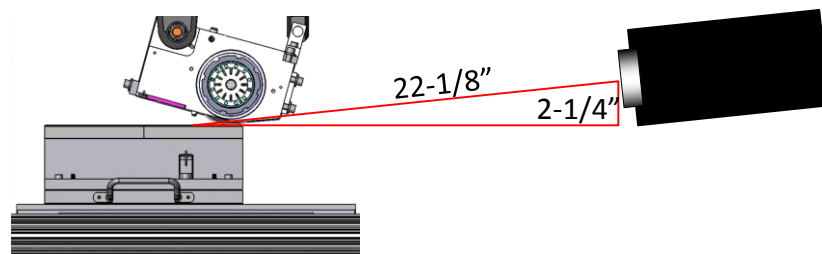


Figure 3.7 IR camera positioning relative to ultrasonic welder

In figure 3.8 many of the key components to emissivity calibration are labeled; remaining unlabeled components include the thermocouple, horn and

calibration sample. The computer records and quantifies the temperatures seen by the IR camera. In order to report accurate temperatures the software, ThermoCAM Researcher 2002, needs to know the emissivity of the object of interest, the ambient temperature, the relative humidity, and the camera's distance to the specimen. Since angle is not included in the software, the entered emissivity must correspond to the current camera angle. The setup dimensions were kept within 1/8 inch of the dimensions shown in figure 3.7 (22-1/8 inch distance and 2-1/4 inch height). As a result the variability in the setup angle was bound between 5.5° and 6.2°. However, the actual variability in measurement angle during welding must also take into account the specimen length since the camera remained stationary during welding. 5 inch specimens were used exclusively in this study, and the actual length over which data was used was approximately 4 inches. For an ideally positioned camera treated as a point source, a 4 inch measurement range results in an angle range of 5.4° to 6.4°. Adding together the effect of specimen length and setup variability the extremes for camera angle were 5.0° to 6.8°. As measured from nominal this is 5.8° +1.0°/-0.8°.

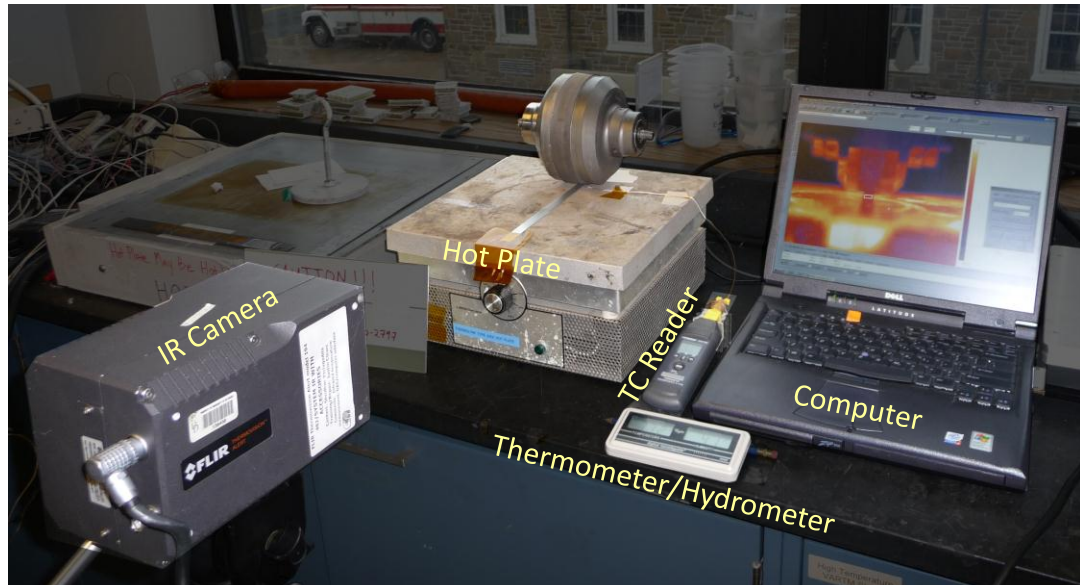


Figure 3.8 Emissivity calibration setup. Live display on computer screen.

The emissivity calibration setup was similar for both foils and tapes. The setup on the hot plate follows figure 3.8 where the welder horn is placed on top of the sample, and a thermocouple is placed under the foil or tape just in front of the nip point. Figure 3.9 shows the positioning of the horn, thermocouple, and sample tested. For calibration of MMC tape air gaps due to high surface roughness and its inability to conform around the thermocouple probe were filled with a commercial thermal paste, Arctic Silver 5.



Figure 3.9 General foil/tape emissivity calibration setup

The emissivity of a welded MMC tapes was also determined to assess the change in emissivity during tape processing. The same general setup used for unwelded tapes was employed for welded tapes. However, since the layers were all welded together the thermocouple was embedded below the surface by milling out a relief hole which was then sealed with a dowel pin and thermal paste. The multi-layer sample is shown in figure 3.10. The embedded location of the thermocouple is indicated by the yellow dashed lines and circle labeled *TC*.

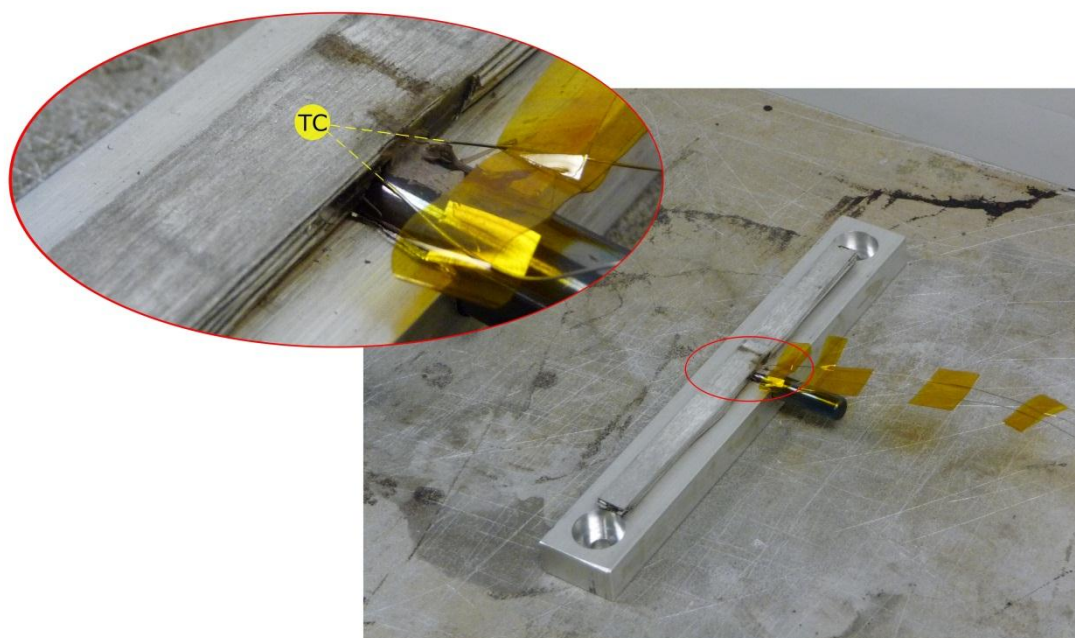


Figure 3.10 Preprocessed MMC sample with embedded thermocouple sitting on hot plate. Thermocouple (TC) location indicated in yellow.

3.3.2.2 Data Analysis

Each pixel recorded by the camera corresponds to a specific temperature. Pixels on screen also correlate to a specific spatial dimension. The foils used in this study were 12.7 mm wide and the tapes were approximately 10 mm wide. In pixels, sample width dimensions equated to 18 pixels and 14 pixels, respectively. The software that interfaces with the camera allows the user to obtain all data points or just a portion (i.e. temperature at a point/pixel, along a line, or within an area of interest). The temperature of the area of interest can then be viewed as an average of all points, or as discrete temperatures at each point within the area. The temperature(s) used will depend on the task at hand.

3.3.2.2.1 Temperature Dependent Emissivity

When creating an emissivity calibration curve, the emissivity vs. temperature function for a specific sample, the steady state average temperature of a small region is used, see figure 3.11. The area is chosen such that it contains only the material to be calibrated and is within close proximity to a thermocouple measuring the *known temperature*. Using the built in emissivity calculation tool the known temperature (i.e. what the thermocouple reports) is input and the corresponding *new emissivity* is output. In figure 3.11 the initial (*old*) emissivity was 0.56, by inputting the known temperature, 144.6 °C, the *new* (correct) emissivity, 0.58, was calculated.

Using the hot plate setups for foil and tape described in section 3.3.2.1, emissivity-temperature curves were generated using thermocouple values and the software emissivity calculation tool at various steady state temperature points. The emissivity calibration curves for foils and tapes are presented in figure 3.12.

Implementation of the calibration curve was achieved by modeling emissivity as a linear function of temperature.

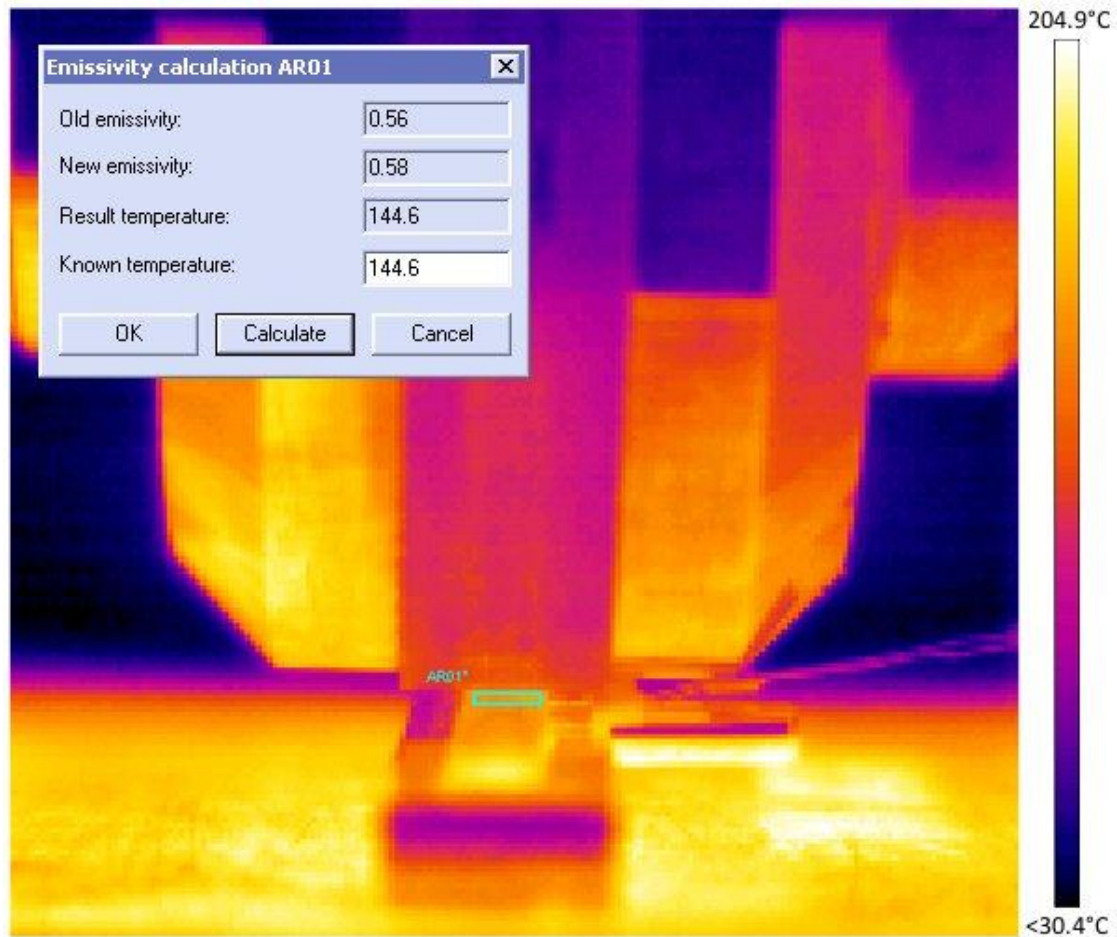


Figure 3.11 Emissivity calculation screen. Sample shown is multilayer MMC tapes welded to an aluminum substrate with an embedded thermocouple.

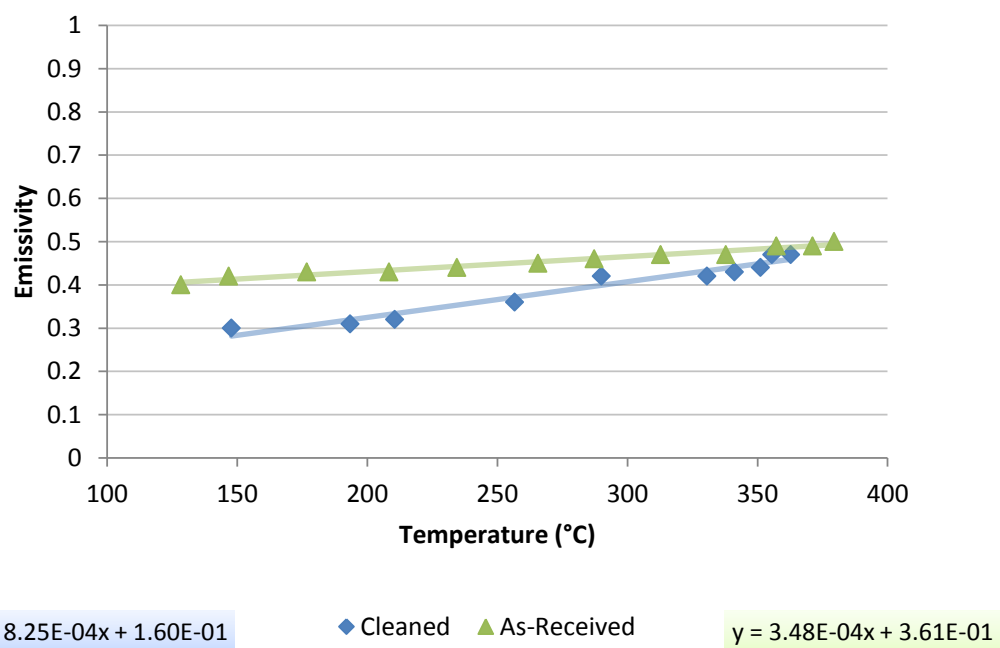
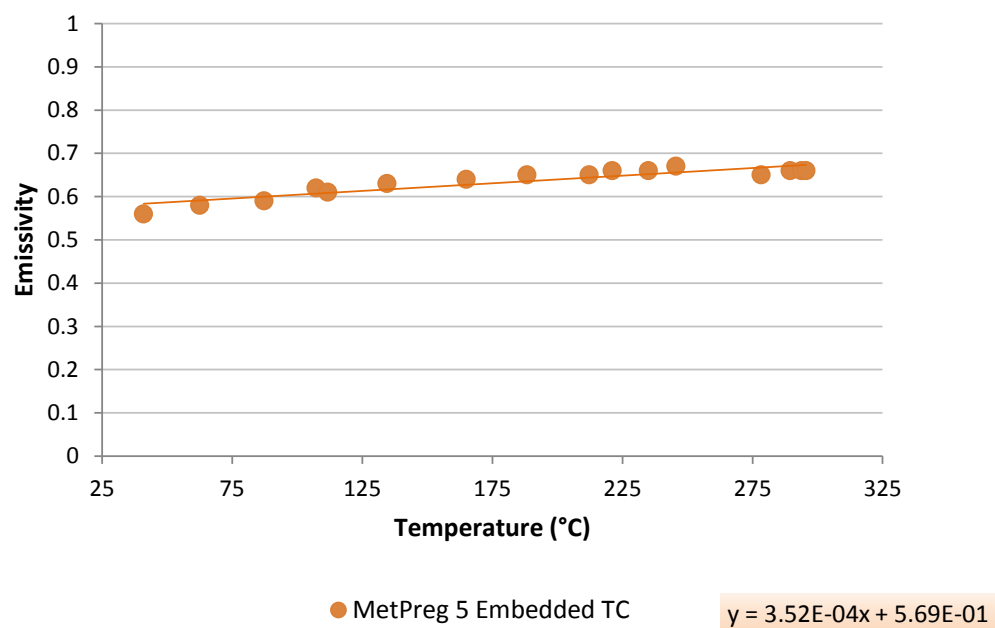


Figure 3.12 Emissivity vs. temperature curves for MetPreg MMC Tape (top) and foils (bottom)

3.3.2.2.2 In Situ Temperature Acquisition

For temperature measurement during UC temperature is recorded at incremental steps along the sample length every 0.25 seconds (the camera's max frame rate) as the horn rolls across the sample. Sample emissivity is adjusted at each time step such that the recorded temperature (or average temperature when multiple data points are involved) has the appropriate emissivity based on the emissivity calibration curve (from figure 3.12). Convergence between the recorded temperature and the samples temperature dependent emissivity must be manually iterated for the software used in this study. This iteration process makes data reduction quite time consuming. To simplify the data reduction process for materials with uniform temperature distributions (e.g. foils), max temperature is used. The ramifications to the accuracy of the reported values as a result of this simplification will be discussed in the accuracy section, §3.3.2.3. In most cases, max nip temperature is the hottest point in the camera's field of view; however, this is not always the case. Reflections can cause falsely observed hot zones, and if the temperature varies longitudinally (such as from sample resonance detailed in section 4.1, Material Resonance Effects) a previously welded area could still be hotter than the area currently being welded. This issue is apparent and easily avoided during data reduction since the horn moves at a uniform speed allowing one to know the expected location of the nip point regardless of the temperature distribution in a single frame. .

For materials with non-uniform temperature distributions (e.g. tapes), the entire temperature distribution along the nip point is captured and analyzed. The tasks involved with determining the full temperature profile of a single specimen will now be detailed.

First the sample is welded while the IR camera records, then the data is postprocessed. A reference box is drawn around the entire weld zone, AR01, and then filled with horizontal lines, LI 01 thru LI 15 (see figure 3.13). The ThermoCAM Researcher analysis software can be linked to Microsoft Excel via Visual Basic programming. This allows the qualitative IR image to be interpreted quantitatively in the Excel environment, figure 3.14. The use of color coded conditional formatting helps one visualize hot and cold points while working in the Excel environment. At any instant in time during welding the most recently welded area will appear at the nip point between the horn and sample. This appears in Excel as the line with the hottest average temperature. The average is calculated based on data captured on the foil or tape surface only. This is accomplished by ensuring the right number of pixels is used in the width direction (18 for a foil and 14 for a tape). The pixels extending beyond the sample boundary represent the adjacent anvil or substrate surface, and are thus not used to compute sample temperature.

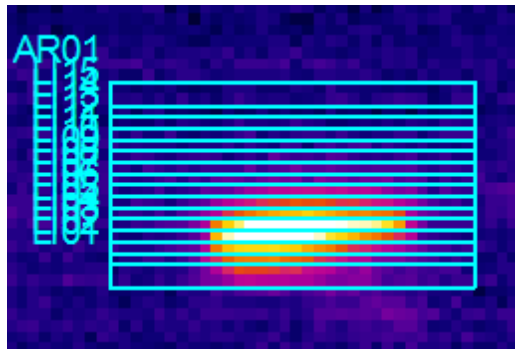


Figure 3.13 IR camera analysis grid in ThermoCAM Researcher 2002

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15	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

Figure 3.14 Temperature analysis grid viewed in Excel at one instant in time.

Once the true nip point (technically a nip-line) temperature distribution is known it is saved in a separate table, similar to the one shown in figure 3.15. The camera image is then advanced one frame, and the next weld temperature profile can be obtained and added to the weld temperature summary table, figure 3.15. The primary temperature data is shown in bold font. Temperature data outside of this region represents data off the sample surface or unused transient data. When the horn first contacts the sample, and when the horn lifts back up, the full amount of weld energy is not being delivered to the sample. This results in cooler areas at the specimen beginning and end. In figure 3.16 the first and last two times/temperatures (noted with open diamonds) correspond to the abovementioned transient temperature regions and are not used in any calculations pertaining to that sample.

Line	Time (s)	0.00	0.25	0.51	0.76	1.02	1.27	1.53	1.78	2.04	The Average Line	STDEV Across Length	
	Position (mm)	3	5	7	9	12	15	16	16	16			
1	-4.6	30	30	30	30	30	30	30	30	30	30	0	
2	-3.9	30	30	30	31	30	30	30	30	30	30	0	
3	-3.2	30	30	30	30	31	31	32	31	31	31	1	
4	-2.5	30	30	30	30	33	33	36	35	33	32	2	
5	-1.8	30	31	33	38	34	36	37	32	31	35	3	
6	-1.1	30	34	40	52	40	43	47	39	37	43	6	
7	-0.4	37	49	56	64	50	58	58	41	36	56	6	
8	0.4	58	79	95	107	83	89	95	51	44	91	10	
9	1.1	84	112	130	130	130	126	126	69	58	125	7	
10	1.8	101	131	137	134	139	139	138	103	92	136	3	
11	2.5	113	140	144	141	143	144	143	109	98	142	2	
12	3.2	118	145	149	145	142	148	147	112	101	146	2	
13	3.9	118	148	155	146	144	150	151	114	105	149	4	
14	4.6	116	150	159	150	142	153	153	116	106	151	6	
15	5.3	112	151	164	150	142	154	155	119	109	153	7	
16	6.0	111	152	167	151	141	157	156	118	108	154	8	
17	6.7	107	153	171	153	139	157	155	120	109	155	10	
18	7.4	105	152	172	155	137	157	152	119	105	154	11	
19	8.1	100	148	174	155	135	156	151	117	107	153	13	
20	8.8	94	146	174	155	133	154	145	116	104	151	14	
21	9.5	88	141	174	154	132	151	141	116	104	149	15	
22	10.2	79	134	171	151	129	142	133	113	103	143	16	
23	10.9	73	127	166	146	125	127	112	107	96	134	19	
24	11.6	68	115	158	137	118	97	82	102	94	118	27	
25	12.3	59	102	125	109	100	59	65	80	75	93	26	
26	13.1	52	81	78	68	57	43	44	51	49	62	17	
27	13.8	45	58	47	45	41	32	35	39	36	43	9	
28	14.5	40	44	37	39	37	33	34	36	35	37	4	
29	15.2	32	33	32	32	33	31	30	30	31	32	1	
30	15.9	30	30	30	30	32	30	30	30	30	30	1	
31	16.6	30	30	30	30	30	30	30	30	30	30	0	
32	17.3	30	30	30	30	30	30	30	30	30	30	0	
Average		95	135	155	143	131	137	133	106	95	138.8	For all data	Averages
Max		118	153	174	155	144	157	156	120	109	154.5	174.3	156.6
Min		58	79	95	107	83	59	65	51	44	91.2	58.6	81.1
Std Dev		20	21	21	15	16	28	27	19	18	19.8	22.9	21.3
CV		0.21	0.15	0.14	0.10	0.12	0.20	0.20	0.18	0.19	0.14	0.165	0.154
ε		0.39	0.41	0.42	0.41	0.41	0.41	0.41	0.40	0.39	0.41		

Figure 3.15 Nip point temperature profiles for each camera frame. Temperatures reported in degrees Celsius.

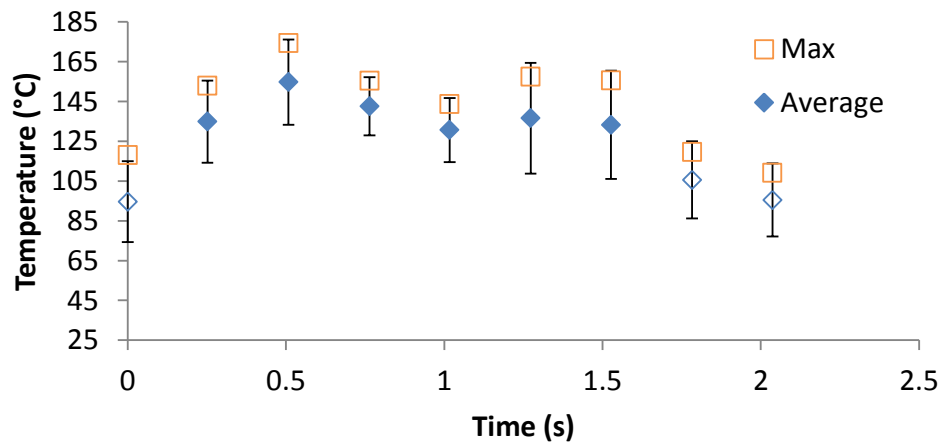


Figure 3.16 Average and max temperature vs. time for a typical foil-foil weld. **Note:** each time step corresponds to the next camera frame and relative nip point being welded at that instant in time. Error bars denote $\pm$ one standard deviation as determined by the temperature variation across the sample width for each IR image. Open diamonds indicated transient data not used for data analysis.

The average temperatures in figure 3.16 (and figure 3.17) were obtained by averaging the nip temperatures on the sample from a single camera frame. Rather than using camera frame number to track weld progression, elapsed time and length traveled are utilized. Since the camera records at a fixed rate (4 Hz), there's no visual difference in the appearance of data between using time or camera frame as the dependent variable. However, time is a less abstract as it clearly illustrates the temporal gap between measurements from one point to the next. Alternatively, the same temperature data can be presented as a function of its spatial location on the sample. This is most readily done via the on screen vertical pixel number, y , associated with the grid line, LI y from figure 3.13. Figure 3.17 shows the temperature vs. length plot using pixels. The relationship between relative pixel distances apart and actual distance is related to viewer positioning (i.e. camera location) and sample

length. In figure 3.18 a sample of length $2a$ is being viewed from a point source, P. The apparent distance from the center of an object, length $2a$, to the front is b , and to the back is c . The discrepancy in apparent distances compared to the actual distance is attributable to the parallax cause by the difference in viewing angles. On screen c will appear smaller than b. Also, when plotting temperature vs. length, data will appear to skip points. This occurs because distance in pixels is an integer value while the actual distance traveled is not. Because the camera distance (pixels) does not perfectly sync up with the distance traveled some perceived skipping around occurs. This can generate the illusion that the horn's rotational speed is non-uniform.

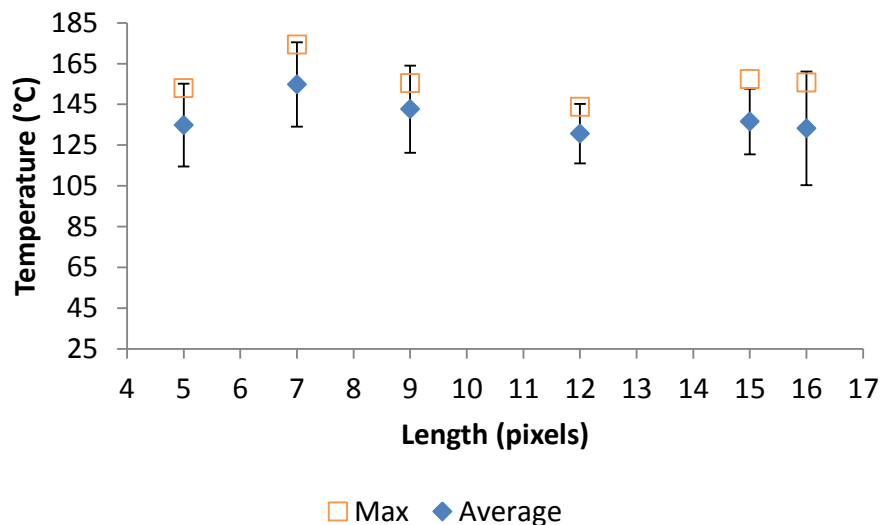


Figure 3.17 Average and max temperature vs. length for a typical foil-foil weld. **Note:** each time step corresponds to the next camera frame and relative nip point being welded at that instant in time. Error bars denote $\pm$ one standard deviation as determined by the temperature variation across the sample width for each IR image.

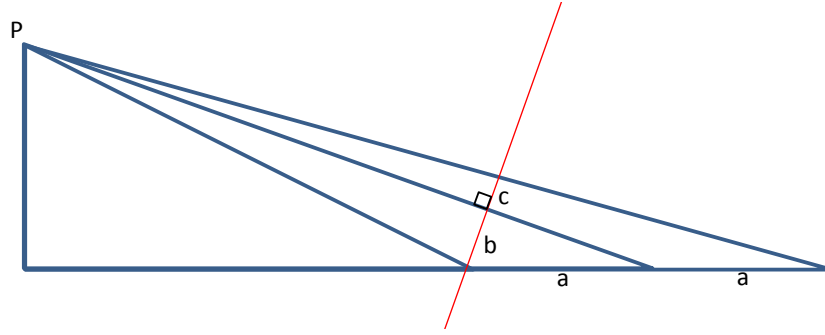


Figure 3.18 Sketch of parallax effect on the IR camera's viewing plane

The correlation between pixel position and spatial position, assuming a point source, for the camera distance used in this study is shown in figure 3.19. As indicated by figure 3.18 the farther back on a sample the smaller apart objects appear (i.e. the pixels are larger spatially). However, the difference is very small for the setup used in this study. A linear fit, starting at 0 inch = 0 px (the starting edge of the sample), correlates very well to the variation in pixel size ($R^2=0.997$). Therefore one pixel, at the start or end of the sample, is approximately 0.36 inches of sample length (note the width of a pixel is about 0.028 inches).

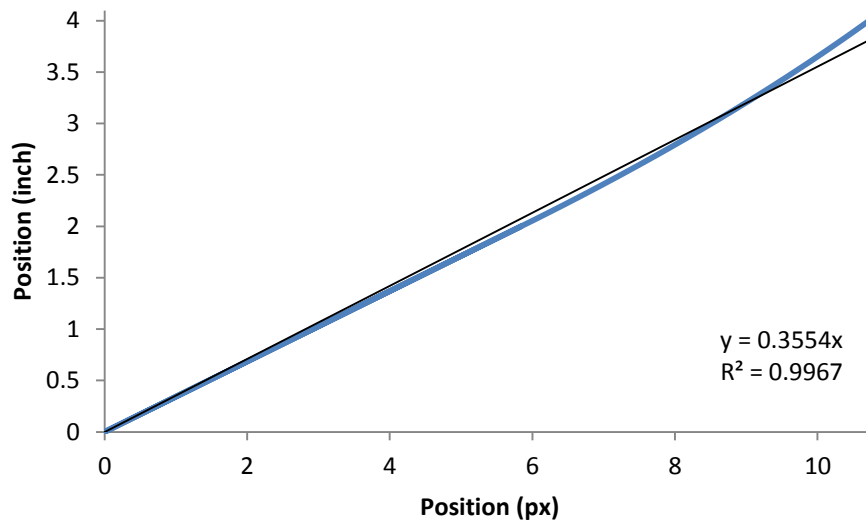


Figure 3.19 Plot of parallax effect on the IR camera's viewing plane

In addition to viewing the temperature along the length of a sample (Figure 3.16 and 3.17) temperature can be viewed across the width. For the data from the sample shown in figure 3.15, temperature across the width is obtained by plotting the corresponding temperatures for positions 0.4 mm to 12.3 mm for each time from 0.25 s to 1.53 s (the non-transient process times). The resulting plot is shown in figure 3.20. This data is more conveniently viewed by vertically averaging all temperature curves with respect to width-wise position. The resulting plot is figure 3.21. Both figures 3.20 and 3.21 indicate there was some variability on the right side of the specimen; this can occur from sample misalignment or geometric variations of the foil. Error bars are included denoting the standard deviation at each spatial location, $\pm \sigma$. This is the manner in which two-dimensional temperature data will be presented.

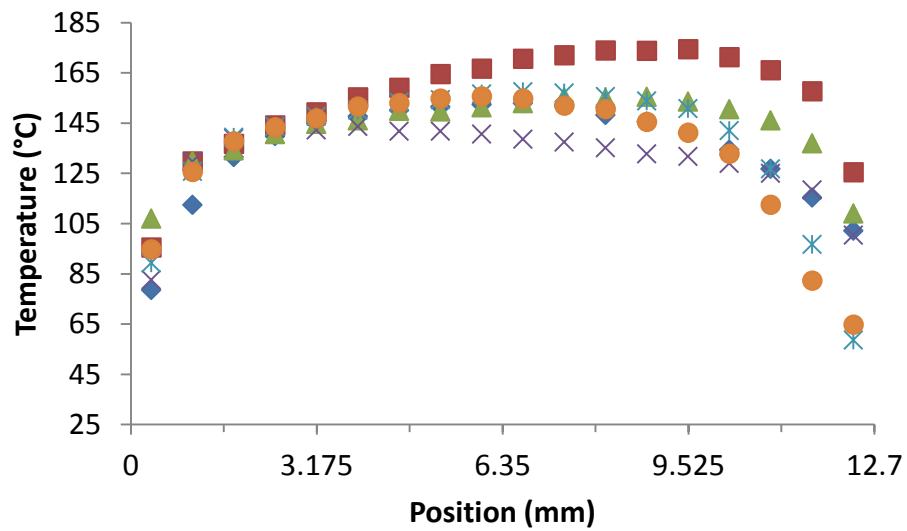


Figure 3.20 Typical foil-foil width-wise temperature distributions during UC process. The various data marker shapes correspond to each IR image taken during the welding process as the horn travels down the sample.

