FABRICATION OF LONG-FIBER-REINFORCED METAL MATRIX COMPOSITES USING ULTRASONIC CONSOLIDATION

by

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Abstract

Fabrication of Long-fiber-reinforced Metal Matrix Composites Using Ultrasonic Consolidation

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This research is a systematic study exploring a new fabrication methodology for long-fiber-reinforced metal matrix composites (MMCs) using a novel additive manufacturing technology. The research is devoted to the manufacture of long-fiber-reinforced MMC structures using the Ultrasonic Consolidation (UC) process. The main objectives of this research are to investigate the bond formation mechanisms and fiber embedment mechanisms during UC, and further to study the effects of processing parameters on bond formation and fiber embedment, and the resultant macroscopic mechanical properties of UC-made MMC structures.

From a fundamental research point of view, bond formation mechanisms and fiber embedment mechanisms have been clarified by the current research based on various experimental observations. It has been found that atomic bonding across nascent metal is the dominant bond formation mechanism during the UC process, whereas the embedded fibers are mechanically entrapped within matrix materials due to significant plastic deformation of the matrix material during embedment.

From a manufacturing process point of view, the effects of processing parameters on bond formation and fiber embedment during the UC process have been studied and optimum
levels of parameters have been identified for manufacture of MMC structures. An energy-based model has been developed as a first step toward analytically understanding the effects of processing parameters on the quality of ultrasonically consolidated structures.

From a material applications point of view, the mechanical properties of ultrasonically consolidated structures with and without the presence of fibers have been characterized. The effects on mechanical properties of UC-made structures due to the presence of embedded fibers have been discussed.
To my parents and wife
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Chapter 1
Introduction and Literature Review

1.1 Introduction

1.1.1 Problem Statement and Motivation

A composite is a kind of material which consists of two or more components (reinforcements and matrices), so that the reinforcements and matrix materials can be purposely selected to achieve mechanical and/or thermal properties that cannot be obtained from a single material. Various reinforcements can be added to matrix materials during composite manufacturing processes according to diverse design criteria. In the current study, research interests are in long-fiber-reinforced metal matrix composites (MMCs), meaning the composites are of metallic matrices with fibrous reinforcements.

Fiber-reinforced MMCs are traditionally fabricated using powder metallurgy, liquid-metal infiltration, casting, diffusion bonding, metal spraying, and/or electrodeposition techniques. Short-fiber-reinforced (a.k.a discontinuous-fiber-reinforced) MMCs are typically produced by powder metallurgy or casting techniques, whereas long-fiber-reinforced (a.k.a continuous-fiber-reinforced) MMCs are mainly produced by casting, diffusion bonding, metal spray, or electrodeposition techniques [1-3]. Some of the major disadvantages of these processes are: i) elevated processing temperatures, ii) high cost of tooling, and iii) limitations on geometrical complexity.

Recent research has shown that a rapid prototyping technique known as Ultrasonic Consolidation (UC), which manufactures three-dimensional structures from metal tapes in a layer-by-layer manner, has been successfully utilized to embed continuous fibers within a metal matrix [4,5]. Thus UC is considered a potential candidate technique for manufacturing continuous-fiber-reinforced MMCs. This fabrication method has the advantages of being a
low-temperature, computer-controlled process which eliminates many of the disadvantages of conventional MMC fabrication techniques.

Feasibility studies of fiber embedment using ultrasonic consolidation processes have been reported in previous publications by Kong [5]. However, the understanding and knowledge obtained through the feasibility studies have not been sufficient for practical application of UC for manufacturing of metal matrix composites. Some critical issues for fabrication of MMCs using UC process have not been investigated and discussed in the feasibility studies. In addition, the previous studies were completed on a simplified, manually-operated version of the commercial UC machine. As the simplified machine is not capable of fabricating parts which could be implemented for mechanical property testing, mechanical properties of UC-made MMC structures have not been investigated, which are crucial knowledge for any application of MMCs. Additionally, for fabrication of MMCs using UC, two important phenomena have not been clearly understood, which are (1) the bond formation mechanisms which dominate between metal tapes during UC and (2) the mechanisms by which fibers are embedded during UC. Since the bonds established between matrix material itself and between fibers and matrix materials significantly affect the macroscopic performance of the ultrasonically consolidated MMC structures, these are important aspects of this current study.

1.1.2 Research Goals

As the motivations stated above, the engineering goals of the current study are to:

1. experimentally and analytically investigate the effects of processing parameters on fiber embedment,

2. understand bond formation mechanism(s) during fiber embedment, and

3. characterize the mechanical properties of UC-produced MMC structures.

As a result of these goals, a set of experimental and analytical studies were conducted to develop a repeatable methodology for fabricating MMCs using UC, to understand the
bond formation mechanism(s) of the UC process as it relates to fiber embedment, and to identify the mechanical properties of UC-produced MMCs.

1.1.3 Structure of Dissertation

This dissertation is prepared in a multi-paper format, following the requirements of the Graduate School of Utah State University. The structure of this dissertation is shown in Fig 1.1. Every individual chapter from Chapter 3 to Chapter 6 is composed of a journal article (Table 1.1). With the background knowledge related to UMW and UC reviewed in Chapter 1, an experimental processing parameter optimization study for fiber embedment using UC is described in Chapter 2. This chapter is followed by an energy model to analytically study effects of each processing parameter on bond formation during UC in Chapter 3. According to observations in various experimental studies, the bond formation mechanisms between metal foils and the mechanisms of fiber embedment during UC are investigated in Chapter 4. This chapter is followed by the characterization of mechanical properties of ultrasonically consolidated parts in Chapter 5, where the mechanical properties of resultant MMCs made with embedded fibers are presented and discussed. Chapter 6 discussed the overall scope of the work, and the major conclusions and future work which can be deduced from the results presented in this dissertation.

Two journal articles are included in the appendices of this dissertation. In Appendix A, the paper “Effects of Processing Parameter on Bond Formation during Ultrasonic Consolidation of Al 3003” is included. In this paper, the experimental results and findings are the foundation of the discussions about general bond formation mechanisms during UC. The paper of “Use of Ultrasonic Consolidation for Fabrication of Multi-material Structures” is also included in Appendix B. In this paper, a number of microstructures of ultrasonically consolidated samples from multiple materials have been presented, which contribute pronouncedly to the resulting discussion and understanding of the bond formation mechanisms and fiber embedment mechanisms which dominate during UC processing. Therefore, these two papers have been included in the appendices as a resource for the reader and as a basis for discussion and conclusions in Chapter 6.
Fig. 1.1: Structures of this dissertation.
Table 1.1: Details of Individual Journal Articles Included in This Dissertation

<table>
<thead>
<tr>
<th>Authors</th>
<th>Article Title</th>
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<tr>
<td>Y. Yang, G.D. Janaki Ram, and B.E. Stucker</td>
<td>Bond Formation and Fiber Embedment during Ultrasonic Consolidation</td>
<td>Journal of Materials Processing Technology</td>
<td>Submitted</td>
<td>Chapter 4</td>
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1.2 Literature Review

1.2.1 Introduction to Ultrasonic Metal Welding

1.2.1.1 Applications of Ultrasonic Metal Welding

Since the 1950s, ultrasonic metal welding (UMW) has been implemented as a versatile joining technology. It has been extensively utilized in various industrial applications, including the electronics industry, automotive industry, aerospace industry, and more. In the electronics industry, UMW has been applied as a major methodology for producing wired connections or making small connections in delicate circuits [6]. In automotive and
aerospace industries, structures made from metals which are difficult to be joined with fusion welding technologies, such as aluminum alloys, have been successfully fabricated using UMW [7]. In addition, the applications of UMW include encapsulation and packaging applications, manufacturing of solar energy systems, and others [8].

Compared to the conventional fusion welding technologies for metallic materials, UMW is superior in several aspects due to its nature as a solid-state joining technology. During most UMW processes, metal melting does not take place as the maximum processing temperature is generally no higher than 50% of the melting point of the joined metals [9]. Therefore, thermal residual stresses and thermally introduced deformation due to re-solidification of molten metal are eliminated in ultrasonically produced weldments. As far as the facilities of UMW processes are concerned, no atmospheric control is necessary to address molten metal oxidation issues. In UMW processes, a smaller amount of heat is generated than fusion welding processes, since the processes are completed at relatively low processing temperatures. In addition, ultrasonic metal welding is an environment-friendly process with reduced health and safety hazards, such as burns, toxic fumes, and irradiation.

A number of research efforts have focused on investigation of ultrasonic-weldabilities of metallic materials. Metals, such as Al 3000 and 6000 grades [10-17], copper [10,11], brass [18], magnesium [12,19], nickel-based alloys [20], titanium [20], gold [21], stainless steel [22-24], zirconium [24], zinc [25], and other alloys, have been successfully joined by UMW technology. Yet, there exists a need for exploring the ultrasonic-weldability of other metallic materials. Even for metals which have been shown to be ultrasonically-weldable, the geometries of welded parts can constrain the successful implement of UMW. Most commercial UMW systems have limitations related to the geometries of joined parts. One major limitation is the thickness of welded parts. For weldable metals, such as Al alloy 1100, the upper limitation was approximately 3mm, and parts thicker than 3mm were not ultrasonically welded in previous studies [8]. This limitation is mainly due to the low power output of conventional ultrasonic welding systems. Recently, new UMW equipment with high power have emerged for joining thick metal parts [22,23,26-28].
1.2.1.2 Typical Apparatus of Ultrasonic Metal Welding

Ultrasonic metal welding processes are performed on an ultrasonic welding apparatus. The apparatus is generally composed of five major functional portions (Fig 1.2), which are (i) power supply, (ii) transducer, (iii) booster, (iv) sonotrode, and (v) clamping mechanism [11,29]. Functions of each portion are described as follows. The power supply is typically fed with 110V alternating current (AC) at 50-60Hz and generates a series of sinusoidal electric pulses at ultrasonic frequencies. These electric pulses are converted to mechanical vibration by the transducer. From an energy points of view, the transducer transmits electrical energy to mechanical energy. At early ages of ultrasonic metal welding, transducers were made of ferromagnetic materials by taking advantage of magnetostrictive effects (ferromagnetic materials undergo a change in physical dimensions when subjected to switching magnetic fields caused by alternating electric currents). However, due to the low efficiency of magnetostrictive effects, ferromagnetic materials have been replaced by piezoelectric materials. Piezo-ceramics, which are the most commonly used piezoelectric materials in ultrasonic welding systems today, periodically change dimensions due to the piezoelectric effect. When the piezo-ceramic transducer is loaded with the sinusoidal electric pulses generated by a power supply, its geometry changes periodically and ultrasonically. However, the dimensional changes of a transducer are typically on the order of a few nanometers. Hence a booster is required to amplify the geometrical changes of a transducer to the applicable mechanical vibrations of several microns needed for most UMW applications. The welding tip which contacts the workpiece and delivers ultrasonic energy is called a sonotrode. It is connected to the, booster and thus vibrates ultrasonically at a prescribed amplitude. The sonotrode is used to generate displacements of materials being joined at their interface. Typically the sonotrode is vibrated along a plane parallel to the interface and results in the establishment of metallurgical bonds across the interface. A normal force is applied through the sonotrode, perpendicular to the interface plane, in order to keep the sonotrode in tight contact with the workpiece, to avoid any slippage between the sonotrode and workpiece, and to improve the efficiency of ultrasonic energy delivery to the interface.
Fig. 1.2: Schematic of basic functional components in an ultrasonic welding apparatus [29].

between the materials which are being joined.

1.2.2 Experimental UMW Research

1.2.2.1 Bond Formation Mechanisms of Ultrasonic Metal Welding

Although fundamental research on ultrasonic metal welding processes have been conducted for decades, the metallurgical bond formation mechanisms of UMW are still unclear, as the reasons for bond formation during UMW have not been well understood, and numerous bond formation mechanisms have been identified for different material combinations and/or processing conditions. For ultrasonic metal welding, four basic mechanisms of bond formation have been postulated by various researchers [21,30-32]: (i) mechanical interlocking; (ii) melting of interface materials; (iii) diffusion bonding, (iv) atomic forces across nascent metal surfaces (e.g. solid state metallurgical bonding without significant diffusion).

1.2.2.1.1 Mechanical Interlocking

Most of the postulated explanations listed above have been experimentally confirmed by previous researches. Mechanical interlocking appears to dominate bond formation during ultrasonic welding of certain dissimilar materials, especially materials with significant hard-
ness differences. In experiments involving ultrasonic welding between aluminum and gold, Joshi clearly showed the presence of a liquid-like material flow using scanning electron microscopic (SEM) images of the bonded interface [21]. This interlocking was credited as the reason for the excellent bond strength between Al and Au. Recently, stainless steel 304 wire meshes were successfully embedded between Al 3003 foils using ultrasonic metal welding processes [18]. It was found that the stainless steel meshes were not chemically bonded to Al 3003 foils, while mechanical interlocking between Al and SS meshes caused by plastic deformation of Al was the major bond formation mechanism in this case (Fig 1.3). In other work, it was concluded that mechanical entrapment and interlocking was the bond type between fibers and metal matrix materials, when the fibers were embedded using UMW [18]. However, mechanical interlocking phenomena were not demonstrated in most of other research results. With the assistance of orientation imaging microscopy (OIM), the interface of ultrasonically welded Ni 201/Ni 201 samples were studied in detail (Fig 1.4) [31].

As shown in the figure, their polycrystalline structures persisted to a flat metal/metal interface, and no evidence of mechanical interlocking was observed. Thus, although material mechanical interlocking can take place during ultrasonic metal welding processes, assisting bond formation for certain processing conditions and material combinations, it has only been demonstrated for material combinations between dissimilar metals, or between materials with significant hardness differences. For material combinations of similar materials or materials with similar hardness values, material interlocking appears not to be a principle bond formation mechanism.

1.2.2.1.2 Metal Melting

Occurrence of molten metal was not observed in most research results for ultrasonic metal welding. However, some researchers observed conditions that led them to believe that metal melting occurs for certain material combinations and processing conditions. Metal melting and re-solidification can establish excellent metallurgical bonds in joining processes, so melting or lack of melting during UMW is important to determine.

A direct method for establishing the presence of melting is to measure the temperature
Fig. 1.3: Microstructure of stainless steel mesh embedded between Al 3003 using ultrasonic consolidation process. (white arrows indicate gaps between SS mesh and Al 3003, while black arrows indicate SS mesh bonding to itself.)
Fig. 1.4: An image of several inverse pole figures of contiguous areas along a well-bonded Ni-Ni interface stitched together. The grains in the image are color coded to reflect their orientation. Grains that have been plastically deformed typically show a smooth intra-grain color transition indicating rotations of the crystal lattice.

of the interface during UMW. Several methods have been utilized to characterize the actual processing temperature at the metal/metal interface during UMW. Those methods include (1) embedding small thermocouples between the metals at their interface [12,21], (2) measuring the thermoelectric electromotive forces (e.m.f) between workpieces during welding [9,20,12,23,32,33], and (3) measuring temperature with an infrared camera [34]. It should be noted that a huge discrepancy exists among the reported temperature measurements. Jones [12] claimed that in his research the measured temperature in UMW of pure aluminum was around 40°F (204°C) using a thermocouple, and 1000°F (538°C) for combination of Monel and aluminum sheets using the e.m.f method. None of these temperatures, however, approach the melting temperature of the welded metals. Although no measurements were listed, Daniels [9] reported that processing temperature was no more than 40% of the melting point of the welded metal. Using the e.m.f method, Weare [10] suggested a maximum processing temperature of 450°F (232°C) during UMW between copper and Monel. The maximum processing temperature at the interface of an iron-constantan weld was found to be approximately 345°F (174°C) by Hazlett using the e.m.f. method [32]. Joshi [21] measured the processing temperature of ultrasonic welding between thin gold wire and a
gold substrate with a thermocouple, and the temperature was found to be no more than 120°C. Tsujino used the e.m.f method to identify the processing temperature in ultrasonic welding of thick metal sheets. He found the maximum processing temperature was 198°C for ultrasonic welding of 6mm-thick aluminum sheet and stainless steel sheets, and 235°C for welding of 6mm-thick aluminum and copper sheets [23]. Tsujino [33] also studied the processing temperature of ultrasonic welding between aluminum wire (0.1mm in diameter) and a 1mm-thick aluminum substrate using the e.m.f. method. The maximum processing temperature was 436°C. An infrared camera with an accuracy of ±10°C was used by E. de Vries [34], measuring a temperature of 314°C (597°F) during ultrasonic welding of aluminum 6061 sheets.

In addition to the methods mentioned above, another method recently developed to determine the processing temperature during ultrasonic metal welding with higher accuracy is embedment of micro thermal sensors into the workpiece substrate closely adjacent to the welding area using MEMS technologies. These thermal sensors were six K-type thin film thermocouples (TFTCs) and one thin film thermopile (TFTP) [35]. The micro thermal sensors exhibited both excellent static and dynamic response, as the dynamic response time of the TFTC was as quick as 50ns, which is superior to all commercial thermal sensors [36,37]. During joining of alloy 110 copper onto a Nickel substrate, the processing temperature was measured as 220°C under a vibration amplitude of 29µm, welding duration of 0.5s, and clamping pressure of 30MPa [38].