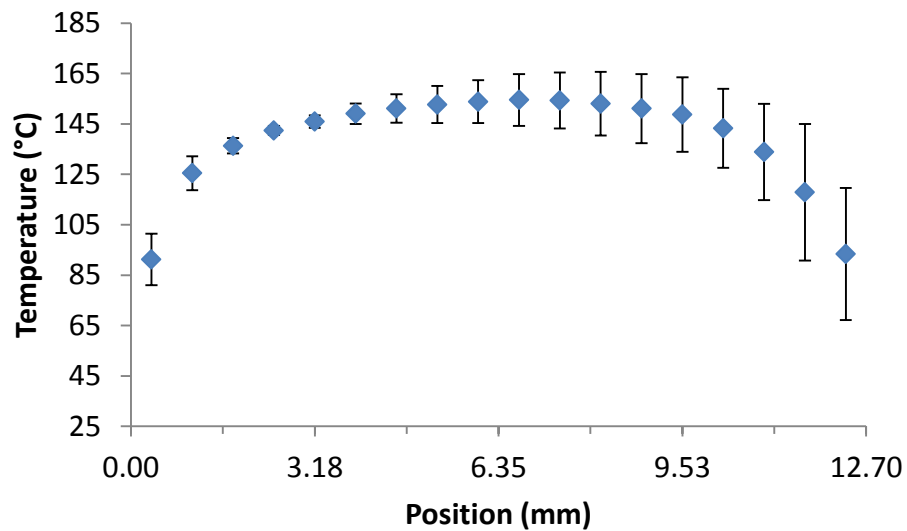


Figure 3.21 Average foil-foil width-wise temperature distribution during UC process. Error bars denote standard deviation.

3.3.2.3 IR Accuracy

Best efforts were taken to minimize measurement error; however, some sources of error were not eliminated as they were not of significant size, namely measurement angle variability. As indicated in the camera setup section, §3.3.2.1, variability in camera position and the length of the welded specimen resulted in measurement angles between 5.0° and 6.8° (nominally $5.8^\circ \pm 1.0^\circ/-0.8^\circ$). A brief study was done to investigate the significance of such variation.

Using the same hotplate setup used for emissivity calibration two tests were carried out. Both were performed at a constant 204.4°C temperature (400°F). The first varied the camera measurement angle and the second varied the software emissivity set point. Camera angle was varied between 3.6° and 8.0° and the emissivity value required to correctly measure the sample temperature was determined. The dependence of emissivity on measurement angle is shown in figure 3.22. For a $\pm 1.0^\circ$ and -0.8° angle variation about 5.8° , the true emissivity values will be $0.539 \pm 0.009/-0.008$.

To interpret the significance of unaccounted for emissivity variations, the sensitivity of temperature to a false emissivity is considered. From the actual temperature, 204.4°C , temperatures were entered into the emissivity calculator at 5.6°C (10°F) increments to generate emissivity values. The resulting relationship between predicted temperature and the emissivity set point for a fixed actual temperature is shown in figure 3.23. For the max angle variation anticipated emissivity deviation was $\pm 0.009/-0.008$; from the identified temperature vs. emissivity relationship this corresponds to a temperature error of $\pm 1.1\%/-0.9\%$.

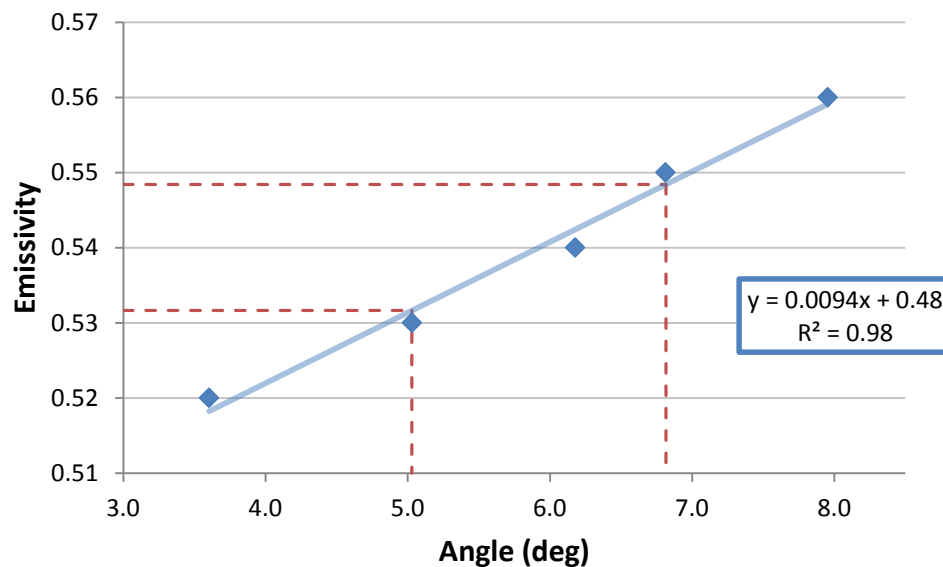


Figure 3.22 Emissivity vs. measurement angle for a sample at 204 °C. Dashed red lines denote anticipated measurement angle range extremums.

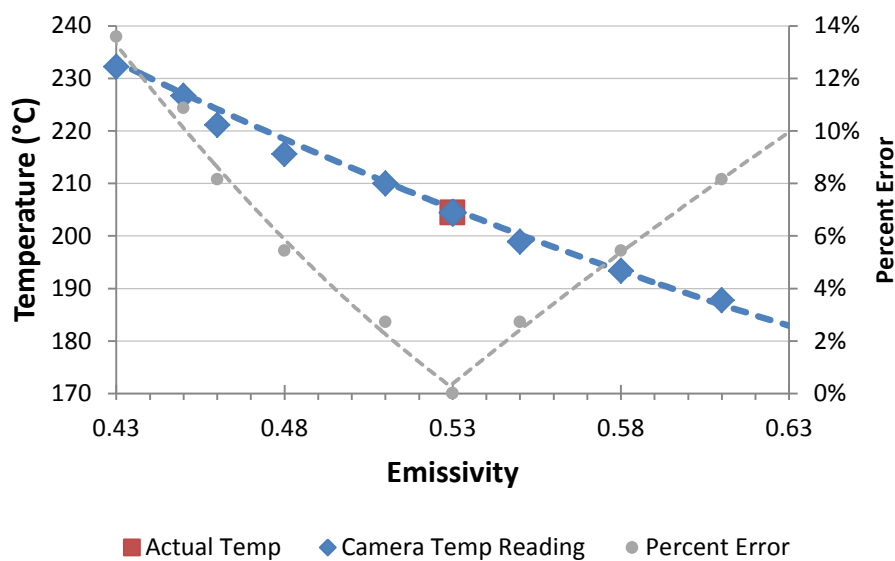


Figure 3.23 Temperature vs. emissivity for a sample at 204 °C.

The IR camera control and analysis software, ThermoCAM Researcher 2002, only accepts emissivities to 2 decimal places. From figure 3.23 it is seen that a 0.01 emissivity variation is approximately a 1% temperature difference, so emissivity induced errors on the order of 1% are largely unavoidable.

While angle variations based on setup and sample length are within acceptable error bounds care should be taken when working around a tripod mounted IR camera. The setup used for this work was easily dislodged. It was useful to mark the tripod foot locations and always confirm sample location on the camera screen before welding. Data reduction is also more easily performed if the weld area remains digitally stationary. For this case the same analysis grid can be used for multiple samples (see figure 3.13).

The use of max temperature for expedited data reduction is an acceptable simplification when the main interests are general temperature levels, temperature trends, or max temperatures. As illustrated by figures 3.16 and 3.17, average and max temperature follow the same trends, so qualitative assessments are possible. For a fully analyzed foil sample (figures 3.15, 3.16, 3.17, 3.20, and 3.21), the difference between average and max temperature was 12%, so care should be taken if more precise temperatures are needed.

A final note on error sources. Objects of interest at low temperatures (20 °C to 40 °C) are difficult to capture without interference. Reflective heat radiation from the welder operator or other surrounding heat emitters will bias measurements. If recording must be done on objects at near room/body temperatures IR shielding (e.g. an acrylic window) should be used to block light in the IR spectrum from the

camera lens and sample's field of view. Above these temperature reflections were not apparent on the IR camera recordings.

3.4 Materials (Properties, Geometry, Uniformity)

Several different materials were utilized for samples and welder tooling. The horn is made of Ti-6Al-4V. For welds using a knurled anvil (i.e. foil-foil welds) the anvil is tool steel. The horn and anvil both have a knurled surface width of 1.1 inches. In figure 3.24 the knurled anvil and horn are shown with a foil sample ready to be consolidated. Alternatively to the knurled anvil, a mild steel block was used as a mount for welds using bolted down materials (i.e. the substrate in tape-substrate welds). Geometric and thermal properties for all consolidated samples are summarized in table 3.1.

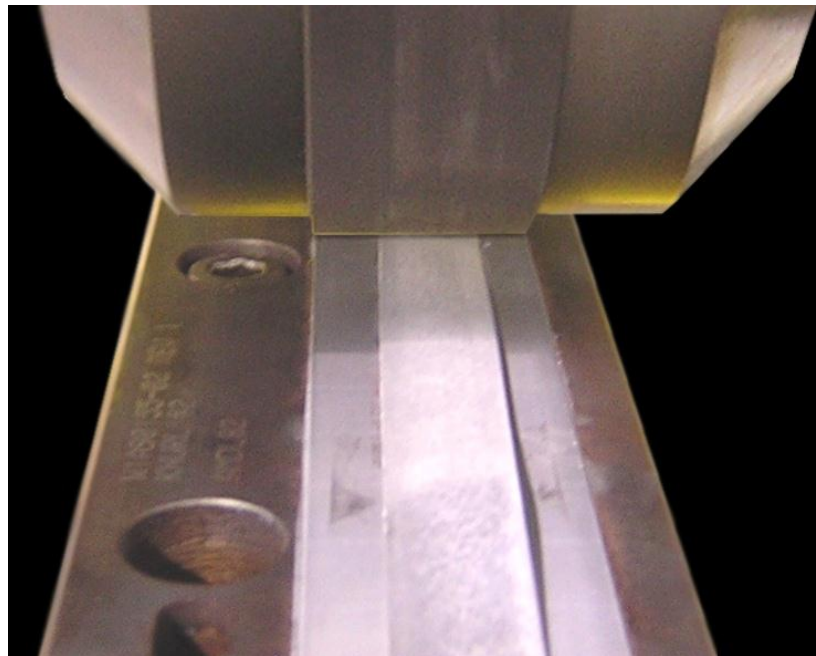


Figure 3.24 Knurled horn and anvil with foil to be welded

3.4.1 Aluminum Alloy 6061-T6 – Foils, Substrates, and Oxide Layer

The foils and substrates used for testing were aluminum alloy 6061 heat treated to the T6 condition. The Askeland and Phulé (2003) textbook reports that the T6 temper designation indicates the material has been solution treated and artificially aged to strengthen it. The foils in this study were heat treated in an oxygenated environment resulting in a very thick oxide layer. This layer can be removed with a low concentration nitric acid bath (3% for 18 hours). Foils treated with nitric acid will be referred to as cleaned foils. Untreated foils will be referred to as oxidized foils. This step was not necessary for substrate welding as no thick oxide existed; implying that, unlike the foils, the heat treatment process was performed in a more inert environment.

3.4.2 Metal Matrix Composite Tape

The MMC tapes were provided by the Army Research Laboratory. The tapes, commercially known as MetPreg, were fabricated by Touchstone Research Laboratory (TRL). MetPreg consists of Nextel 610 alumina fibers in a pure aluminum matrix. A partially submerged vertical die is located in molten aluminum, numerous fibers tows (bundles) are pulled through aluminum bath into and out of the die forming the MMC tape. The roll used in this study was 57% fiber volume fraction (FVF). Micrographs of a potted cross section of MetPreg are shown in figure 3.25. There is a large amount of variation in thickness from the edge (0.43 mm) of the specimen to the center (0.32 mm), 30% difference. This may be due to the die design and/or unevenly collimated fibers. After UC tape thickness, and variation, was reduced (-8%), and width increased (+9%). For thermal modeling the tape geometry was held constant and assumed rectangular; an in situ geometry was used that

consisted of an average of pre and postprocessed measured tape dimensions (table 3.1). Foils on the other hand had no measureable variation in thickness or width, pre or post UC. Unlike the pure Al matrix of the MMC tape, the high yield strength of Al 6061-T6 is more resistant to plastic deformation. Thus for foils the model geometry was also the pre and post weld measured thickness and width. The fact that the MMC tape deforms during UC will not significantly affect the thermal development, since deformational contributions are expected to be on the order of 1%, as indicated in section 2.3.

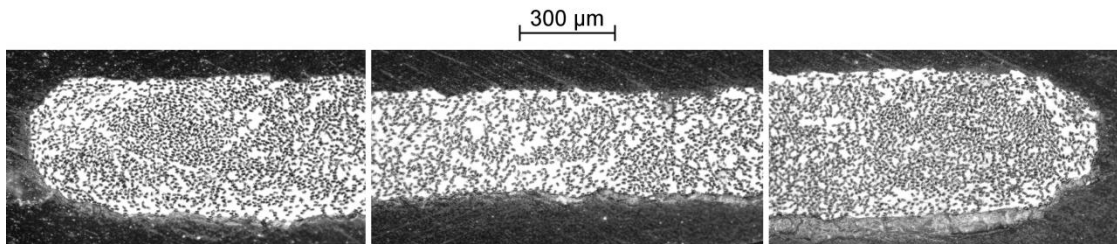


Figure 3.25 Optical microscope images of a through thickness cross section of MetPreg. Images show left, center, and right views. (Koellhoffer et al. 2011)

3.5 Pressure Film – Parallelism, Uniformity, Contact Area

Pressure sensitive film is a useful tool to check for tooling parallelism (e.g. between the horn and anvil or substrate) and sample compliance. When pressure exceeds a specific threshold red die capsules burst leaving behind a record of the contact points between surfaces. In figure 3.26 the contact area of foils and tapes on top of an aluminum substrate can be seen. The foil used to generate this pressure distribution had the same nominal dimensions as the MMC tape, and was compacted

with the same force, 2600 N. However, the pressure distributions are not the same. This is due to the non-uniform cross section of the MetPreg MMC tape, as illustrated in figure 3.25. Because the MMC tapes are thin at the center of its cross section, it does not contact the substrate under typical processing pressures without the application of ultrasonic energy.



Figure 3.26 Pressure distribution for MMC tape (top) and aluminum foil (bottom). The reddest areas denote those of greatest pressure.

3.6 COMSOL – Finite Element Analysis Program

COMSOL Multiphysics is a commercially available finite element analysis (FEA) software package (COMSOL 2008). COMSOL version 3.5a was used to execute the FEA work in this thesis. COMSOL is capable of solving many problems governed by differential equations. Specific environments include thermal, mechanical, fluid, electronic, magnetic, and many more. The software is heavily oriented towards *multiphysics* problems containing two or more coupled loadings

where material properties and/or loads are changing based on the behavior of a separate discipline. For example, an object exposed to heat will deform differently than an object at room temperature. COMSOL allows the user to input variables like temperature dependent elastic/plastic properties. The focus of this study was solely thermal, but the option for the model to incorporate mechanical phenomena is readily available. The package was validated by performing a thermal study on a square plate and comparing the results with an analytic solution which is detailed in Appendix G.

3.7 Summary

The welder process parameter ranges and calibration procedures were detailed in this chapter, and measurement equipment was introduced. Thermocouples were not found to be suitable for temperature measurement due to spatial and temporal limitations. Instead an infrared camera was determined to be best suited for measuring in process weld temperatures. By calibrating for specimen emissivity and maintaining the same camera positioning, temperature measurement error is approximately 1%. To predict tape-substrate temperatures, COMSOL v3.5a was used.

Details of the materials used for welding were also included in this chapter. The welding horn and tooling materials consisted of Ti-6Al-4V and tool steel, respectively. Most welds were either foil-foil, which comprised of a pair of aluminum alloy 6061-T6 foils, or tape-substrate, which comprised of a 6061-T6 substrate and aluminum/alumina metal matrix composite (MMC) tape. The MMC tapes were welded to substrates due to observed dimensional non-uniformities of the tapes revealed from optical microscopy and pressure film testing, which otherwise results in non-uniform heating. In the next chapter, the aforementioned equipment and models are utilized to characterize the ultrasonic consolidation process.

Chapter 4

EXPERIMENTAL TESTING AND VALIDATION

In this chapter experiments are presented that recorded the temperature of the foil or tape during the UC process at various welder settings and investigated ancillary phenomena and properties related to UC. This includes sample resonance, surface roughness, and contact length. Temperature data for each material pair was compared separately to the values predicted from the model based on the best fit value for a single valued constant friction coefficient, $\mu_{constant}$, and for a coefficient of friction, μ_{RSM} , that is allowed to vary with the process variables. Once μ was known, using a subsequent test array a validation experiment was executed assessing the quality of fit of the model proposed. The final simulation results and experimental validation are also included in this chapter.

Both oxidized and cleaned foils were subjected to UC. Oxidized foils are not expected to bond while cleaned foils are. This is due to the thick oxide layer present. The bonding process relies on the breakup of the oxide layer to produce clean metal surfaces that provide paths of diffusion. In Janaki Ram et al.'s (2007) work of UC of multi-material systems it is discussed that if the oxide layer is not broken apart and properly dispersed voids will remain as the UC bonding process relies on metal-metal contact. Due to the lack of bond formation, welds using oxidized foils will be representative of pure slip, friction only condition. Inconsistencies in friction coefficient trends between oxidized and cleaned foils may, in part, be attributable to potential deformational heating effects, which are expected to be small. All foils are

consolidated using a foil-foil setup as shown in figure 4.1. In this arrangement, both the horn and anvil contacting surfaces are knurled to prevent foil slip at the tool-foil interfaces.

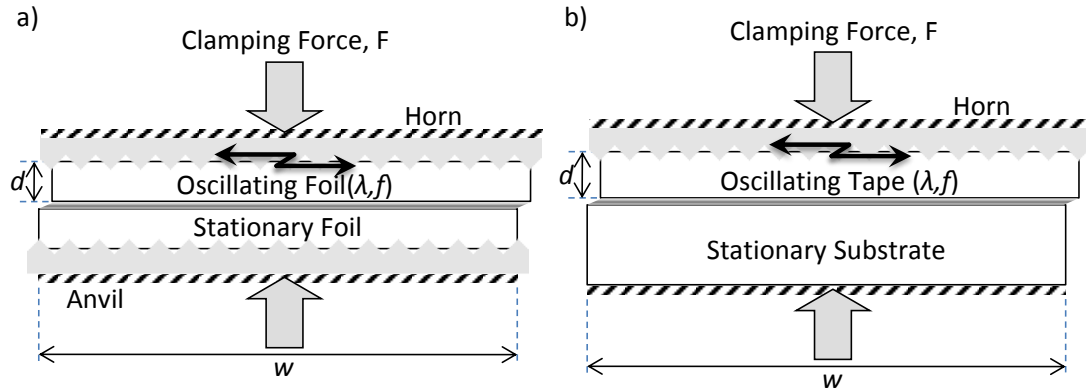


Figure 4.1 Welding geometries: (a) foil-foil with knurled anvil; (b) tape-substrate with bolt down substrate. (Koellhoffer et al. 2011)

For MMC tape welds, a tape-tape geometry was not used. Stacking two unprocessed tapes on top of each other amplifies the tape's geometric non-uniformities resulting in non-uniform temperatures. Figure 4.2 illustrates the difference in temperature distributions across the sample's width of a tape-tape and tape-substrate weld. The samples compared have similar (4 % difference) average temperatures, but substantially different process settings. Weld settings for force, speed, and amplitude were: 1451 N, 51.3 mm/s, and 28.4 μm for the tape-tape weld and 2461 N, 19.3 mm/s, and 25.8 μm for the tape-substrate weld. While sufficient energy can be delivered to permit gap closure of a tape-tape sample; this resulted in tool sticking at the anvil-tape interface. By welding to a substrate (figure 4.1b), energy levels can be increased, as

the anvil is no longer present, and thermal non-uniformities are greatly reduced. Note that for tape-substrate welds a knurled anvil is not used to prevent slip, instead the substrate is bolted in place (as shown in figure 3.6).

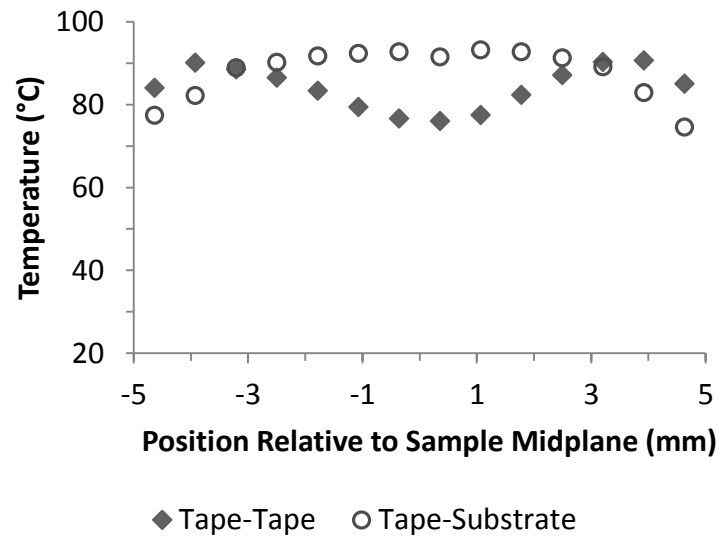


Figure 4.2 Comparison of temperature uniformity across the width of a tape-tape weld and a tape-substrate weld. (Koellhoffer et al. 2011)

4.1 Material Resonance Effects

In this section experiments were carried out investigating sample resonance. Substrate mode shapes at natural frequencies close to the weld frequency were determined using COMSOL’s FEA package. The connection between thermal oscillations and material pairing (Al substrates of various widths and Al-to-steel welds) was determined experimentally.

4.1.1 Substrate Weld Energy and Simulated Oscillation Mode Shapes

As indicated in section 3.1.2 there is a possibility for resonance of the sample to cause constructive or destructive interference. The substrates that will be welded on for investigation of the UC of MMC tapes may experience this phenomenon. A basic two-dimensional FEA model was created to view the free vibration response of a pinned substrate. Figure 4.3 is an image of the model's geometry and boundary conditions. All elements are unrestrained, except at the blue nodes located 0.5 inches from the substrate edge. In figure 4.3 a one inch wide substrate is shown, the same setup was used for a 3 inch wide substrate. If there are eigenfrequencies near the welding frequency, 20 kHz, additional testing should be performed.

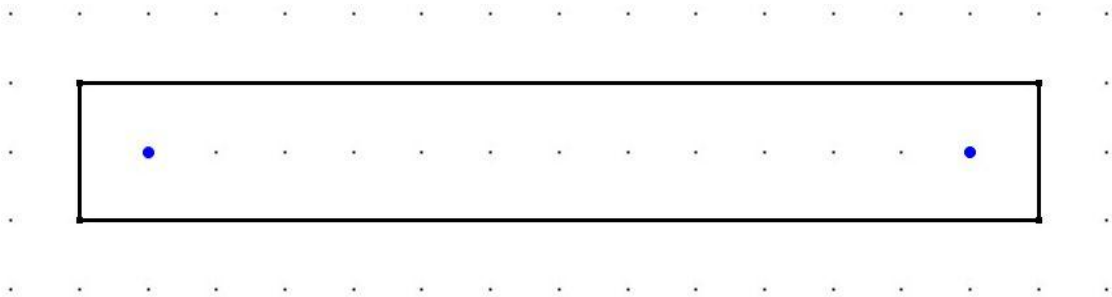


Figure 4.3 Eigenfrequency model setup. Blue dots are pinned; no displacement in the longitudinal and transverse directions.

Execution of the model revealed modal shapes 3-4 kHz above and below the 20 kHz welding frequency for both 1 and 3 inch substrates. Contour plots for the transverse displacement (the direction parallel to the welder's oscillatory motion) for the two eigenfrequencies closest to 20 kHz are shown in figures 4.4 and 4.5 for the one inch substrate and figures 4.6 and 4.7 for the 3 inch substrate. For both substrate

widths one mode has minimal deflections, while the other mode has large sinusoidal deflections. Intuitively, one would expect the substrate's oscillatory deflection to be suppressed by increasing the substrate width; comparing simulated deflections of one and three inch substrates support this reasoning.

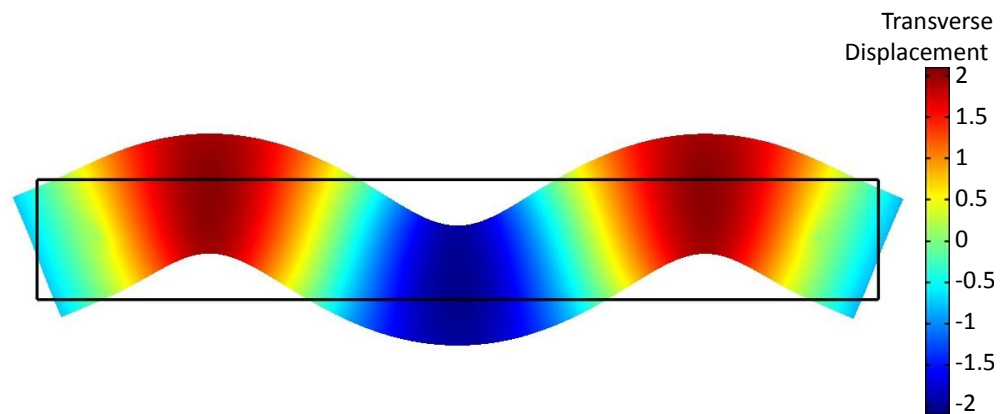


Figure 4.4 Standard 1" x 7" x ½" substrate fastened with 2 bolts (pinned), oscillating at 4th eigenfrequency, 16199 Hz. Scale bar is a qualitative measure of displacement.

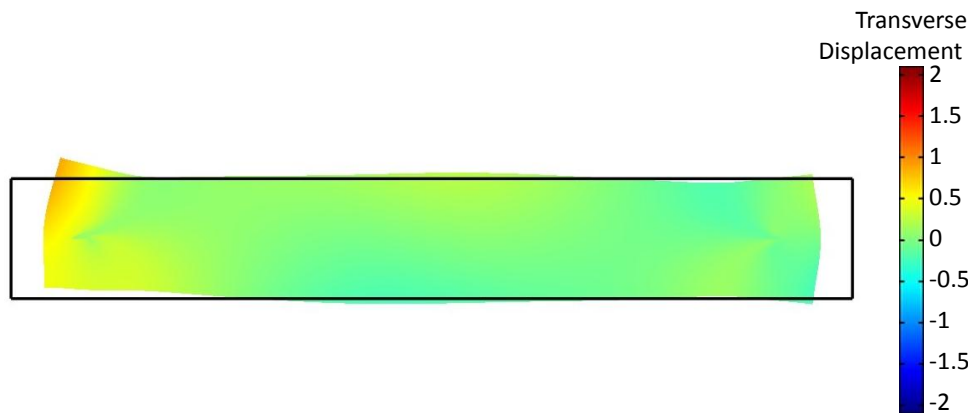


Figure 4.5 Standard 1" x 7" x 1/2" substrate fastened with 2 bolts (pinned), oscillating at 5th eigenfrequency, 23313 Hz. Scale bar is a qualitative measure of displacement.

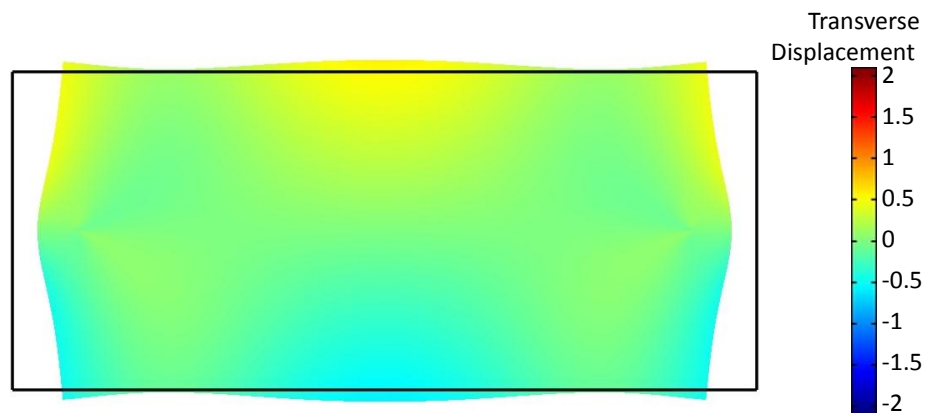


Figure 4.6 3" x 7" x 1/2" substrate fastened with 2 bolts (pinned), oscillating at 6th eigenfrequency, 17288 Hz. Scale bar is a qualitative measure of displacement.

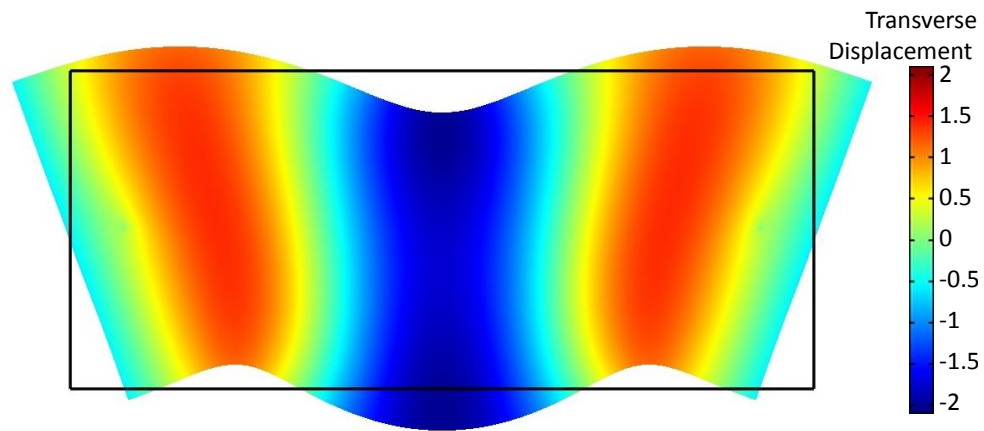


Figure 4.7 Standard 3" x 7" x ½" substrate fastened with 2 bolts (pinned), oscillating at 7th eigenfrequency, 23346 Hz. Scale bar is a qualitative measure of displacement.

This model investigating the oscillation frequency and shape of the eigenfrequencies has limited use because the horn's presence is not taken into account. A fully dynamic three dimensional harmonic simulation may be more accurate, but is outside the scope of this work as it would require significant work to accurately capture the mechanical aspects of UC. Nonetheless, as predicted by the free vibration analysis model, experimental data supports the manifestation of harmonic interference. When MMC tape is welded to a 1 inch substrate there are areas of varying energy visible on both the specimen surface and the IR thermal imaging data. The peaks and valleys are not a perfect match for the predicted modal shapes, but a sinusoidal response is evident. In figure 4.8 the IR nip point temperature vs. time data has been overlaid on a picture of the corresponding post UC sample to illustrate both the physical and thermal influence of harmonic interference. While the magnitude of the interference varies for different welder settings, the spatial location of the peaks

remains constant. To alter the mode shape or amplitude one can change the weld geometry.

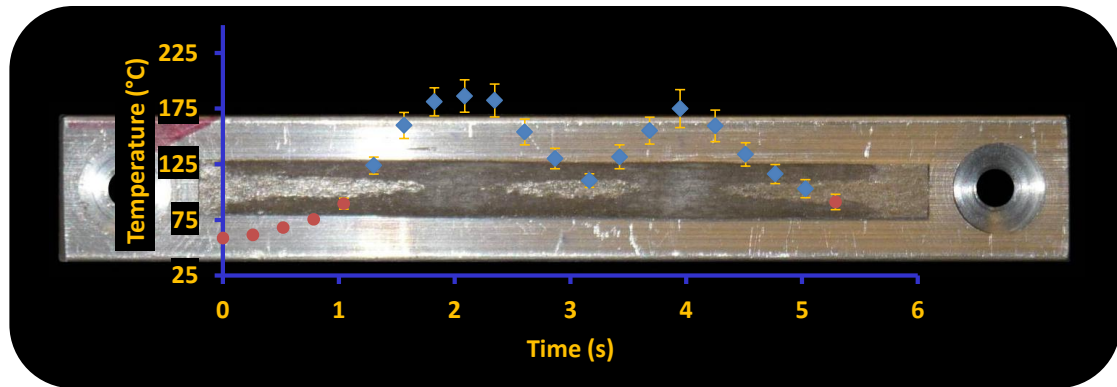


Figure 4.8 Temperature profile overlaid on post UC tape-substrate sample. Red markers indicate average transient (entry/exit effects) temperatures, blue are steady state (full horn contact), and error bars denote $\pm$ one standard deviation of the reported width-wise temperatures.