Although various temperature measurement methods have been used, a drawback of all the methods listed above is that all the measured temperatures were averaged temperatures of a certain volume of material at the metal/metal interface. At some localized spots, it is possible that the temperature may reach or exceed the melting point, even if averaged temperature at the welding interface are well below the melting point. Therefore microscopic analyses were also conducted as an alternative method to investigate the possibility of material melting. In most microscopy examinations, no fusion welded microstructures were observed [6,9,10,12,39]. However, Kreye [40] found evidence of metal melting during
ultrasonic welding of $Cu_2Co$. Because the metal was heat treated before welding with some cobalt rich particles identified, and after welding these particles dissolved at the interface region, Kreye took this as evidence that melting of the interface materials took place to some extent. In a recent research paper, Gunduz and his colleagues reported their experimental results of ultrasonic welding of zinc sheet and aluminum foils. They conducted EDS analysis across the metal interface, and the profile of zinc concentration is shown in Fig 1.5 [25]. They observed a region of less than $1\mu m$ at the interface where Zn% was constant at 80%. They claimed molten metal occurred in this region. Thus, although it appears that necessary conditions to initiate metal melting can be found during UMW of certain materials under various process parameter settings, the presence of metal melting is not universally observed, and in most cases no evidence of metal melting was found. Metal melting can improve bonding strength of UMW-made weldment to some extent; however, the associated thermal-induced residual stresses and distortions are not desired.

1.2.2.1.3 Diffusion

Elemental diffusion across metal/metal interfaces was found in some studies of ultrasonic welding between dissimilar metals. In the results shown in Fig 1.5 [25], the Zn concentration within the Al plate shows an error-function profile starting at the depth of $1\mu m$. The width of the area, where the element concentration asymptotically changed, was $6\mu m$. The experiment result verifies the occurrence of diffusion during ultrasonic welding between Al and Zn. It is interesting to notice the occurrences of diffusion in this case, as the diffusivity of Zn was significantly enhanced. The diffusivity of Zn in this case was found by the authors to be five orders of magnitude higher than normal diffusivity at the same temperature [25]. The reason for the enhance diffusivity was expected due to the extremely high strain rate during ultrasonic metal welding processes. The strain rate during ultrasonic welding was found as high as $10^3/s$. This high strain rate facilitates the formation of vacancies within welded metals, and thus excess vacancy concentration grows rapidly [41]. As a result, the diffusivity of the metal is enhanced pronouncedly [25,42-44]. Therefore, it appears that ultrasonic welding can provide necessary conditions for significant element
Fig. 1.5: EDS profile across the interface of ultrasonically welded Al and Zn (re-generated) [20].
diffusion. However, in recent studies of ultrasonically welded Al 3003/Ni 201 samples, EDS line scan results indicated no measurable diffusion of Ni into Al and vice versa [31]. Similar, no measurable diffusion between Al and Cu was found in samples of ultrasonic welded Al alloy 3003/high purity Copper [45]. Therefore, although diffusion could happen during ultrasonic metal welding processes under certain processing conditions and material combinations, the mechanism of bond formation during ultrasonic welding does not depend heavily on diffusion. When diffusion occurs, it will help the overall bonding processes.

1.2.2.1.4 Atomic Force Across Nascent Metal Surfaces

While material mechanical interlocking, metal melting, and diffusion all can occur during ultrasonic metal welding, they are specific to certain material combinations and processing conditions without universal presence in all UMW processes. Metallurgical bonding in UMW appears, in most cases, to be due to solid-state atomic forces across the nascent metal contact areas. As is the case with all solid-state welding processes, two conditions must be fulfilled for establishment of bonding during ultrasonic metal welding: (i) generation of atomically clean metal surfaces, and (ii) intimate contact between clean metal surfaces. Both these conditions can be satisfied by the combination of ultrasonic vibration and normal force applied by the sonotrode during ultrasonic welding processes.

As all engineering metallic materials contain surface oxide layers, it is necessary to remove these surface layers for generation of atomically clean metal surfaces. In ultrasonic welding processes, the sonotrode has a “surface effect” on the mating metal surfaces. The term “surface effect” contains any phenomena occurring on the metal surface during ultrasonic metal welding, including the break-up and removal of the surface metal oxide layers [9,19,33]. Researchers have discussed the fact that surface effects are essential for the establishment of metallurgical bonding during the initial stage of welding. The ease with which oxide layers can be removed during ultrasonic welding depends on the ratio of metal oxide hardness to nascent metal hardness - higher ratios facilitate easier removal. This is the reason why Al 3003 alloys are one of the best-suited materials for ultrasonic welding [15]. For ultrasonic welding of aluminum, due to the significant hardness differences between
aluminum and aluminum oxide ($Al_2O_3$), aluminum deforms plastically under a certain level of stress while the aluminum oxide is pulverized into sub-micron particles [31,40,46]. Noble metals such as gold, which do not have a surface oxide layer, have been reported to be quite amenable for ultrasonic welding as well [21]. Materials with difficulty to remove oxide layers have been reported to be problematic for ultrasonically welding. For example, Al 6061 alloys were found to be difficult to ultrasonically consolidate, which was attributed to difficulties with oxide layer removal, thought to be due to the presence of MgO in surface oxide layers of these alloys [16]. Interestingly, such difficult-to-weld materials have been shown to be ultrasonically weldable when employing techniques for removing surface oxide layers just prior to welding [9,16].

It has been observed that oxide layers or oxide patches are not present in locations where there is good bonding at the metal interfaces, while oxide layers are observed at unbonded regions of the metal interface [31]. Therefore, there is ample evidence that oxide layer removal is crucial in ultrasonic metal welding. Successful removal of metal surface oxide layers prepares atomically clean surface across which metallurgical bonds are established. Under the normal forces applied by the sonotrode, the mating metal surfaces are brought into intimate contact, establishing metallurgical bonds.

The procedure of removing oxide layers and establishing metallurgical bonds detailed above occurs ideally over the whole contacted area during ultrasonic metal welding. However, as all material surfaces are characterized by surface roughness at microscopic level, when two metal surfaces are pressed against each other, the hills and valleys pattern on the mating surfaces prevent 100% surface contacting (see Fig 1.6). It has been suggested that initially oxide layers at the contacted asperities are broken and removed, while the oxide layers at other no-contact areas persist. At the surface locations where oxide layers persist, metallurgical bonds are not established.

In experimental studies, ultrasonically bonded areas were found to reach almost 100% over the whole interface area. Thus the initial no-contact areas are brought together by plastic deformation at the material interface. Recent research revealed that some amount of
plastic deformation occurs near the interface of the materials (Fig 1.4) at a microscopic level [26] and is responsible for material coming into contact in the voids left between the hills and valley pattern due to natural surface roughness. Thus plastic deformation, however even though not macroscopically significant, is believed to be crucial for ultrasonic metal welding to bring the materials into intimate contact across the interface, filling the surface roughness which exists, and breaking up the surface oxide layer.

The occurrence of plastic deformation is enhanced by the effect of ultrasonic excitation on deformation behavior of metals. In the presence of ultrasonic energy, metallic materials are known to experience significant softening, which is not connected to any rise in temperature, resulting from being subjected to an ultrasonic field. This phenomenon is known as the “Blaha effect” or “acoustic softening.” Following early work by Blaha and Langenecker [47,48], acoustic softening has been observed by several other researchers in their experiments involving tube and wire drawing [49-51]. Although the softening effects are similar, it appears that ultrasonic energy is more effective than thermal energy at reducing the flow stress of a metallic material. For example, Eaves et al. [52] reported that bulk heating can reduce stresses by 45% while ultrasonic vibration reduces it by 75%. Considering energy density, it takes approximately $10^{22}eV/cm^3$ of thermal energy density to produce a zero stress in aluminum without ultrasonic superimposition, while only about $10^{15}eV/cm^3$ using ultrasonic energy [48]. Langenecker [48] explained, “acoustic energy is
assumed to be absorbed only at those regions in the metal lattice which are known to carry out the mechanisms of plastic deformation. Heat, on the other hand, is distributed rather homogeneously among all the atoms of the crystal including those which do not participate in the mechanisms of plastic deformation."

In addition to acoustic softening, thermal softening can also occur at the weld interface due to frictional heating, further contributing to a reduction in flow stress. According to most investigators, interface temperatures during ultrasonic welding reach up to 40-50% of the melting point of the base materials. Thus, although the forces involved in a typical ultrasonic welding operation are generally modest, there seem to be sufficient conditions for plastic deformation and metal flow, when considering the combined acoustic and thermal softening effects.

To summarize, the removal of surface oxides prepares atomically clean metal surfaces for bond formation due to atomic forces, plastic deformation of materials facilitates elimination of unbonded areas producing weldments with high welding density.

1.2.2.1.5 Bond Mechanisms of Ultrasonic Metal Welding

As discussed above, metallurgical bonds formed between welded metals have been shown to be by the mechanisms of mechanical interlocking of materials, metal melting and re-solidification, diffusion and atomic forces across nascent metal surfaces. However, mechanical interlocking of materials, metal melting and re-solidification and diffusion are not universally observed. The occurrences of these phenomena are significantly dependent upon the welded material combinations and processing conditions, while the bonds formed by atomic forces across nascent metal/metal interfaces appears to be universally confirmed in various material combinations and processing conditions. Thus bond formation during ultrasonic metal welding should typically be considered to be caused by atomic level forces across nascent metal interfaces, whereas the conditions to initiate mechanical interlocking of materials, metal melting and re-solidification and diffusion should be expected only for specific process parameter and material combinations. The occurrence atomic bonding is preferred when the microstructure of the materials being bonded must be retained near
the surface, when dissimilar metals which might otherwise form brittle intermetallics are being joined, or when the temperature rise must be minimized for some reason. However, the other mechanisms for bonding will almost always result in a higher strength across the interface of the ultrasonically made weldment.

In the case of nascent atomic bonding, the bonding process in ultrasonic welding can be recognized as repeated and successive occurrence of two distinct stages: (i) generation of contact points (Contact Stage), and (ii) formation of bonds across the contact points (Bond Stage). These stages are discussed below.

Surface roughness on all metal/metal surfaces does not allow 100% surface contact at the interface; instead, the mating surfaces contact only at surface asperities. Thus, in a way, the first Contact Stage is immediately accomplished as the mating surfaces are brought into contact under the influence of applied normal force (Fig 1.6). It is at these oxide-covered contact points that bonding initially occurs. As the sonotrode travels over the layer to be deposited, simultaneous application of normal and oscillating shear forces results in generation of dynamic interfacial stresses between the two mating surfaces at the contact points. The stresses produce cracks in the surface oxide layers as well as induce plastic deformation in a thin layer of metal near the contact points. Plastic deformation further facilitates the cracking in the oxide layer. As this happens, nascent metal from beneath extrudes through the cracks in the oxide layer causing disintegration of oxide layers into smaller pieces, which are dispersed in the vicinity of the bond zone by metal flow. This process generates atomically clean metal surfaces and brings them into intimate contact, establishing a metallurgical bond. This completes the first Bond Stage of the overall process. After the first Bond Stage, there may be numerous “no-bond” regions (corresponding to the original “no-contact or void” regions) along the interface because of metal surface roughness, still covered with oxide layers.

As the process progresses, the bonded regions (formed in the first Bond Stage) grow in size, aided by plastic deformation. Plastic deformation at the bonded regions results in squeezing of metal into the voids and the mating surfaces across the void regions approach.
As this happens, new points come into contact. This marks the completion of the second Contact Stage of the process. Continued application of ultrasonic energy results in friction, oxide layer break-up and bonding across these new contact points (in the same manner as described in the first Bond Stage) in what can be called the second Bond Stage of the process. This will be followed by another Contact Stage, and subsequently by another Bond Stage and so on. Thus ultrasonic metal welding involves repeated and successive occurrence of Contact and Bond Stages at every region along the weld deposit.

1.2.2.2 Effects of Processing Parameters on Bond Formation

Research results have demonstrated that the major controllable variables of ultrasonic metal welding processes are (i) clamping force or clamping pressure applied on workpieces by the sonotrode, (ii) ultrasonic energy input to workpiece, (iii) welding exposure time, (iv) geometric configuration of the sonotrode, and (v) physical properties of the welded materials. It has been revealed that the quality of ultrasonically welded structures is significantly influenced by the processing parameters listed above. As a result, extensive experimental investigations have been conducted, studying the effects of the processing parameters on the quality of weldment made by UMW.

1.2.2.2.1 Clamping Forces (Clamping Pressure)

Clamping force or pressure is the normal force or pressure applied on the workpiece by the sonotrode during UMW processes, which assures an initiate contact between the workpieces so that the ultrasonic vibration energy can be effectively delivered for establishment of metallurgical bonds across the welding interface. This processing parameter is found to have a non-linear effect on the strength of the weldment, with an optimized level of clamping force or pressure required to achieve best bonding. In an early research article, Weare et al. [10] found that an optimum clamping force existed to achieve highest breaking loads for ultrasonically welded samples using copper and Monel. Kong et al. [17] found that the optimum clamping force, in terms of contact pressure, lies between 172 and 276kPa for ultrasonic welding of 100µm thick aluminum 3003-H18 foils using an 50 mm diameter
sonotrode. Any clamping pressure higher or lower than the optimum level could degrade the quality of weldments. Janaki Ram et al. [39] claimed that the ultrasonically welded part with highest linear welding density (LWD) was obtained with clamping force of 1750N for a wheel-shape sonotrode diameter of 147mm during a study on ultrasonic seam welding of aluminum 3003 foils of 150µm in thickness. When considering the area of contact, the results of Kong et al. and Janaki Ram et al. are comparable. Thus, it has been found by several independent research groups that bond quality is improved when the clamping force increases from low levels to an optimum level of clamping force, but that the bond strength decreases when the clamping force further increased beyond the optimum clamping force level.

From a bond formation point of view, surface oxide layer removal and mating interface plastic deformation is strongly influenced by the applied clamping force, as clamping force or pressure along with the reciprocal vibrating motion of the mating interface directly determines the dynamic stress conditions during UMW processes. Therefore, more severe stress conditions will result from an increased clamping force or clamping pressure. But when the clamping force or clamping pressure goes beyond a certain level, the stress condition at the mating interface may be so severe that the formed bonds are damaged, therefore reducing the quality of weldments [39].

1.2.2.2 Ultrasonic Power Input

Ultrasonic power input directly affects the degree of elastic/plastic deformation between mating metal interfaces [12]. For given material combinations, the frequency and amplitude of sonotrode vibration significantly determines the amount of ultrasonic energy available for bond formation. In most UMW systems, the frequency of vibration is adjustable, since it has been pre-set based on the sonotrode geometry, piezo and booster hardware and the power supply. In most UMW equipment, the directly controllable factor for ultrasonic power input is the vibration amplitude of the sonotrode [9,53,54]. Thus vibration amplitude is usually used as an adjustable processing parameter for UMW systems. Generally speaking, the higher the vibration amplitude, the greater the ultrasonic energy delivered, consequently
the more plastic deformation which occurs at the mating metal interface, and therefore the better the welding quality achieved.

Ultrasonic energy input, however, can have a non-linear influence on bonding quality of UMW-made weldment if the energy becomes too large. An optimum level of energy is required to achieve the best bonding performance for a certain application. In another words, there is an optimum vibration amplitude which exists for certain material combinations and applications. It was found by Tsujino [55] that the strongest welds between stainless steel and aluminum sheets are obtained at an amplitude of 12.7\(\mu m\), with any higher or lower amplitude resulted in a decrease in weld strength. During Kong’s studies on parameter optimization of ultrasonically welded Al 3003-H13 foils of 100\(\mu m\) thickness, he [17] established the processing window of vibration amplitude from 8.4 to 14.3\(\mu m\). Janaki Ram [39] found that amplitude of 16\(\mu m\) was the optimum level for ultrasonic consolidation of Al 3003 foils of 150\(\mu m\) in thickness. As the ultrasonic energy input strongly influences the elastic/plastic deformation of mating interface, this processing parameter facilitates the elimination of unbonded areas due to metal surface roughness along the welding interface. Higher ultrasonic energy input results in stress condition which helps fill the voids with metal flow, as shown in Fig 1.6, therefore producing weldments with higher linear weld density. When the energy exceeds a critical level, the weldments deteriorate because of excess plastic deformation, which can damage bonding at the welding interface [9,14].

1.2.2.2.3 Welding Exposure Time

A number of experimental studies have shown that welding exposure time has a non-linear effect on the bond strength of ultrasonic welds [10,23,39,56]. It was found that for various material combinations, different optimum welding exposure times exist to obtain the best bonding performance. Associated with ultrasonic power input, welding exposure time can directly determine the total amount of ultrasonic energy delivered to the welding interface at a particular location. More energy is delivered with increased duration, but over-input of ultrasonic energy may cause destruction of formed metal bonds and metal fatigue, which results in a deterioration of bonding strength [21,57,58]. Thus to avoid bond
damaging caused by excess ultrasonic energy, a proper welding exposure time is important for strong bonds.

1.2.2.2.4 Configurations of Sonotrode

The sonotrode is the component which is mechanically coupled with the welded parts, delivering the ultrasonic energy to the welding interface by applying combined ultrasonic vibrations and normal clamping forces. The functionality of a sonotrode requires it to be made from materials with high fatigue strength and high thermal conductivity, often titanium. Sonotrodes can be of various shapes and sizes to meet requirements of differing applications. Three different sonotrode geometries are commonly commercially available, which are flat surface sonotrodes, hemispherical sonotrodes, and cylindrical sonotrodes. Flat sonotrodes are commonly used in ultrasonic welding of plastics, while the last two types are common for ultrasonic metal welding processes. Hemispherical sonotrodes are typically used in spot ultrasonic metal welding systems for metal wire connections and thin metal foil joining [10,34]. Cylindrical, or wheel-shaped, sonotrodes are used for seam ultrasonic welding systems for metal sheet joining. The contact surfaces of sonotrodes are typically roughened using electrical discharge machining (EDM). The roughened surfaces facilitate reducing energy loss caused by welding tip sliding at the welding interfaces, and improving energy delivery efficiency. In addition, the roughened sonotrode surfaces prevent joined parts from being welded to the sonotrode, hence destroying the welded structure when moving the sonotrode away [34]. The drawback of a roughened sonotrode is that it leaves a roughened impression on the topmost surface of the joined materials.

For all commercialized UMW apparatuses, the sonotrode vibrates reciprocally along one direction within the plane of the welding interface. More novel UMW systems have been developed for research purposes with complex motion patterns. In these systems, the sonotrode is driven in two perpendicular directions with identical or different vibration amplitudes at the same frequency. Depending on the amplitude setting, the motion pattern of the sonotrode can be circular (same amplitude) or elliptical (different amplitudes). A complex motion pattern for a sonotrode has been shown to improve the ultrasonic energy
transmission efficiency through thick welds, thus making these systems more capable of joining thick structures [26].

1.2.2.2.5 Physical Properties of Welded Materials

The material characteristics and properties of the welded materials are the most important factors to consider for ultrasonic metal welding processes. Different combinations of welded materials determine the optimum levels of the machine-related processing parameters, such as clamping force, ultrasonic energy input, and welding exposure time. Important material characteristics and properties include material hardness, ductility, thermal conductivity, surface cleanliness, oxide to bulk material hardness ratio, oxide layer thickness, surface roughness, and workpiece geometry. Effects of some major material-related variables are detailed below.

Material hardness has an important influence on achieving mechanically desirable weldments. The hardness of the welded materials directly determines the plastic deformation possible at the interface, which is a necessary condition for bond formation during UMW [21, 31, 32]. From this point of view, soft metals are more easily ultrasonically welded than hard metals, as soft materials are more readily plastically deformed.

Ductility is an important material variable determining ultrasonic-weldability. In UMW processes, fatigue and failure due to excess ultrasonic energy input occurs at bonded metal interfaces, which produce defects in the bond. For ductile materials, the excess energy input can be absorbed by material plastic deformation. Generally, the more ductile, the more easy it is to ultrasonically weld a material.

Thermal conductivity can partially affect the ultrasonic weldability of metals [21]. It was found that heat generation caused by friction and scratching between vibrating metal surfaces plays an important role in bond formation during ultrasonic metal welding. It was noticed that there was a minimum temperature required before significant metallurgical bonding occurs [10]. Hence, when other processing parameters are fixed, materials with higher thermal conductivity are more difficult to weld. However, since UMW is a solid-state joining process, temperature and thermal conductivity is often a secondary factor.
Thus, the thermal conductivity of ultrasonically welded metals is not as critical as it is for fusion welding.

Ultrasonic welding is capable of joining many metals to a satisfactory bond strength without surface preparation. This means that surface oxide films and/or contaminate layers are broken and displaced from the surface by the reciprocal motion and plastic deformation of the welded materials. Research has shown that oxides can affect bonding to some extent, for some welded materials. Joshi [21] explained the superior bondability of gold may be attributed to the lack of oxide film on the surface. Results revealed that for Al 3003, removal of oxide layers before ultrasonic welding minimally improved bonding strength [17]. But for Al 6061, metal oxides must be removed to obtain metallic bonding, since the oxide layers for Al 6061 are more magnesium-rich than those of Al 3003, which makes the surface oxide layer for Al 6061 less brittle. This magnesium-rich oxide layer was found not to be efficiently removed during ultrasonic welding, resulting in poor bonding strength [16]. In addition, the authors have experienced, using various metals in unpublished experiments, that stripping the surface oxides using chemical means has a positive effect on bonding for other Al, Ti and Ni alloys. Thus, surface preparation should be considered on a metal to metal basis, depending on the composition of the surface films.

Metal thickness is another important factor to be considered. Thin metal foils and sheets are more weldable than thick metal plates. In order to weld thick metal plates, an ultrasonic welding system with large power capacities is needed, i.e. 100kW [22]. Complex vibration systems having both transverse and torsional vibratory motion can also facilitate bond formation for thick metal plates [26].

1.2.2.3 Studies on Optimization of Processing Parameters of UMW

According to the statements above, for given combinations of welded materials and welding apparatus, the three major adjustable processing parameters are clamping force applied on the workpiece by the sonotrode, oscillating amplitude of the sonotrode, and welding exposure time (or welding speed for ultrasonic seam welding processes). These three variables are considered the major controllable processing parameters in most ultrasonic
metal welding processes. Temperature, which some apparatuses can control, has also been found to be an important variable.

Tsujino and his colleagues successfully joined thick stainless steel plates of 6mm with optimized processing parameters [28]. Kong [17] has and achieved optimum processing parameter windows for ultrasonic seam welding of 100µm thick 3003-H18 aluminum and aluminum 6061-T6 foils. Recently, Janaki Ram et al. [39] utilized a Design of Experiment method (Taguchi method) to investigate the optimum process parameters for ultrasonically welded structures produced using Al 3003-H18 foils of 150µm thickness.

1.2.3 Analytical & Numerical Modeling of Ultrasonic Metal Welding

Ultrasonic metal welding is challenging, when it comes to analytically or numerically modeling, as UMW involves many complex, interrelated physical phenomena. Major challenging issues include material properties modification due to ultrasonic excitation, metallurgical bond formation mechanisms, bonded metal fatigue, crack initiation and propagation, energy conversion of sonotrode vibration to heat through dynamic friction, transfer of heat due to frictional heating, acoustic heating, and more.

As discussed earlier, during ultrasonic metal welding processes, the physical properties of metallic materials are modified by exposure to ultrasound excitation. One primary phenomenon is the Blaha effect, in which metal being ultrasonically excited is significant softened [47,48]. In other words, the static stress necessary for metal plastic deformation is reduced when the metal is ultrasonically excited. This phenomenon has been experimentally investigated [49]. However, theoretical modeling of this phenomena is not fully developed, and mathematically rigorous relationships between the amount of ultrasonic energy input and the resultant degree of softening for most metallic materials have not been developed.

In ultrasonic metal welding processes, welded materials experience very high strain rates, as high as $10^3/s$. It has been found that high strain rates facilitate the formation of vacancies, and thus excess vacancy concentration grows rapidly [41]. As results, two physical properties of welded metal are modified significantly, which are the enhancement of diffusivity of the welded metal and depression of the melting point of the welded metal.
Enhanced metal diffusivity has been observed by many researchers, but quantitative relationships describing the enhancement of metal diffusivity due to creation of excess vacancies have not been fully developed. In one recent study on ultrasonic welding between Al and Zn, various phase diagrams for Al-Zn systems subjected to different level of vacancy fractions was generated using a chemical thermodynamic model [25]. For other metal combinations, similar studies are were not found. Hence, modifications of metal properties due to these phenomena during UMW process modeling have not being fully investigated or understood. Some of these properties are critical for accurate modeling of ultrasonic metal welding processes, and thus current model efforts do not account for these phenomena.

Another major challenging task when modeling ultrasonic metal welding is that the bond formation mechanisms during UMW processes is not fully understood. The particular bond formation mechanism, or combination of mechanisms, will change depending upon the material and process parameter combination. Integrating all possible bond formation mechanisms is a major difficulty for accurately modeling UMW processes.

In spite of these challenges, several research groups have expended significant effort toward the development of models to simulate ultrasonic metal welding processing conditions under various material-related and machine-related factors. Jeng and Horng [59] used an asperity model to compute real contact area and flash temperature between welder and substrate. The theoretical results and experimental observations indicated that the contact temperature plays an important role in bonding strength in the initial period of joining, and surface roughness is a dominant factor in the final period of joining. Gao and Doumantis [60-63] analyzed the mechanics of metal ultrasonic welding processes as a basis for a new solid freeform fabrication technology. They developed a 2-D, quasi-static/dynamic, elasto-plastic numerical model of the stress/strain field using finite element analysis. The frictional boundary conditions at the foil/substrate interface were described via an elastic plain stress, static formulation. The calibrated computational simulation was validated in the laboratory and applied to the study of elastic stress concentrations, plastic deformation initiation and propagation patterns, slippage at the interface surface, and the dynamic
effects of ultrasonic loading on the bonding process.

Recently, E. D. Vries [34] developed a mechanics based model to simulate heat generation, processing temperature changes and the interfacial shear force between welded metal parts during ultrasonic welding. Compared with experimental results, correlations between bonding strength and processing conditions, such as temperature changes and interfacial shear force, were studied.

Most of the developed models simulated processing conditions analytically and numerically. Processing temperature conditions, force conditions, stress and strain conditions during UMW have all been simulated. The model results showed good agreement with experimental trends.

1.2.4 Ultrasonic Consolidation (UC)

1.2.4.1 Solid Freeform Fabrication Concepts

Solid freeform fabrication (SFF) technologies, also known as rapid prototyping (RP) or additive manufacturing technologies, are recognized as a family of technologies for fabricating complex three-dimensional structures directly from computer-aided design (CAD) data in a layer-by-layer or additive fashion. In all solid freeform fabrication processes, the structure begins as a three-dimensional CAD model. The CAD model is further processed with customized software programs associated with each SFF process, and the model is typically periodically sliced into a number of 2D cross-sectional layers, which when stacked closely approximate the desired geometry. During an SFF process, 3D structures are fabricated by creating and joining these cross-sectional layers to fabricate a physical structure finished. Because of its additive nature, SFF technologies are better than conventional manufacturing processes at forming complex three-dimensional structures, such as those with internal features, or multi-material structures. A number of SFF technologies have been widely commercialized, including Stereolithography, Selective Laser Sintering, 3D Printing, Fused Deposition Modeling, Laser Engineered Net Shaping, and more [64]. SFF technologies have brought immense benefits to product development, with demonstrated saving in time and
cost during product development as high as 90%.

One major limitation of most SFF technologies is that they are limited to polymeric materials. For metallic materials, almost all developed SFF technologies use some form of melting or thermal sintering to bond materials together. However, there are many drawbacks of thermal processes for forming complex metal structure, including unavoidable microstructural changes during melting and solidification as well as oxidation and other high temperature problems. The limitations of thermal processes for metal SFF formed the intellectual basis for an emerging SFF process, termed Ultrasonic Consolidation, being commercialized using UMW of metal tapes for fabrication of 3D complex structures.

1.2.4.2 UC Equipment and Process Fundamentals

Ultrasonic Consolidation (UC) is a novel additive manufacturing process based upon the combination of ultrasonic metal welding and CNC milling [4]. UC is conducted on a machine tool which was commercially introduced by Solidica, Inc., USA in 2000. The Solidica Formation™ UC machine incorporates an ultrasonic metal seam welding head, a foil feeding apparatus, a 3-axis milling machine, and a software program to automatically generate tool paths for material deposition and machining. Four major controllable processing parameters for the UMW portion of the UC process are: (i) vibration amplitude of the sonotrode, (ii) normal force applied by the sonotrode, (iii) traveling speed of sonotrode, which determines the welding exposure time, and (iv) temperature of the base plate. Each of these parameters are set when generating machine codes using the software program which controls the UC machine. After being loaded with the machine code (which contains the desired geometry descriptions) the UC machine fabricates the designed structure automatically.

In the manufacturing process, a computer program is used to slice the CAD model into a number of horizontal layers, whose thickness is identical to the thickness of the metal tapes used in the process. The structure is built up on a base plate bolted onto the heating plate, and fabricated from bottom to top, layer by layer. Each layer can be composed of one single metal tape or several tapes, depending on the width of that layer. Each
metal tape is laid and welded using the same procedure, as shown in Fig 1.7. During this welding procedure, the rotating sonotrode travels along the length of a thin metal tape placed over the substrate. The thin tape is held closely in contact with the base plate by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of motion, at a frequency of 20kHz and user-set oscillating amplitude, while traveling over the metal tape. After depositing a strip of tape, another tape is deposited adjacent to it, if necessary. This procedure is repeated until a complete layer is placed. The next layer is bonded to the previously deposited layer using the same process. Subsequently, the computer controlled milling head shapes the layer to its slice contour. This milling can occur after each layer or after several layers have been deposited. This additive-subtractive fabrication process continues until the final geometry of the part is achieved.

UC enables complex 3D parts to be formed with high dimensional accuracy and surface finish, including objects with complex internal passageways, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors and instruments [4,5,20,65-70]. Because the process does not involve melting, one need not worry about the typical dimensional errors due to shrinkage, residual stresses and distortion experienced in other SFF metal processes. One unique aspect of UC is that highly localized plastic flow around embedded structures is possible, resulting in sound physical/mechanical bonding between the embedded material and matrix material [4,5,68]. This ability to embed materials within the matrix can be utilized in a number of ways, including manufacture of fiber-reinforced metal matrix composites with structural fibers for localized stiffening, optical fibers for communication and sensing, shape memory fibers for actuation, or wire meshes for planar or area stiffening. It is possible to simply insert pre-fabricated components (such as thermal management devices, sensors, computational devices, heat pipes, etc.) into machined cavities of the part under construction prior to encapsulation by subsequent material addition [69].
Fig. 1.7: Schematic of UC processes.
1.2.4.3 Microstructures of Ultrasonic Consolidated Parts

Since the additive operations during UC are essentially ultrasonic metal welding processes of thin metal tapes, the microstructure between ultrasonic consolidated metal foils is not different from that of ultrasonic welded sample significantly. Three major difference from typical UMW processes, however, are important to note. First, the repeated addition of layers means that the upper-most surface of one deposited layer, which has been roughened by the sonotrode, becomes the surface on which a subsequent layer is deposited. This is different than a typical UMW operation in which smooth, non-roughened surfaces are brought into contact as the interface across which bonding occurs.

The second major difference involves the placement of foils adjacent to each other. As each layer can be made up of multiple foils laid side-by-side, the quality of the bonding between adjacent foils will determine some of the mechanical properties of the material (particularly the properties in the direction transverse to the tape direction).

The third major difference is geometric variations between tapes. Within a layer, each tape may have portions of its geometry fully supported by the previous layers or partially unsupported. This changes the effective area of bonding at each point. In between layers, the rigidity of the structure will typically lessen the taller the structure becomes. This will create a different vibrational state in the material that is geometry-dependent.

A typical microstructure of an ultrasonically consolidated sample made from Al 3003 alloy tapes is shown in Fig 1.8. As shown, the Al foils have been successfully bonded with few unbonded areas along the metal interfaces. The average percentage of bonded length to unbonded length of each interface in a micrograph is termed the linear welding density (LWD), which is a factor being used commonly by UC researchers to evaluate bond quality. It was found that linear welding density is significantly affected by processing parameters, including vibration amplitude, normal force, welding speed, and temperature. The highest reported LWD with the most commonly used Al 3003 alloy is as high as 98% without any form of surface modification between layers [39].

Most studies on bonding in UC have occurred with Al 3003. Unless otherwise noted,
Fig. 1.8: Typical microstructures of ultrasonically consolidated Al 3003 parts.
general observations for UC are for Al 3003 materials. During UC, mechanical interlocking of metal appears not to be significant, except for the case of embedment of fibers or meshes, as metal tapes retain distinct surface topologies without interlocking between mating surface (Fig 1.8). Hence, in UC processes, mechanical interlocking appears not to be a significant reason for bond formation.