4.1.2 The Influence of Substrate Width on Weld Energy Oscillations

Four different substrate widths ranging from 1 inch to 3 inches will have MetPreg MMC tape welded to them under identical processing conditions to assess the influence of the substrate width on weld energy oscillations. Thermal differences will be used to quantify the magnitude of any weld energy oscillations. Figure 3.26 reveals that the pressure distribution is constant along the length of a substrate when ultrasonic energy is not being applied, therefore variations in weld energy will be attributed to fluctuations in the applied amplitude and not geometric material variations. Figure 4.9 shows the variation in nip point temperatures as the horn rolls across MMC tapes being welded to a one inch and three inch substrate. The average

temperatures for welds on each substrate are only 7% different from each other. The minimum to maximum temperature percent difference along the stable weld region (the blue diamond data points) is 66% (88 °C) for the one inch substrate and 20% (28 °C) for the 3 inch substrate. 1.5 inch and 2 inch substrates were also tested. The results of this experiment are summarized in figure 4.10 where average nip point temperature, standard deviation and coefficient of variation are plotted. Average temperature varies slightly as substrate width changes, but standard deviations fall in overlapping regions. This indicates that the average weld temperature is not heavily influenced by the substrate width. The coefficient of variation can be used to quantify the amount of weld energy variation, and is calculated based on the standard deviation of the nip temperature vs. time. This is done so that variation along the width does not obscure the effects of harmonic interference. The coefficient of variation consistently decreases as the substrate width is increased from one inch (22% CV) to 3 inches (6% CV). Nip temperature data for each weld and welder setup information is available in Appendix D. Several other welding arrangements were tested with both foils and MMC tape and are also presented in appendix D.

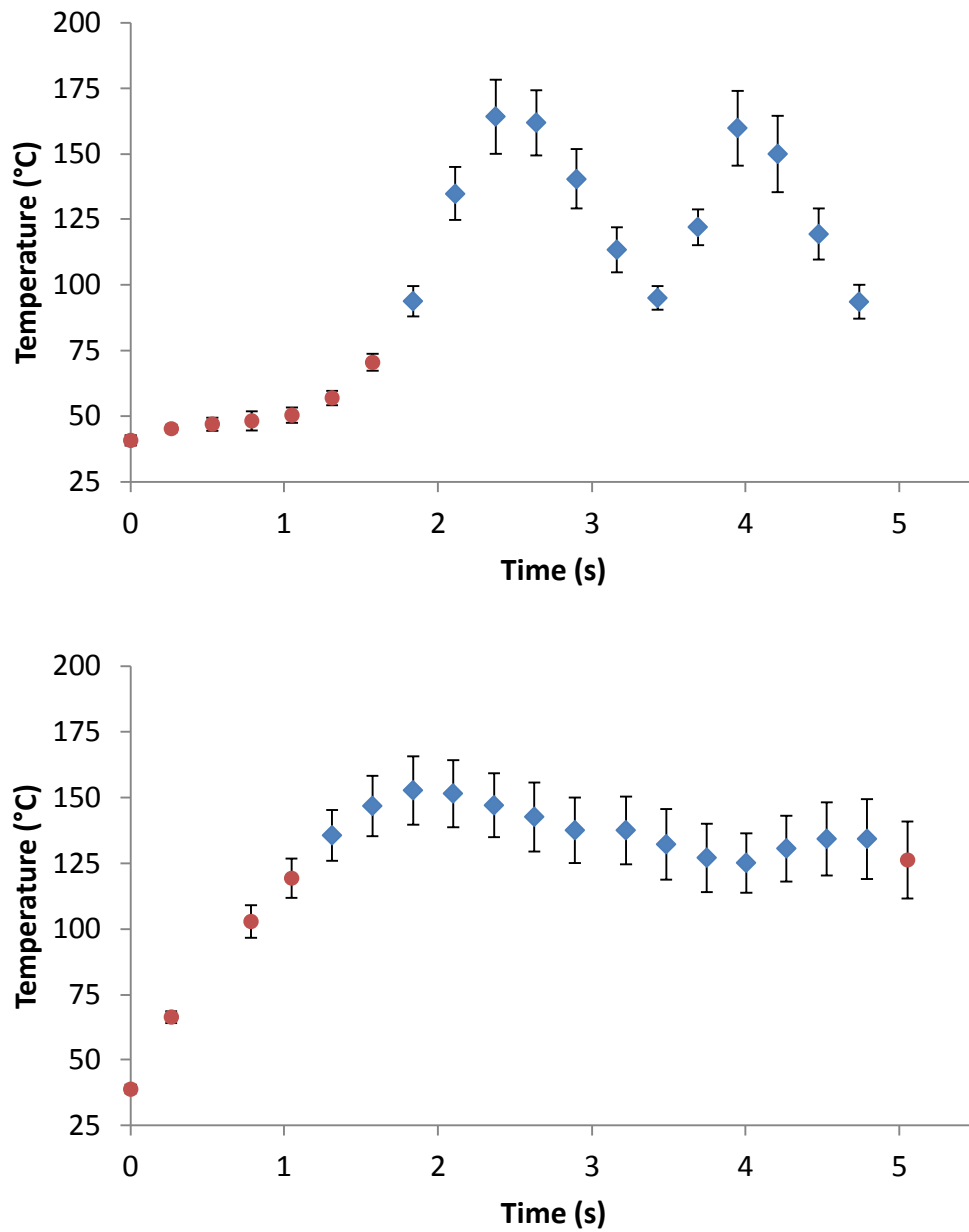


Figure 4.9 MetPreg MMC Tape welded to 1 inch (top) and 3 inch (bottom) substrates under identical processing conditions. Red markers indicate average transient (entry/exit effects) temperatures, blue are steady state (full horn contact), and error bars denote $\pm$ one standard deviation.

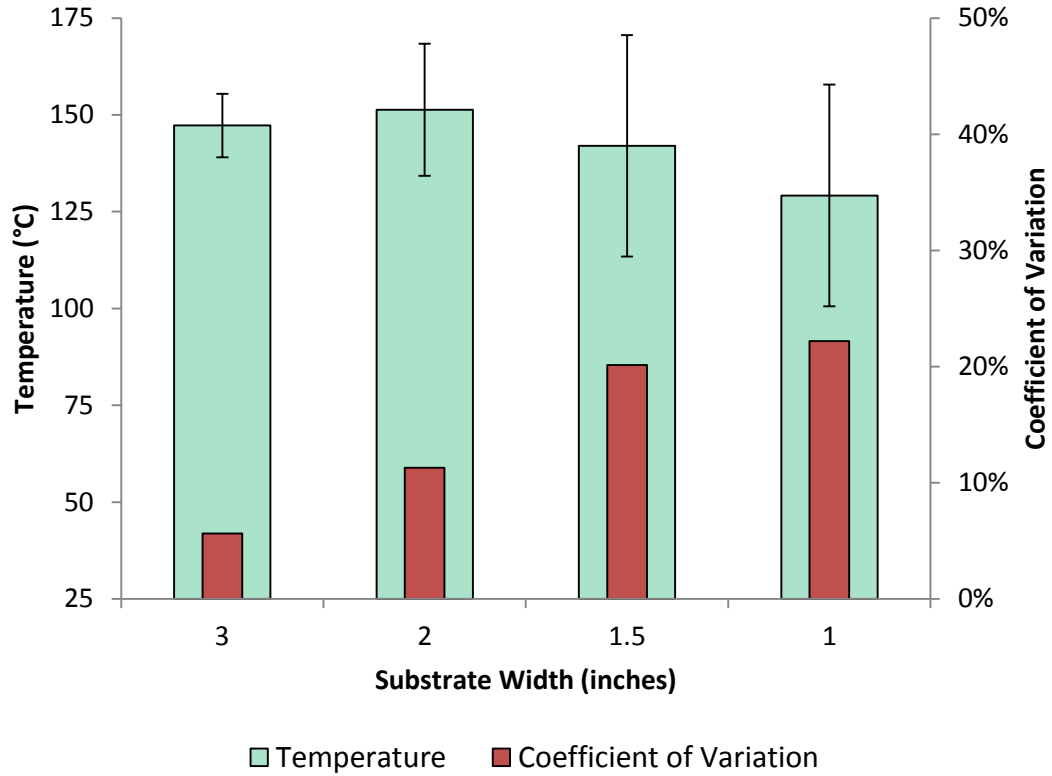


Figure 4.10 Effect of substrate width on average weld temperature and average nip point temperature coefficient of variation

4.2 Surface Roughness and Topography

An overview of the observations of unprocessed and UC surfaces using the scanning white light interferometer are presented in this section. Of interest quantitatively is the surface roughness and knurl indentation depth from the horn. Surface roughness reported is the average roughness, R_a . R_a is the average distance features of a surface profile are from the centerline (see equation 4.1). The position of

the centerline can be determined by averaging the position of all features relative to an arbitrary reference line.

$$Ra = \frac{(|x_1| + |x_2| + \dots + |x_n|)}{n} \quad \text{Eq. 4.1}$$

Knurl indentation depth is measured from the sample surface to the bottom of the indent (see figure 4.11). Any build up from displaced material around the indentation is not included in the measurement.

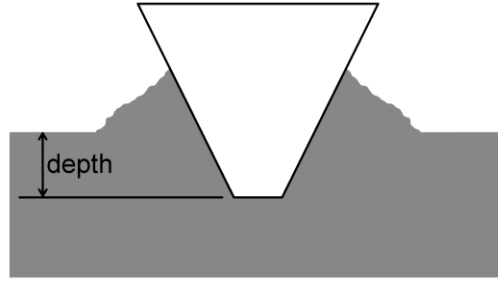


Figure 4.11 Knurl indentation depth measurement schematic

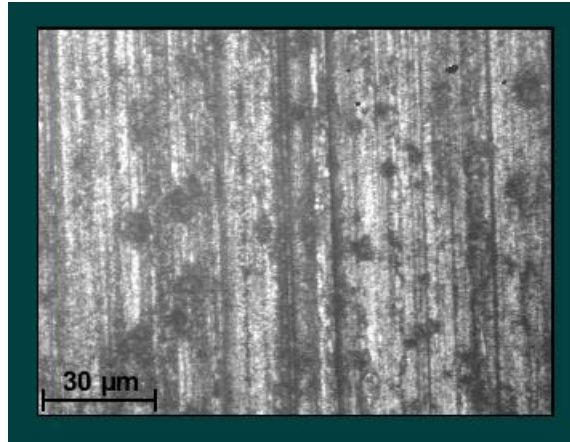
4.2.1 Unprocessed Samples

Both oxidized and cleaned foils have approximately the same surface roughness (Ra), $0.74 \mu\text{m}$ and $0.71 \mu\text{m}$ respectively, prior to UC. Substrates and MMC had much higher Ra values than foils, $2.3 \mu\text{m}$ and $2.8 \mu\text{m}$ respectively. This can be attributed to the process in which they were manufactured. Foils were likely rolled, while the tape and substrates were extruded. All of the materials show a grainy structure in the longitudinal direction. This may be from the tooling surfaces, and in the case of the MMC tape, also the fiber orientation. Figures 4.12, 4.13, 4.14, and 4.15 show the output from the SWLI for unprocessed materials (i.e. no exposure to UC). The data includes an image of the surface, a contour plot and a line profile. On

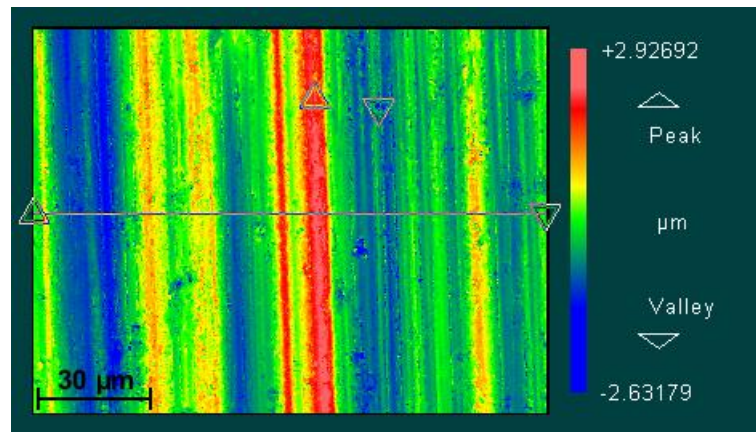
the contour plot two triangles mark the lowest and highest point on the surface. The pair of triangles with a line connecting them marks the area of interest displayed in the line profile.

While the Ra of oxidized and clean foils is similar, the effects of the acid cleaning are apparent. In figure 4.12a dark spots (likely precipitates) are visible, but not distinct. The cleaned foil on the other hand, figure 4.13a, image details are sharper, and the precipitates, now removed, appear as craters on the contour plot, figure 4.13b.

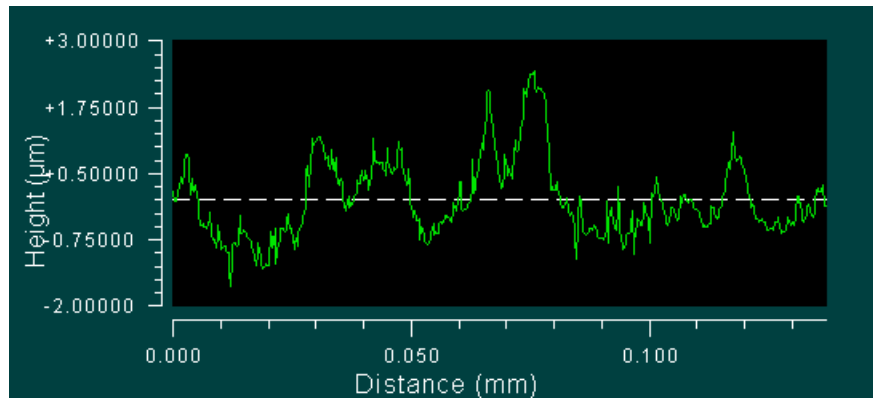
In addition to longitudinal grooving on the Al substrates there are additional shallow scratches in other various directions. Randomness suggests these may have occurred from impact and abrasion with other materials incurred during typical handling and machining practices. The MetPreg MMC tapes also present some additional irregularities on the surface, including nicks which may result in some fiber breakage. The Al_2O_3 fibers are approximately 10 micrometers in diameter, the same diameter of some of the *grooves*. This suggests that most of the grooves are actually the alumina ceramic reinforcement fibers.



(a)

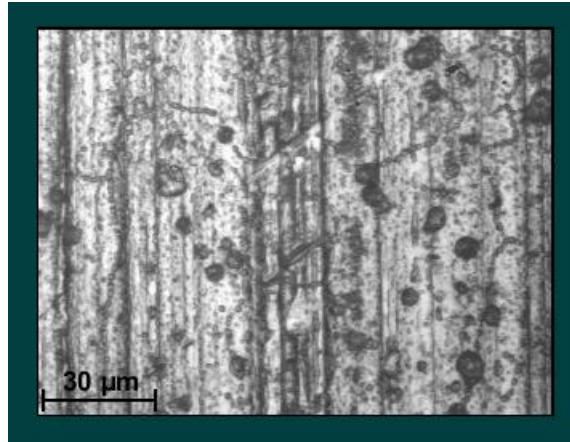


(b)

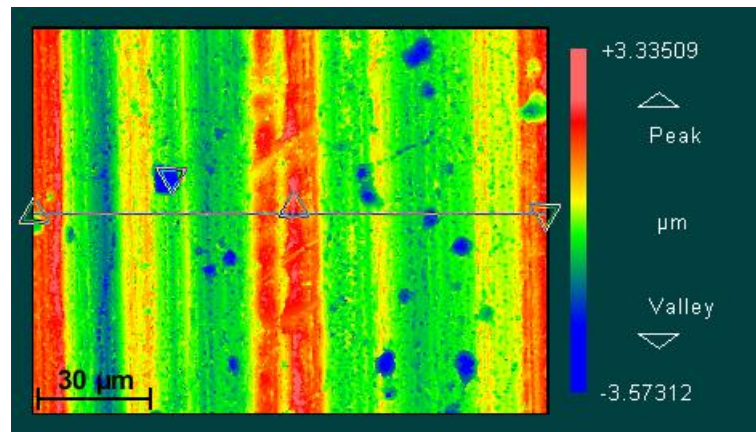


(c)

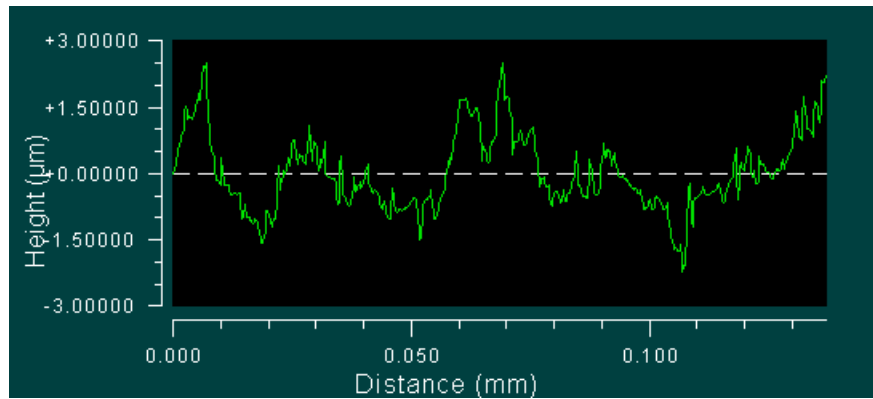
Figure 4.12 SWLI results for the surface of unprocessed oxidized foils. a) Surface image, b) contour plot, c) line profile.



(a)

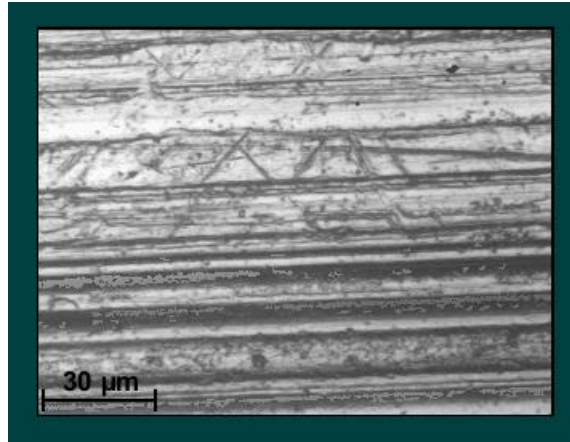


(b)

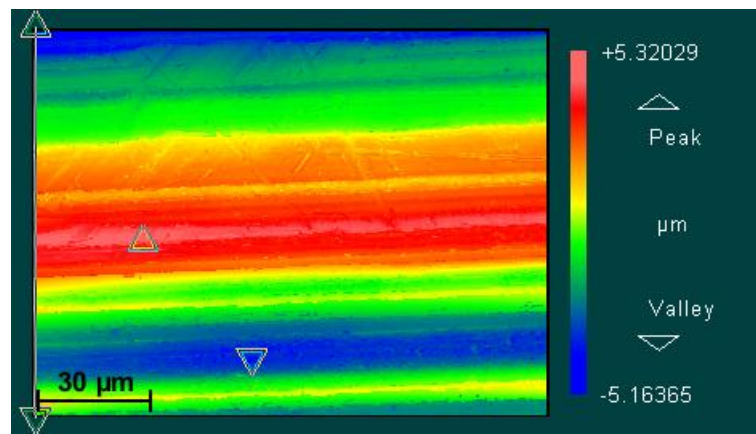


(c)

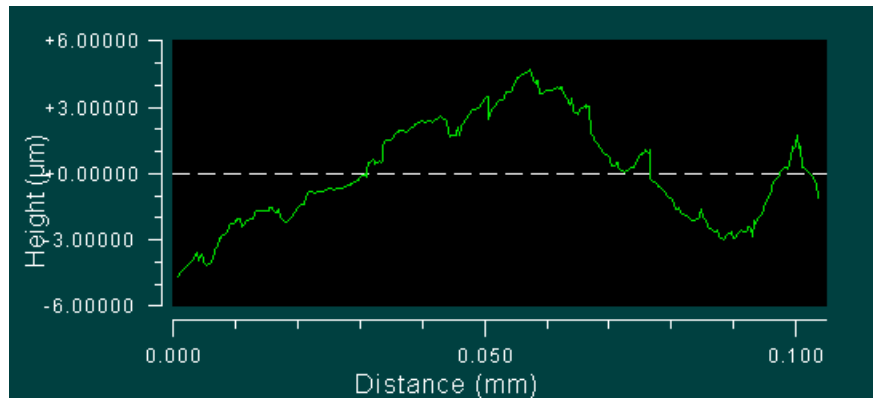
Figure 4.13 SWLI results for the surface of unprocessed cleaned foils. a) Surface image, b) contour plot, c) line profile.



(a)



(b)



(c)

Figure 4.14 SWLI results for the surface of unprocessed Al substrates. a) Surface image, b) contour plot, c) line profile.

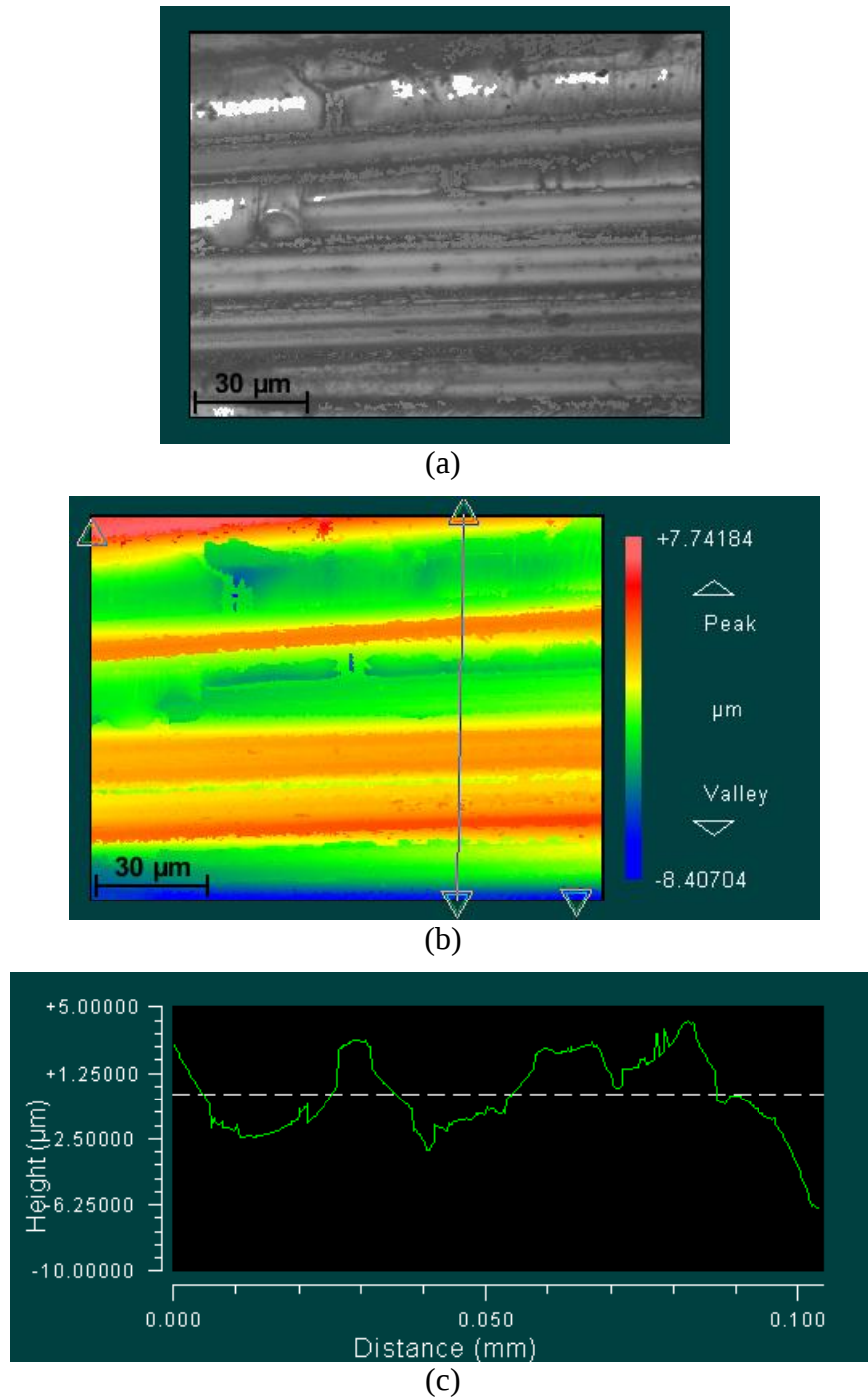
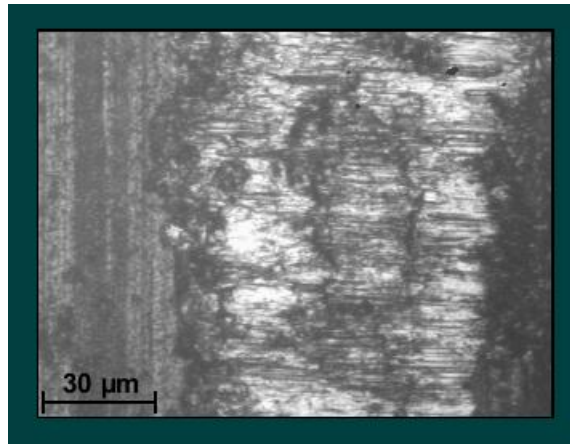


Figure 4.15 SWLI results for the surface of unprocessed MMC Tapes. a) Surface image, b) contour plot, c) line profile.

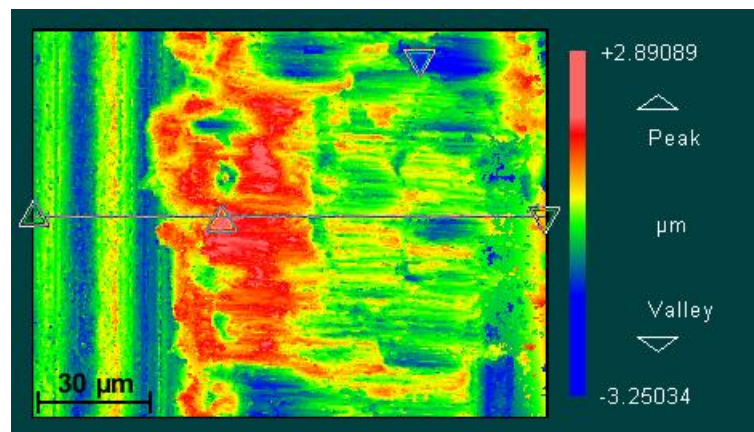
4.2.2 Post UC

Since welds performed with oxidized foils do not bond, the surface characteristics of the post processed weld interface are readily observed. While there is no significant change in surface roughness, there is evidence of wear due to the mating surfaces rubbing together. The SWLI results for the weld interface of UC foils are shown in figure 4.16 (versus the virgin surface shown in figure 4.12). Note smearing occurs perpendicular to the, now barely visible, original foil grooves, and parallel to the direction of applied ultrasonic oscillation.

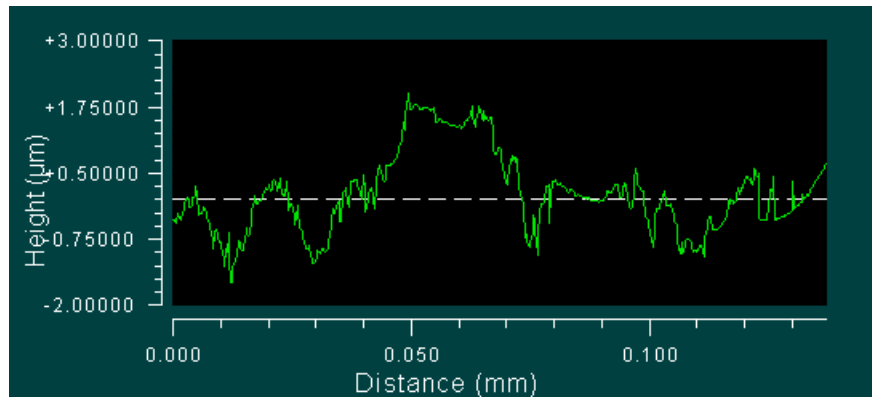
While the weld interface cannot be viewed for tape-substrate and clean foil-foil welds, the exposed post weld surface can be. The horn which grips the sample is knurled. The intent is to prevent slip, but as a consequence of the knurled surface an imprint is left behind altering the exposed surface for subsequent welds. This will in turn alter the weld dynamics, as any displaced material may need to be replaced to form an ideal weld. Figures 4.17 and 4.18 are images taken with the SWLI of the post weld knurl imprint left on foils and tapes, respectively. Images shown are of two different regions along the sample width, one is near the center, and the other is close to the edge. Since the MMC tapes used are thicker near the edges, the indentation depth is greatest near the edge and smallest at the center. This is confirmed by the SWLI data. For MetPreg MMC tape on average the knurl penetrates 20 μm deeper at the sample's edge than at the center. The foils are much more uniform geometrically, thus the indentation depth difference from edge to center was only 4 μm .



(a)



(b)



(c)

Figure 4.16 SWLI results for the weld interface surface between oxidized foils.
 a) Surface image, b) contour plot, c) line profile.

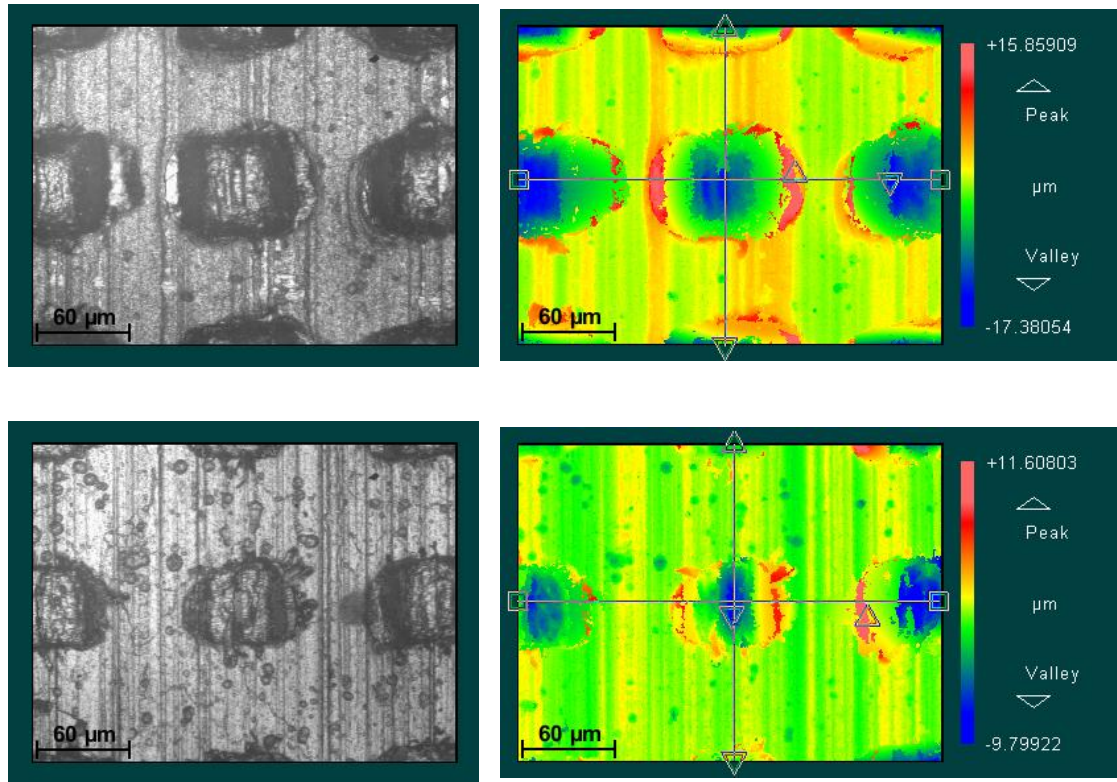


Figure 4.17 SWLI results of the knurl imprint imparted on foils during UC. Top images are from a region close to edge of the sample. Bottom images are from a region close to center of the sample.

Knurl indentation depths are summarized in figure 4.19. The MMC tape consists of a pure Al matrix, which has a yield Strength 8-16 times lower than the material used in the foils (Al alloy 6061 hardened to the T6 condition). The lower yield strength of the matrix material of the MMC tape requires more contact with the sonotrode to resist the clamping force. For this reason, indentation depths are larger for tapes than foils.