In microstructural results (Fig 1.8), metal melting is not observed, indicating metal melting and re-solidification is not a relevant bond formation mechanism. Two-dimensional element mapping was conducted on ultrasonically consolidated parts from Ni/Al and Al/Cu [36,50] (Fig 1.9 and Fig 1.10). Measurable elemental diffusion was not noted in either result (as the variation in elements was on the order of the spot size of the experimental apparatus). So bonds are not strongly linked to diffusion. Thus, bond formation during UC appears to be by atomic level forces. The two necessary conditions to created such bonds have been experimentally studied by analysis the interfacial microstructures. First, metal surface oxides are not found at the bonded metal interfaces, while significant oxygen levels were noted at the unbonded regions. The welded metal does have a surface oxide layer, as observed in the unbonded regions, but during the UC process the oxide layers are displaced, allowing atomically clean metal surfaces to come into contact. Secondly, although metal surface is highly roughened after being deposited by the sonotrode, the gaps between the metal mating surfaces due to surface roughness do not persist through subsequent bonding at optimum parameters, as they are filled with welded metal. Hence the surface metal experiences significant deformation and metal flow during UC processing. The plastic deformation of the metal at the surface layer has been experimentally visualized by OIM. Grains that have been plastically deformed typically show a smooth intra-grain color transition indicating rotations of the crystal lattice. As shown in Fig 1.4, such smooth color transitions are evident in the picture, indicating that the foil interfaces plastically deform during the bonding process. Therefore, two necessary conditions to establish bond by atomic force are fulfilled during UC processing, and bond formation during UC appears primarily to be due to atomic level forces.
Fig. 1.9: (a) SEM image of ultrasonically consolidated Ni 201/Al 3003 interface, (b) EDS line scan results across the Ni 201/Al 3003 interface (along scan line shown in Fig.9a, scan started on the Ni side).
Fig. 1.10: (a) SEM image of ultrasonically consolidated Cu/Al 3003 interface, (b) EDS line scan results across the Cu/Al 3003 interface (along scan line shown in Fig.10a, scan started on the Cu side).
In UC machines, the automatic tape feeding mechanism is designed to work with tapes that are 25mm wide. Any geometry wider than 25 mm transverse to the tape lengthwise direction will require multiple tapes to be deposited within one layer. The junction between adjacent metal tapes is an area which must be considered. Although ideally the metal tapes should be deposited side by side without any physical discontinuity, in reality gaps between adjacent tapes during deposition are created due to the limited positional accuracy of the UC machine and its tape feeder (Fig 1.11). In addition, UMW has always been used to bond foils on top of each other, and bonding of adjacent tapes (e.g. a butt weld) is not well understand, nor are UMW apparatuses designed with this in mind. As a result, one can see that bond quality at tape edges are poor compared to bonding away from tape edges. This phenomena associated with gaps between metal tapes or near these joints are known as “edge defects” in UC. The most common method for minimizing “edge defects” in UC is to overlap adjacent metal tapes during deposition (space them in such a way that they overlap slightly), so that the edge of each metal tape is consolidated twice and the physical gap is minimized [71]. In addition, proper placement of new tape layers with respect to previous tape layers is important, as alignment of edge defects in the vertical direction will dramatically degrade the part’s properties. Thus, a controlled randomization process (random within certain constraints) is used to try to ensure that edge defects are randomly placed through the structure, creating a more isotropic material.

1.2.4.4 Process Capabilities

As ultrasonic consolidation integrates additive ultrasonic metal welding and subtractive CNC milling, UC exhibits the geometric and material fabrication advantages of SFF processes. UC is capable of producing three-dimensionally complicated structures which are difficult or even impossible to be fabricated with conventional manufacturing technologies. Additionally, UC provides unique processing opportunities for various applications, including manufacture of structures from multiple materials, manufacture of structures with complex internal geometries, fiber embedment, manufacture of smart structures, and more. A number of these unique processing capabilities are discussed below.
Fig. 1.11: Edge effect observed in ultrasonically consolidated Al 3003 parts.
1.2.4.4.1 Material Flexibility and Multi-material Structures

A wide range of metallic materials are available for UC. Theoretically, any metal which can be ultrasonically welded is a candidate material for ultrasonic consolidation. Materials have been successfully processed using UC include Al 3003 (H18 condition), Al 6061, Al 2024, Inconel® 600, brass, stainless steel AISI 347, Ni 201, and high purity copper [15-19,39,45,66]. Ultrasonic weldabilities of a number of other metallic materials have been demonstrated in previous research publications [15-28]. Associated with these materials, there is significant material flexibility for the UC processes. In addition to the metal foils listed above, other pre-fabricated materials could also be used in ultrasonic consolidation processes. For example, MetPreg®, which is Al₂O₃ fiber reinforced Al matrix composite tape, has been successfully ultrasonically consolidated to Al 3003 tapes [69]. And pre-woven stainless steel AISI 304 wire meshes have been embedded between Al 3003 tape using UC.

By depositing different ultrasonically weldable metal tapes at different desired layers or locations during UC processes, multi-material structures can be manufactured. The benefits of multi-material structures are numerous. For example, ultrasonically consolidated Cu foils within an Al panel could significantly improve the thermal conductivity of the structure, and thus the whole panel could be more responsive to temperature variation [72]. Additionally, the secondary metallic materials being embedded through the UC process can improve the strength of the structure or protect the structure from being damaged by exterior environmental conditions depending, on design requirements [20].

1.2.4.4.2 Structures with Internal Features

One unique processing capability of UC is the fabrication of 3D structures with complex internal features from metallic materials. Internal features refer to the functional geometrical designs within structures, such as honeycomb structures, internal pipes or channels, and more [66,73]. During UC, three-dimensional geometrical features of parts are fabricated by shaping welded metal tapes of one layer or several consecutive layers by defining the inner contour of the deposited metal tapes, while the external geometry of the part is manufactured by defining the outer contour of the deposited metal tapes. After the fabrication
of internal feature is completed, metal tapes are placed over the cavities or channels, thus enclosing the internal features.

One major concern when fabricating internal features, such as cavities or channel, is that when these features exceed a certain height to width ratio or if an internal channel or cavity is too large, the bonding strength at locations above the internal feature are significantly degraded; and sometimes metal tapes will not joined at all at these locations. When a metal tape is insufficiently restricted from vibrating due to a lack of support from material underneath, the vibratory energy does not result in reciprocal friction between metal tapes (i.e. there is a lack of differential motion between metal tapes) which results in poor bonding quality at locations above internal features. One solution to this problem is to use support materials within internal cavities or channels, which will firmly support internal features and the metal tape above for good bonding strength. After completion of the whole structures, the support materials must be removed. Current research is ongoing related to water-soluble support materials for UC.

1.2.4.4.3 Fiber Embedment

Another interesting processing capability of UC is fiber embedment within metal matrix materials. Embedment of silicon carbide (SiC) fibers within Al matrices through UC has been extensively studied [29,68]. This processing capability makes UC as a candidate manufacturing process for fabrication of fiber-reinforced metal matrix composites. Successful embedment of SiC fibers is aided by enhanced plastic deformation of matrix materials during UC. The embedded fibers are mechanically entrapped within the matrices, without any chemical bonding between fiber and matrix materials. Mechanical properties of the structure with embedded fibers were found to be improved due to the presence of the fibers.

Optical fibers are also being embedded within metal matrices using ultrasonic consolidation [69]. As ultrasonic consolidation is a solid-state manufacturing process at relatively low processing temperatures, the optical fibers are fully functional after embedment. Thus, UC is also recognized as a manufacturing methodology for fabrication of optical sensors.
1.2.4.4 Smart Structures

Smart structures are structures which can sense, control and react to their environment in a predictable and desired manner [74]. Various elements, such as fibers, sensors, actuators, processors, and more are integrated within smart structure to achieve desired functionality. Fabrication of smart structures is difficult for conventional manufacturing processes. Due to its inherent benefits of additive material addition at low temperatures, UC offers excellent processing capability for fabrication of smart structures. Since UC can create internal features, such as cavities and channels, the required sensors or electronics can been placed within the internal cavities during manufacturing. Embedded electronics and sensors have been shown to working properly after embedment using UC [70].

1.2.4.5 Modeling of UC

Analytical studies of the UC process have been undertaken along with experimental investigations. As mentioned previously, accurately modeling of the ultrasonic seam welding portion of UC is challenging.

Kong et al. [75] have developed a model involving both surface effects and volume effects to predict the weld strength of ultrasonically consolidated structures. This model is designed to correlate linear welding density and processing parameters to the strength of UC produced parts.

There several research groups worldwide devoting significant effort toward numerical simulation of the UC process with commercial finite element analysis (FEA) programs [76,77]. The ultrasonic consolidation process has been numerically modeled with a 3D thermomechanical coupled model to simulate fundamental governing phenomena during UC processes, including stress, strain and temperature fields. The results of modeling and simulation give a clearer view of the physical phenomena during UC processing and a better understanding of the experimental results.
1.2.5 Conclusions of Literature Review

- In this chapter, the bond formation mechanisms during ultrasonic metal welding have been reviewed. Four mechanisms were discussed, including mechanical interlocking, metal melting, diffusion, and atomic force across nascent metal interfaces. Although all postulated mechanisms have been observed in experimental investigations, the mechanisms of mechanical interlocking, metal melting and diffusion do not universally occur during UMW. Bond formation during UMW is expected to be primarily initiated by atomic force across nascent metal surfaces, while other mechanisms can be significant depending upon processing conditions. UMW is expected to be recognized as a two-stage manufacturing process represented by a repeated Contact Stage and Bond Stage. During the Contact Stage the oxide layers on metal surface are removed preparing atomically clean surface for bond formation. During the Bond Stage, metallurgical bonds are established due to atomic forces across nascent metal surface.

- The quality of an ultrasonic weldment is highly dependent on the selected level of the relevant processing parameters. For most applications there are three machine-related processing parameters which are controllable in a UMW process, which are vibration amplitude, welding exposure time, and clamping force. Optimum levels of these parameters are required to be identified to achieve desired welding quality. The levels chosen for each parameter are material, frequency and sonotrode geometry dependent.

- Ultrasonic Consolidation is an emerging solid freeform fabrication technology implementing ultrasonic metal welding for the fabrication of 3D complex parts. UC has demonstrated strong processing capabilities in manufacturing multi-material structures, metal matrix composites, objects with complex internal features, smart structures and more.
References


Chapter 2

An Experimental Determination of Optimum Processing Parameters for Al/SiC Metal Matrix Composites Made Using Ultrasonic Consolidation\(^1\)

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Abstract

Ultrasonic Consolidation (UC), an emerging additive manufacturing technology, is one of the most recent technologies considered for fabrication of metal matrix composites (MMCs). This study was performed to identify the optimum combination of processing parameters, including oscillation amplitude, welding speed, normal force, operating temperature and fiber orientation, for manufacture of long fiber-reinforced MMCs. A design of experiments approach (Taguchi L25 orthogonal array) was adopted to statistically determine the influences of individual process parameters. SiC fibers of 0.1mm diameter were successfully embedded into an Al 3003 metal matrix. Push-out testing was employed to evaluate the bond strength between the fiber and the matrix. Data from push-out tests and microstructural studies were analyzed and an optimum combination of parameters was achieved. The effects of process parameters on bond formation and fiber/matrix bond strength are discussed.

2.1 Introduction

Ultrasonic Consolidation (UC) is a novel solid freeform fabrication process developed

\(^1\)Co-authored by: Y. Yang, G. D. Janaki Ram, and B. E. Stucker.
by Solidica Inc., USA, implementing ultrasonic welding for manufacturing 3D structures from metal foils [1]. Previous research has demonstrated the process capabilities of UC for embedding shape memory alloy fibers within Al 3003 metal matrices [2], which makes UC a candidate manufacturing method for long-fiber reinforced metal matrix composites (MMCs). Compared to other established long-fiber MMC fabrication technologies, such as casting, diffusion bonding or spray deposition techniques [3], UC processing has several advantages. First, it does not involve high temperatures. Although temperatures can reach up to 50% of the material melting point at the interface due to frictional heating [4], heat build-up in the bulk part is practically negligible. Second, UC combines the advantages of additive and subtractive fabrication approaches allowing complex 3D parts to be formed with high dimensional accuracy and surface finish, including objects with complex internal passageways, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors and instruments. Further, because the process does not involve melting, one need not worry about dimensional errors due to shrinkage, residual stresses and distortion in the finished parts. Lack of melting also helps overcome the problems of brittle intermetallic formation and immiscibility when dealing with metallurgically incompatible dissimilar material combinations.

In the UC manufacturing process, a three-dimensional CAD model of the component to be built is generated and a computer program slices the model into a number of horizontal layers, whose thickness is equal to the metal foils used. These layers are systematically created and stacked from bottom to top, producing a three-dimensional object. Fig 2.1 illustrates the basic UC additive manufacturing process. In the process a rotating ultrasonic sonotrode travels along the length of a thin metal foil placed over the substrate. The thin foil is held closely in contact with the substrate by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of welding at a frequency of $20kHz$ and at a user-set oscillation amplitude, while traveling over the metal foil. The combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses at the interface between the two mating surfaces [1,4,5]. The stresses
produce elastic-plastic deformation of surface asperities, which breaks up the oxide film, producing relatively clean metal surfaces in intimate contact, establishing a metallurgical bond (Fig 2.1(b)). Atomic diffusion, in addition to plastic deformation, may also aid in the bonding process. Oxide films, broken up during the process, are displaced in the vicinity of the interface or along the weld zone. Local temperatures at the interface and the surrounding affected region (about 20µm) can reach up to 50% of the melting point of the material being deposited [4]. After depositing a strip of foil, another foil is deposited adjacent to it. This process repeats until a complete layer is placed. After placing a layer, a computer controlled milling head shapes the layer to its slice contour. This milling can occur after each layer or, for certain geometries, after several layers have been deposited. Once the layer is shaped to its contour, the chips are blown away using compressed air and foil deposition starts for the next layer.

Kong et al. have successfully embedded shape memory alloy (SMA) fibers, optical fibers, and SiC fibers in an Al 3003 matrix using the UC process [6-8], demonstrating the process capabilities for manufacture of continuous fiber reinforced MMCs. Efforts have also been made to evaluate the broad effects of process parameters and identify the process window for successful fiber embedment. However, much of their parameter optimization studies were conducted on the SMA fiber/Al alloy 3003 matrix combination, which cannot be directly applied to embedment of ceramic fibers in metal matrices. Further, in their studies Kong et al. [6,7] have not evaluated the effect of substrate temperature and fiber orientation with respect to welding direction on fiber embedding characteristics. These two aspects are expected to play a role in ultrasonic consolidation of MMCs. Substrate temperature is important because it can strongly influence the plastic deformation process at the interface, which is considered to be the basic mechanism of bond formation during ultrasonic welding of metals [2]. The effect of fiber orientation on bond formation is important as, during actual part fabrication, it is necessary to change fiber orientation with respect to part axes in order to enable effective design of MMC mechanical properties.

In view of the above, the current work was undertaken to explore the possibility of
Fig. 2.1: (a). Solidica Formation™ Ultrasonic Consolidation machine. (b). Schematic of the Ultrasonic Consolidation process (not to scale).
manufacturing SiC fiber reinforced Al matrix composites using the UC process. Specific objectives of this study include: i) evaluation of the effects of process parameters on fiber embedment and fiber/matrix bond strength, and ii) identification of an optimum combination of process parameters which can result in high-quality MMC parts.

Macroscopic properties of fiber reinforced MMCs are known to be strongly dependent on fiber/matrix interfacial bond strength. Strong bonding enables efficient transfer of loads from the matrix to the fiber. However, accurate evaluation of the fiber/matrix bond strength presents a number of challenges. Various methods have been attempted in the past [3]. Despite considerable standardization efforts, the test methods are still widely debated on a number of issues, including their universal applicability and accuracy. Kong et al. [6] have used fiber pull-out tests with reasonable success to characterize the bond strength of ultrasonically embedded SMA fibers in an Al alloy 3003 matrix. While this test method has been shown to work well for relatively ductile fibers, such as SMA fibers, it cannot be used in situations where a brittle fiber, such as SiC, is involved, as in the present study. After a review of available test methods, a method, termed a “push-out” test, has been adopted to evaluate the fiber/matrix bond strength in the present study. The push-out test was originally demonstrated by Marshall and Oliver [9], which was found to satisfactorily evaluate the fiber/matrix interfacial bond strength in a SiC fiber reinforced glass-ceramic composite. Push-out testing is relatively simple and can be performed using a microhardness tester. In this test, debonding is caused by pushing the fiber along its axis under the influence of a gradually increasing load, being applied by a microhardness indenter. Test accuracy is primarily determined by the accuracy with which the initial debonding event is detected and debonding load is recorded. In the current study, an acoustic emission (AE) sensor and a load cell, carefully synchronized and interfaced to a microhardness tester, were used for accurate determination of the initial debonding loads.
2.2 Experimental Work

2.2.1 Materials and Sample Fabrication

The matrix material used in this study was Al alloy 3003 (nominal composition by wt.\%: Al-1.2Mn-0.12Cu) foil, 150\(\mu\)m thick and 25\(\times\)mm wide. Deposition experiments were conducted on an Al 3003 base plate (dimensions: 175 \(\times\) 175 \(\times\) 12mm) firmly bolted to the heat plate of the UC machine. Silicon carbide fibers of 100\(\mu\)m diameter were used to produce MMCs. The SiC fiber contained a tungsten core (10\(\mu\)m diameter) and a 1\(\mu\)m thick pyrolytic carbon coating on the outer surface.

A design of experiments (DOE) approach was adopted to statistically evaluate the effect of individual process parameters on fiber embedment and fiber/matrix bonding. A Taguchi L25 orthogonal array was utilized for this purpose. The process parameters and their levels chosen for this study are shown in Table 2.1. Variation of each parameter at five different levels was considered necessary to assess any non-linear effects. The levels for each of the process parameters were selected based on preliminary experiments, available literature [2,6-8,10-12] and machine-related considerations. Table 2.2 lists the parameter combinations used for making the MMC deposits. 100\(\times\)mm long deposits were made for all 25 parameter combinations, which hereafter are identified by run numbers. The experiments were conducted in a randomized order and each run was repeated three times. The deposition procedure consisted of (Fig 2.2): i) depositing a layer of Al 3003 on top of the Al alloy 3003 base plate, ii) placing a SiC fiber on the top of the deposited Al 3003 layer and holding it in place using a custom-designed fixture, and iii) depositing a layer of Al alloy 3003 on the pre-placed fiber. Thus three samples were obtained for each combination of parameters, and each sample was made of two layers of foils and a fiber embedded between them.