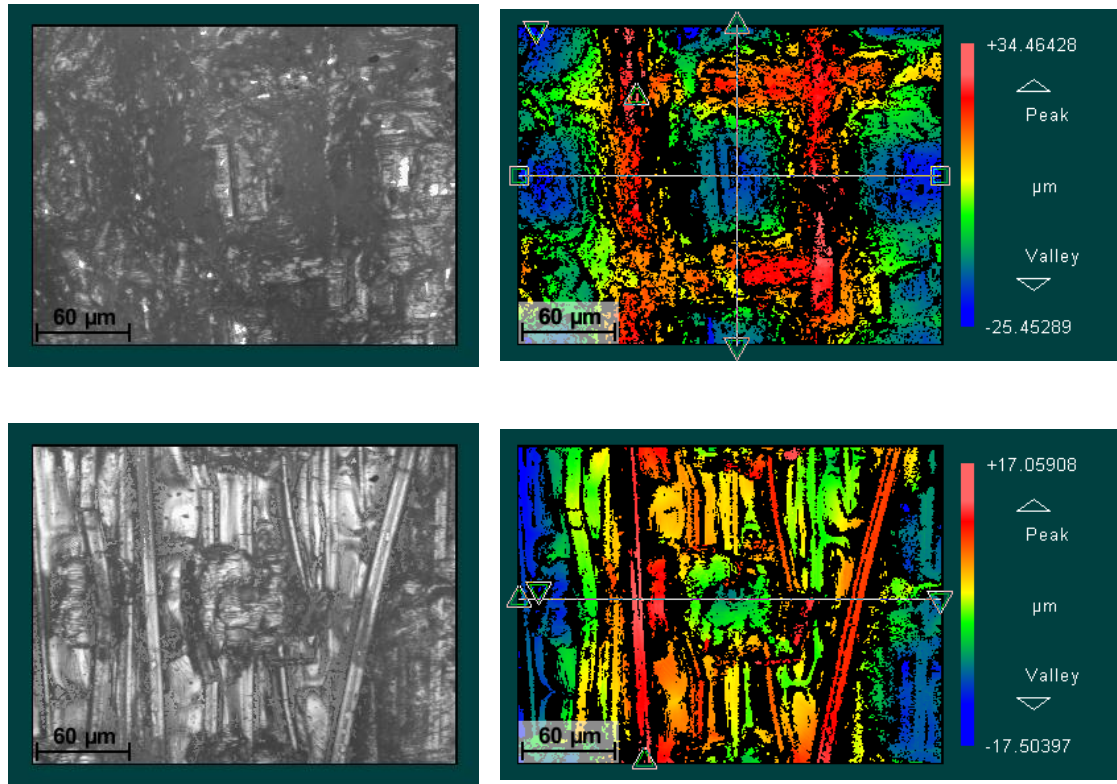


Figure 4.18 SWLI results of the knurl imprint imparted on MMC tapes during UC. Top images are from a region close to edge of the sample. Bottom images are from a region close to center of the sample.

Figure 4.20 illustrates the surface roughness data for each interface and material combination investigated. Values for foils are similar to each other, while the MMC tape is much rougher, particularly after consolidation. Measurements for tapes also vary greatly, in part due to the tapes non-uniformity. Minimizing non-uniformities in the tape supply would help to diminish processing variability.

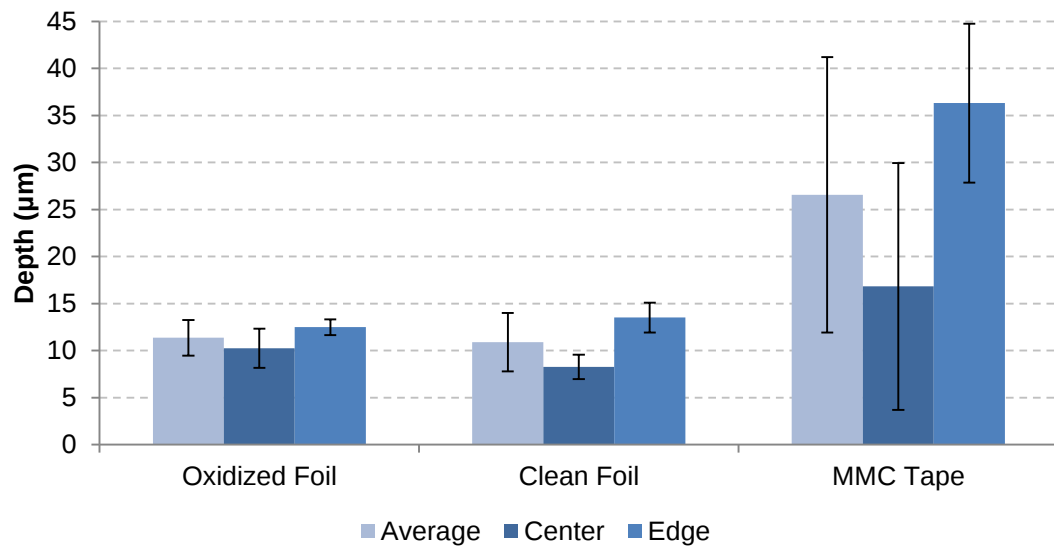


Figure 4.19 Knurl indentation depth and variation from sample edge to center

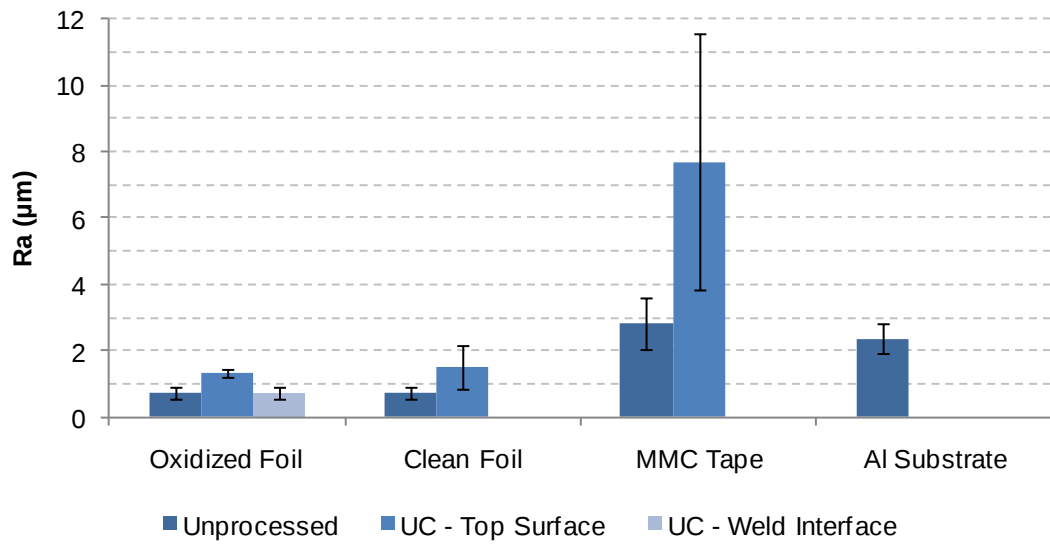


Figure 4.20 Unprocessed and UC sample surface roughness data

4.3 Contact Length, l_c

The contact length between materials to be consolidated was determined by performing a series of spot welds over a range of pressures. Spot welds were performed by welding a sample with a feed rate of 0 mm/s and amplitude of 24 μm for a duration of approximately 0.2 seconds. Upon separation of consolidated samples the length over which friction abraded the contacting surfaces is measured and defined to be the contact length. The abraded area was slightly larger than the previously bonded areas. This prevented any potential bias that could have occurred should tearing of the bonded region take place. Neither foil-foil welds nor tape-substrate bonds showed significant dependence of contact length vs. pressure (see figures 4.21, 4.22, and 4.23). That is to say, the apparent contact area did not depend on pressure; however, the real contact area will be influenced by the applied load since the sample's surface will deform until sufficient area is in contact to balance the applied load. While nip area contact length did not vary as a function of pressure, figure 4.22 qualitatively reveals an increase in real contact area as pressure increases from 10 to 40 psi for tapes. This effect is not apparent for foils, figure 4.23. The variation in real contact area will alter the contact geometry which, according to Blau's (2009) well documented book on friction concepts and applications, is known to affect the friction coefficient, which may be one of the reasons force can influence μ . For this model, apparent area is used, so variation in real contact area is not quantified. For foils and tapes the average contact lengths were 2.55 mm and 7.22 mm, respectively. The longer contact length between the tape and the substrate can be attributed to several factors including: narrower tape width, greater thickness, and softer base metal.

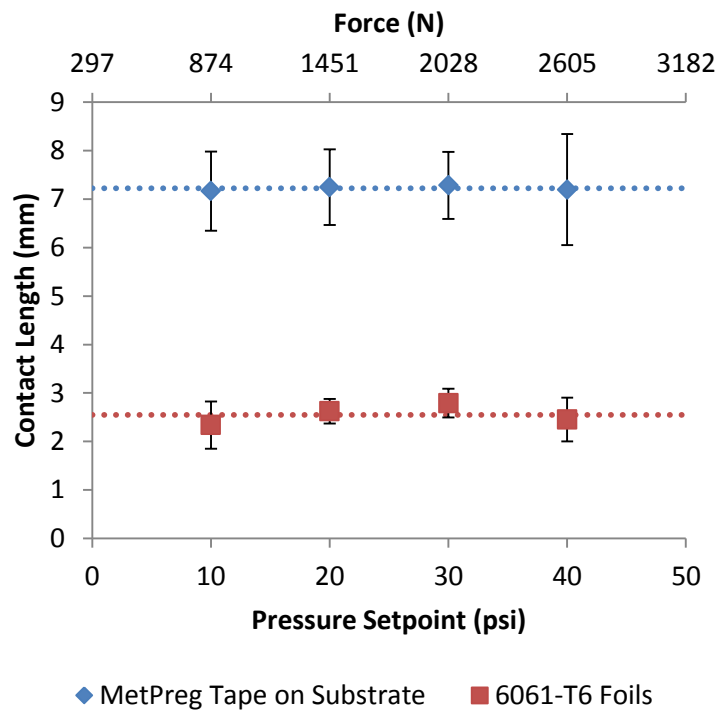


Figure 4.21 Contact length between consolidated materials as a function of applied load. (Koellhoffer et al. 2011)

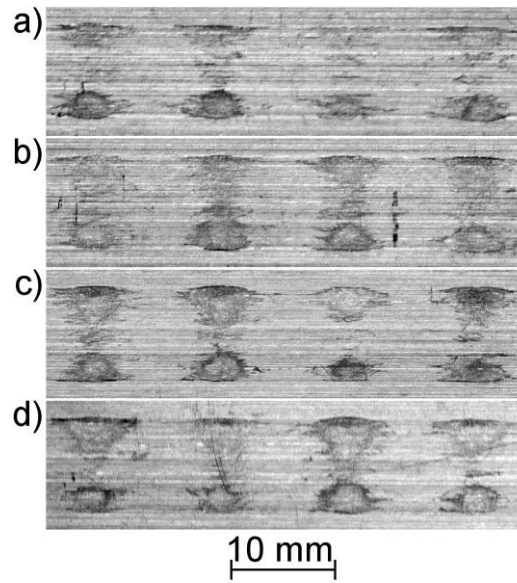


Figure 4.22 Contact length images of Al substrate surface for a) 10 psi, b) 20 psi, c) 30 psi, and d) 40 psi spot welds

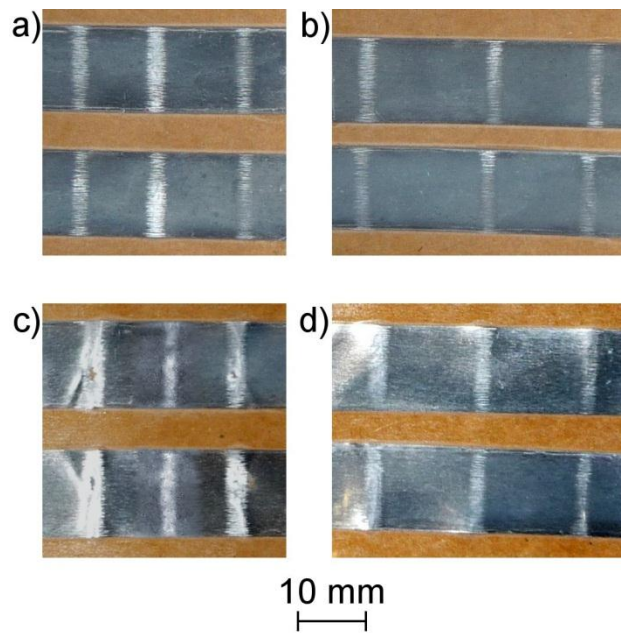


Figure 4.23 Contact length images of Al foil surfaces for a) 10 psi, b) 20 psi, c) 30 psi, and d) 40 psi spot welds.

4.4 Weld Temperature Testing

The temperatures measured from an initial test array for foils and tapes are presented in this section. This data will be used in section 4.5 to experimentally determine the friction coefficients. A subsequent validation test using the determined friction coefficients was then executed to indicate the model's accuracy and shown in section 4.6.

4.4.1 Parameter Selection

The selection process for welder parameters differed for foils and tapes. To minimize the effects of deformation, oxidized foils were given the maximum amount of energy that did not result in welding, thus allowing for pure slip throughout the welding process. The same parameter array was employed for cleaned foils to allow for direct comparisons. The oxide layer is much thinner for cleaned foils, so bonding did occur during consolidation. Therefore, cleaned foils may not slip throughout the entire weld duration. The modifications in surface characteristics will alter the frictional behavior. Blau's (2009) book reports that surface oxide presence has a lubricating effect, reducing μ . Therefore, increases in μ are anticipated and can be attributed to the pretreatment acid removal of lubricating surface oxides. Variations in μ may also result from bonding/no-slip deformational influences. While the additive contribution of deformational heat is small, the prevention of slip could result in less frictional heat generation; if this is the case the apparent μ (i.e. the μ calculated with this approach) will be smaller than the real μ at regions experiencing slip.

Tape welding parameters were chosen to achieve good bonding and uniform heating. A good bond is one in which the tape, or foil, breaks in tension or

flexure prior to fully debonding from its mating surface. This test is performed qualitatively. To date there is not an established testing method that can fully characterize the bond strength between UC materials; though, an extensive body of work on mechanical testing of ultrasonically consolidated thin foils has been performed at Loughborough University. In 2003 Kong et al. began their method development of mechanical testing of UC Al 6061 welds. In 2004(a) Kong et al. continued their work with Al 3003; methods such as lap-shear and peel test have been attempted; however typical failure modes do not occur uniformly in the bonded interface. Samples either break outside of the bonded region, or tear non-uniformly failing to capture the stable debonding load. Nevertheless, the peel test is the most commonly used method in Loughborough's work and was recently employed in Friel et al.'s (2010) paper to investigate the effect of surface topography for UC of Al.

Uniform heating is characterized by removal of the thermal edge peaks, or double peaks, shown in figure 4.2. As load levels increase, pressure in particular, greater levels of uniformity are achieved. Due to the thermal mass of the horn and substrate, edge effects cannot be completely eliminated.

The corresponding parameter ranges found to fit the desired welding criterion specified in this section are summarized in table 4.1. Note that tape-substrate welds used higher levels of all parameters than foil-foil welds. This was necessary to achieve uniform heating.

Table 4.1 Experimental parameter ranges used during UC. (Koellhoffer et al. 2011)

	Foil-Foil	Tape-Substrate
Amplitude (μm)	9.4 to 18.4	24 to 34
Force (N)	874 to 1739	1739 to 2605
Speed (mm/s)	87 to 123	10 to 56

4.4.2 Parameter Implementation

A design of experiments approach was taken to generate the UC test array. Design of experiments is a method often used to optimize or predict a system response, in this case temperature. A four level L16 orthogonal Taguchi array was employed to determine the friction coefficient by equating the experimental temperature and the predicted temperature. The L16 array used for the foil-foil tests and the tape-substrate test were run according to the sequence shown in table 4.2.

Table 4.2 Initial L16 Taguchi array. (Koellhoffer et al. 2011)

	Amplitude (μm)		Force (N)		Speed (mm/s)	
Sample #	Foils	Tape	Foils	Tape	Foils	Tape
1	9.4	34.0	1162	2028	99.2	25.4
2	12.4	24.0	874	1739	99.2	56.2
3	18.4	27.3	1739	2028	87.2	56.2
4	12.4	27.3	1451	1739	123	40.8
5	9.4	34.0	874	1739	87.2	10.1
6	15.4	24.0	874	2317	111	25.4
7	9.4	27.3	1451	2605	111	25.4
8	15.4	30.7	1451	2028	87.2	10.1
9	15.4	24.0	1162	2605	123	10.1
10	18.4	34.0	1162	2605	111	56.2
11	12.4	30.7	1739	1739	111	25.4
12	18.4	24.0	1451	2028	99.2	40.8
13	12.4	27.3	1162	2317	87.2	10.1
14	9.4	34.0	1739	2317	123	40.8
15	18.4	30.7	874	2317	123	56.2
16	15.4	30.7	1739	2605	99.2	40.8

4.4.3 Weld Temperature Results

The temperature results from the initial L16 array are shown in figure 4.24. Sample numbers from table 4.2 correspond to the test numbers in figure 4.24. Tape-substrate temperatures were obtained by averaging all temperature contours in the length and width direction. Foil temperatures were obtained by averaging the maximum temperature recorded for each contour. As previously indicated maximum temperature was used for foils because it is less computationally intensive to obtain. Since the Biot number of the foils is low (i.e. temperature is spatially invariant), maximum and average temperatures are comparable and follow the same trends. As

expected there is a large amount of variability among the computed friction coefficients.

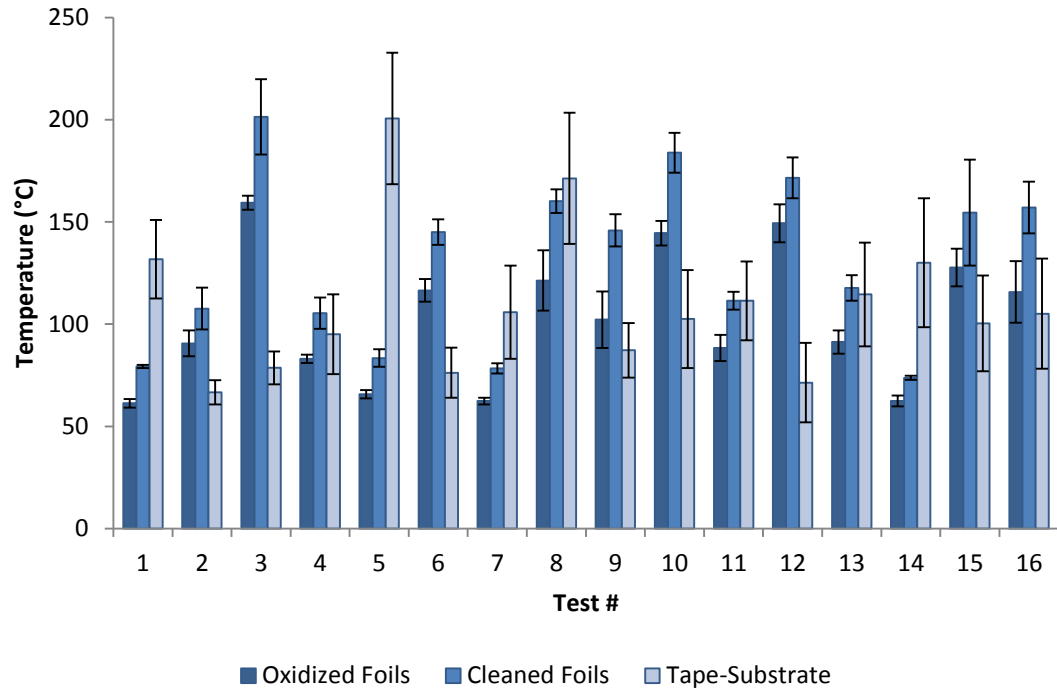


Figure 4.24 L16 temperature results. (Koellhoffer et al. 2011)

4.5 Friction Coefficient Determination

For foils, equation 2.12 was solved explicitly for μ as a function of temperature. For tapes, μ was found iteratively from inverse modeling. Equation 2.12 could also be used to determine approximate friction coefficient values for tapes if a FE package is not available, however spatial variations of temperature would not be captured if using the lumped parameter model for tapes. Therefore, if temperature

gradients are a concern, the lumped parameter approach is not recommended for predicting tape processing temperatures.

With a 16 sample test array, the end result for both foils and tapes is a series of 16, likely different, friction coefficients; one for each weld. These values are averaged if one wants to report a single value, μ_{constant} , or further analysis is carried out to determine a parameter dependent function, μ_{RSM} .

To determine μ_{constant} all 16 values were averaged. This results in a single valued constant friction coefficient, $\mu_{\text{constants}}$ which is valid over the range of processing parameters tested. To find μ_{RSM} a response surface model (RSM) was generated which fits a surface to the experimentally determined friction coefficients. This is done by fitting a quadratic equation, which includes all linear combinations of parameters according to a second order polynomial, equation 4.2, to the experimental data.

$$\begin{aligned} \mu_{RSM} = & b_0 + b_{\lambda}\tilde{\lambda} + b_F\tilde{F} + b_s\tilde{s} + b_{\lambda\lambda}\tilde{\lambda}^2 + b_{FF}\tilde{F}^2 + \dots \\ & \dots + b_{ss}\tilde{s}^2 + b_{\lambda F}\tilde{\lambda}\tilde{F} + b_{\lambda s}\tilde{\lambda}\tilde{s} + b_{Fs}\tilde{F}\tilde{s} \end{aligned} \quad \text{Eq. 4.2}$$

Where the b 's are the fitting coefficients and $\tilde{\lambda}$, $\tilde{F}$, and $\tilde{s}$ are coded welder parameters; all of which are dimensionless. Coded parameters vary between -1 and 1 taking the form:

$$\tilde{x} = \frac{x - x_{avg}}{\Delta x} \quad \text{Eq. 4.3}$$

$$\Delta x = \frac{x_{max} - x_{min}}{2} \quad \text{Eq. 4.4}$$

The credibility of μ , constant or variable, is assessed by comparing the trends in μ determined from the experiments to the expected trends from the literature

(figures 1.2, 1.3, and 1.4). Once the coefficient of friction is characterized a new test array was created to evaluate the model's predictive accuracy.

4.5.1 Constant Friction Coefficient Results ($\mu_{constant}$)

Calculated friction coefficients from the initial L16 array temperatures (figure 4.24) are shown in figure 4.25. Sample numbers from table 4.2 correspond to the test numbers in figure 4.25. A summary of friction values obtained is shown in table 4.3. The range of results determined in this study fall within the same range as reported in the literature (see figures 1.2, 1.3, 1.4, and 1.5).

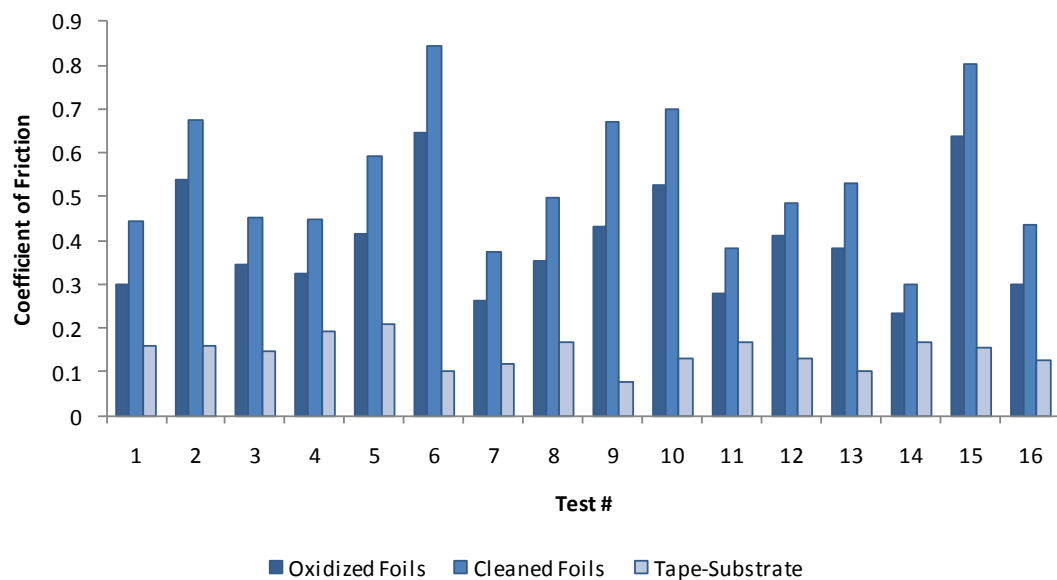


Figure 4.25 L16 results – friction coefficients. (Koellhoffer et al. 2011)

Table 4.3 L16 friction coefficients. (Koellhoffer et al. 2011)

	Average	Minimum	Maximum	Coefficient of Variation
Oxidized Foils	0.399	0.233	0.644	32%
Cleaned Foils	0.539	0.301	0.843	29%
Tape-Substrate	0.145	0.076	0.211	24%

The friction coefficient for tape-substrate welding is substantially lower than that of the foil-foil. This is a result of differing loading conditions and material properties. For foil-foil welds, loads were chosen specifically to avoid plastic deformation. However, this was not the case for the MetPreg tape-substrate welds. For tape welds the applied clamping force alone produced an average normal stress of 30 MPa which is comparable to the matrix material's room temperature yield strength of 17 to 34 MPa. Additionally, changes to the tapes cross sectional area post-welding also support the presence of bulk plastic deformation during consolidation. Bhushan's (1999) comprehensive textbook on tribology presents a preliminary derivation for plastic contact of ductile metals which suggests $\mu \leq 1/5$; this is much lower than typical sliding friction coefficients. Blau (2009) also reports significant reductions in μ , from 0.71 to 0.18, for pure aluminum at high forces. This supports the decreased friction coefficient observed during UC of tapes.

Friction coefficients also differed when comparing oxidized and cleaned foils. Oxidized foils have a larger amount of aluminum oxide, Al_2O_3 , present on the surface as compared to cleaned foils. Bhushan's (1999) textbook reports self-mated friction coefficient values for Al are higher than that of Al_2O_3 . In addition to changing the surface oxidation levels, cleaning can remove trace lubricants and other contaminants. Blau's (2009) book describes that the more thorough the cleaning process, the higher the friction coefficient can become.

An interesting observation is the amount of variation during testing for each material pairing. The coefficient of variation, CV, of measured temperatures, T-CV, was just over 30% for all material pairings. For foils, oxidized and cleaned, this correlated to a μ -CV of roughly 30%, while tape-substrate welds had a μ -CV of only 20%. Thus, the friction behavior of an ultrasonically consolidated tape-substrate interface is not as easily influenced by welder parameters as a foil-foil interface. This could be a function of the large difference in time scales. Weld times were on average more than 10 times longer for tapes than foils. Thus it is more likely for the friction coefficient to have fully stabilized (figure 1.4, μ vs. N). Fiber reinforcement may also play a role by affecting the abrasion resistance of the contacting surfaces. By limiting wear, the surface properties could be less susceptible to external forces (i.e. welder parameter settings). An investigation into the wear mechanics of UC materials may provide more insight into this phenomenon.

4.5.2 Variable Friction Coefficient Results (μ_{RSM})

Minitab (2003) was used to perform the response surface model calculation as described in section 4.5. The RSM coefficients are shown in table 4.4. The values from table 4.4 are then paired with equation 4.2 to plot the trends of the friction coefficient for each material pairing over a range of amplitudes, forces, and speeds (figures 4.26, 4.27, and 4.28). For the coefficient of friction versus force plots, corresponding contact pressures are included based on the ratio of applied clamping force to apparent contact area. Note the scale bar differences between foil and tape friction coefficient trends. As indicated in section 4.5.1, the process sensitivity of the friction coefficient for foil-foil welds (oxidized or cleaned) is larger than that of MMC tape-to-aluminum substrate welds.