In addition to SiC fibers, an electrical grade copper wire (140\(\mu\)m in diameter) and an AISI 304 stainless steel wire mesh (25\(\mu\)m wire diameter) were used as embedding materials to see if the hardness/strength of the material being embedded (relative to the Al 3003 matrix) plays any role in the embedment process. The objective in conducting these ex-
Table 2.1: Process Parameters and Their Levels Selected for UC Experiments

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
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<td>1550</td>
<td>1700</td>
<td>1850</td>
<td>2000</td>
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<td>Welding speed (mm/s)</td>
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<td>38 (90in/min)</td>
<td>42 (100in/min)</td>
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<td>Temperature (°C)</td>
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<td>121 (250°F)</td>
<td>149 (300°F)</td>
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<td>Fiber orientation (°)</td>
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<td>90</td>
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Table 2.2: Taguchi L25 Experimental Matrix along with Corresponding Push-out Test Results

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<th>Force (N)</th>
<th>Temp. (°C)</th>
<th>Fiber ori. (°)</th>
<th>Debonding load (N)</th>
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<td>1550</td>
<td>93</td>
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<td>23</td>
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<td>121</td>
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<td>42</td>
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Table 2.3: Process Parameters Used for Embedding Cu Wire and Stainless Steel Mesh

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<tr>
<th>Embedded materials</th>
<th>Amplitude (µm)</th>
<th>Speed (mm/s)</th>
<th>Force (N)</th>
<th>Temperature (°C)</th>
<th>Fiber orientation (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu wire</td>
<td>20</td>
<td>34</td>
<td>1700</td>
<td>149</td>
<td>90</td>
</tr>
<tr>
<td>Stainless steel mesh</td>
<td>16</td>
<td>28</td>
<td>1750</td>
<td>149</td>
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</tbody>
</table>

Experiments is to ascertain whether the excellent metal flow and consequent fiber embedment observed in SiC/Al3003 MMC deposits was due to the remarkable difference in hardness between the matrix material and embedded SiC fiber. Table 2.3 lists the process parameters utilized for these experiments. The procedure used for embedding the Cu wire is similar to the SiC embedment procedure described above. In the case of stainless steel wire mesh, the deposition procedure consisted of: i) depositing a few layers of Al alloy 3003 on the top of Al alloy 3003 base plate, (ii) placing the wire mesh on the top of deposited Al 3003 layers, (iii) running the ultrasonic head directly over the mesh, and (iv) depositing a layer of Al alloy 3003 over the mesh.

2.2.2 Microstructural Studies

All MMC deposits were metallographically examined to assess the fiber/matrix bond quality. Samples corresponding to transverse sections (perpendicular to fiber direction) were extracted from each of the deposits and were prepared for microstructural study following
standard metallographic practices. Microstructural observations were conducted on as-polished samples using optical and scanning electron microscopes (SEM).

2.2.3 Push-Out Testing

The fiber/matrix bond strength was evaluated by push-out testing. The test involved pushing the fiber to achieve an initial debonding from the matrix using a microhardness tester (Fig 2.3). Samples for these tests were prepared using the following procedure. Initially, 1mm thick slices (±0.2mm) containing the fiber region were extracted from each MMC deposit using a low speed diamond saw. These slices were mechanically polished using emery paper to produce a flat and even surface. This was followed by locally etching the tungsten core at the center of the SiC fiber (using a solution consisting of 15mL HNO₃, 3mL HF and 80mL H₂O) in order to produce a small depression for the microhardness indenter to rest. This etch procedure was found helpful for preventing sliding of the indenter during the push-out test. Push-out tests were performed using an Antonik microhardness tester, which has a maximum load capacity of 9.8N (1kg). Push-out tests were not conducted on the Cu wire/Al 3003 and stainless steel wire mesh/Al 3003 deposits.

The push-out test was monitored by synchronizing a force sensor and an acoustic emission (AE) sensor using a dual channel digital oscilloscope (Fig 2.4). The load cell recorded the loading history while the AE sensor detected the initiation of debonding between fiber and metal matrix. The load at which initial debonding occurred was observed by analyzing the loading and acoustic emission signal history. The AE sensor selected for this study has a frequency response of 600kHz, which is suitable for detecting cracking/debonding related signals in a normal laboratory environment [13]. After a 60dB total amplification, AE signals were recorded along with loading information. Using this data, AE signals were plotted along with the loading force as a function of time. The force value recorded at the instance when the first negative spike occurred on the AE signal plot was taken as the threshold force required to cause initial fiber debonding, which is indicative of the fiber/matrix bond strength. The reasons for taking the first negative spike (instead of the first positive spike) as the time of initial debonding are explained in Section 2.4.3.
Fig. 2.3: Schematic of push-out testing (not to scale).

Fig. 2.4: Experimental set-up for push-out testing.
At first glance, test specimen thickness may appear to be a significant variable affecting the initial debonding load for these tests. However, small variations in test specimen thickness do not result in significant variations in test results. This is because the debonding loads measured in this study correspond to the load at which initial debonding occurs. According to Chandra and Ananth [14], debonding in push-out tests occurs in several stages. The initial debonding event occurs in a very thin region close to the top surface of the test specimen under the influence of increasing load application. Since initial debonding is confined to a very thin region close to the top surface of the test specimen, the load at which it occurs is practically unaffected by the specimen thickness (as long as significant deflection of the matrix material does not occur). The same has been confirmed by Eldridge and Brindley [15] using test specimens of different thicknesses. Since the area over which initial debonding occurs is very difficult to determine, no attempt has been made in the current study to estimate an exact fiber/matrix bond strength (debonding load debonding area) from the measured initial debonding loads; instead, the measured initial debonding load was taken as a relative measure of fiber/matrix bond strength.

### 2.2.4 Confirmation Experiment

Based on microstructural and push-out test data, an optimum combination of process parameters was identified for fabrication of SiC fiber reinforced Al 3003 matrix composites. Using these optimum parameters, three MMC deposits were produced. Microstructural studies and push-out tests were conducted on these deposits to confirm the validity of the parameter optimization exercise.

### 2.3 Results

#### 2.3.1 Microstructures

The SiC fiber was found to embed well, without undergoing any shape distortion, within the Al alloy 3003 matrix in all of the experimental MMC deposits, as can be seen from the microstructures of one of the experimental deposits (Run # 5). It was observed
that in all the deposits, the top and bottom Al 3003 layer were very well bonded in the
vicinity of the fiber, although a few unbonded regions were always present at regions away
from the fiber (Fig 2.5(a)). There is extensive plastic flow around the fiber, evidenced
by flow lines in a circular pattern around the fiber (Fig 2.5(a) and Fig 2.5(b)), resulting
in excellent fiber embedment. The fiber/matrix interface looked tight without any large
physical discontinuities in all the deposits (Fig 2.5(c)). Similarly, the Cu wire and the
stainless steel wire mesh appeared well embedded in the Al 3003 matrix without any physical
gaps at the interfaces, as can be seen in Fig 2.6. However, it was observed that the Cu wire,
which originally had a circular shape, underwent significant distortion (Fig 2.6(a)). On the
other hand, there was no distortion of the stainless steel mesh wire shape (Fig 2.6(b)), as
in the case of SiC fibers.

2.3.2 Push-Out Test Results

The fiber/matrix bond strength was characterized by push-out testing, as described
in Section 2.2.3. The AE sensor used in this study was found to facilitate satisfactory
observation of the fiber/matrix debonding events. A typical AE sensor signal vs. time
plot obtained during the fiber push-out test is shown in Fig 2.7(a). Superimposed on the
AE signal vs. time plot is the load vs. time plot. In most cases, the AE signal was
found to rise first (positive spike) and then drop down below the background level (negative
spike) while the applied load increased. Most of the AE signal vs. time plots showed
a single sharp maximum negative spike which asymptotically approached the background
level, typically immediately following a positive spike. All these events occurred before the
applied load reached its maximum value. After the load reached its maximum value, the AE
signal generally remained at the background level with occasional positive/negative spikes,
which correspond to small downward sliding movements of the fiber under the influence of
the applied load. After the load was removed, a final positive or/and negative spike was
observed in most cases. In contrast, as can be seen from Fig 2.7(b), during microhardness
indentation on the matrix material, with no fiber present, no spikes were observed, which
confirms that the AE signal spikes recorded during fiber push-out tests are indeed due to
Fig. 2.5: SEM images of Run #5: (a) 200X, (b) 500X, (c) 1000X.
Fig. 2.6: (a). SEM microstructure of an embedded Cu wire (100X). (b). SEM microstructure of an embedded stainless steel wire mesh (200X).
debonding and related events.

Debonding loads for all MMC deposits were measured from synchronized plots of AE signal vs. time and load vs. time plots, taking the time of the maximum negative spike as the time of initiation of fiber/matrix debonding, which are presented in Table 2.2. Debonding loads for some of the samples could not be measured as the samples failed during sample preparation due to an extreme lack of bonding, resulting in delamination of the Al 3003 layers (for example, Run # 4 (all three samples), and Run # 21 (two samples)). The process parameters used where the aluminum layers delaminated are parameter sets which showed significant defect formation at the interface when no fibers were present [16] and thus their delamination was no surprise. The debonding load value for delaminated specimens were identified as “-.” With the exception of Run # 4 and Run # 20, at least one valid test result was available for each parameter combination, and only the valid test results were used when calculating the average load for a particular Run.

2.3.3 Bond Strength-Microstructure Correlations

As can be seen from Table 2.2, the debonding load levels were found to vary significantly among the various experimental runs. However, debonding loads measured for the three samples of a given experimental run are reasonably consistent, except in cases where delamination occurred. The SEM microstructures of MMC deposits corresponding to various bond strength levels are shown in Fig 2.8. As can be seen, there is no obvious correlation between microstructural features and the observed variation in push-out test results among the various experimental runs. All the deposits showed good fiber embedment with sound metal flow around the fiber and there were no gross defects at the fiber/matrix interface. It is interesting to note that only some of the 25 runs showed distinct flow lines in a circular pattern around the fiber (for example, Runs # 3 and 5). However, the occurrence of distinct flow lines or lack thereof appears to have no direct correlation with the observed bond strength levels. For instance, Runs # 3 and 5, both with distinct flow lines, showed a wide variation in debonding loads (respective debonding loads were 2.3 N, and 6.6 N). Similarly, Runs # 2 and 13, both without distinct flow lines, also showed a wide variation
Fig. 2.7: AE signal and applied load plotted as a function of time during push-out test: (a) Indentation on fiber (Run #1), (b) Indentation on matrix material when no fiber is present (the load remains constant at 9.8 N after reaching the maximum loading capacity of the machine).
Fig. 2.8: SEM microstructures of MMC deposits: (a) Run #3 (2.3 N) (b) Run #13 (2.8 N), (c) Run #2 (4.0 N), (d) Run #5 (6.6 N). All images are 500X. Values in brackets are the respective average debonding loads.

in debonding loads (respective debonding loads were 4.0 N, and 2.7 N).

2.3.4 Effect of Process Parameters

The debonding loads were found to change significantly among the experimental runs, ranging from 2.3 N (Run # 19) to 9.0 N (Run # 24). Analysis of variances (ANOVA) was performed to statistically evaluate the effect of each parameter on fiber/matrix bonding strength, following standard statistical procedures [17]. The results of ANOVA are summarized in Table 2.4 and Table 2.5. As can be seen, all the parameters have a statistically significant influence on bond strength (99% confidence level). Fiber orientation has the strongest effect on fiber/matrix bond strength among the five parameters studied in this
Table 2.4: Results of ANOVA Analysis

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\[ F_{(table,4,54)} \text{ at 99\% confidence} \approx 3.7 \]

Table 2.5: Mean Debonding Loads (N) at Each Selected Level of Process Parameters

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<tr>
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investigation. Oscillation amplitude was found to be the second most significant parameter. Normal force and welding speed were found to have similar levels of influence on debonding load. Substrate temperature was found to have the least influence on bond strength among the five process parameters evaluated in the current study. The effects of individual process parameters on fiber/matrix bond strength are graphically shown in Fig 2.9 in accordance with Table 2.5. It should be noted that the debonding load for each level of a particular parameter in Fig 2.9 corresponds to an average of five experimental runs at that level, typically with three replicates, representing an average of 15 push-out experiments.

Based on the ANOVA results, the following combination of parameters should produce the best fiber/matrix bond strength amongst the parameters tested: oscillation amplitude - 20\( \mu m \), welding speed - 34\( mm/s \) (80\( in/min \)), normal force - 1700N, substrate temperature - 149\( ^\circ C \) (300\( ^\circ F \)), and fiber orientation - 45\( ^\circ \).
Fig. 2.9: Variation in average debonding load (Y-axis) as a function of chosen levels for various parameters (X-axis): (a) debonding load vs. oscillation amplitude, (b) debonding load vs. normal force, (c) debonding load vs. temperature, (d) debonding load vs. welding speed, and (e) debonding load vs. fiber orientation.
2.3.5 Confirmation Experiment

The optimum parameter combination identified based on statistical analysis did not coincide with any of the 25 experimental runs, necessitating a confirmation experiment. Thus, three MMC deposits were made using the optimum parameter combination to confirm the validity of the parameter optimization study. The SEM micrographs of one of these deposits are shown in Fig 2.10. As can be seen, the sample showed excellent fiber embedment, without any physical discontinuities at the fiber/matrix interface.

Fiber push-out tests were also conducted on the deposits made in the confirmation experiment. During push-out tests on all three deposits, no spikes were observed in the AE signal, indicating that no fiber/matrix debonding or fiber sliding occurred during the test. This means that the initial debonding load for these samples is greater than 9.8 N (the maximum load that can be applied with the microhardness tester used in the present study). Since the debonding load of the deposits made in the confirmation experiment could not be experimentally determined, a prediction of the debonding load for the optimum combination of parameters was made, based on statistically determined parameter effects, using the following expression [17]:

\[
Y_{opt} = T/N + (A_{opt} - T/N) + (B_{opt} - T/N) + (C_{opt} - T/N) + (D_{opt} - T/N) + (E_{opt} - T/N) \quad (2.1)
\]

Where, \(Y_{opt}\) = Debonding load for the optimum combination of parameters; \(T\) = Grand total of all the response values; \(N\) = Total number of results; \(A_{opt}, B_{opt}, C_{opt}, D_{opt}, \) and \(E_{opt}\) = Average response values at the optimum level for each of the parameters: A (oscillating amplitude), B (welding speed), C (normal force), D (substrate temperature), and E (fiber orientation), respectively.

Table 2.6 lists the values for all the above terms, calculated from the experimental data. Using this data, the debonding load for the optimum combination of parameters was estimated to be 10.9 N, which is in line with the experimental observation that the
Fig. 2.10: SEM microstructures of confirmation deposits: (a) 100X, (b) 500X.
Table 2.6: Data Used for Estimating the Debonding Load for the Optimum Parameter Combination

<table>
<thead>
<tr>
<th>Term</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand total of all the response values (T)</td>
<td>116.4 N</td>
</tr>
<tr>
<td>Total number of results (N)</td>
<td>25</td>
</tr>
<tr>
<td>Average response values at the optimum level of oscillation amplitude ($A_{opt.}$)</td>
<td>0.94 N</td>
</tr>
<tr>
<td>Average response values at the optimum level of welding speed ($B_{opt.}$)</td>
<td>1.54 N</td>
</tr>
<tr>
<td>Average response values at the optimum level of normal force ($C_{opt.}$)</td>
<td>0.64 N</td>
</tr>
<tr>
<td>Average response values at the optimum level of substrate temperature ($D_{opt.}$)</td>
<td>1.14 N</td>
</tr>
<tr>
<td>Average response values at the optimum level of fiber orientation ($E_{opt.}$)</td>
<td>1.94 N</td>
</tr>
</tbody>
</table>

debonding load for these samples is greater than 9.8 N, the maximum load that can be applied with the microhardness tester used in the present study.

2.4 Discussion

2.4.1 Microstructures

For successful embedment of fibers, there must be adequate plastic flow of the matrix material to close the gaps that are created by placing a fiber between matrix layers. The results presented in Section 2.3.1 conclusively show that SiC fibers can be successfully embedded in an Al 3003 matrix, making UC a viable process for fabrication of parts out of continuous fiber reinforced metal matrix composites. Kong et al., through detailed elemental mapping studies on shape memory alloy fibers embedded in an Al 3003 matrix, concluded that the matrix and the embedded fiber were not chemically or metallurgically bonded [2,6]. Similarly in the present case, bonding between the SiC fiber and Al 3003 matrix is expected to be physical/mechanical. However, formation of some amount of chemical/metallurgical bonding cannot be ruled out, although it appears unlikely. The SiC fiber used in this study contained a thin carbon coating, which can react with matrix Al to form aluminum carbide at the interface (aluminum carbide formation can occur at temperatures as low as 500°C [18]). Kong and Soar [8] also suggested the possibility of aluminum carbide formation in ultrasonically consolidated SiC/Al 3003 MMCs. Aluminum carbide formation at the interface may be beneficial, in that it can result in strong chemi-
cal bonding at the fiber/matrix interface enhancing the interfacial strength. On the other hand, aluminum carbide formation could be undesirable as it is brittle and can promote easy crack propagation along the fiber/matrix interface. Detailed microstructural studies are necessary to assess whether carbide formation does occur at the fiber/matrix interface. Further, the current work could not establish a clear correlation between microstructural features and bond strength levels of the MMC deposits, as seen in Section 2.3.3, making it necessary to examine the microstructures in greater detail at some future date.