Table 4.4 μ_{RSM} - response surface model coefficients. (Koellhoffer et al. 2011)

RMS Coefficient	Oxidized Foils	Cleaned Foils	Tape-Substrate
b_0	0.3885	0.5430	0.1462
b_λ	0.0952	0.0897	0.0238
b_F	-0.1547	-0.1771	-0.0269
b_S	0.0015	0.0221	0.0087
$b_{\lambda\lambda}$	-0.0173	-0.0470	-0.0077
b_{FF}	0.0561	0.0464	0.0067
b_{SS}	-0.0201	-0.0067	-0.0018
$b_{\lambda F}$	-0.0326	-0.0082	-0.0040
$b_{\lambda S}$	-0.0383	-0.0094	-0.0119
b_{FS}	0.0129	-0.0122	0.0018

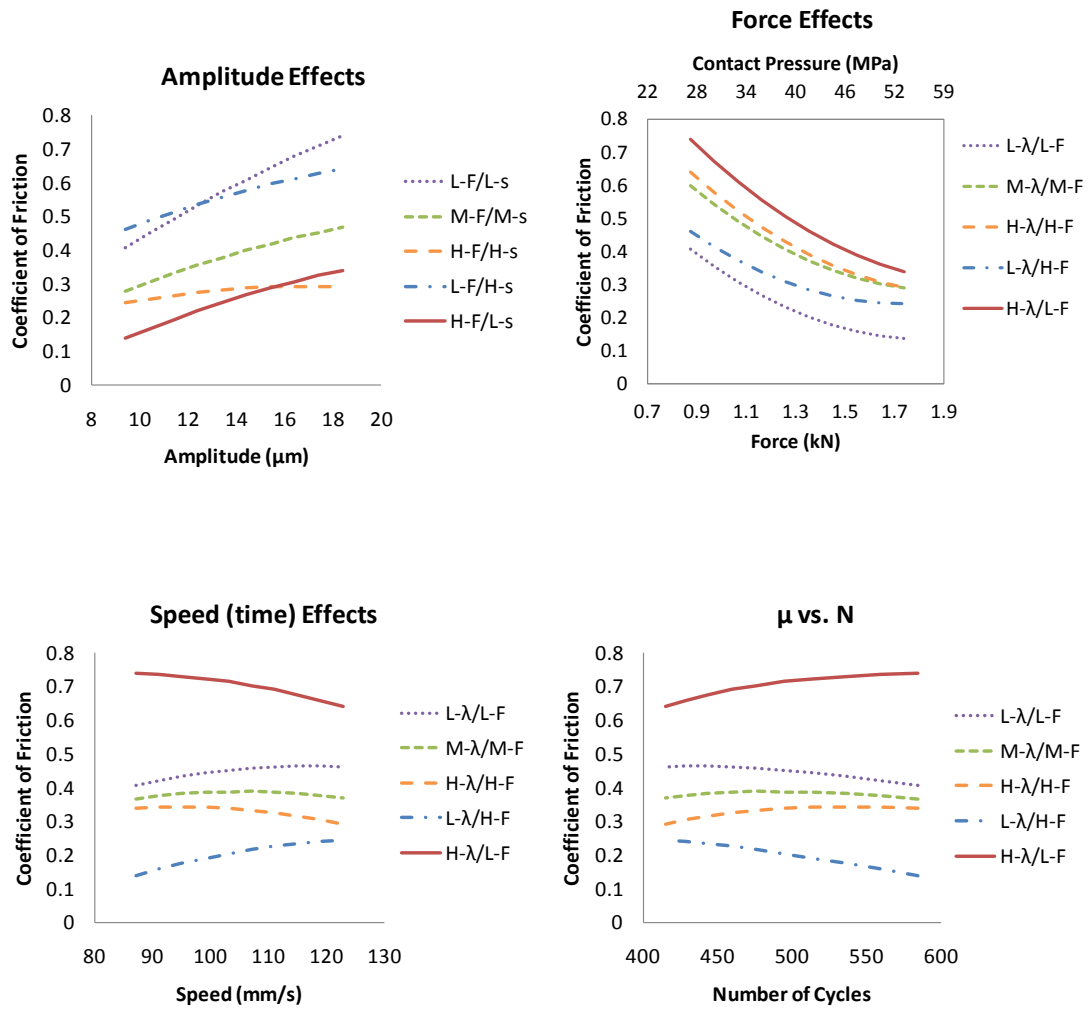


Figure 4.26 Friction Coefficient Trends – Oxidized Foils - L, M, and H correspond to Low, Medium, and High welder parameter levels respectively. Low is the lowest setting tested experimentally, Medium is the average, and High is the highest. (Koellhoffer et al. 2011)

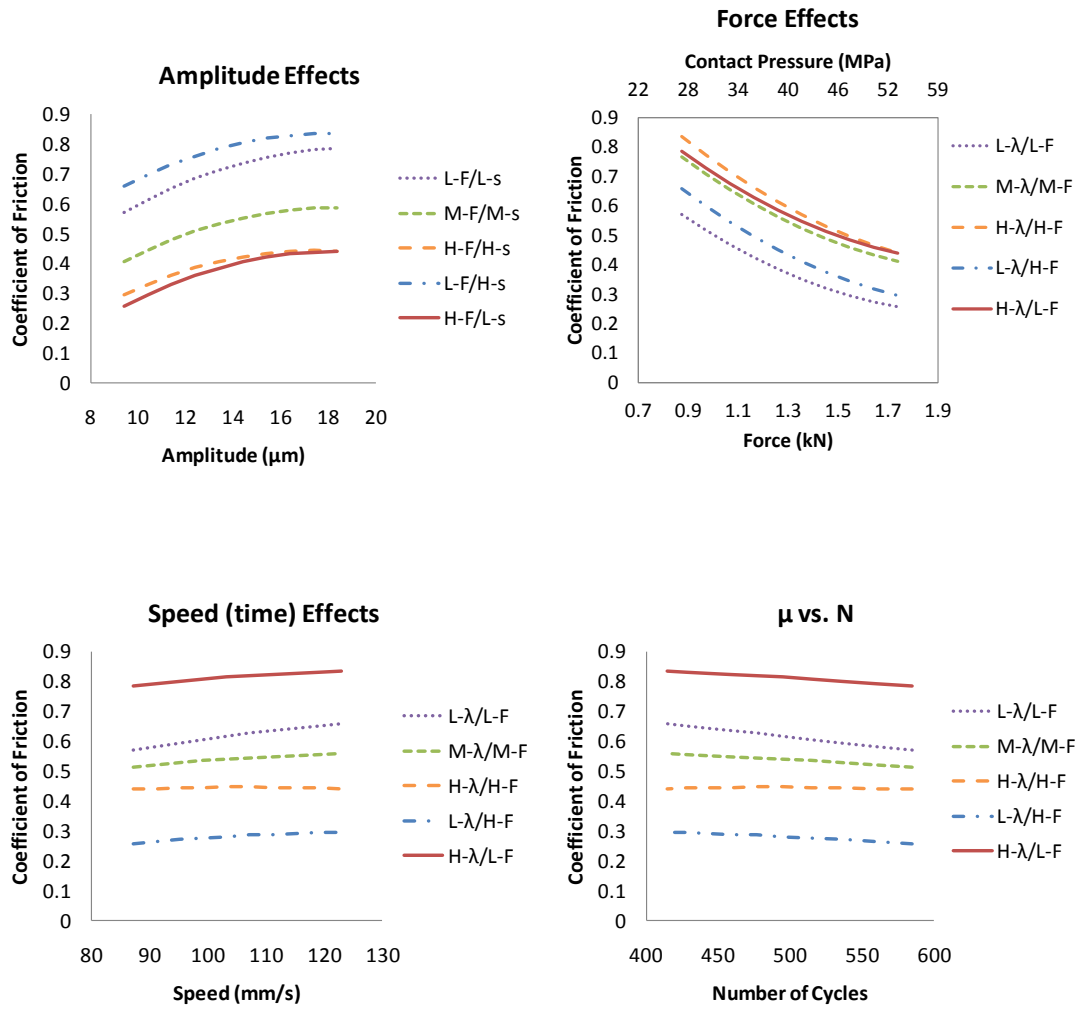


Figure 4.27 Friction Coefficient Trends – Cleaned Foils - L, M, and H correspond to Low, Medium, and High welder parameter levels respectively. Low is the lowest setting tested experimentally, Medium is the average, and High is the highest. (Koellhoffer et al. 2011)

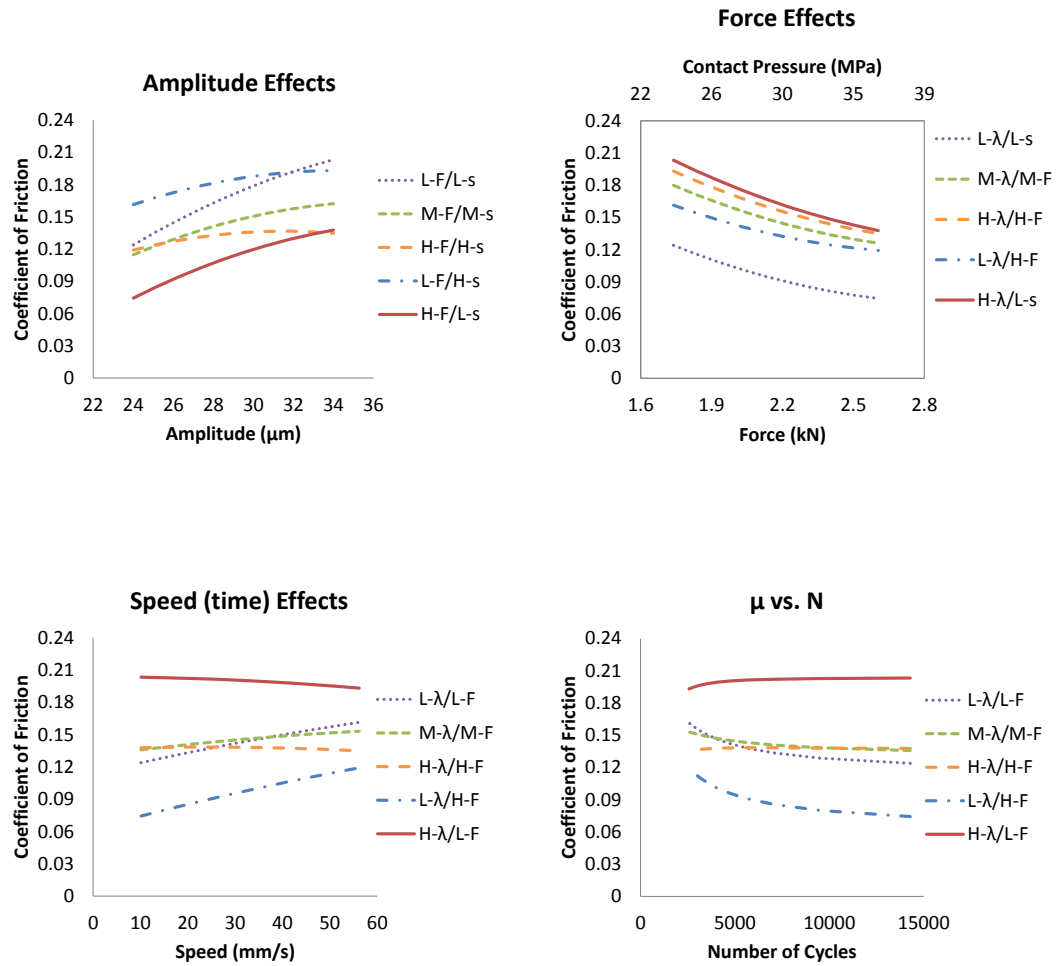


Figure 4.28 Friction Coefficient Trends – Tape on Substrate - L, M, and H correspond to Low, Medium, and High welder parameter levels respectively. Low is the lowest setting tested experimentally, Medium is the average, and High is the highest. (Koellhoffer et al. 2011)

4.5.3 Friction Coefficient Validity

There is good correlation in the coefficient of friction trends when comparing the experimental results here, figures 4.26, 4.27, and 4.28, to fretting fatigue experiments done by Naidu and Raman (2005), figures 1.2, 1.3, and 1.4. In

figures 4.26, 4.27, and 4.28, L, M, and H correspond to Low, Medium, and High welder parameter levels respectively. Low is the lowest setting tested experimentally, Medium is the average, and High is the highest. From figures 4.26, 4.27, and 4.28, an increase in oscillation amplitude causes an increase in μ , while normal force has a diminishing effect. This directly correlates to the literature findings. On the other hand, speed, or number of cycles, N , has little effect on μ . Under isothermal conditions, speed should have no effect on μ , however, UC is not an isothermal process, and thus lower speeds (higher N) correspond to higher temperatures. This introduces the potential for error since μ does depend on temperature as illustrated by Zhang and Li's (2007) experimental results previously discussed in figure 1.5. As a result, the friction coefficient for both foils and tapes exhibit some dependence on speed which may be attributable to this effect. Thus, assuming μ does not depend on temperature introduces a small amount of error.

Another potential source of error is the presence of deformational heating. This model assumes that heat into the system is provided only by friction throughout the entire welding process. Thus, any heat generated due to the plastic deformation during the experimental process will be intrinsically lumped into the friction coefficient. However, contributions from deformation are small (section 2.3) and the μ trends across all material pairings are very similar suggesting the driving force behind the thermal development is also similar. When welding oxidized foils it was made certain that machine parameters were chosen so as to avoid effects from the deformational regime, in particular bonding. Thus, oxidized foils were welded under pure slip conditions, therefore it was friction dominant. Since trends in the friction coefficient from the friction dominated oxidized foil welds are similar for the other

material pairings, this supports that friction is also the dominant heating mechanism for cleaned foils and tape-substrate welds.

4.6 Validation

A new 3-by-3 test array was used to assess the model's temperature prediction accuracy and limitations. As both μ_{constant} and μ_{RSM} were characterized by minimizing the error between the predicted and experimental temperatures from the initial L16 array, a new test array was required for model validation. The 3-by-3 array used for the foil-foil validation tests and the tape-substrate validation test utilized the test sequence shown in table 4.5. The new test array consisting of three distinct values for each of the three processing parameters (F , s and λ) was executed experimentally and the values for the temperature field were recorded.

Table 4.5 Validation (3-by-3) array. (Koellhoffer et al. 2011)

Sample #	Amplitude (μm)		Force (N)		Speed (mm/s)	
	Foils	Tape	Foils	Tape	Foils	Tape
1	16.9	32.5	1595	2172	111	50.0
2	16.9	25.8	1018	1884	99.2	50.0
3	13.9	25.8	1018	2461	111	19.3
4	16.9	29.1	1307	2461	87.2	34.7
5	13.9	32.5	1307	1884	87.2	19.3
6	10.9	32.5	1018	2461	123	50.0
7	13.9	29.1	1595	1884	123	34.7
8	10.9	29.1	1307	2172	99.2	34.7
9	10.9	25.8	1595	2172	87.2	19.3

The thermal model (see equation 2.12 for foil welds and section 2.5.3 for tape welds) was used with the characterized value of both μ_{constant} and μ_{RSM} to predict the

temperatures and compare them to the experimental values. Predicted and experimental temperatures for each material pairing are shown in figure 4.29. Good agreement was achieved. A constant friction coefficient results in an error of 16% on average. While a parameter dependent friction coefficient reduces this error to 7%. The fitting error of the RSM is of the same order; therefore, 7% error is very good agreement. The average, maximum and minimum error percentages are summarized in table 4.6. While μ_{constant} did not result in a high average error, it did result in very high maximum error. The highest errors occurred when force and amplitude were out of phase with each other (i.e. one high, the other low). As with the L16 array used in section 4.4, temperature is reduced to an average value for each test. This is the case for both measured and predicted values. For foil predictions this is the only option since a lumped parameter model was employed. For tape welds temperature contours can be plotted across the foil width, and when plotted follow a parabolic distribution similar to that of the measured data in figure 3.6. The complete sets of predicted and measured average nip temperature distributions for the validation array are shown in figures 4.30 through 4.38. To facilitate quantitative comparisons of accuracy average temperature was used.

Table 4.6 Model accuracy within the range of parameters in which the friction coefficient is characterized. Error between model and experiments reported in percentages. (Koellhoffer et al. 2011)

	Oxidized Foils		Cleaned Foils		MetPreg MMC Tape	
	T(μ_{constant})	T(μ_{RSM})	T(μ_{constant})	T(μ_{RSM})	T(μ_{constant})	T(μ_{RSM})
Average	15%	9%	16%	5%	17%	7%
Min	2%	4%	3%	1%	5%	2%
Max	36%	21%	46%	8%	52%	16%

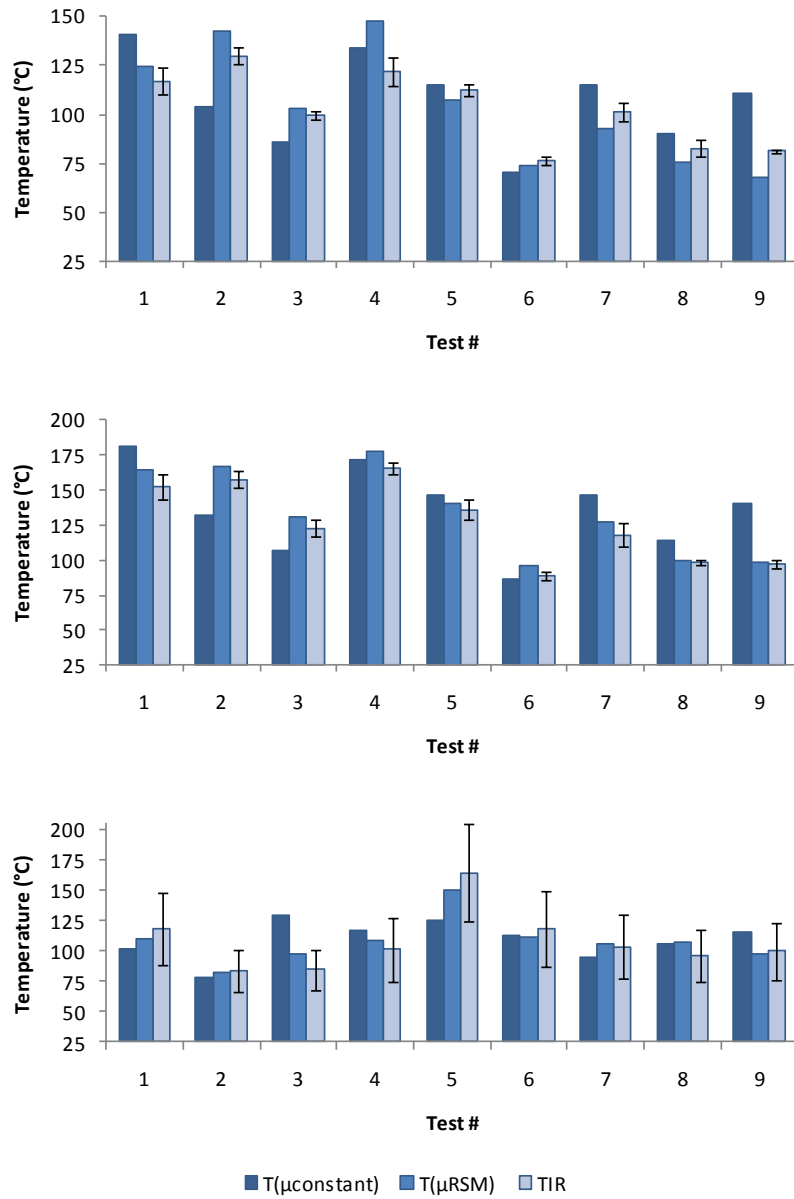


Figure 4.29 Model Validation Array (3-by-3 array): top, oxidized foil-foil; middle, cleaned foil-foil; bottom, tape-substrate. T IR is the experimentally measured average temperature (average maximum for foils and average of all data for tapes) with error bars indicating the size of the standard deviation, plus and minus. “T(μconstant)” and “T(μRSM)” are the analytic (foils) or FEA (tape) temperature solutions using a constant and parameter dependent (RSM) friction coefficient, respectively. (Koellhoffer et al. 2011)

The MMC tape accuracy values presented in table 4.6 are based on average temperature across the sample width for the FEA solutions, and average temperature across the sample length and width for the experimentally measured values. Since both experimental and model temperatures can be viewed two-dimensionally, it is also interesting to plot the width-wise temperature distribution of the FEA solution and the experimentally measured values. The two-dimensional experimental data is presented using spatially (*vertically*) averaged temperature curves (method described in section 3.3.2.2.2). The two-dimensional results for samples 1 through 9 of the 3-by-3 tape validation test are shown in figures 4.30 through 4.38.

While welding to substrates facilitated temperature uniformity for tape welds, samples still exhibit some non-uniformity. Qualitatively, sample 2 has the most width-wise variability. Conversely, samples 3, 5, and 9 have the most parabolic temperature distributions, and are indicative of uniform heating. Samples 3, 5, and 9 correspond to all welds performed at the lowest tested speed setting, 19.3 mm/s. Sample 2 utilized the highest test speed, 50 mm/s. All other samples exhibit some variability, and were welded at speeds of 34.7 mm/s to 50 mm/s. Lower speeds correspond to longer weld times. It is believed that the longer weld times permitted increased smoothing out (eroding) of geometric non-uniformities resulting in more uniform (parabolic) temperature distributions indicative of a uniformly applied (constant) frictional heat flux.

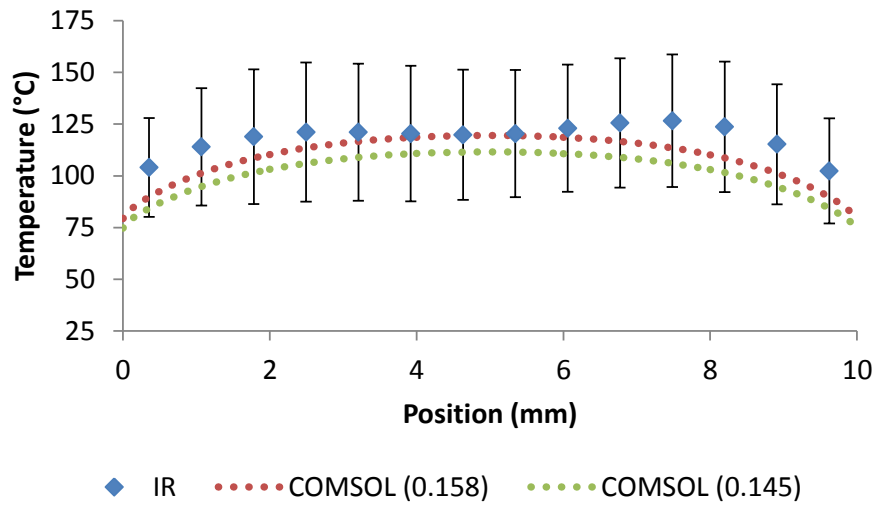


Figure 4.30 Tape validation sample 1. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.158$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

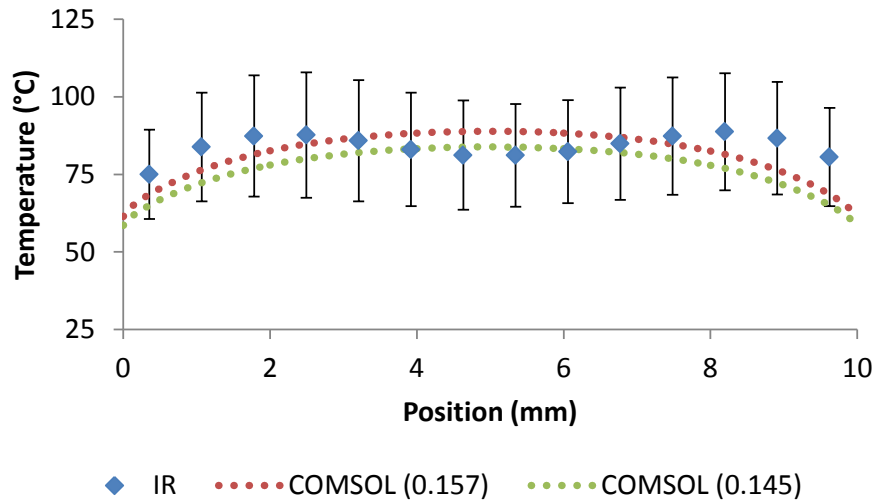


Figure 4.31 Tape validation sample 2. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.157$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

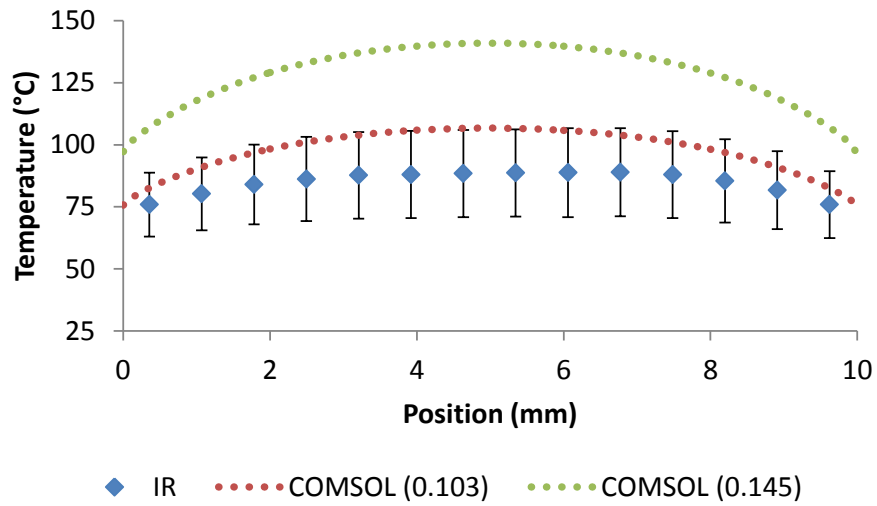


Figure 4.32 Tape validation sample 3. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.103$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

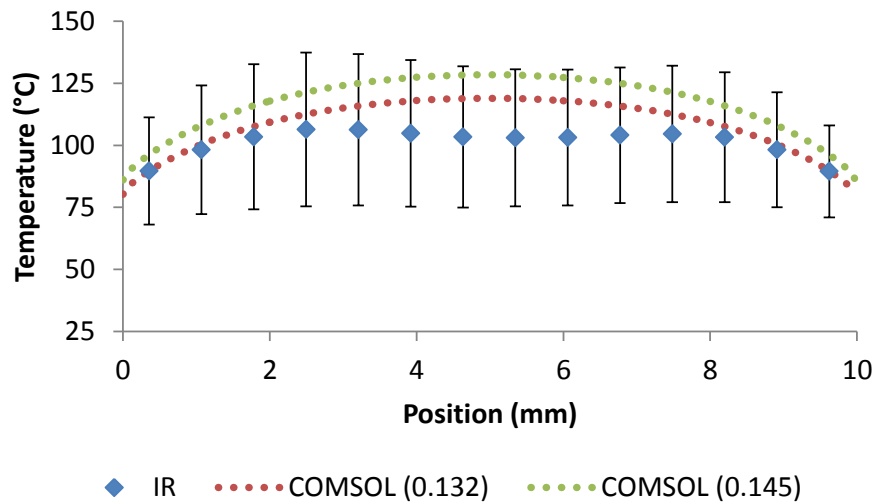


Figure 4.33 Tape validation sample 4. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.132$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

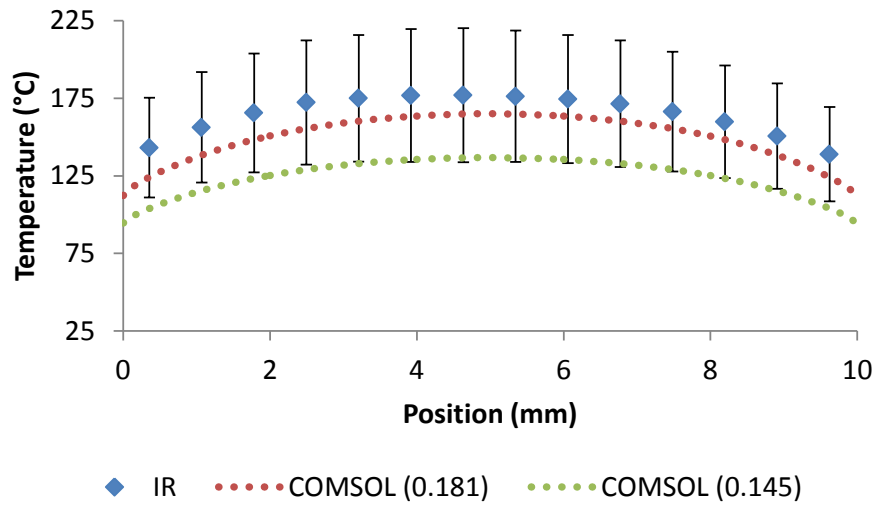


Figure 4.34 Tape validation sample 5. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.181$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

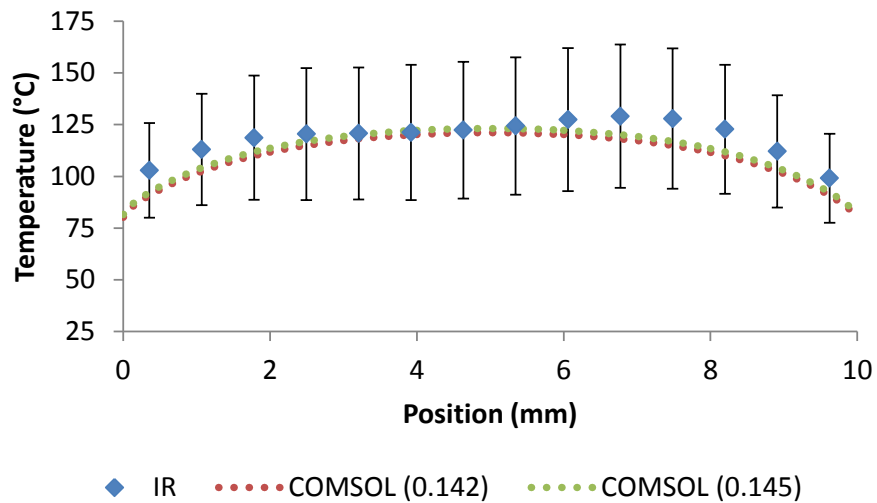


Figure 4.35 Tape validation sample 6. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.142$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

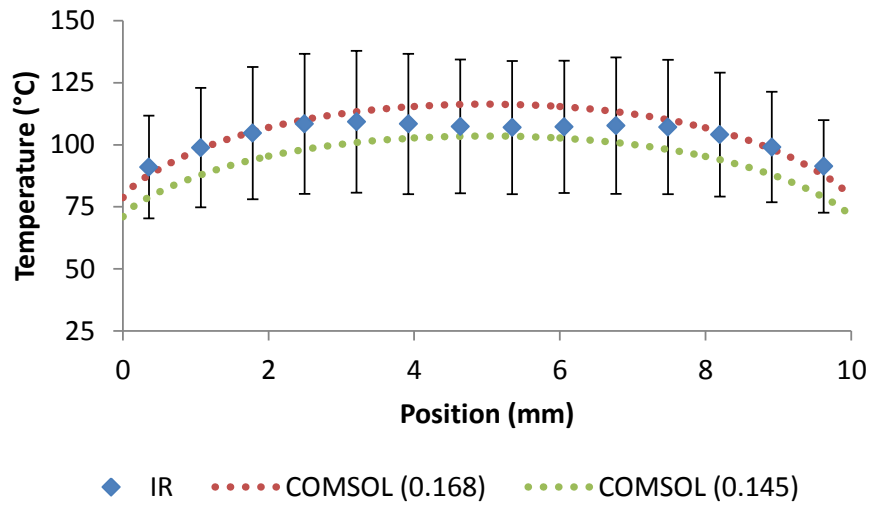


Figure 4.36 Tape validation sample 7. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.168$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

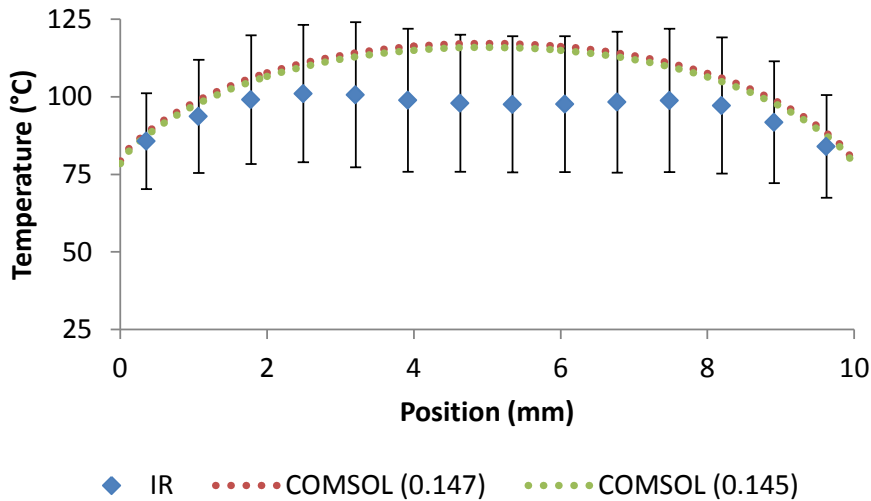


Figure 4.37 Tape validation sample 8. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.147$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

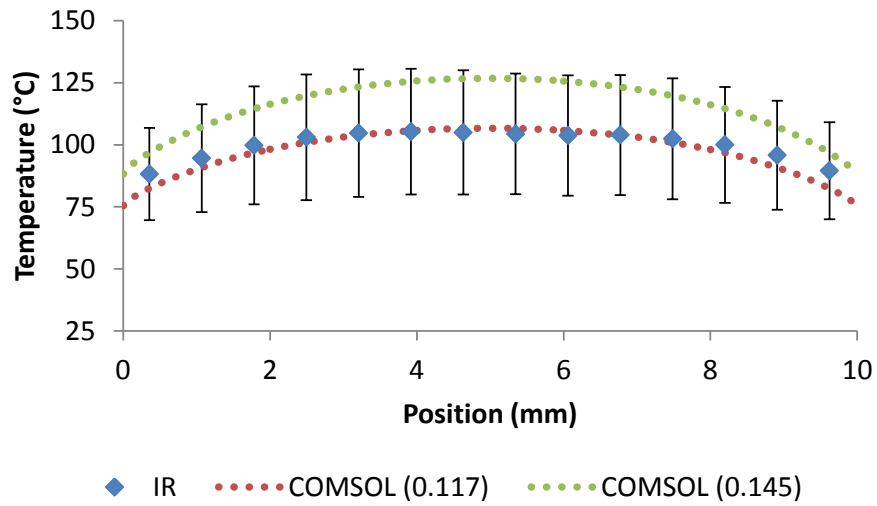


Figure 4.38 Tape validation sample 9. Temperature variation across tape width for experimental data (IR) and simulated data (COMSOL) for both variable $\mu = 0.117$ and constant $\mu = 0.145$. Variable, or process dependent, μ is determined via equation 4.2 and tables 4.4 and 4.5.

4.7 Summary

In this chapter all experimental testing and validation was presented. It was shown that given varied substrate dimensions, sample resonance can cause interference manifesting as sinusoidal temperature fluctuations. Narrower substrates resulted in larger fluctuations, while wider, and consequently stiffer, substrates diminish the interference.

The surface roughness and horn knurl indentation depth of foils and tapes, pre and post ultrasonic consolidation was measured using a scanning white light interferometer. Surface roughness and dentation depths are largest for tapes due to the fibers and soft matrix, respectively. Broken fibers were also evident on the tape surface where the knurl indented the tape's surface.

Horn-sample contact length was determined by performing spot welds. It was shown that the apparent contact length is largely independent of pressure. For all model inputs apparent area is used, therefore a constant contact length is sufficient for modeling applications.

To execute the thermal model, the friction coefficient must be known. By welding an array of samples at distinctly different speed, amplitude, and pressure process settings, and equating the experimental and predicted temperatures, the friction coefficient can be empirically determined.

Clean foils were found to have the highest friction coefficient, a result from increased bare metal contact, while tapes had the lowest coefficient of friction resulting from ductile contact points. Both clean and oxidized foils had similar amounts of process dependent friction coefficient variability, while tapes had considerably less.

Validation testing at additional process settings revealed model accuracies of approximately 16% for a constant friction coefficient and 7% for a process dependent friction coefficient.

In the next chapter a summary and conclusions for the entire body of research covered in this thesis are presented, as well as the contributions to the field from this research and the future work needed to make ultrasonic consolidation successful in manufacturing.

Chapter 5

SUMMARY AND CONCLUSIONS

Ultrasonic consolidation (UC) was used in this work to join aluminum (6061-T6) foils together and metal matrix composite (MMC) tapes (alumina reinforced pure aluminum) to aluminum (6061-T6) substrates. Both heavily oxidized and cleaned (via dilute nitric acid) foils were utilized to contrast welds maximizing friction and minimizing deformation (oxidized samples) to welds more susceptible to deformation (clean foils and MMC tapes). Oxidized foils bonded weakly or not at all, thus minimizing deformation. This allowed for experimental confirmation that deformation is not a major thermal contributor thru the comparison of experimentally determined friction coefficient trends.