2.4.2 Effect of Hardness/Strength Levels of Fiber and Matrix Materials

As noted in Section 2.2.1, additional embedding experiments using a Cu wire and a stainless steel wire mesh were conducted to ascertain whether the excellent metal flow and consequent SiC fiber embedment was due to the remarkable difference in hardness between the matrix material and embedded SiC fiber. As seen in Fig 2.6, the weaker/softer Cu wire as well as the stronger/harder stainless steel mesh appeared well embedded in the Al alloy matrix without any physical gaps at the interfaces. While UC processing did not result in any distortion of the harder/stronger SiC fiber and stainless steel mesh wire shapes, there was significant shape distortion in the case of the softer/weaker Cu wire. The shape distortion of the Cu wire indicates that it has undergone a large amount of lateral deformation during UC processing. In other words, the Cu wire has consumed or absorbed a portion of the applied energy. Consequently, the matrix metal flow around the fiber is expected to be lower. Thus, when the embedded object is softer, embedment occurs due in part to lateral deformation of the embedded object itself rather than just matrix metal flow. On the other hand, when the embedded object is stronger and harder than the matrix (which is the case with the stainless steel mesh and SiC fiber) the applied energy causes matrix metal flow. The study thus suggests that hardness/strength difference between the fiber and matrix material is an important factor in determining the degree of matrix plastic flow induced in the matrix during UC processing.

The extensive plastic flow induced by introducing a hard fiber between Al 3003 metal foils also explains why bonding between Al alloy 3003 layers is far superior in the vicinity of
the fiber compared to other regions in all the deposits, as noted in Section 2.3.1. The stress concentration effect associated with the hard fiber results in greater plastic deformation at the foil interfaces, leading to better bonding.

2.4.3 Measurement of Fiber/Matrix Bond Strength

The push-out test results along with the observations made on AE signal vs. time and load vs. time plots are presented in Section 2.3.2. As noted earlier, the debonding loads for all MMC deposits were measured from synchronized plots of AE signal vs. time and load vs. time plots, taking the time of the maximum negative spike as the time of initiation of fiber/matrix debonding. While one might consider identifying the time of initial debonding from one of the positive spikes, preferably from the first, our experience showed that the sharp maximum negative spike was a more consistent indicator of the debonding event. Debonding load values measured from the first positive spike were found to be random with respect to parameter variations. While the reasons for this are not clear, it is suspected that sliding or skidding of the indenter on the fiber as the applied load is increasing can result in spurious, randomly positive spikes.

As seen in Fig 2.7(a), a final positive or/and negative spike was observed in most cases on the AE signal vs. time plot after the load was removed. This final positive and/or negative spike can be ascribed to a reverse movement of the fiber due to elastic effects at the fiber/matrix interface. Marshall and Oliver [9], who developed the fiber push-out test method, also noticed this reverse sliding of fibers during studies on fiber-reinforced ceramic composites.

2.4.4 Effects of Process Parameters

As noted in Section 2.3.4, all five process parameters were found to have a statistically significant effect on the fiber/matrix bond strength (Table 2.4). Based on ANOVA analysis, the process parameters were ranked in terms of their relative influence on the fiber/matrix bond strength (Table 2.5) - fiber orientation and substrate temperature being the most and the least significant parameters, respectively, among the five parameters at the selected
levels used in this study. An optimum combination of process parameters was identified based on the statistically determined parameter effects. Further, the results of confirmation experiment clearly indicate that the optimum combination of process parameters identified in this study is statistically meaningful, which can consistently produce high quality SiC/Al 3003 MMC deposits. The effects of each process parameter is discussed below in detail.

**Effect of Oscillation Amplitude**

The oscillation amplitude is the second most significant factor in terms of its influence on the fiber/matrix bond strength. It has a relatively linear effect on bond strength, as can be seen in Fig 2.9(a). The average debonding load was found to increase from 3.0 N to 5.6 N with increase in oscillation amplitude from 10.0 m to 20.0 m. At a particular oscillation frequency, the higher the oscillation amplitude the higher would be the amount of applied ultrasonic energy into the system. This energy together with the static applied normal force determines the total energy available for weld formation. Therefore, an increase in oscillation amplitude increases the magnitude of oscillating shear forces and, hence, the magnitude of dynamic interfacial stresses at the interface between the two mating surfaces. In addition, the increase in amplitude directly results in a larger displacement of foil surfaces and thus deformation at interface contact points. This enhances elastic-plastic deformation at the surface contact points and facilitates easier removal of surface oxide layers and plastic flow around the fiber. It is likely for these reasons the deposits showed an increase in fiber/matrix bond strength with increase in oscillation amplitude from 10 to 20µm.

Kong et al. [11] observed improvements in bond strength with increasing oscillating amplitude in ultrasonically welded Al alloy 3003 foils. However, they observed a drop in bond strength, determined using peel-off testing, after a certain value of amplitude. Similarly, Janaki Ram et al. [16] reported a slight decrease in linear weld density in ultrasonically consolidated Al 3003 structures when the oscillation amplitude was increased beyond a certain level. The authors have ascribed this behaviour to generation of microcracks as well as strain hardening and fatigue related effects at the interface as a result of excessive ultrasonic energy input [11,16]. In the present case, however, such non-linear effects of oscillation am-
plitude on fiber/matrix bond strength were not observed and the best results were obtained at an amplitude of 20\(\mu m\).

**Effect of Normal Force**

As shown in Fig 2.9(b), increase in normal force from 1400 N to 1700 N did not result in any change in debonding load, with a deviation less than 1%. However, further increases in normal force resulted in a considerable drop in debonding load, from an average value of 5.3 N at 1700 N to 3.1 N at 2000 N. Similar observations were reported by Kong et al. [11] and Janaki Ram et al. [16] during ultrasonic consolidation of Al alloy 3003. While the exact reason for this behavior is not clear at present, there are several potential explanations. As discussed previously, use of too high a normal force might result in excessive interfacial stresses leading to breakage of already formed bonds. Also, an increase in normal force will necessitate an increased sonotrode oscillatory force to maintain the same frequency. Excessive normal force might reduce the ability of the sonotrode to vibrate at its optimum frequency or set amplitude, thus leading to an overall reduction in operational performance. Another possible explanation is when the normal force is high enough to create a stress state above the yield point of the material around the fiber, when released it can put the interface into tension, weakening the interface. While further studies are necessary to fully assess the role of normal force during bond formation, the best results were obtained at an applied normal force of 1700 N in the present investigation.

**Effect of Substrate Temperature**

Substrate temperature was found to have a nonlinear effect on fiber/matrix bond strength. As can be seen in Fig 2.9(c), an increase in substrate temperature from 66\(^\circ\)C (150\(^\circ\)F) to 149\(^\circ\)C (300\(^\circ\)F) resulted in an increase in fiber/matrix bond strength; however, a further increase in substrate temperature to 177\(^\circ\)C (350\(^\circ\)F), resulted in a considerable drop in bond strength. During ultrasonic welding, the in-situ raise in interface temperature as a result of friction plays a key role in bond formation by (i) reducing the flow stress of the material, (ii) enhancing atomic diffusion, and (iii) promoting recrystallization [5]. In
addition, any strain hardening effect during plastic deformation would be reduced at elevated temperatures. Use of external thermal energy input in the form of elevated substrate temperature would further enhance these effects and thus promote bond formation during ultrasonic welding. This explains why the fiber/matrix bond strength increased with increasing substrate temperature up to 149°C (300°F). It is not clear, however, why bond strength decreased with further increase in substrate temperature. It is suspected that too high a substrate temperature can result in oxidation of metal foils and/or the C coating on the SiC fiber, which can affect the fiber/matrix bond quality.

**Effect of Welding Speed**

As can be seen in Fig 2.9(d), the fiber/matrix bond strength improved when the welding speed increased from 25 mm/s (60 in/min) to 34 mm/s (80 in/min). The debonding load reached a maximum average value of 6.2 N when a MMC deposit was produced at a welding speed of 34 mm/s (80 in/min). The average value of debonding load decreased when the welding speed further increased from 34 mm/s (80 in/min) to 42 mm/s (100 in/min). Thus MMCs should be fabricated at an intermediate welding speed. Given a certain amount of energy input, welding speed determines amount of energy input per unit length or, in other words, the time over which energy is applied at any particular point along the sonotrode traveling direction during ultrasonic welding. Use of higher welding speeds actually reduces sonotrode resident times and hence does not facilitate transfer of sufficient welding energy. Consequently, the magnitude of shear stresses generated at the fiber/matrix interface will be insufficient to cause complete oxide layer removal and to induce adequate plastic deformation of matrix metal. This explains why the MMC deposits showed decrease in fiber/matrix bond strength with increase in welding speed from 34 mm/s (80 in/min) to 42 mm/s (100 in/min).

The reasons for the drop of debonding load at low welding speed levels are unclear. Several potential explanations for this, however, follow. First, low welding speed is in essence a long sonotrode resident time at a particular point, which may destroy the already formed fiber/matrix bond by some fatigue mechanism, which results in a drop in bond strength. Another potential explanation is that long sonotrode resident times can enhance
the friction-induced heat build-up along the fiber/matrix interface, thus resulting in a high temperature issue, as discussed in Section 2.4.4, which reduces the debonding load.

**Effect of Fiber Orientation**

Fiber orientation was found to be the most important processing parameter in the current study. As can be seen in Fig 2.9(e), the 45° orientation resulted in the highest fiber/matrix bond strength. Average debonding loads at other fiber orientation angles were found to be significantly smaller than those at 45°. The effect of fiber orientation on fiber/matrix bond strength can be explained as follows. As mentioned previously, plastic flow of matrix metal around the fiber is critical for satisfactory fiber embedment and for achieving a high level of fiber/matrix bond strength. The extent of plastic flow around the fiber depends, among other factors, on the magnitude of shear stress induced in the matrix material (top and bottom layers) along the fiber orientation direction under the influence of applied normal force and ultrasonic vibrations. It is well known that a loaded body experiences greatest shear stress in a direction 45° to the loading axis. In the present case, the maximum shear stress induced in the matrix material occurs in a direction 45° to the sonotrode travel direction [10,19]. As a result, plastic flow of the matrix material in this direction is expected to be significantly higher than in other directions, which experience relatively lower shear stress levels. Therefore, plastic flow of the matrix metal around the fiber would be higher when the fiber is oriented 45° to the sonotrode travel direction, leading to superior fiber/matrix bond strength.

The current study clearly shows variations in fiber orientation result in significant variations in fiber/matrix bond strength, which introduces an important design consideration. During MMC manufacture it may be desirable in many cases to change fiber orientation (with respect to the part axes) in order to achieve optimum or nearly isotropic material properties in the end product. Therefore, a good MMC manufacturing process should be capable of achieving consistently high fiber/matrix bond quality in all possible fiber orientations so that there is freedom to change the fiber orientation as needed. Such freedom is not available with current commercially available UC machines. However, by incorporating
a turntable anvil mechanism, it may be possible to change fiber orientation as needed with respect to the part axes while maintaining a 45° fiber orientation in all cases with respect to the sonotrode travel direction. Thus, the current lack of freedom with respect to fiber orientation does not seem to be a serious impediment to MMC manufacturing using the UC process.

2.5 Conclusions

SiC fibers can be successfully embedded in an Al alloy 3003 matrix using ultrasonic consolidation. Plastic deformation and flow of matrix metal appears to be the essential mechanism for fiber embedment. In the presence of a fiber with greater hardness than the matrix material, ultrasonic consolidation induces significant matrix metal flow, resulting in sound fiber embedment. Bond strength between embedded SiC fibers and an Al 3003 metal matrix was found to be strongly dependent on process parameters. Variations in oscillation amplitude, welding speed, normal force, substrate temperature, and fiber orientation contribute to statistically significant variations in fiber/matrix debonding loads. It was found that push-out testing using a microhardness indenter coupled with an acoustic emission sensor was a practical method to compare and contrast the fiber/matrix bond strength of MMCs. Based on ANOVA, the following combination of parameters was found to produce the best fiber/matrix bond strength: oscillation amplitude - 20 m, welding speed - 34 mm/s (80 in/min), normal force - 1700 N, substrate temperature - 149°C (300°F), and fiber orientation - 45°.

References


Chapter 3

An Analytical Energy Model for the Effects of Processing Parameters on Bond Formation During Ultrasonic Consolidation

This chapter is a paper submitted as a journal article to the Rapid Prototyping Journal.

Abstract

Purpose - Recently, a number of research projects have been focused on an emerging solid freeform fabrication process, termed Ultrasonic Consolidation (UC). In the current study, an analytical energy-based model aimed at investigating the effects of processing parameters on bond formation during UC is presented.

Design/methodology/approach - In the model, two factors were defined, energy input to the workpiece within a single cycle of ultrasonic vibration ($E_0$) and total energy input to the workpiece ($E_t$), to evaluate the magnitude of transmitted energy into the workpiece during UC processing.

Findings - It was found that linear weld density, $E_0$ and $E_t$ were affected by processing parameters in a similar manner. Linear weld density was found to be strongly correlated to $E_0$ and $E_t$.

Originality/value - The current model gives a useful understanding of the energy effects of process parameter changes on the quality of bond formation (i.e. LWD) for UC-made structures and can be used to estimate an optimum level of energy necessary for bond formation.

Limitations - The current model does not consider energy losses during ultrasonic consolidation.

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3.1 Introduction

Ultrasonic consolidation (UC) is an emerging metal-based solid freeform fabrication process developed by Solidica Inc., USA, in which complex 3D structures are fabricated from thin metal foils [White, 2003]. The UC process is conducted on a commercialized machine tool (Figure 3.1), which is composed of an ultrasonic metal seam welding head, a 3-axis CNC milling machine, an automatic metal foil feeding mechanism, and a software package to generate machine tool paths for foil deposition and machining. Structure fabrication takes place on a firmly bolted base plate on the top of a heat plate.

In the UC process, a three-dimensional CAD model of the structure to be built is generated initially and a computer program is used to slice the model into a number of horizontal layers. These layers are systematically created from bottom to top, producing a three-dimensional object. Figure 3.2 illustrates the basic additive manufacturing operation during the UC process. In this operation, a rotating ultrasonic sonotrode travels along the length of a thin metal foil placed over the substrate. The thin foil is held closely in contact with the substrate by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of welding at a frequency of 20 kHz and at a user-set oscillation amplitude, while traveling over the metal foil. The combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses at the interface between the two mating surfaces [Daniels, 1965; White, 2003]. The shear stresses produce elastic-plastic deformation of surface asperities, which breaks up the oxide film, producing relatively clean metal surfaces, across which metallurgical bonds are established. After depositing a strip of foil, another foil is deposited adjacent to it. This operation repeats until a complete layer is deposited. After depositing a layer, a computer controlled milling head shapes the layer to its slice contour. This milling can occur after each layer or, for certain geometries, after several layers have been deposited. Once the layer is shaped to desired contour, machining chips are blown away using compressed air and foil depositions start for the next layer. Hence, the UC process is a combination of repeated material addition by ultrasonic metal seam welding and material subtraction by CNC milling. The
combined addition-and-subtraction manufacturing process continues until a structure is completed.

Experimental studies have revealed that there are four major controllable processing parameters affecting bond formation between metal foils in the UC process, which are the vibration amplitude of the sonotrode, the welding speed (traveling speed) of the sonotrode, the normal force applied to the workpiece by the sonotrode, and the temperature of the base plate [Janaki Ram et al., 2007a]. Studies on the optimization of processing parameters for UC have been conducted extensively [Kong et al., 2003; Kong et al., 2004; Janaki Ram et al., 2007a]. In these studies, bond formation between welded metal foils were characterized using linear weld density (LWD), which is defined as the percentage of unbonded length divided by total length between two ultrasonically consolidated metal tapes, as viewed using microscopy. LWD was found as an informative response variable to variations processing
Fig. 3.2: Schematic of ultrasonic consolidation process (not to scale).
parameters. Several theories related to the effects of processing parameters on the LWD of ultrasonically consolidated parts have been suggested. However, most of the suggestions were conceptual and qualitative, since bond formation mechanisms during UC have not been fully understood yet. It has been generally agreed that the bond formation during UC is the result of energy transmission from the vibrating sonotrode to the interface between the welded metal tapes, which results in a combination of interfacial shear forces and reciprocal motion between the metal tapes. Therefore, the transmitted energy to the workpiece is a piece of valuable information to study when considering bond formation during UC. With that in mind, in the current study, an energy-based analytical model was developed to characterize the influence of process parameters on the transmitted energy during UC processing, and further to investigate any correlation between the transmitted energy and LWD.

3.2 Analytical Model

This analytical model is developed to characterize the energy input due to interfacial shear forces at the metal/metal interface during metal tape deposition. In the UC process, as shown in Figure 3.3, a metal tape is fed between the sonotrode and the substrate. This metal tape is pressed against the substrate by the sonotrode at a pre-set normal force. The sonotrode travels parallel to the foil direction at a pre-set speed and oscillates perpendicular to the rolling direction at pre-set vibration amplitude. The metal tape, which is in intimate contact with the substrate, welds to the substrate in a small area directly below the sonotrode. The portions of the metal tape which are not directly beneath the sonotrode, do not bond to the base plate. Thus, in this model, the small volume of material immediately underneath the sonotrode, which is affected by the sonotrode vibration, is of interest (Figure 3.4). The width of area of contact along the X-axis is equal to the width of the metal tape used, which is 25.4mm. Determination of the length of contacted area along the Y-axis is well-known as a "Hertz Problem" in contact mechanics, and can be calculated using classic contact mechanics formulas [Johnson, 1987]. The thickness of the metal tape in the Z direction is 150µm.
Fig. 3.3: (a) 3D schematic of UC process. (b) 2D view on Y-Z plane. (c) 2D view on X-Z plan.

Fig. 3.4: Forces applied on top workpiece and base plate during UC process.
In the current model, several simplifying assumptions are made, which are:

1. The top metal tape is assumed to be rigidly connected to the sonotrode, meaning it vibrates along with the sonotrode by an identical displacement, velocity and acceleration. The bottom base plate is assumed to be rigidly bolted without any motion.

2. Materials during UC processing are assumed to be deformed elastically.

3. All the energy delivered to the workpiece is assumed to be used for bond formation, meaning no energy input is attenuated, lost or used to break previously formed bonds.

As seen in Figure 3.4, normal force $P$ is applied to the top workpiece through the sonotrode. Being tightly clamped to the sonotrode by force $F_s$, the top workpiece moves with the sonotrode as a result of friction between the sonotrode and workpiece. The motion of the sonotrode is assumed to be:

$$\xi(t) = \xi_0 \sin(2\pi ft) \quad (3.1)$$

where $\xi(t)$ is the displacement of the sonotrode and the top workpiece at time $t$; $\xi_0$ is the vibration amplitude set by the user; and $f$ is the ultrasonic frequency at which the machine is operated, which is 20kHz for the current model.

Thus the velocity and acceleration of the sonotrode and top workpiece are calculated as:

$$v(t) = \xi'(t) = 2\pi \xi_0 f \cos(2\pi ft) \quad (3.2)$$

$$a(t) = \xi''(t) = -(2\pi f)^2 \xi_0 \sin(2\pi ft) \quad (3.3)$$

If the top workpiece is considered separately, as shown in Figure 3.5, there is an interfacial shear force between the top workpiece and base plate, which is $F_i$ in the figure. For the top workpiece, the equation of motion is:
where $F_s(t)$ is the friction force between the sonotrode and top workpiece, which has a value of $\mu P$ ($\mu$ is the friction coefficient between the sonotrode and the top workpiece) and always has opposite sign to the velocity of the sonotrode; and $m$ is the mass of the top workpiece. Thus Equation 3.4 can be expressed as:

$$F_s(t) + F_i(t) = ma(t)$$  \hspace{1cm} (3.4)

where $A$ is contact area, $d$ is metal tape thickness, and $\rho$ is density of the metal tape.

As stated earlier, determination of the contact length along the metal tape direction in the Y-Z plane has been well studied in contact mechanics. The contact length, $a$, is computed using Equation 3.6:
\[ a = \sqrt{\frac{4PR}{\pi E^*}} \]  \hspace{1cm} (3.6)

where \( R \) is the radius of the sonotrode used in the current study, \( P \) is the normal force applied by the sonotrode, and

\[
\frac{1}{E^*} = \frac{1 - \gamma_1^2}{E_1} + \frac{1 - \gamma_2^2}{E_2} \quad \hspace{1cm} (3.7)
\]

where suffix 1,2 indicate the two materials in contact, \( \gamma \) is Poisson’s ration, and \( E \) is Young’s modulus. So the contact area \( A \) is computed as:

\[ A = 2aw \] \hspace{1cm} (3.8)

where \( w \) is the width of the metal tape. Therefore, the equation of motion for the top workpiece becomes:

\[ F_s(t) + F_i(t) = 2awdpa(t) \] \hspace{1cm} (3.9)

The interface shear force can be calculated by:

\[ F_i(t) = 2awdpa(t) - F_s(t) \] \hspace{1cm} (3.10)

By the interfacial shear force and reciprocal velocity between metal tapes, the energy input, \( E_0 \), due to interfacial motion within one single cycle of motion can be computed by:

\[ E_0 = \int_0^T F_i(t) \times v(t) dt \] \hspace{1cm} (3.11)

where \( T \) is the period of ultrasonic motion of sonotrode, which is 0.00005s. Dwelling time of sonotrode at the contact area is determined by the length of contact area divided by the traveling speed of the sonotrode. Given the dwelling time of the sonotrode, the number of motion cycles while the sonotrode is above the contact area is computed by the
Table 3.1: Material Properties Used in the Energy Model

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration frequency</td>
<td>$f$</td>
<td>20kHz</td>
</tr>
<tr>
<td>Friction coefficient between sonotrode and top workpiece</td>
<td>$\mu$</td>
<td>0.3</td>
</tr>
<tr>
<td>Density of Al alloy 3003</td>
<td>$\rho$</td>
<td>2730 kg/m$^3$</td>
</tr>
<tr>
<td>Metal tape thickness</td>
<td>$d$</td>
<td>150 $\mu$m</td>
</tr>
<tr>
<td>Metal tape width</td>
<td>$w$</td>
<td>25.4 mm</td>
</tr>
</tbody>
</table>

dwelling time divided by the period of one cycle. The total energy, $E_t$, delivered to metal/metal interface is computed using the number of motion cycles times the amount of energy input within a single cycle, $E_0$.

3.3 Results

3.3.1 Calculation of $E_0$ and $E_t$

Energy within a single cycle of motion ($E_0$) and total energy delivered to the metal/metal interface ($E_t$), as stated above, were both computed using the material properties and processing parameter combinations listed in Table 3.1 and Table 3.2, respectively. The LWD produced with these parameter combinations have been presented in a previous publication [Janaki Ram et al., 2007a]. In the previous experimental studies, two sets of experiments were conducted (hereafter referred to as “Experiment set I” and “Experiment set II”), Experiment set I was completed by changing all processing parameters at various levels whereas set II varied only welding speed and held the other parameters constant.

3.3.2 Effects of Processing Parameters on $E_0$

The effect of individual process parameter on $E_0$ and LWD is graphically shown in Figure 3.6. As can be seen, vibration amplitude had a positive effect on $E_0$ (Figure 3.6(a)). When the amplitude varied from 10 $\mu$m to 19 $\mu$m, $E_0$ increased, and thus more energy per cycle of ultrasonic motion was delivered to the workpiece. As can be seen in Figure 3.6(a), LWD of UC samples were affected by vibration amplitude in a non-linear manner. LWD increased when vibration amplitude increased from 10 $\mu$m to 16 $\mu$m, then LWD decreased when amplitude further increased from 16 $\mu$m to 19 $\mu$m. Generally, the trends show that
Table 3.2: Processing Parameter Combination along with Corresponding LWD% and Energy Input Results

<table>
<thead>
<tr>
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<th>Amplitude (µm)</th>
<th>Speed (mm/s)</th>
<th>Force (N)</th>
<th>LWD% [Janaki Ram et al., 2007a]</th>
<th>$E_0$ (J)</th>
<th>$E_t$ (J)</th>
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vibration amplitude and $E_0$ have a similar trend from 10$\mu m$ to 16$\mu m$, when the amplitude further changed to 19$\mu m$, LWD dropped due, possibly, to over-stressing, causing bond failure of previously created bonds [Janaki Ram et al., 2007a], while $E_0$ kept increasing.

Welding speed has no direct influence on $E_0$ when other factors are held constant, but the average $E_0$ values shown in Figure 3.6(b) are calculated based on a combination of welding speed and other parameter changes, and thus the average value for $E_0$ fluctuates. As depicted in Figure 3.6(b), welding speed had a nearly linear effect on LWD. LWD increased with decreasing welding speed from 40mm/s to 28mm/s. Thus the energy absorbed during a single cycle cannot explain LWD differences which occur due to welding speed.

Normal force had a linear effect on $E_0$ as can be seen in Figure 3.6(c). $E_0$ increased with increasing normal force from 1450N to 1900N. It was noticed that an optimum level of normal force was identified corresponding to the most desirable LWD. Generally, until normal force increased to a relatively medium level of 1750N, it affected $E_0$ and LWD in a similar manner, where $E_0$ and LWD both increased linearly. When normal force further increased to 1900N, $E_0$ kept increasing linearly, while LWD dropped, possibly due to over-stressing, as discussed previously [Janaki Ram et al., 2007a].

### 3.3.3 Effects of Processing Parameters on $E_t$

The effect of individual process parameter on $E_t$ and LWD is graphically shown in Figure 3.7. Vibration amplitude was found to have a linear effect on $E_t$ (Figure 3.7(a)). $E_t$ increased with vibration amplitude from 10$\mu m$ to 19$\mu m$. Compared with the results in Figure 3.6(a), it was found that vibration amplitude had a similar effect on $E_0$, $E_t$ and LWD when it changed between the range of 10$\mu m$ to 16$\mu m$. After vibration amplitude exceeded the level of 16$\mu m$, LWD dropped, likely by exceeding an energy threshold, while $E_0$ and $E_t$ kept increasing linearly.

An increase in welding speed causes a decrease in total energy $E_t$ (Figure 3.7(b)). Welding speed has a direct effect on $E_t$, as it determines that total number of cycles seen in a particular location, whereas $E_0$ does not change when only welding speed changes (Figure 3.6(b) and Figure 3.7(b)). Welding speed affected $E_t$ and LWD in a similar manner, in
Fig. 3.6: Variation of LWD and $E_0$ with changing level of processing parameters: (a) LWD and $E_0$ versus vibration amplitude, (b) LWD and $E_0$ versus welding speed, (c) LWD and $E_0$ versus normal force.
which $E_t$ and LWD both decreased with increasing welding speed from 28mm/s to 40mm/s.

As can be seen in Figure 3.7(c), normal force $a$ had a linear effect on $E_t$. $E_t$ increases with increasing normal force from 1450N to 1900N linearly. As shown in Figure 3.6(c) and Figure 3.7(c), when normal force increased from 1450N to 1750N, $E_t$, $E_0$ and LWD were affected by normal force in a similar manner. After the level of normal force exceeded 1750N, LWD dropped, again likely due to exceeding a material-dependent energy threshold.

### 3.3.4 Correlations Between Energy Input and LWD

A graph which shows the correlation for all parameter combinations between LWD and $E_0$ can be seen in Figure 3.8(a). LWD follows the same general trends as energy input within a single cycle of ultrasonic vibration ($E_0$). Generally speaking, low LWD levels correspond to low $E_0$ values, while samples with high LWD produced relatively high $E_0$ levels. However, the highest LWD did not correspond to the highest level of $E_0$, but to an optimum level of $E_0$ (Figure 3.8(a)). In previous experimental studies on processing parameter optimization of UC, it has been argued that LWD can be significantly affected by energy input during the UC process [Janaki Ram et al., 2007a]. From a low level to a medium level of energy input, it was found that LWD increased with each incremental increase of energy input, meaning that increasing energy input within a certain range was helpful for bond formation between metal tapes. However, LWD seems to drop after the energy input exceeds a certain level, because excess energy input over-stresses the metal/metal interface and results in bond damage and breakage. Observations from the current study agreed with the research conclusions from previous publications. The balance between bond formation and bond breakage is affected by the energy input into the workpiece within a single cycle of the ultrasonic motion, $E_0$. An optimum level of $E_0$ likely exists for certain combinations of consolidated materials. From a low level to this optimum level, $E_0$ facilitates the formation of bonds between metal tapes. If $E_0$ exceeds the optimum level, the superfluous energy input causes damage to the formed bonds.

It was observed that LWD was strongly correlated to the total energy input ($E_t$). Low LWD corresponded to low $E_t$, while high LWD corresponded to high $E_t$. It was found that
Fig. 3.7: Variation of LWD and $E_t$ with changing level of processing parameters: (a) LWD and $E_t$ versus vibration amplitude, (b) LWD and $E_t$ versus welding speed, (c) LWD and $E_t$ versus normal force.
LWD approaches 100% asymptotically with increasing $E_t$ in Figure 3.8(b). From these experiments, there does not appear to be a threshold of total energy ($E_t$) input above which bond breakage occurs, as long a threshold level of energy input within a single cycle of ultrasonic motion ($E_0$) is not exceeded.

### 3.4 Discussion

#### 3.4.1 Roles of Input Energy in Bond Formation During UC Process

The bond formation mechanisms during UC process have been experimentally investigated. It was revealed that metallurgical bond are created by atomic forces across the nascent metal surface during the UC process. Two necessary conditions for bond formation are: (i) preparation of atomically clean metal surface by removal of surface oxide layers, and (ii) intimate contact of atomically clean metal surface [Janaki Ram et al., 2007b]. These two necessary conditions are achieved by the dynamic stresses between two mating metal surfaces, which are initiated by the combination of interfacial shear forces and normal force. For applications of ultrasonic consolidation for certain material combinations, given the properties of materials, the magnitude of the interfacial dynamic stresses are a function of the processing parameters, i.e. vibration amplitude and normal force. From an energy transmission point of view, for the whole system of welded metals and sonotrode, the only energy resource for bond formation during UC processes is mechanical energy transmitted through the vibrating sonotrode. When the sonotrode contacts the welded metal with a certain magnitude of normal force, the mechanical energy of the sonotrode is transmitted to the welded structures, in forms of dynamic stresses between mating metal surfaces, reciprocal motion of welding surfaces, elastic/plastic deformation of welded materials, frictional heating and others [Janaki Ram et al., 2007b; Yang et al., 2008]. Therefore, the extent to which the two necessary conditions could be fulfilled is strongly dependent upon the amount of transmitted energy. In other words, bond formation is significantly affected by the amount of energy input.

However, increase of transmitted energy does not always benefit bond formation. A
Fig. 3.8: (a) Correlation between LWD and $E_0$. (b) Correlation between LWD and $E_t$. 
number of experimental studies have demonstrated that optimum energy input is desired for good ultrasonic weldment, while excess energy can over-stress the previously formed bonds and thus result in poor welding quality [Daniels, 1965; Chang 1974; Janaki Ram et al., 2007b].

Between the two defined factors ($E_0$ and $E_t$) in the current study, the factor of energy input within a single cycle of ultrasonic motion ($E_0$), which is directly derived from the interfacial shear force conditions, is representative of the completeness of the two necessary conditions for bond formation during UC. As shown in Figure 3.8(a), the highest LWD was found under an optimum level of energy input, instead of the largest level of energy input. The optimum level of $E_0$ could be recognized as a threshold for the UC process. It is beneficial to achieve such a threshold energy level by adjusting the processing parameters of vibration amplitude and normal force for good LWD results. The determination of this optimum level is pronouncedly affected by combination of material properties and processing parameters.

The factor of total energy delivered to the metal/metal interface ($E_t$) cannot be used to find an optimum energy level for bond formation for Al 3003 materials. Although $E_t$ also incorporates the interfacial shear force conditions, as the value of $E_t$ is an accumulation of $E_0$ within a period of time, $E_t$ is also affected by the parameter of welding speed. Therefore, higher levels of $E_t$ does not necessarily correlate to greater levels of interfacial shear stress.

It is interesting to note the correlations between $E_t$ and the results of Experiment set II. The LWD of the samples of Experiment set II approached 100% with increasing $E_t$. It should be noted that the associated $E_0$ values for the samples created for Experiment set II were at an optimum level. Hence, given a level of $E_0$ which does not result in bond failure due to over-stressing, an increased amount of $E_t$ caused by a reduction in welding speed can facilitate improved bond formation. From a practical point of view, the LWD improvement by reduced welding speed must be considered with respect to the productivity of UC processing. For certain applications, the tradeoff between improvement of LWD by low welding speed and the time/cost of UC processing should be carefully considered.
Finally other researchers [Joshi, 1971; Tsujino and Ueoka, 1988] have noted that there is a maximum dwell time for ultrasonic metal welding which will result in a decrease in bond quality. Thus, for certain materials which are susceptible to fatigue, there will likely be not only an optimum $E_0$ value, but also a maximum $E_t$ above which fatigue will result in bond breakage and degradation.

### 3.4.2 Future Research

The energy based model developed in the current study is a simplifying analytical investigation on effects of processing parameters on bond formation during UC process. Further objectives of research have been identified to improve the implementation of the current model.

The assumptions made for the model are idealized for simplification of the model. However, these assumptions are not universally valid for UC process. The reciprocal motion between top metal tape and base metal plate was assumed to identical to the vibration amplitude of sonotrode. But, the knowledge about the magnitude of the interfacial reciprocal motion is limited, as it is a challenging engineering problem to accurately characterize the amplitude of the interfacial reciprocal. Also the deformation of welded materials was assumed to be elastic. In reality, the welded metal was observed to deform both elastically and plastically. The most important assumption required to be modified is the assumption of no energy was attenuated, lost or used to break previously formed bonds. A number of experimental results have indicated the bonding degradation due to superfluous energy input. Thus, if an energy criterion of bond damaging could be induced to the current model in further research, the model would be capable to evaluate both bond formation and degradation.