Thermal models based on friction as the sole heat input term were utilized to first determine a material pair's friction coefficient under ultrasonic loadings, and then predict temperature for subsequent welds. The frictional heat flux term is based on the average work friction performs during UC. Foil-to-foil welds have minimal spatial variation of temperature, as proven via Biot's number and finite element analysis (FEA) simulations. For these materials, the thermal model was an analytic lumped parameter analysis (LPA) solution. However, an FEA model was used for foil-foil welds to determine a convective loss term representative of thermal losses to the foils' surroundings for the LPA solution. Conversely, tape-to-substrate welds were shown, via simulation and Biot's number, to have spatially varying temperatures. As

such, the model exclusively employed a two-dimensional FEA model to determine weld temperatures.

Experimental in situ weld temperatures were determined using infrared (IR) imaging. Images taken indicate the material's weld temperature just as the sample exits the horn-sample nip point. An L16 orthogonal Taguchi array for 16 samples was created using a design of experiments approach to develop a profile of temperatures linked to distinctly different speed, amplitude, and pressure welder settings for each material pairing. Using the LPA and FEA models, values for the friction coefficient were determined. This approach allowed for the determination of both a single valued, average, friction coefficient for each material pairing and a multivalued welder process setting parameter dependent friction coefficient. The trends observed for the process dependent friction coefficient were similar to literature values and each other. This supports the validity of the use of a heat input due to friction only in the UC thermal model. Average friction coefficients varied notably. Welded tapes revealed the lowest coefficient of friction of 0.15. Oxidized foils were found to have a friction coefficient of 0.40, and cleaned foils, 0.54. The low friction coefficient of tapes is attributed to plastically deforming contact points at the slip interface. The difference between oxidized and cleaned foils is due to the hardness and cleanliness of the surfaces. Oxide interactions have lower friction coefficients than base metal contact of cleaned foils.

Using the experimentally determined friction coefficients and the developed UC thermal models, three additional 9 sample test arrays (one for each material pairing) were modeled and then experimentally tested. The entire process used to develop the model for the MMC tapes is summarized in the MetPreg

processing flow chart, figure 5.1. Temperature prediction capabilities of both the constant and the process dependent friction coefficients were on average good for all tested materials. Errors were on average lowest for the process dependent friction coefficient, 7% versus 16% for a constant μ . However, maximum error was as high as 52% for a constant friction coefficient, versus 21% for a process dependent μ . Low amplitudes and high pressures (or vice versa) will cause the largest change in the friction coefficient, as both are decreasing (or increasing) μ from the average value. Therefore, if one wishes to accurately predict temperature for process settings of this type, a variable friction coefficient should be employed. The friction trend results from this thesis could be used as a scaling tool for additional material pairs when used in conjunction with an estimated friction coefficient.

In addition to the role of friction in the thermal development of UC it was also observed that welding to narrow substrates, pinned only at the ends, yields the potential for material resonance to affect the weld temperature. The resonance generated spatially consistent sample to sample thermal minimums and maximums. A modal response analysis revealed mode shapes with transverse sinusoidal deflections similar to observed thermal oscillations at frequencies within 20% of the applied welder frequency. A wider, and thus stiffer, substrate was shown both experimentally and numerically, thru the simulated modal analysis, to have decreased peak resonance amplitudes. More supported welds utilizing steel bars showed no obvious signs of harmonic interference. In a lab setting a well-supported anvil or substrate will minimize or eliminate thermal oscillations from sample resonance. For larger scale welds the part must be well supported, or have means to dampen horn imparted resonance.

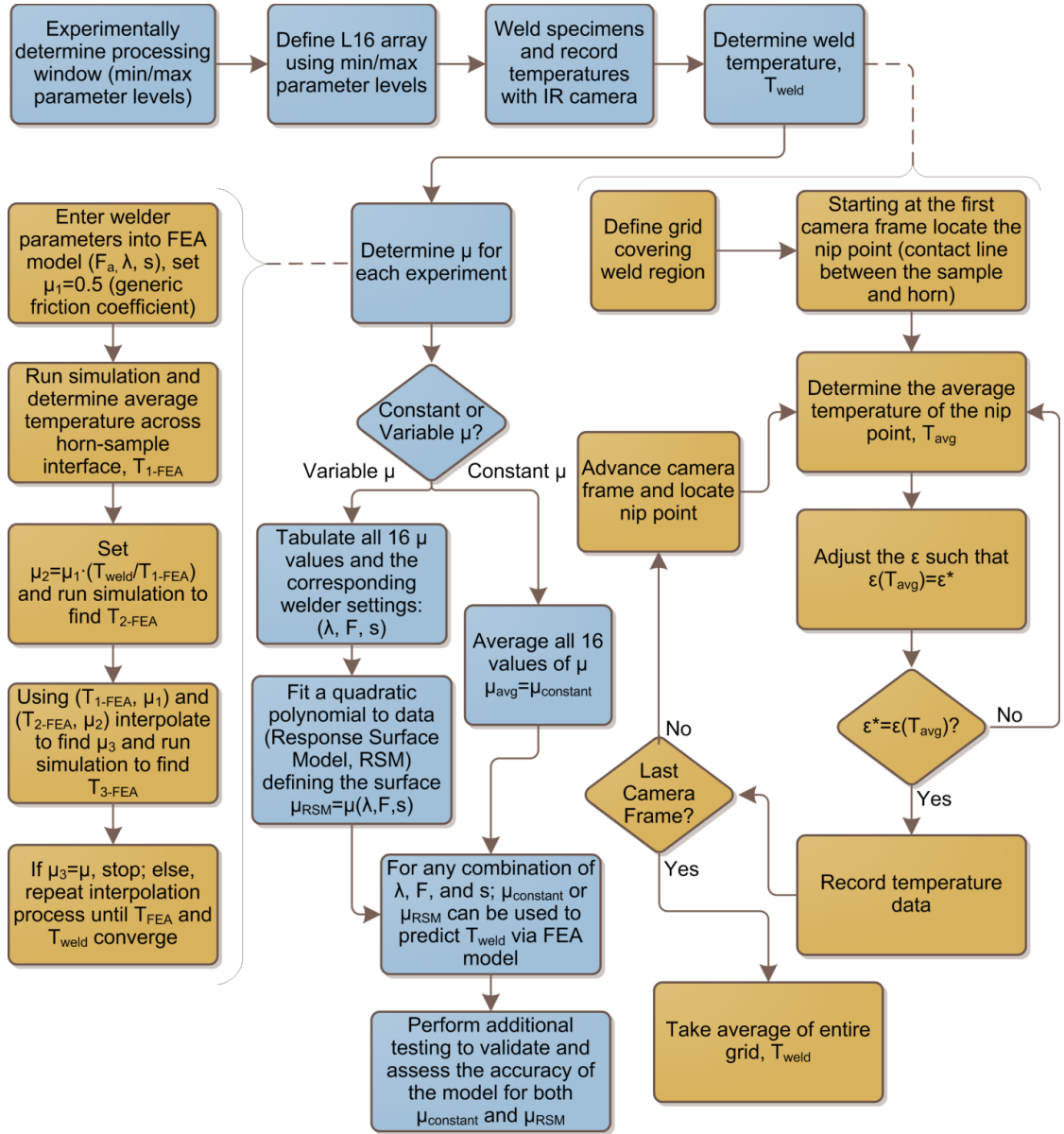


Figure 5.1 MetPreg Processing Flow Chart

5.1 Contributions and Future Work

The model and ancillary experiments performed in this body of work have served to clearly connect theoretical thermal models and UC theory to experimental data. For future work the findings of this study are hoped to be incorporated into material diffusion models, thermal models for new material pairings, and thermal mechanical models. For diffusion predictions, temperature and time data may be used, and for mechanical modeling, the process dependent friction coefficient.

To make this process successful in manufacturing a fair amount of work remains to be done. Tape placement is already employed in the polymers industry; this will aid the development of machinery and control systems to produce automated parts. However, metals are not likely to flow as much during processing. Layup orientations may depend on the raw material and process flexibility as well as the desired orientation of strength and rigidity. Determining acceptable limits on raw material properties and dimensions will be more critical, as well as the precise placement of strips during part buildup.

There is currently limited availability of continuous fiber MMC prepreg tapes, so establishing a more consistent and affordable tape supply will be very beneficial to industry implementation.

Additional work also needs to be done to optimize bond strengths. Such as developing a strength test that can be applied to both small and larger layered metallic parts, or tailoring the interfacial diffusion profiles based on process settings and outputs.

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Appendix A

IMPLEMENTATION OF NON-UNIFORM FRICTIONAL HEAT GENERATION FLUX

To apply a non-uniform heat flux, the sample was divided into 3 zones (1, 2, and 3; as illustrated in figure A.1). Heat can now be applied at varied levels in each zone. If there was a gap at zone 2 (e.g. the sample had a center groove), one could apply heat at zones 1 and 3 only. Figure A.2 is an example of uniform heat applied only at zones 1 and 3. Rather than restrict the model to constant flux terms a scaling factor can be used to linearly vary the magnitude of the flux term as a function of position. Figure A.3, A.4 and A.5 are print screens from a MS Excel worksheet that can be used to facilitate model setup.

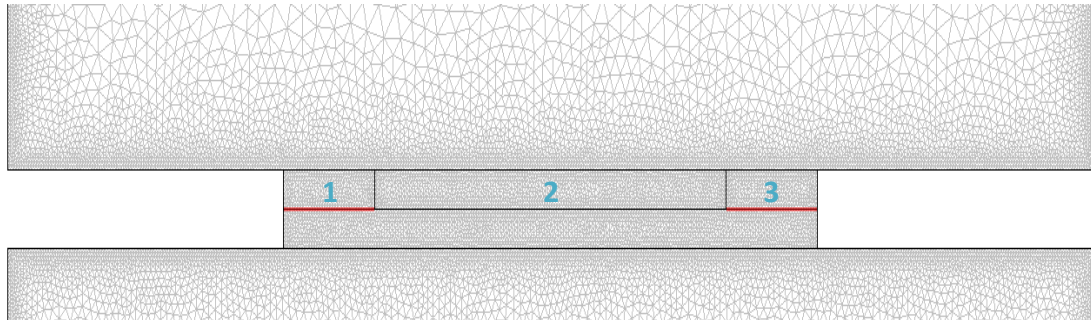


Figure A.1 Mesh view of non-uniform q''_{fr} FEA model for two tapes

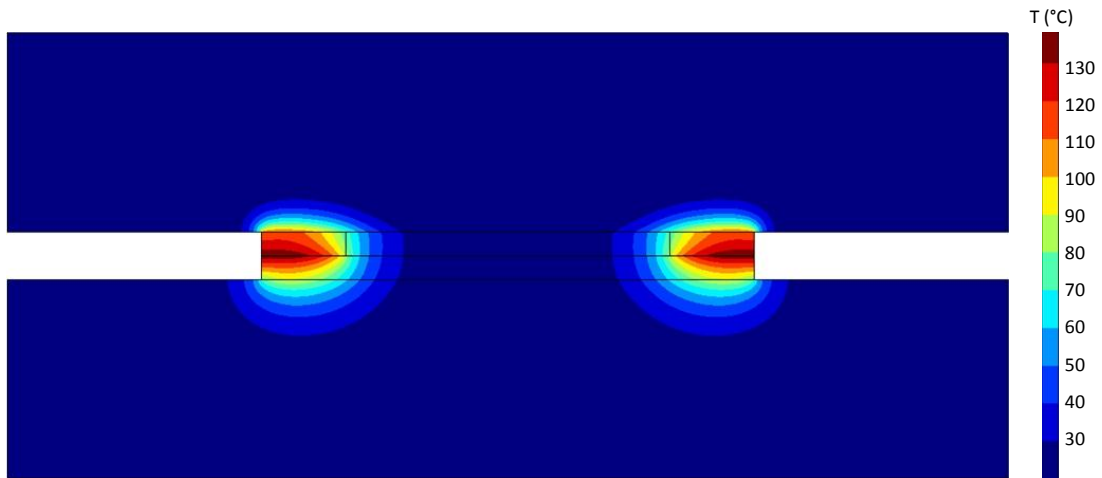


Figure A.2 Temperature profile for a uniform q''_r applied along regions 1 & 3

In the model setup worksheet the inputs of interest are *Width %* and *Angle Rating*. The *Width %* is the size of zones 1 and 3 relative to the total width, and represents the % of the width in contact at the weld interface. *Angle Rating*, AR, is a multiplier between 0 and 100 that varies the slope of the scaling factor. AR=0, correspond to a 0 slope. AR=100 is the maximum slope possible given the *Width %* specified. For all AR values, the total energy applied is fixed such that it equals that of a constant flux term (the area under the curve). The *COMSOL Inputs* section contains the geometric information necessary to define the sizes of zones 1, 2, and 3 based on the contact width %.

q Properties

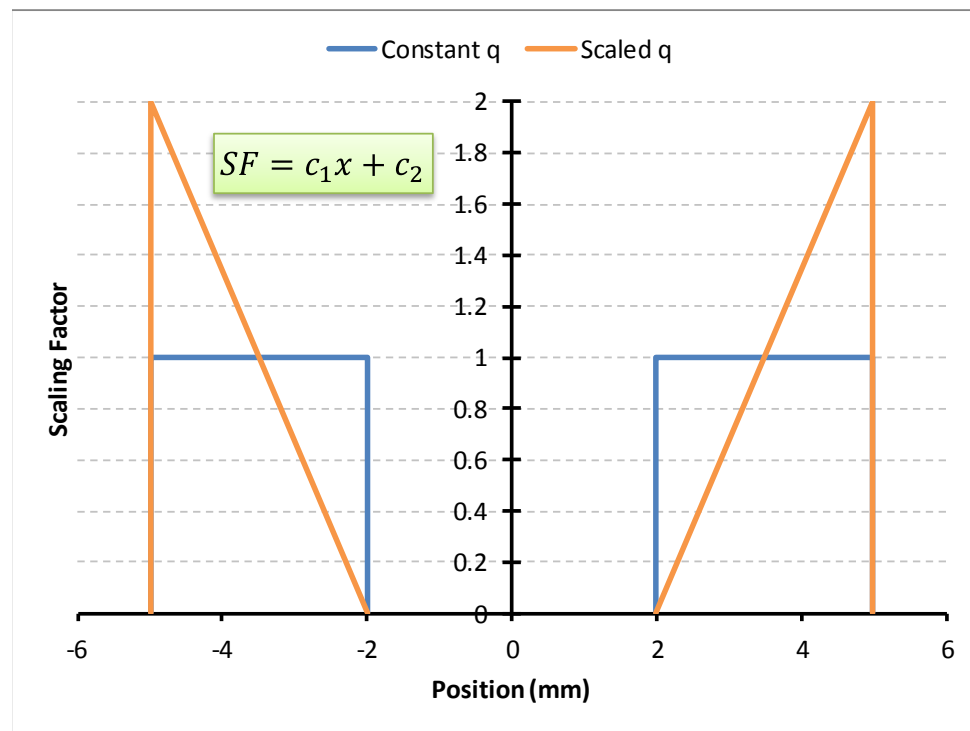
Angle Rating (0-100)	100
Slope (norm. q/mm)	0.668
a	1.996
b	4.990

Width %	60.0
1.996	a
4.990	b

Slope	-0.668
a	-1.996
b	-4.990

c_1 (mm ⁻¹)	0.668
c_2	-1.333

c_1 (mm ⁻¹)	-0.668
c_2	-1.333



COMSOL Inputs

	w (mm)	h (mm)	x (mm)	y (mm)
Shape 1 - Left Contact Area	2.99	0.47	-4.99	0
Shape 2 - No Contact Area	3.99	0.47	-2.00	0
Shape 3 - Right Contact Area	2.99	0.47	2.00	0

Figure A.3 Non-uniform scaling factor calculator: 60% contact, 100 AR

q Properties

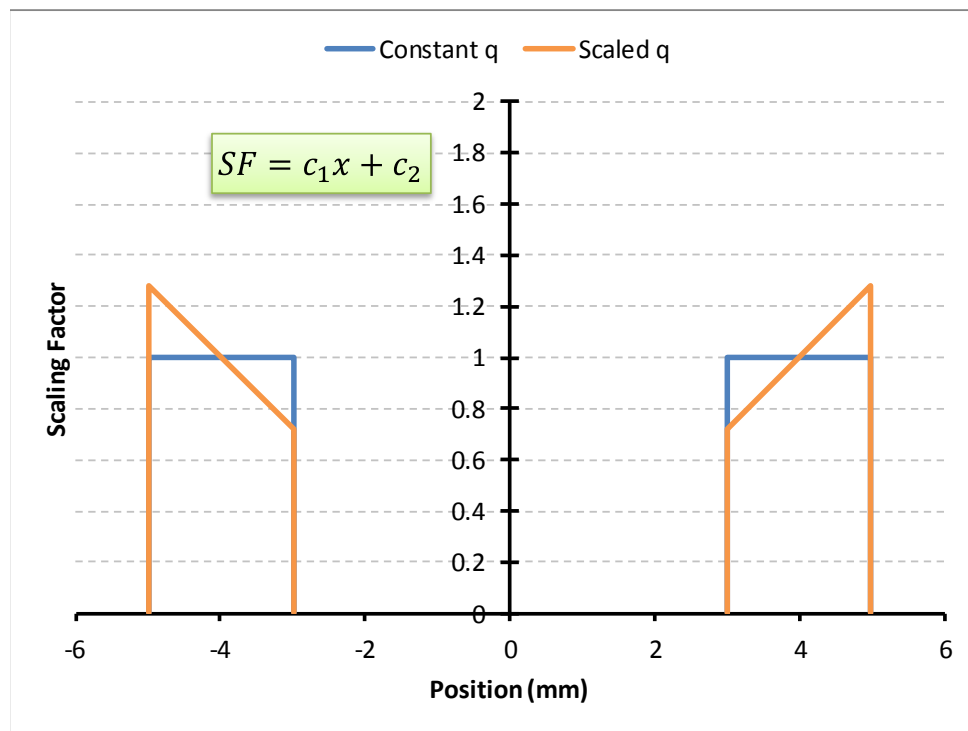
Angle Rating (0-100)	35
Slope (norm. q/mm)	0.282
a	2.994
b	4.990

Width %	40.0
2.994	a
4.990	b

Slope	-0.282
a	-2.994
b	-4.990

c_1 (mm ⁻¹)	0.282
c_2	-0.127

c_1 (mm ⁻¹)	-0.282
c_2	-0.127



COMSOL Inputs

	w (mm)	h (mm)	x (mm)	y (mm)
Shape 1 - Left Contact Area	2.00	0.47	-4.99	0
Shape 2 - No Contact Area	5.99	0.47	-2.99	0
Shape 3 - Right Contact Area	2.00	0.47	2.99	0

Figure A.4 Non-uniform scaling factor calculator: 40% contact, 35 AR

q Properties

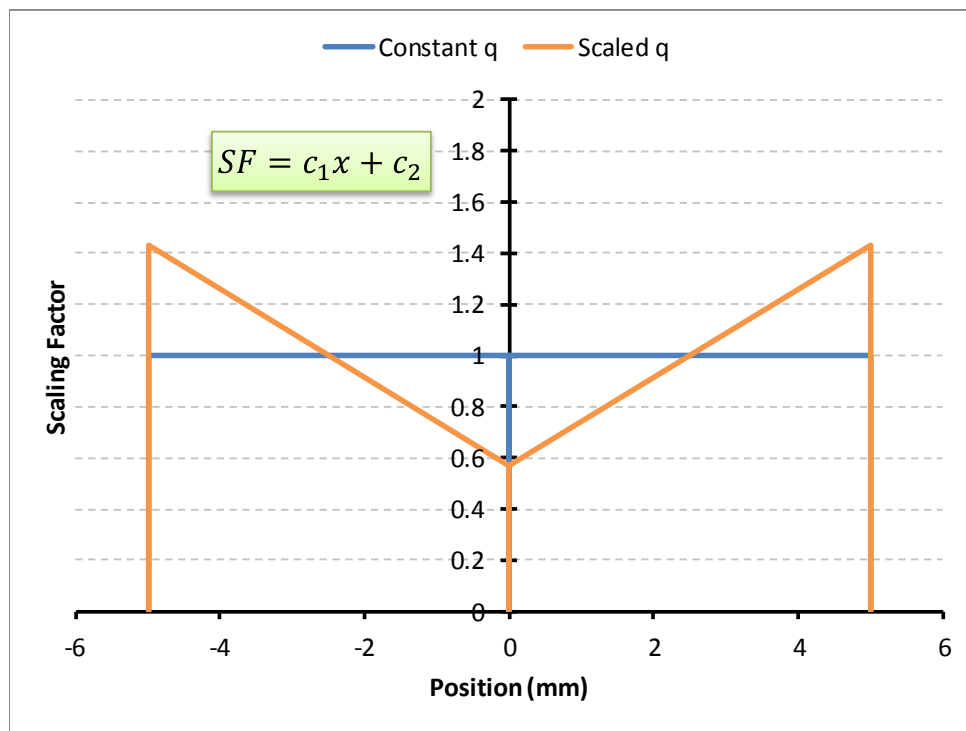
Angle Rating (0-100)	45
Slope (norm. q/mm)	0.173
a	0.000
b	4.990

Width %	100.0
0.000	a
4.990	b

Slope	-0.173
a	0.000
b	-4.990

c_1 (mm ⁻¹)	0.173
c_2	0.568

c_1 (mm ⁻¹)	-0.173
c_2	0.568



COMSOL Inputs

	w (mm)	h (mm)	x (mm)	y (mm)
Shape 1 - Left Contact Area	4.99	0.47	-4.99	0
Shape 2 - No Contact Area	0.00	0.47	0.00	0
Shape 3 - Right Contact Area	4.99	0.47	0.00	0

Figure A.5 Non-uniform scaling factor calculator: 100% contact, 45 AR

Figure A.6 and A.7 show simulation results for 100% contact and 45 AR.

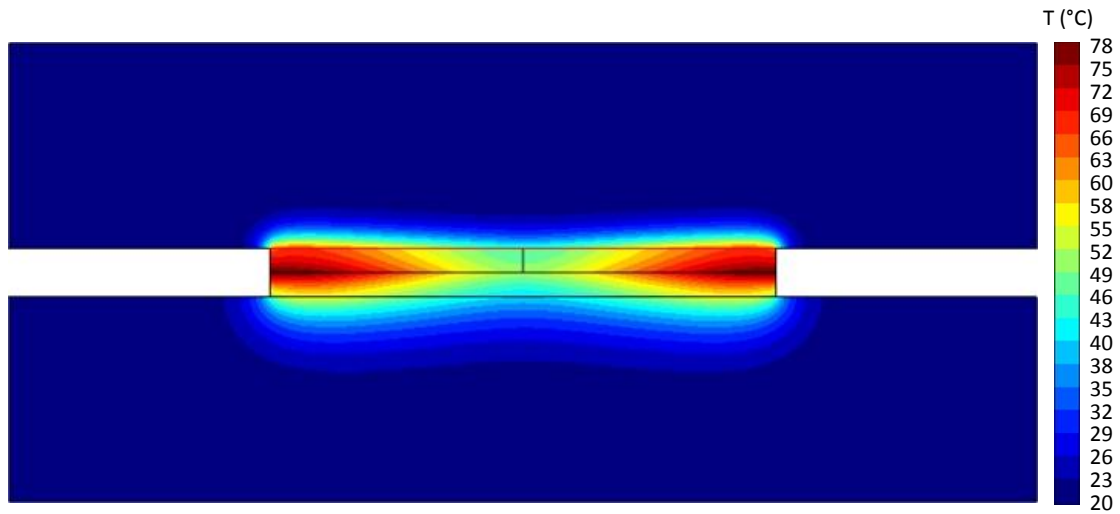


Figure A.6 COMSOL FEA results, full view: 100% contact, 45 AR

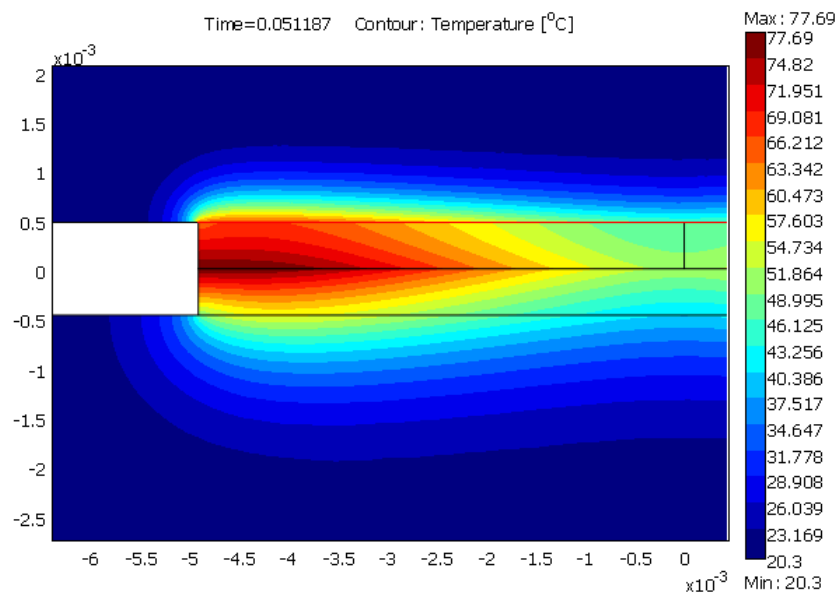


Figure A.7 COMSOL FEA results, left side view: 100% contact, 45 AR

Simulation set points used for figures A.8, A.9, and A.10 are not based on process settings or sample topography; they are best fit parameter choices used to illustrate the ability for the zoned thermal model to closely mimic experimentally measured temperature profiles. To scientifically apply this nonlinear model, the connection between heat flux variations and tape properties should be determined.

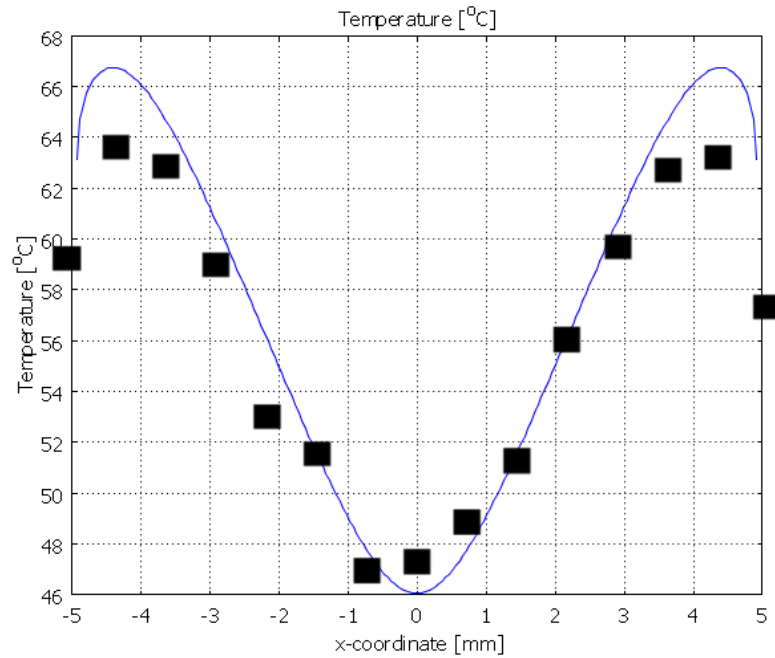


Figure A.8 COMSOL results overlaid on a tape-tape weld. Black markers are experimental data. Blue line is simulated temperatures.

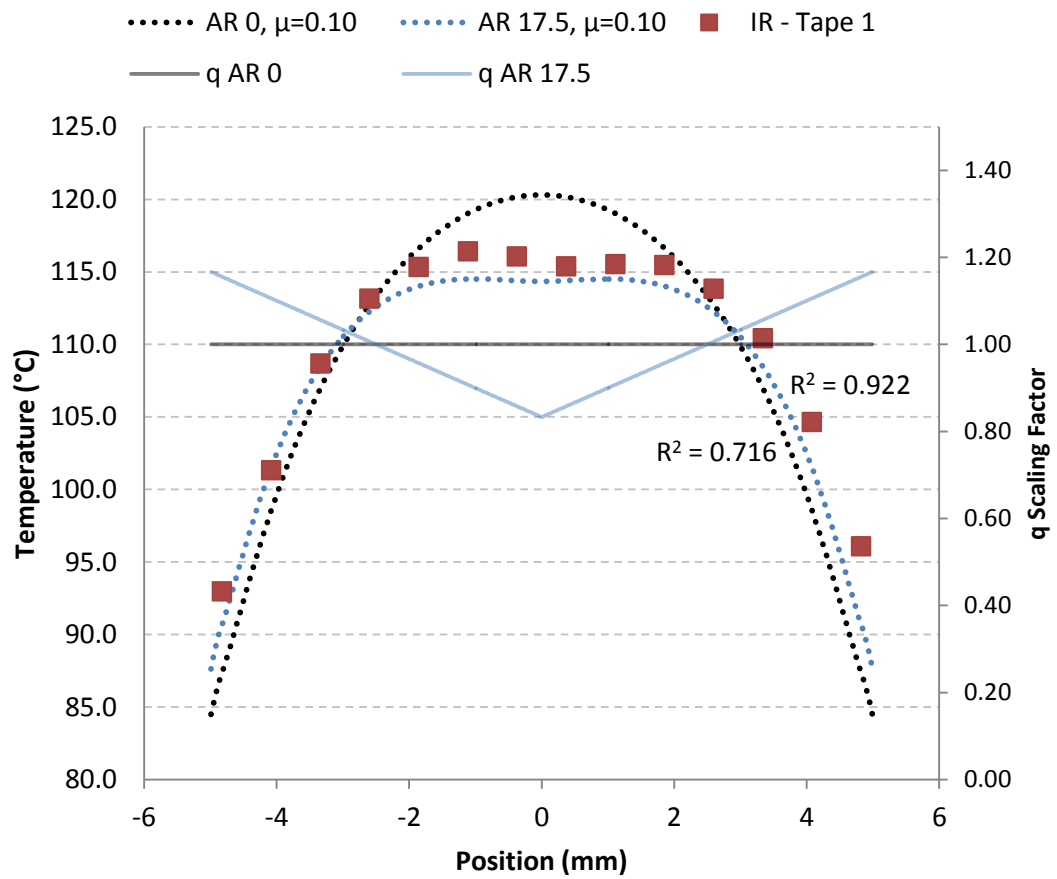


Figure A.9 Symmetric, non-uniform q''_{fr} . Tape-Substrate weld.

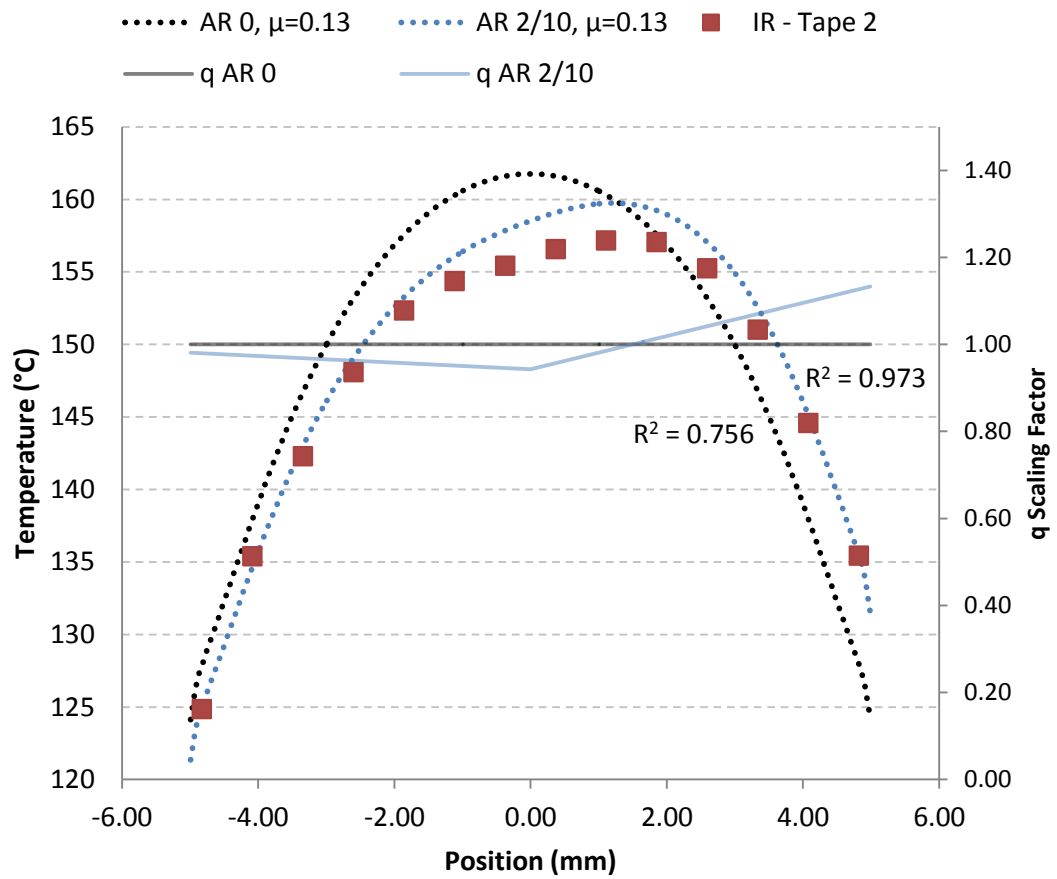


Figure A.10 Non-symmetric, non-uniform q''_{fr} . Tape-Substrate weld.

Appendix B

THERMOCOUPLE TEMPERATURE VS. SURFACE TEMPERATURE

A two dimensional thermal model was performed to verify that the amount of thermal variation from the thermal couple to the sample surface measured by the IR camera, as well as the variation across the width caused by the dowel pin's mass, is negligible. Figure B.1 is a photograph of the sample being simulated, the multilayered MMC part with embedded thermocouple. This MMC tape sample represents the *worst case scenario* for largest temperature difference between the thermocouple and the sample surface. This is due to the large distance between the thermocouple and the surface (3 tapes thick) and lower thermal conductivity relative to Al foils.

Temperature variations will be of greatest magnitude at higher temperatures due to larger convective losses, therefore a hotplate temperature of 200 °C will be used, as this is representative of the hottest recorded welds in this study. The simulation uses a 1 inch thick plate with its lower boundary fixed at 200 °C to emulate the behavior of the hot plate. The hot plate and dowel pin are given the properties of steel ($k = 51.9 \text{ W/m} \cdot \text{K}$, $\rho = 7870 \text{ kg/m}^3$, $C_p = 486 \text{ J/kg} \cdot \text{K}$); the substrate, Al 6061-T6; and the MMC tape, 57% FVF Al/Al₂O₃. Emissivity measurements using the hot plate were done at equilibrium, therefore the transient response is not of interest, and the simulation will calculate the steady state solution. The only thermal loss present is free convection to air. Typical convection coefficients range from 2 W/m²·K to 25 W/m²·K (Incropera and DeWitt 2001). 25 W/m²·K was used as this will yield the largest temperature gradients.

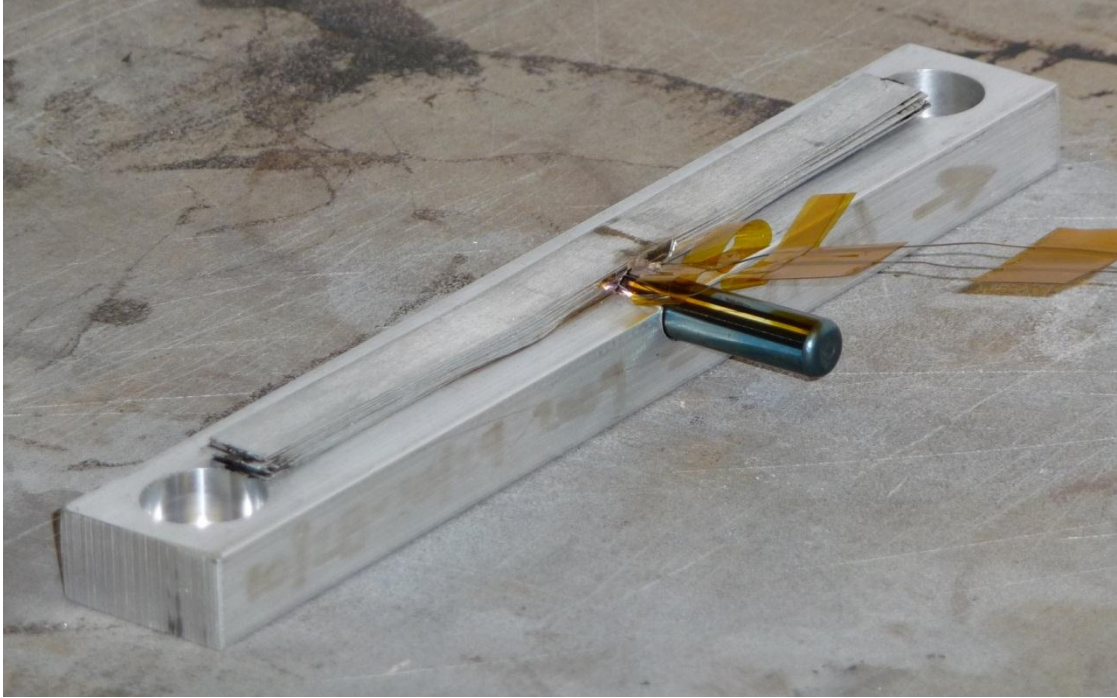


Figure B.1 MMC Tapes on Substrate with embedded thermocouple

Figures B.2, B.3, B.4, B.5 and B.6 are taken from the modeling environment. Figure B.2 illustrates the entire solved model. The temperature scale bar captures the min and max temperatures on the model, 185 °C and 200 °C. Figure B.3 is a close-up of the mesh at the thermocouple location, D. The other locations marked in figures B.3, B.4, B.5 and B.6 represent, A, the left most edge of the tape surface, B, the center of the tape at the surface directly above the thermocouple, and C the rightmost edge of the tape surface. The mesh is finest at the surface ABC and gets progressively coarser moving towards the bottom of the *hotplate*. The entire mesh consists of 27,330 elements, which are solved for in about one second on a standard 32-bit windows desktop computer.

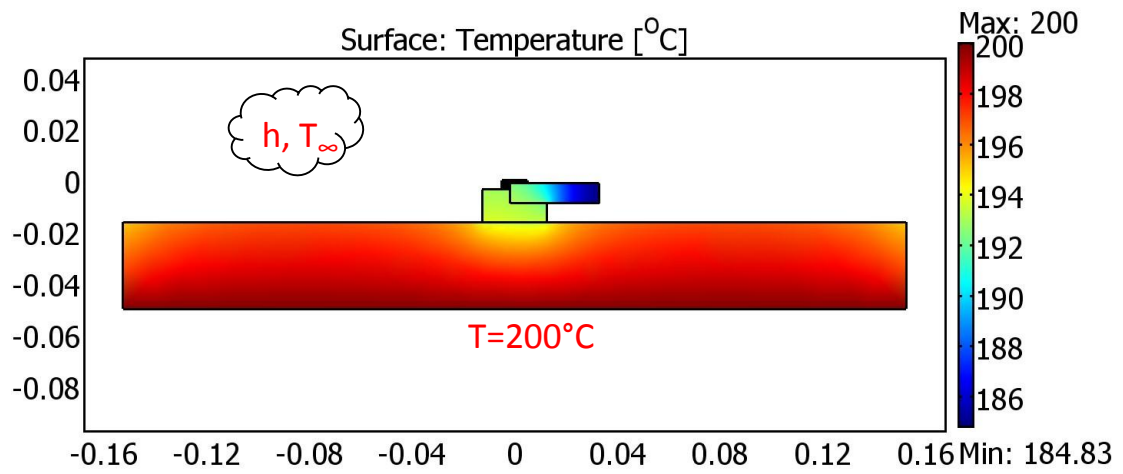


Figure B.2 Steady state temperature solution of MMC part on the hotplate

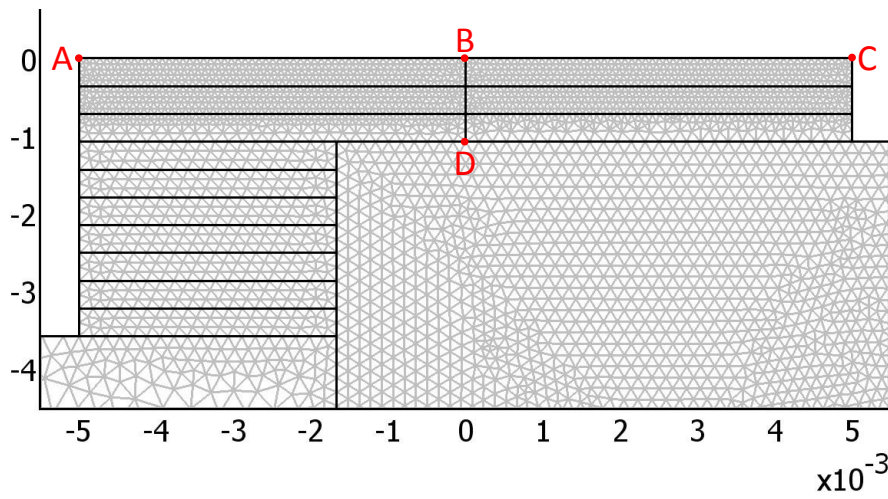


Figure B.3 Zoomed in view of mesh in tape stack and dowel

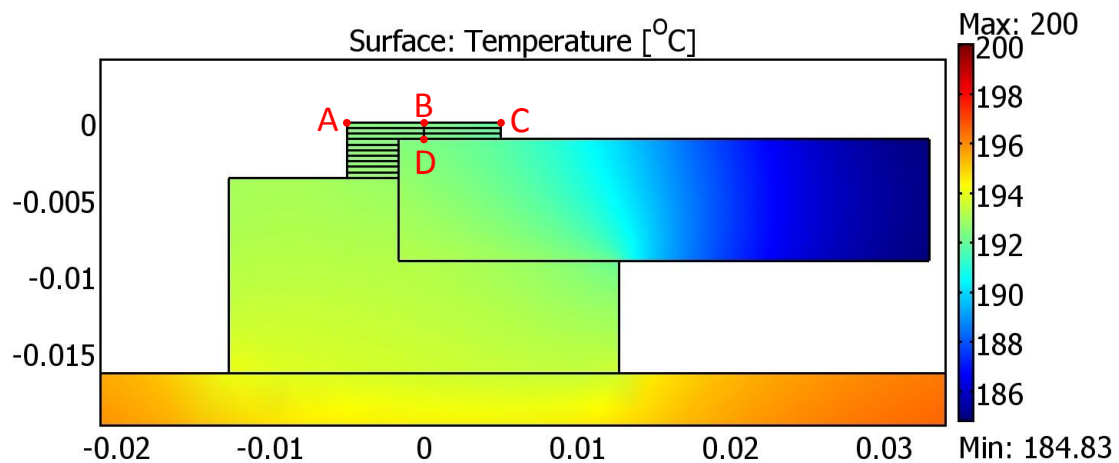


Figure B.4 Zoomed in image of steady state temperature solution

The variation in temperature is most easily seen by plotting temperatures along a line, or path. Figure B.5 is the temperature along the tape surface, path ABC. From this plot the asymmetric effects of the dowel pin are illustrated. There is approximately a 0.3% difference between the min and max temperatures along the tape surface. Of greater interest and significance is the temperature difference along the path DB going from the thermocouple used in emissivity calibration to the tape surface B recorded by the IR camera. Figure B.6 reveals there is virtually no variation between the tape surface and the thermocouple location, 0.03% temperature difference from D to B. Therefore, it has been verified numerically that the temperature difference across the sample surface and to the thermocouple is negligible, thus allowing emissivity to be calibrated effectively with an embedded thermocouple.

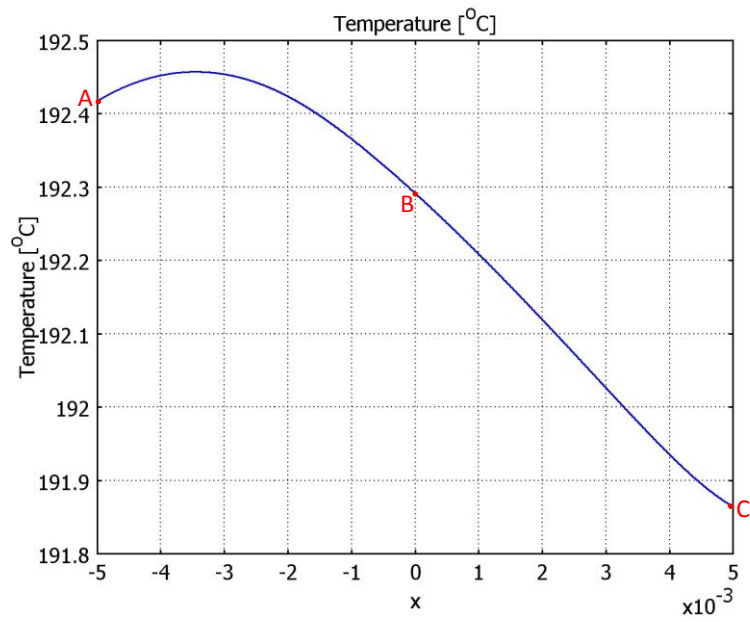


Figure B.5 Temperature variation across the width, on the surface of the tape

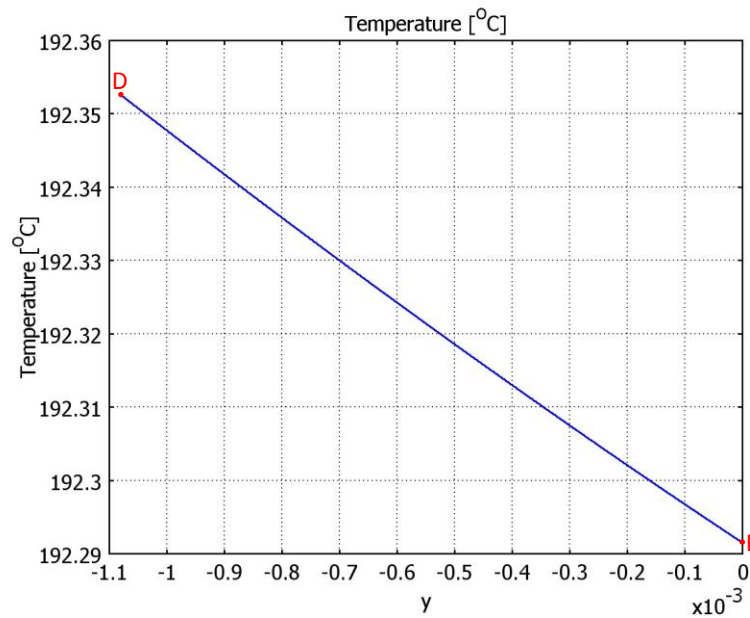


Figure B.6 Through-thickness temperature variation from the thermocouple location, D, to the parts surface, B

Appendix C

SURFACE AND INTERFACIAL TEMPERATURE PROFILES COMPARED

In this appendix experimentally measured surface temperature across the sample width for a typical weld and the corresponding simulated interfacial and surface temperature profiles will be compared. It will be shown that there is little difference between the interfacial temperature profile and the surface temperature profile. Figure C.1 is a plot of three different temperature profiles. All are across-the-width profiles for a typical tape-to-substrate weld. Specifically this data is from tape sample 7 of the 3-by-3 validation array (see table 4.5).

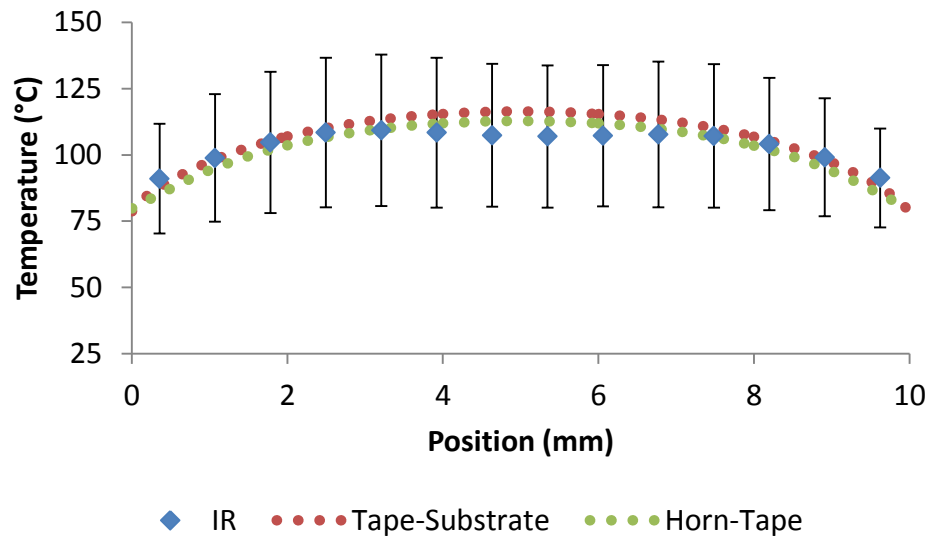


Figure C.1 Temperature variation across the width of a tape-substrate weld

Qualitatively there are few differences between both simulated temperature profiles and the experimentally measured temperatures. The primary differences are between simulated and experimental data, and not between the simulated profiles themselves. The simulated data follows a smooth parabolic trend, while the experimental data has a slight depression midway across the tape's width. Most significant is the variation of the experimental data at any point along the tape width; a 25% coefficient of variation on average.

Differences between the simulated temperature profiles are summarized in table C.1. Variations between the average, minimum, and maximum temperatures, and the coefficient of variation at the tape surface versus the weld interface is about 1% to 3% for the simulated data. Therefore, in comparison to the widely varying experimental data surface and interfacial profile can be treated synonymously.

Table C.1 Simulated weld interface and surface temperature profiles compared

Interface	Horn-Tape	Tape-Substrate	% Diff
Average	103	106	3.1%
Min	80	79	1.3%
Max	113	116	3.1%
CV (%)	9.2%	9.4%	1.8%

Appendix D

HARMONIC INTERFERENCE

D.1 MMC Tape-to-Substrate Test Data

The data presented in this appendix is for MetPreg tape welded to Al 6061-T6 substrates. The substrates were all 7 inches long and 1/2 inch thick. Substrate widths tested were 1 inch, 1.5 inch, 2 inch and 3 inch. Increasing substrate width increases lateral stiffness, thus decreasing the amount of harmonic interference incurred during welding. Eight total welds were performed; two for each substrate width. The welder settings were held fixed at 30 psi, 10% speed using the high torque motor, and 35% amplitude using the 1.9:1 gain booster. This corresponds to the following settings: 2028 N clamping force, 25.4 mm/s linear weld speed, and 30.7 μm peak-to-peak oscillatory amplitude. As the substrate width increases, the amplitude of temperature oscillations along the length of the specimen decreases. The suppression of harmonic interference can be seen by comparing the temperature vs. time plots of successively wider substrates. The progression of this phenomenon is shown graphically in figures D.1, D.2, D.3 and D.4. This data is summarized in figure 4.10.

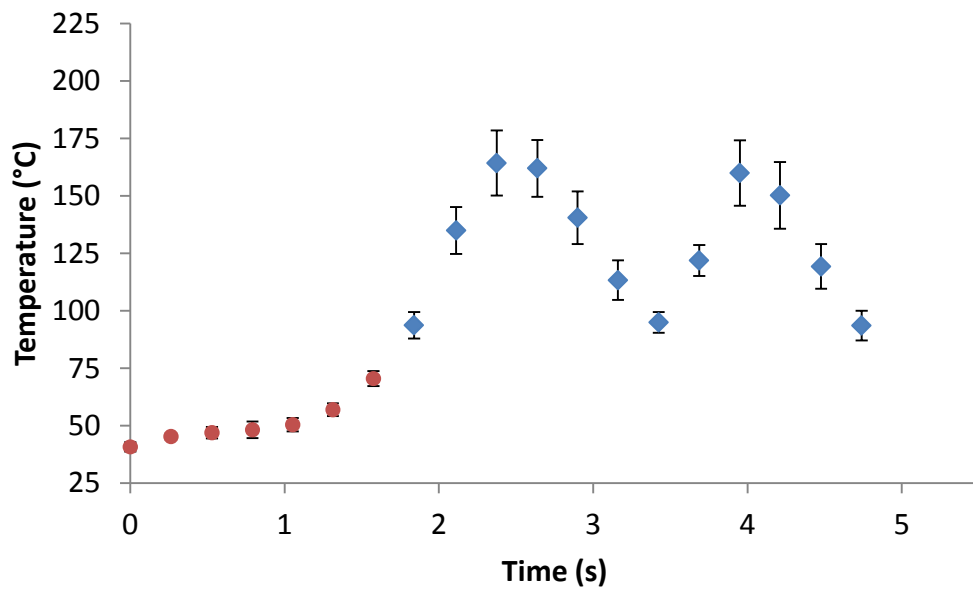
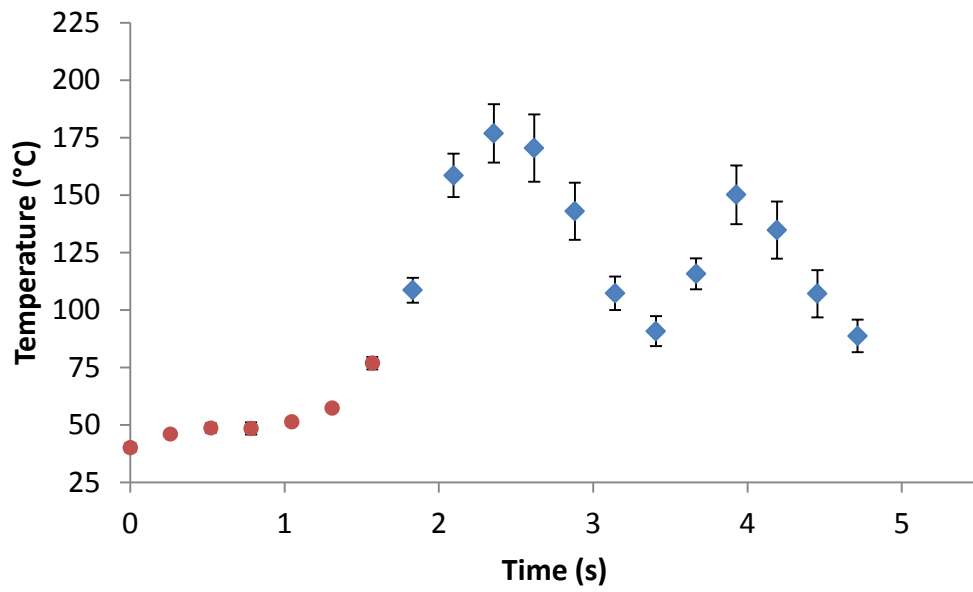


Figure D.1 Average nip point temperature vs. time data for MetPreg tape welded to 1 inch Al substrates

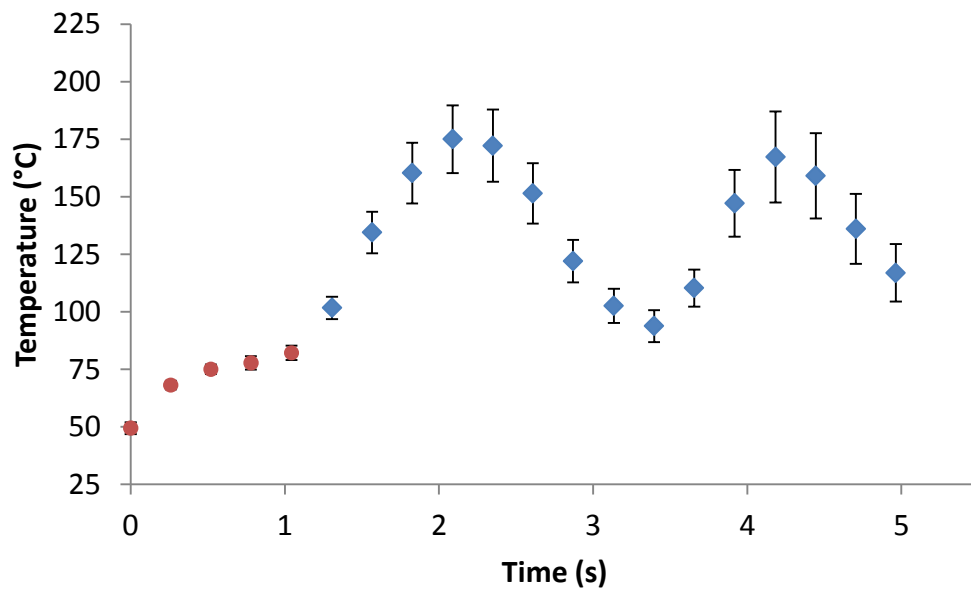
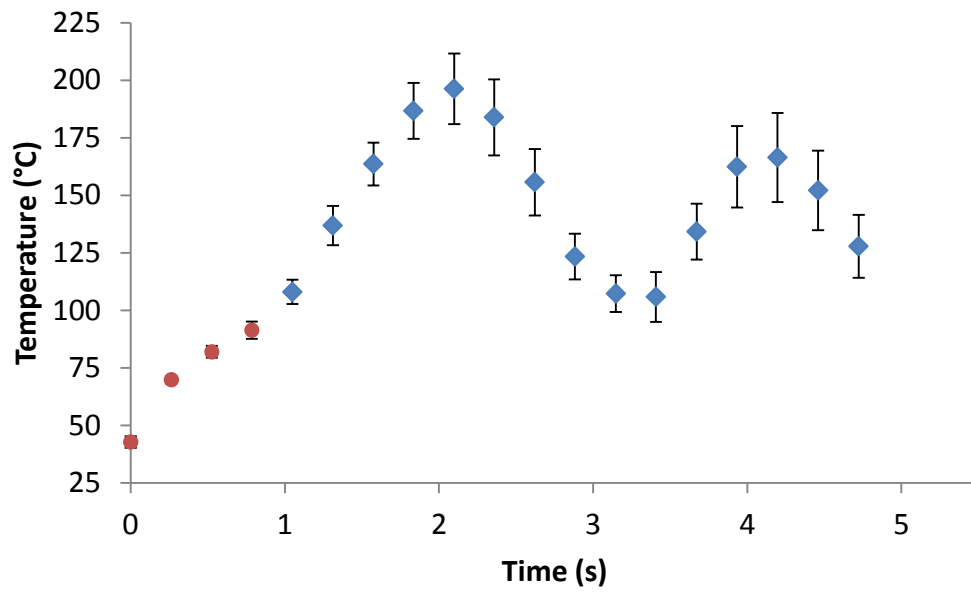


Figure D.2 Average nip point temperature vs. time data for MetPreg tape welded to 1.5 inch Al substrates

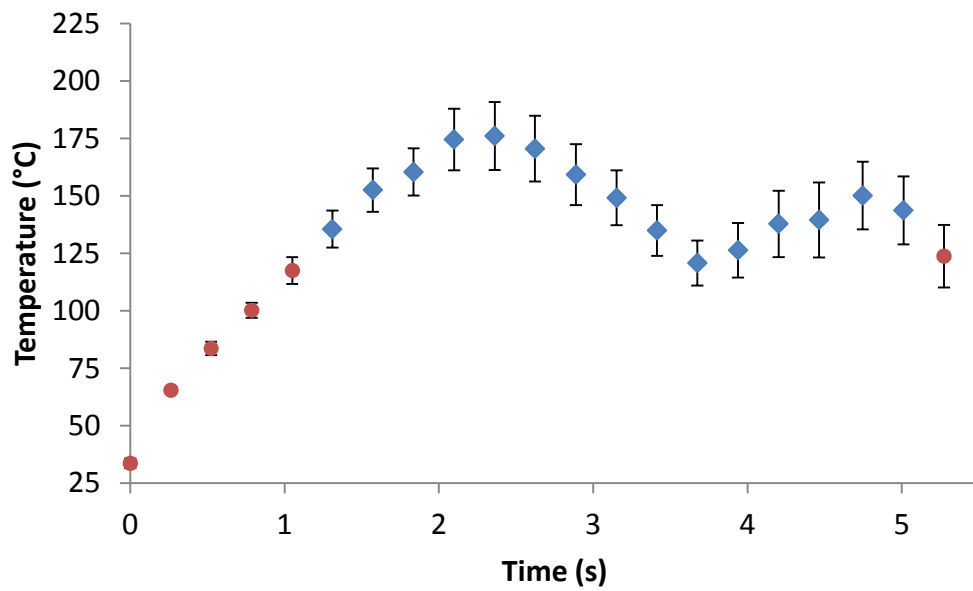
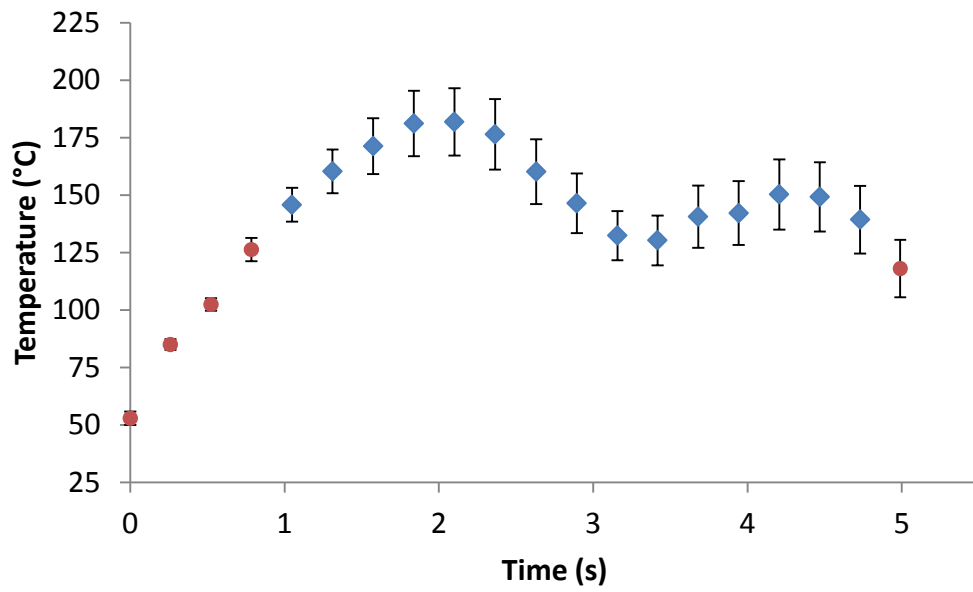


Figure D.3 Average nip point temperature vs. time data for MetPreg tape welded to 2 inch Al substrates

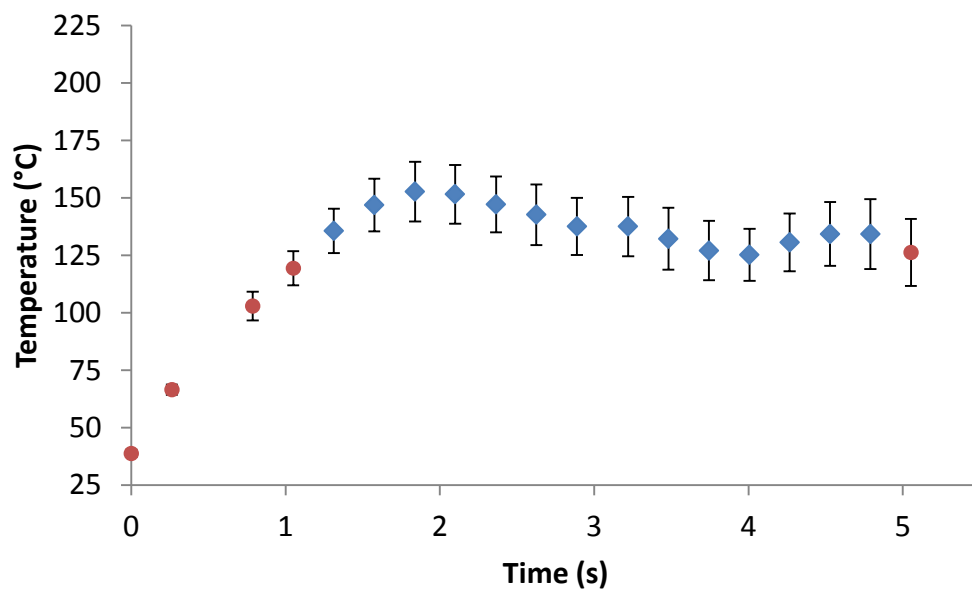
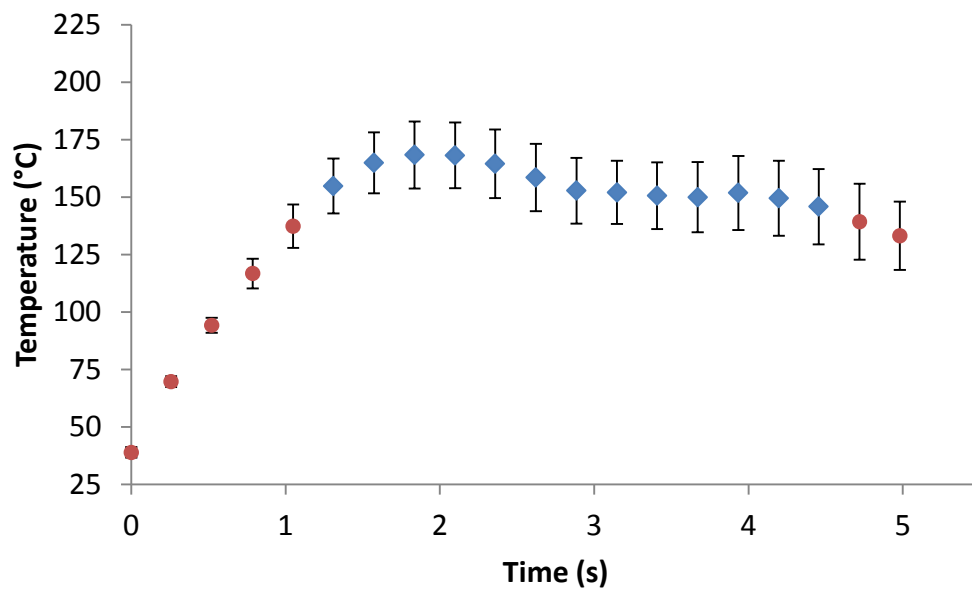


Figure D.4 Average nip point temperature vs. time data for MetPreg tape welded to 3 inch Al substrates

D.2 Weld Energy Oscillations for Additional Welds

While varying the substrate width alters the amplitude of interference, harmonic interference was not evident for welds not using an aluminum substrate. Several other welding arrangements were tested with both foils and MMC tape. All foils in this study were welded using an anvil-foil-foil-horn geometry where the weld is made at the foil-foil interface and no bond is formed at the tooling interfaces. Figure 3.17 shows the nip point temperature variation for said foil-foil weld; there are no signs of harmonic phenomenon present. MetPreg MMC tapes were welded to two different steel bars and are shown in figure D.5. Both steel bars were 2.25 inches wide, 1 inch thick, and bolted in place. One bar was the welder anvil which has a rough knurled surface, the other was an off the shelf piece of mild steel bar stock.

Nip point temperature vs. time plots are shown in figure D.6 for MetPreg welded to the above-pictured steel bars and a one inch Al substrate for comparable welder settings. Several interesting observations are gleaned from these plots. First is that the rough steel tape weld got hotter than the smooth steel weld. This is attributable to a higher friction coefficient resulting from contact with surfaces of significant roughness. Intra-nip point temperature variations (i.e. variations along the sample width) are larger when welding to the steel; evinced by the larger standard deviations at each time step. This may be due to the increased rigidity of steel not conforming to the geometric non-uniformities of the MMC tape as readily as aluminum. Temperatures are higher for welds to steel. This is in part due to slightly higher weld energies required to bond to steel. However, the thermal diffusivity of steel is more than five times lower than that of aluminum. Therefore, more heat is retained in the MMC tape during the weld cycle resulting in a higher weld temperature. With regard

to resonance effects, in comparison to the substrate sample, there is no appreciable harmonic interference causing thermal variations.

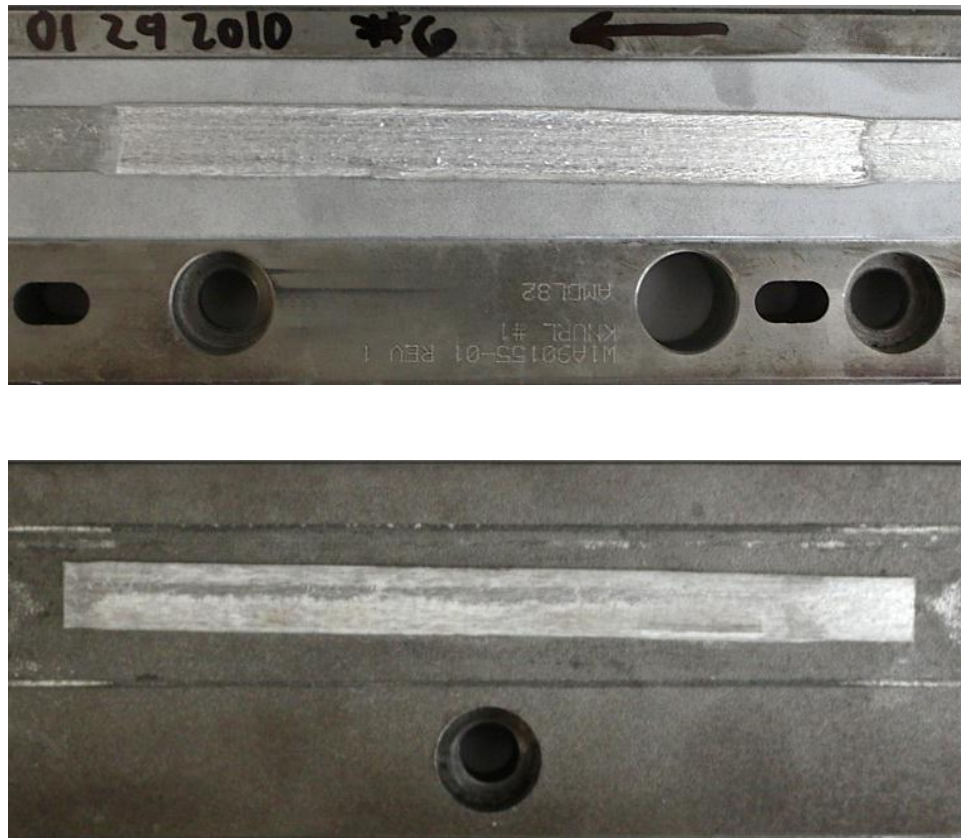


Figure D.5 Photograph of the MetPreg welded to 2.25 inch wide, 1 inch thick, steel bars. Bar used in the top picture is the welder anvil which has a rough knurled surface. The bar in the bottom image has a comparably smooth surface, and is off the self bar stock.

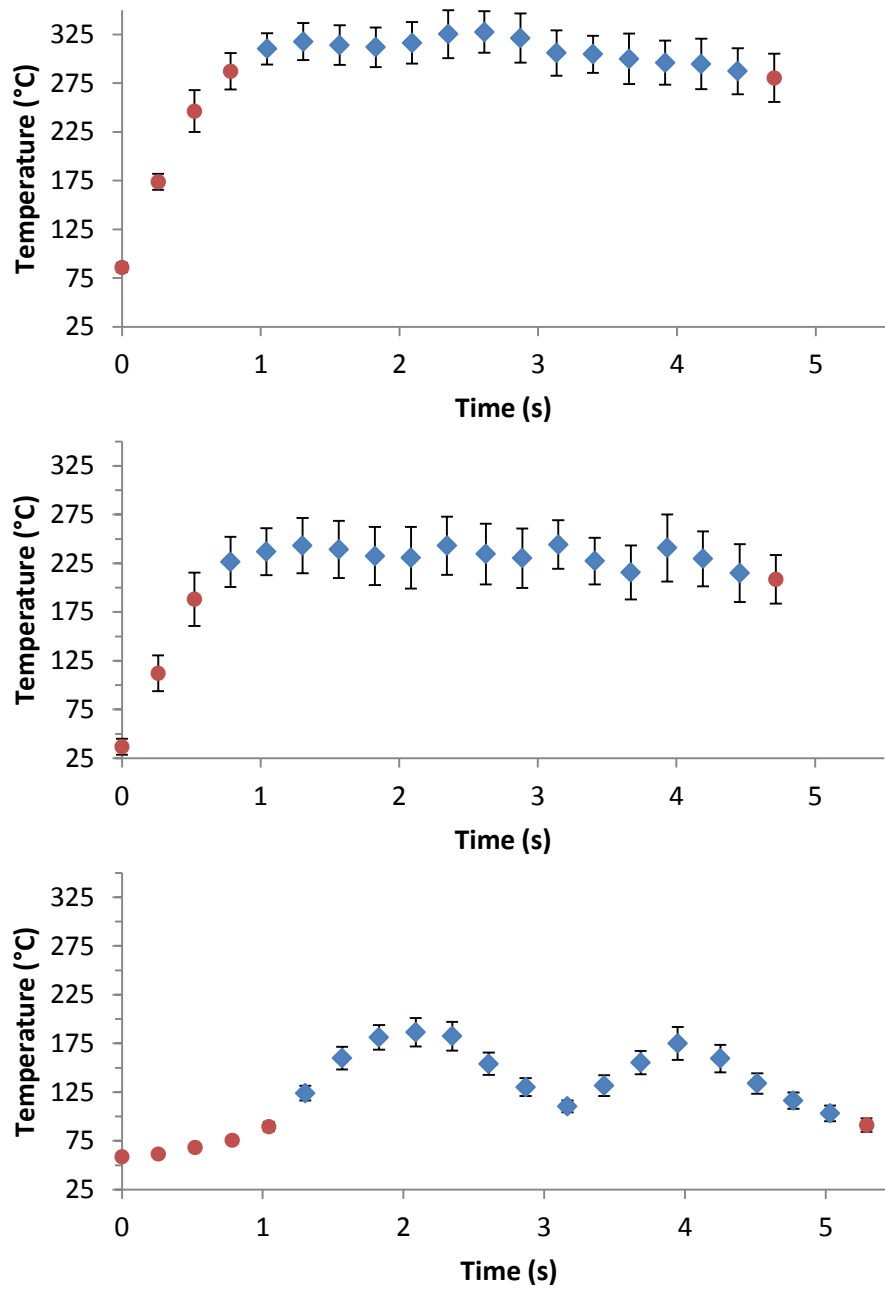


Figure D.6 Temperature vs. time plots for MetPreg welded to three different materials under equivalent welder settings. Bottom plot is for 1 inch wide, 1/2 inch thick, Al substrate. Top and middle plots are for 2.25 inch wide, 1 inch thick steel. Top, rough steel; middle, smooth steel.

Appendix E

AMPLITUDE CALIBRATION DATA

The following data was provided with the purchase of UD-CCM's ultrasonic welder by the vendor, AmTech (see table E.1). The data was then plotted (figure E.1). As expected the data is linear; the correlation coefficient of the fit supports this. Using the fit equations, an interpolation tool was created in excel to determine the amplitude for any gain booster for any set point. See figure E.2 for a screen shot of the spreadsheet. The yellow shaded boxes are the inputs and the grey shaded box is the resulting amplitude as interpolated from the 1.9:1 and 1:1 gain boosters' amplitude at the same amplitude set point.

Table E.1 Amplitude in μm for 1.9:1 and 1:1 gain boosters at incremental welder set points

Welder Amplitude Set Point	Peak-to-Peak Amplitude (μm)	
	1.9:1 Gain Booster	1:1 Gain Booster
0%	23	9.4
10%	25	10.3
20%	27	11.2
30%	30	12.1
40%	32	13
50%	34	13.9
60%	36	14.8
70%	38	15.7
80%	41	16.6
90%	43	17.6
99%	45	18.5

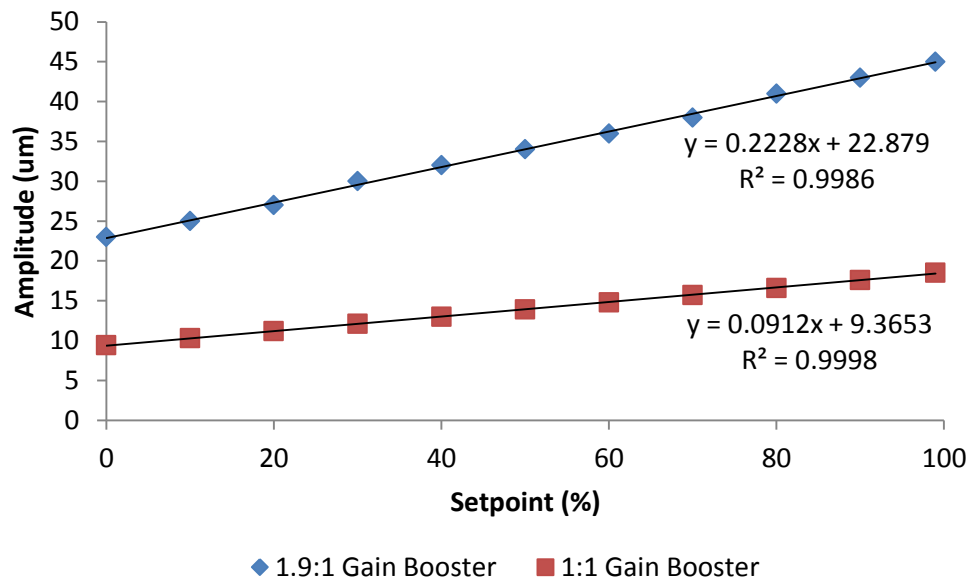


Figure E.1 Amplitude in μm vs. welder set point percentage.

Amplitude Setpoint (%)	Amplitude (um)		Amplitude (um)	
37	31.1	1.9:1 Ultra High Gain	Gain	low (0%) high (99%)
	12.7	1:1 Booster	0.8:1	6.4 12.5
1.6	Gain of Booster Used		1:1	9.4 18.4
0.667	x, quality factor		1.3:1	13.9 27.2
25.0	Amplitude (um)		1.6:1	18.4 36.1
			1.8:1	21.4 42
			1.9:1	22.9 44.9

Figure E.2 Screen shot of Excel based amplitude interpolation tool.

Appendix F

COMSOL SOFTWARE VALIDATION

To ensure the user sets up a problem properly in the FEA environment, and that the software is computing the correct solution the software will be validated. The model used for this study is two-dimensional and transient; therefore the analytic and FEA solutions for a problem of the same class will be compared. Figure F.1 visually and mathematically defines the problem that is to be used for validation.

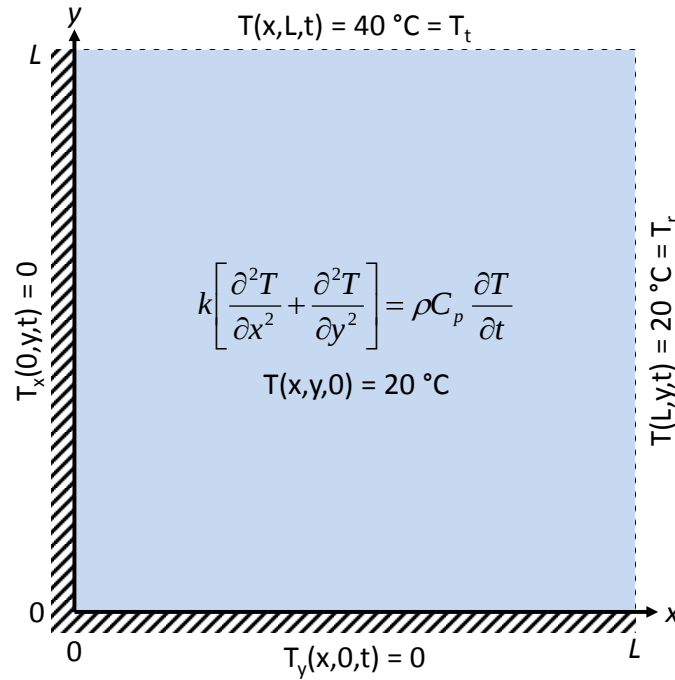


Figure F.1 Transient conduction initial and boundary conditions for a plate with fixed temperature boundaries and quarter symmetry

Figure F.1 represents the upper right quarter of a symmetric plate with fixed temperature boundary conditions. Temperature throughout the plate is governed by the heat diffusion equation. The entire plate is initially at 20 °C. The right boundary is fixed at 20°C, and the top of the plate is kept at 40 °C. Zero heat flux conditions across the bottom and left boundaries establish symmetry planes capturing the quarter symmetry condition.

The solution approach to this problem is typical to any comprehensive text on conduction. For details of the solution presented here consult pages 100 through 109 of Myers' text, *Analytical Methods of Conduction Heat Transfer* (1998). The first step is to assume the solution takes the form $T(x, y, t) = a(x) + b(y) + u(x, y) + v(x, y, t)$ where a , b , and u account for all nonhomogeneity. a and b become separable ordinary differential equations, while u and v are partial differential equation which must be solved using a separation of variables approach. u takes the form $u(x, y) = X(x)Y(y)$, and v takes the form $v(x, y, t) = X(x)Y(y)\Theta(t)$. Since v is a function of three parameters two separation constants are needed, while u will have one. The complete analytic solution takes the form of the following expressions:

$$T(x, y, t) = T_r + u(x, y) + v(x, y, t) \quad \text{Eq. F.1}$$

$$u(x, y) = 2(T_t - T_r) \sum_{n=1}^{\infty} \frac{(-1)^{n+1} \cos \lambda_n x \cosh \lambda_n y}{\lambda_n L \cos \lambda_n L} \quad \text{Eq. F.2}$$

$$\lambda_n L = (2n - 1) \frac{\pi}{2} \quad \text{Eq. F.3}$$

$$v(x, y, t) = \sum_{l=1}^{\infty} \sum_{m=1}^{\infty} A_{lm} \cos(\mu_l x) \cos(\eta_m y) e^{-(\mu_l^2 + \eta_m^2) \alpha t} \quad \text{Eq. F.4}$$

$$A_{lm} = -4(T_t - T_r) \frac{(-1)^{l+m}}{\mu_l L} \frac{\eta_m L}{(\mu_l L)^2 + (\eta_m L)^2} \quad \text{Eq. F.5}$$

$$\mu_l L = (2l - 1) \frac{\pi}{2} \quad \text{Eq. F.6}$$

$$\eta_m L = (2m - 1) \frac{\pi}{2} \quad \text{Eq. F.7}$$

$$\alpha = \frac{k}{\rho C_p} \quad \text{Eq. F.8}$$

Where λ_n, μ_l , and η_m are the separation constants and α is the thermal diffusivity. As indicated in figure F.1 $T_t = 40$, and $T_r = 20$ °C. Material properties were taken to represent Al 6061-T6 (see table 3.1), and length L, was set to 1 m.

Plotting of the analytic solution was done in Maple, a computer algebra system (Maple 2005). All summations for the analytic solution were taken out to 100 iterations (i.e. $\sum_{l=1}^{100} \sum_{m=1}^{100} \dots$). 100 was chosen to balance computing time and solution accuracy, consequently even the *analytic* solution is not exact. Contour plots for both the analytic solution and the COMSOL solution are shown in figures F.2 and F.3, respectively. Since the solutions were generated in separate software packages the contour color values are not the same. Both use a red tone for 20 °C, and blue for 40 °C. While the color values may be different, the spacing between contours is the same for both plots, 0.5 °C. The positioning and spacing of the temperature contours in figures F.2 and F.3 correlate well qualitatively, which indicates agreement of the analytic and FEA solutions spatially at time = 2000 seconds.

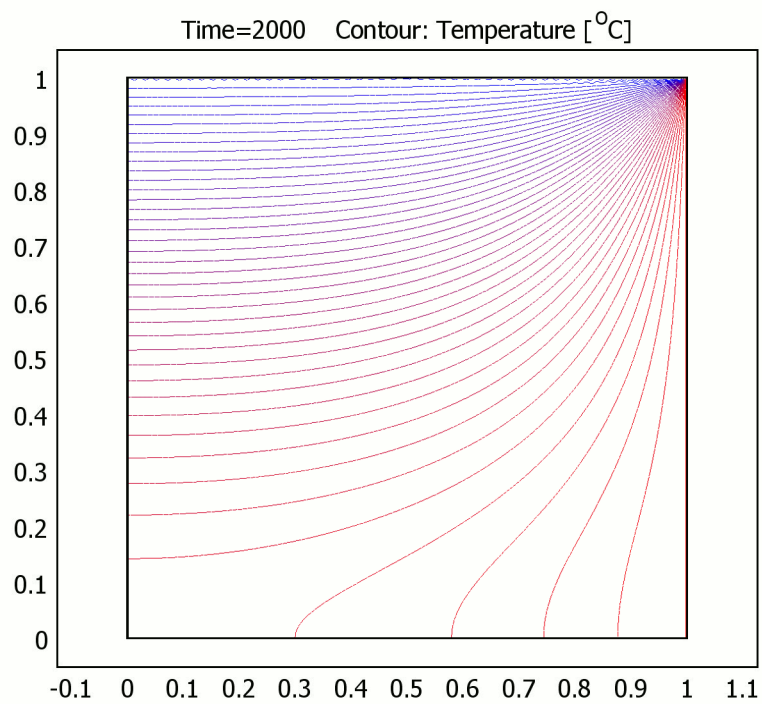


Figure F.2 Contour plot of the analytic solution at time = 2000 seconds. Contours vary from 20 $^{\circ}\text{C}$ (red) to 40 $^{\circ}\text{C}$ (blue) in 0.5 $^{\circ}\text{C}$ increments.

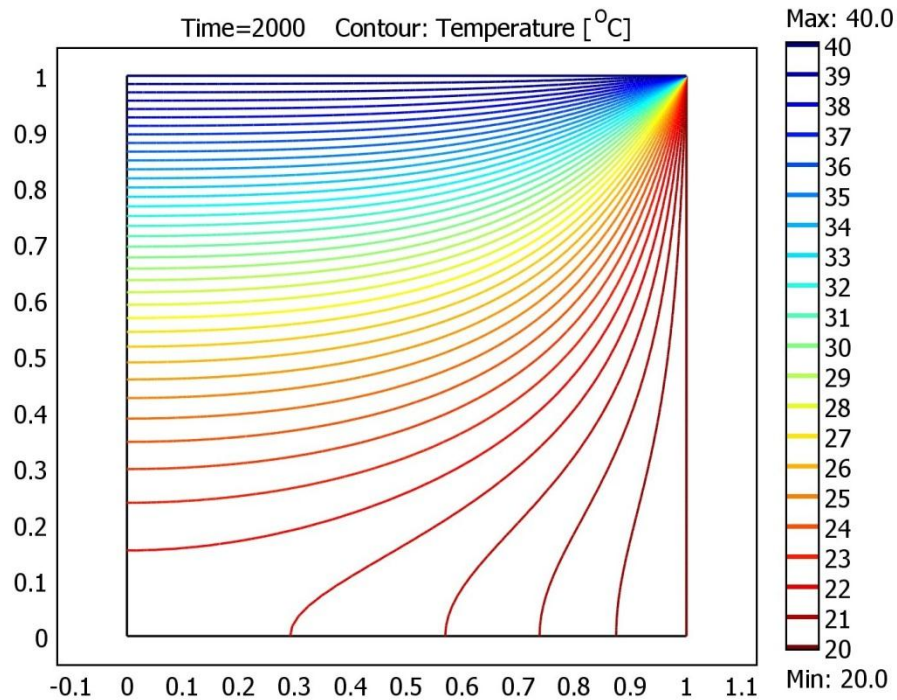


Figure F.3 Contour plot of the COMSOL solution at time = 2000 seconds

Another spatial conformation of the COMSOL solution's validity can be view by looking at the steady state solution. Figure F.4 shows the surface temperature of the plate at a large enough time (12500 seconds) to approximate the steady state condition. At steady state the plate should remain at T_r , 20 °C, along the right edge and T_t , 40 °C, along the top edge. Temperatures should be symmetric across the diagonal going from (0,0) to (1,1) with a temperature equal to the average of T_r and T_t , 30 °C, along the diagonal. All of the abovementioned conditions reflect the solution shown in figure F.4.

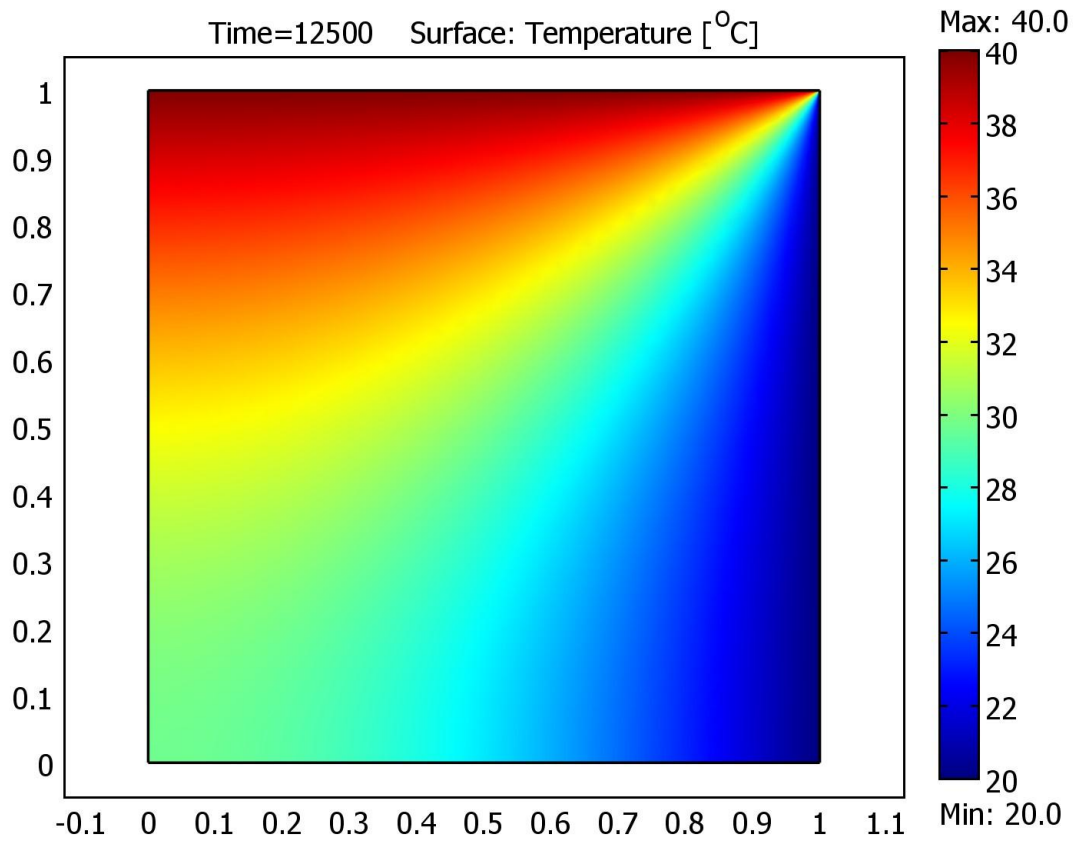


Figure F.4 Surface plot of the COMSOL solution approaching steady state (time = 12500 seconds)

To confirm the temporal validity of COMSOL's solution the thermal development of a specific point will be investigated. Figures F.5, F.6, and F.7 illustrate the thermal evolution of the plate at the point $(x, y) = (0.25, 0.75)$.

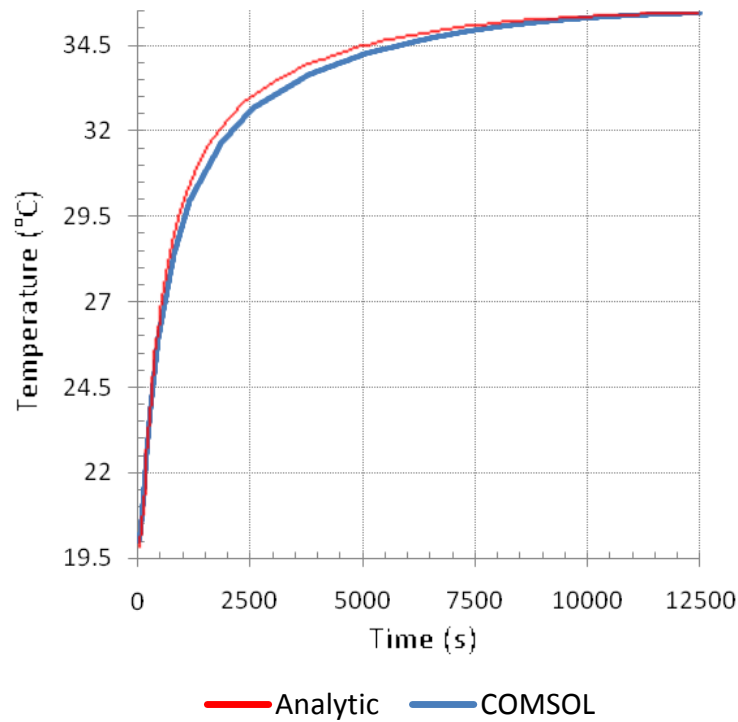


Figure F.5 Temperature vs. time for the point $(x, y) = (0.25, 0.75)$, for $t = 0$ seconds to 12500 seconds

Figure F.5 shows good agreement between the analytic and COMSOL solutions from $t = 0$ seconds to 12500 seconds. At 12500 seconds the solution is approaching the steady state temperature as indicated by both solutions asymptoting. This is confirmed by evaluating the analytic solution at $\lim_{t \rightarrow \infty} T(0.25, 0.75, t) = 35.55$ °C. There is some variation between the analytic and COMSOL between $t = 0$ seconds and steady state. To more clearly quantify the difference between both solutions, temperature vs. time curves at $(x, y) = (0.25, 0.75)$ were plotted for progressively smaller time scales: 1250 seconds in figure F.6 and 125 seconds in figure F.7. Both figures F.6 and F.7 indicate a maximum difference of about 0.5 °C.

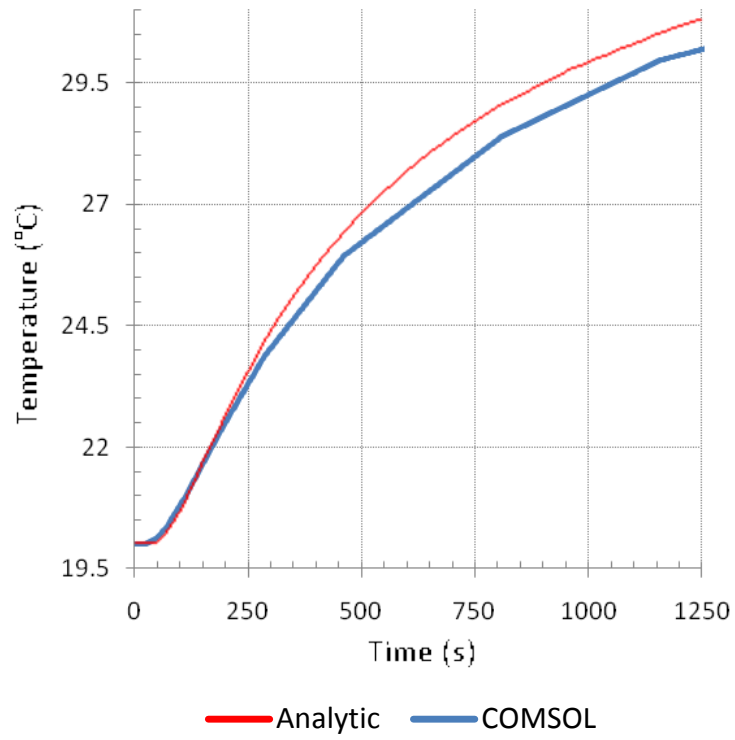


Figure F.6 Temperature vs. time for the point $(x, y) = (0.25, 0.75)$, for $t = 0$ seconds to 1250 seconds

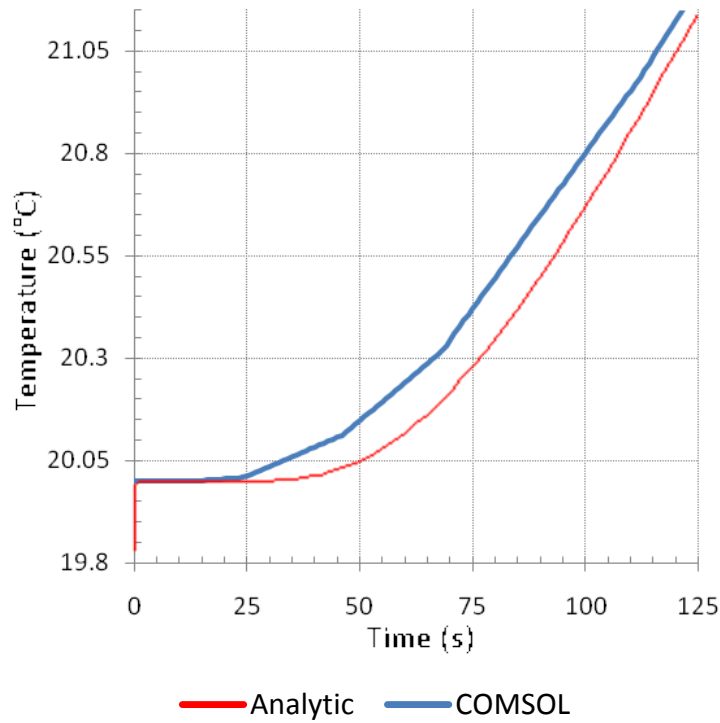


Figure F.7 Temperature vs. time for the point $(x, y) = (0.25, 0.75)$, for $t = 0$ seconds to 125 seconds

Based on the similarities between the analytic solution and the COMSOL generated solution for transient heat conduction within a two-dimensional plate, COMSOL is capable of accurately solving similar heat transfer problems. However, it should be noted that while the solver is capable of solving problems accurately, this is only true if the mesh and time step size is chosen appropriately (i.e. fine enough). If the mesh (or time step) size is not small enough the solution may not converge, or may converge to the wrong solution. To ensure convergence of all COMSOL models used in this study the mesh and time step was progressively refined until the solution differences between refinements was indistinguishable.

Appendix G

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