The material properties used in the computation procedure of this study are from literature. However, these properties, especially friction coefficient and modulus of elasticity, could be modified when the material is exposed to ultrasonic excitation [Langenecker, 1966; Pohlman and Lehfeldt, 1966]. Without exact material properties, the phenomena during UC could not be accurately studied. Hence, extension of knowledge about material property
modification due to ultrasonic excitation is also desired for good analytical investigation of UC processes.

3.5 Conclusions

In the current study, an energy-based analytical model was developed to investigate the effects of processing parameters on bond formation during UC. In this model, two factors, energy input within a single cycle of ultrasonic motion ($E_0$) and total energy delivered ($E_t$), were defined. It was found that LWD and $E_0$ were affected by vibration amplitude and normal force in a similar manner, whereas LWD and $E_t$ were influenced by vibration amplitude, welding speed and normal force similarly.

It was found that LWD could be correlated to levels of these two factors. High LWD levels were found corresponding to high levels of $E_t$ and medium levels of $E_0$. It was likely that the level of the factor $E_0$, energy input within a single cycle of ultrasonic motion, explained the phenomena of bond formation and degradation observed in previous studies. Using the current analytical model, the LWD of ultrasonically consolidated samples can be evaluated by identifying the level of energy input. From a practical point of view, the processing parameter combinations which could result in a high level of $E_t$ when using an optimum level of $E_0$, would be favorable for fabrication of samples with desirable LWD.

There several areas of future work which could be undertaken to improve the applicability of the models defined in this paper. The current model does not consider energy which is lost in the system due to frictional heating, elastic deformation of the materials (i.e. material thickness effects), transmission into the machine, and other potential areas for energy loss. By including these energy loss mechanisms, the amount of energy absorbed at the interface during ultrasonic consolidation could more accurately be estimated.

It is likely that one of the most beneficial outcomes of this current work will be the development of a method for determining the optimum level of energy within a single cycle of ultrasonic vibration for a particular material. This type of a method will help researchers and industrial practitioners to more quickly determine optimum values of processing parameters for a particular material. In addition, materials which have been shown to be
prone to fatigue failure during ultrasonic metal welding should be investigated to determine whether a maximum total energy threshold is also present to avoid damage or breakage of formed bonds due to fatigue.

References


Chapter 4

Bond Formation and Fiber Embedment During Ultrasonic Consolidation

This chapter is a paper submitted as a journal article to the Journal of Materials Processing Technology.

Abstract

The quality of ultrasonically consolidated parts critically depends on the bond quality between individual metal foils. This necessitates a detailed understanding of interface microstructures and bond formation mechanisms during ultrasonic consolidation processes. In this paper, the multi-material samples ultrasonically consolidated from like metal foils (Al 3003/Al 3003 and Ni 201/Ni 201) and dissimilar metal foils (Al 3003/Ni 201 and Al 3003/high purity Cu (99.9%)). SiC fibers were embedded between like metal foils (Al 3003/Al 3003) and dissimilar metal foils (Al 3003/ high purity Cu (99.9%)). The interfacial microstructures of those samples were examined using Scanning Electron Microscopy (SEM), X-Ray Energy Dispersive Spectroscopy (EDS), and Orientation Imaging Microscopy (OIM). Based on the results of microstructural studies, the mechanism of ultrasonic metal welding has been discussed. The fiber embedment mechanism during UC was also identified and discussed.

4.1 Introduction

Ultrasonic Consolidation (UC) is a novel additive manufacturing process implementing ultrasonic metal welding for fabrication of complex three-dimensional structures from metal foils [White, 2003]. UC processes are conducted on a machine tool which was commercially available by: Y. Yang, G. D. Janaki Ram, and B. E. Stucker.
introduced by Solidica Inc. in 2000. The Solidica Formation™ UC machine incorporates an ultrasonic metal welding head, a 3-axis CNC milling machine, a foil feeding apparatus, and a software program to automatically generate tool paths for material deposition and machining. In the UC process, the component to be built is initially modeled with CAD software packages, then converted to an STL file format and systematically sliced into a number of horizontal layers from bottom to top using the customized computer program. Each horizontal layer is the thickness of the metal foil selected for the UC process. Fig 4.1 illustrates the basic UC additive manufacturing operation. In this operation, the rotating ultrasonic welding head, a.k.a. sonotrode, travels along the length of a thin metal foil placed over the base plate. The thin foil is held closely in contact with the base plate by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of traveling at a frequency of 20 kHz and at a user-set oscillation amplitude, while traveling over the metal foil. The combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses at the interface between the two mating surfaces [Daniels, 1965; White, 2003]. The stresses produce elastic-plastic deformation of surface asperities, which breaks up the oxide film, producing relatively clean metal surfaces, establishing a metallurgical bond. After depositing a strip of foil, another foil is deposited adjacent to it. This operation repeats until a complete layer is placed. After placing a certain number of layers, the CNC milling head shapes the layer to its slice contour. This milling can occur after each layer or after several deposited layers. Once the layers are shaped accordingly, the chips are blown away using compressed air and foil deposition starts for the next layer. These additive and subtractive manufacturing operations repeat until the component is finished.

Research on the practical applications of UC has been extensive. Previous research has demonstrated the strong processing capabilities of UC for fabrication of multi-functional 3D structures with high dimensional accuracy and desirable surface finish, including objects with complex internal features, objects made up of multiple materials, and objects integrated with wiring, electronics, and fiber optics [George, 2006; Janaki Ram et al., 2007a;
Fig. 4.1: Schematic of the Ultrasonic Consolidation process (not to scale).
Yang et al., 2007]. One of the interesting research topics is embedding fibers (silicon carbide fibers, shape memory alloy fibers, etc) within metal matrices for production of metal matrix composites (MMCs) and/or smart structures. In this paper, the processing capacity of UC for fiber embedment is investigated by embedding SiC fibers between like metal foils (Al 3003/Al 3003 foils) and dissimilar metal foils (Al 3003/high purity Cu). The fiber embedment mechanism during UC is studied by investigating the microstructures of UC-made samples.

Although the UC process has been successfully implemented in various applications, fundamental aspects of this technology, especially the bond formation between metal foils during ultrasonic consolidation, have not been clearly understood. As the joining (additive) operation of UC is a seam ultrasonic metal welding (UMW) operation, research results and knowledge of bond formation mechanism of UMW can contribute to understanding bond formation during UC. For ultrasonic metal welding, it is generally agreed that this process is a solid-state joining process [Jones and Powers, 1956]. Bond formation during UMW can be attributed to several possible reasons [Joshi, 1971]: (i) mechanical interlocking, (ii) melting of the material at the interface, (iii) metal diffusion at the interface, and (iv) atomic forces across the nascent metal interface. Since different mechanisms dominate bond formation for various processing parameter levels and material combinations, it is important to clarify which mechanisms dominate during UC processing. The lack of consensus on bond formation mechanisms for UC limits further exploitation of its processing capabilities. Therefore, in this study, efforts were put towards investigation of bond formation between similar and dissimilar metal foils during UC by characterizing the microstructure of ultrasonically consolidated parts and characterizing the processing temperature.

4.2 Experimental Procedure

4.2.1 Ultrasonic Consolidation of Like Materials (Al 3003 and Ni 201)

Metal tapes used in the current study are listed in Table 4.1. Tape depositions were conducted on an Al 3003 base plate firmly bolted to the heat plate of the commercial UC
Table 4.1: Materials Used for UC Experiments

<table>
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<th>Material</th>
<th>Nominal Composition (wt.%)</th>
<th>Dimensions</th>
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</thead>
<tbody>
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<td>Al alloy 3003 (H18 condition)</td>
<td>Al-1.2Mn-0.12Cu</td>
<td>25mm wide, 150µm thick foil</td>
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<tr>
<td>Ni alloy 201 (Annealed condition)</td>
<td>Ni-0.02C-0.35Mn-0.25Si-0.25Fe-0.15Cu</td>
<td>25mm wide, 75µm thick foil</td>
</tr>
</tbody>
</table>

machine. The sonotrode diameter on the commercial UC machine is 140mm. The procedure for depositing Al 3003 tapes involved depositing a layer of Al 3003 on the aluminum base plate. Subsequently, another layer of Al 3003 was deposited to the top surface of the previously deposited Al 3003 layer. Al 3003 tapes were automatically fed through the tape feeding mechanism of the UC machine. The processing parameters used for tape depositions were: oscillation amplitude - 16µm, welding speed - 28mm/s, normal force - 1750N, and base plate temperature - 149°C. These parameters were found to produce a high level of linear welding density for Al 3003 using the same UC machine in previous publication [Janaki Ram et al., 2007b].

A similar procedure and processing parameters were implemented for depositing Ni 201 metal tapes. Since the Ni tapes were not capable of being fed by the machine, Ni 201 tapes were manually placed onto the substrate and secured with adhesive tape prior to each pass of the sonotrode.

4.2.2 Ultrasonic Consolidation of Dissimilar Materials (Al 3003 and Ni 201)

Dual-material samples were fabricated from Al 3003 tapes and Ni 201 tapes. Deposition experiments were conducted on an Al 3003 base plate firmly bolted to the heat plate of the commercial UC machine. After depositing a few layers of Al 3003 one over another, a layer of Ni 201 was welded to the top most Al 3003 layer. Subsequently, another layer of Ni 201 was welded to the previously deposited Ni 201 layer. This layer arrangement was chosen to facilitate microstructural study of Ni-Al and Ni-Ni interfaces. As before, Ni tapes were manually placed onto the substrate and secured with adhesive tape while Al 3003 layers were automatically fed. The process parameters were identical to those above.
4.2.3 Microstructure Characterization of Ultrasonic Consolidated Parts

Samples which were ultrasonically consolidated from Al 3003 tapes and Ni 201 tapes were metallographically investigated. For these samples, transverse sections (perpendicular to the foil length direction) were prepared for microstructural examination following standard metallographic practices. Polished samples were etched with a mixture of 1 part 10% aqueous solution of CaCN and 1 part 10% aqueous solution of (NH₄)₂S₂O₈. Metal/metal interface microstructures were examined using scanning electron microscopes (SEM). X-Ray Energy Dispersive Spectroscopy (EDS) was utilized for micro-chemical characterization of the interfaces. Orientation Imaging Microscopy (OIM) was utilized for studying plastic deformation at the interfaces.

4.2.4 SiC Fiber Embedment Experiments

The fiber embedment experiments were conducted on a simplified UC machine at Loughborough University, UK. Silicon carbide fibers of 100µm diameter were embedded between aluminum foils along metal tape length direction to produce samples, following the embedding procedure described in previous publication [Yang et al., 2007]. SiC fibers were also attempted to be sandwiched by Al 3003 foil and high purity Cu (99.9%) foil of 100µm. Processing parameters used in those depositions are listed in Table 4.2. The main reason to embed SiC fiber between dissimilar metal foils is to investigate effects of foils properties on fiber embedment through UC.

Samples fabricated from Al 3003/SiC/Al 3003 and Al 3003/SiC/Cu were metallographically studied. Specimens were extracted from each deposits perpendicular to the fiber direction and prepared following standard metallographic practices. Polished specimens were etched by Keller’s solution (HF-1%, HCl-1.5%, HNO₃ – 2.5%, and H₂O – 95%).
Table 4.3: Processing Parameters and Chosen Levels for Temperature Measurement

<table>
<thead>
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<th>Processing Parameters</th>
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<td>Vibration amplitude</td>
<td>10µm, 12µm</td>
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<tr>
<td>Normal pressure</td>
<td>206kPa, 275kPa</td>
</tr>
</tbody>
</table>

Metal/fiber interface microstructure was observed with SEM. EDS was utilized for microchemical characterization of the interfaces between Al 3003/Cu and Al 3003/ SiC fiber.

4.2.5 Temperature Measurement During UC

Temperature measurements were conducted on a simplified version of the UC machine at Loughborough University, UK. This machine is as capable as the commercial machine in term of joining thin metal foils, and the simple structure of this machine makes it more accessible for process characterization experiments (i.e. temperature measurements). The adjustable parameters of this simplified machine are vibration amplitude, normal pressure and traveling speed of the sonotrode. In the temperature measurement experiments, the first two parameters (vibration amplitude and normal pressure) were considered since these two parameters have major effects on bond formation during UC processing [Janaki Ram et al., 2007b]. The foils used for these experiments were 100µm thick, and the sonotrode diameter was 50mm. The processing parameters and their levels used for the temperature measurements are listed in Table 4.3.

During the temperature measurements, a metal tape was ultrasonically consolidated to the substrate. A small K-type thermocouple of 50µm diameter was placed on the top surface of the previously deposited metal tape. Then a second metal tape was ultrasonically consolidated to the previously laid tape, with the small thermocouple sandwiched in between. Tape laying was performed manually and the tapes were clamped at each end, as the simplified apparatus does not have an automatic tape feeding mechanism. During the depositing of the second layer, the processing temperature was measured at a sampling rate of 1000 samples/second.
4.3 Results

4.3.1 Microstructures

Fig 4.2 shows a typical microstructure for ultrasonically consolidated Al 3003 parts. The dark regions noticed along the layer interfaces are the unbonded regions. Examination of the defects at higher magnifications revealed a thin differently-contrasted layer all around the defect (Fig 4.2(b)). EDS spot analysis showed significantly higher oxygen content in this layer (Fig 4.3(a)) than in the regions adjacent to it (Fig 4.3(b)).

Fig 4.4 shows the SEM microstructures of the Al 3003/Ni 201/Ni 201 multi-material deposit. Generally, Ni 201 seemed to bond well to itself and to Al 3003 (Fig 4.4(a) and Fig 4.4(b)). However, as can be seen in Fig 4.4(c), there were some unbonded regions along the Ni/Ni interface. There was no evidence of metal melting at the interfaces. The interfaces appeared flat and mechanical interlocking did not seem to take place.

Fig 4.5(a) shows an image of the Al 3003/Ni 201 interface at a higher magnification, showing no obvious evidence of intermetallic formation. The results of EDS line scans (for two elements, Al and Ni) performed across the Ni-Al interface (along the scan line shown in Fig 4.5(a) (100 points, 1µm spot spacing, from Ni to Al side)) are shown in Fig 4.5(b). As can be seen, compositions seem to change sharply across the interface, with practically no diffusion of Ni into Al and vice versa.

Fig 4.6 shows an inverse pole figure of a well-bonded Ni/Ni interface (generated from several OIM scans of contiguous areas), which is color coded to indicate the crystallographic orientation (hkl direction parallel to the section normal) of each grain within the sample. Grains that have been plastically deformed typically show a smooth intra-grain color transition indicating rotations of the crystal lattice. Such smooth color transitions are evident in the picture, indicating that the foil interfaces plastically deform during the bonding process. Interestingly, OIM examination of the unbonded regions along the Ni/Ni interface revealed a thin layer of extremely fine grains all around the unbonded region (Fig 4.7), indicating that the defect boundaries are made up of residual nano-grains formed by severe plastic deformation, or that the foil is covered with an oxide layer and/or some kind of contamina-
Fig. 4.2: Unbonded regions in ultrasonically consolidated Al 3003: (a) Low magnification; (b) High magnification (note the thin layer with a different contrast all around the defect (shown by arrow)).
Fig. 4.3: (a) EDS spectra showing a distinct oxygen peak in the thin layer with a different contrast. (b) The oxygen peak is absent in the regions adjacent to, but outside the thin layer.
Fig. 4.4: SEM micrographs of the Al 3003/Ni 201 multi-material deposit. (a) shows a well-bonded Ni/Ni region, (b) shows a well-bonded Ni 201/Al 3003 region (c) shows a few Ni/Ni unbonded regions.
Fig. 4.5: (a) Ni 201/Al 3003 interface, (b) EDS line scan results across the Ni 201/Al 3003 interface (along scan line shown in Fig. 4.5a, scan started on the Ni side).
Fig. 4.6: An image of several inverse pole figures of contiguous areas along a well-bonded Ni-Ni interface stitched together. The grains in the image are color coded to reflect their orientation. The line across the center of the image defines the Ni-Ni weld interface.

tion at these locations. Such fine grains were not observed along the well-bonded portions of the Ni-Ni interface, as can be seen in Fig 4.6.

As shown in Fig 4.8, the SiC fiber was successfully embedded between Al 3003 foils. The fiber was not deformed during the process, retaining its circular external geometry. Matrix foils were bonded perfectly with little discontinuity at the foils’ interface. The cavity created by the placement of a SiC fiber between two foils was fully filled by the matrix metal, indicating significant plastic deformation of the matrix material during UC processing. A two-dimensional element mapping study was conducted on the Al 3003/SiC/Al 3003 sample surface with EDS, as shown in Fig 4.9. Diffusion of Al and Si was not observed at the Al 3003/SiC interface.

An SEM image of an Al 3003/SiC/Cu sample is shown in Fig 4.10. The SiC fiber was successfully embedded between Al 3003 and Cu foils. Compared with Fig 4.8, where the center of fiber located at the interface between the upper and lower foils, it is notable that the center of the SiC fiber does not align along the interface between metal foils, instead it was displaced into the Al foil. Since the aluminum foil used is softer than the copper foil, the SiC fiber was pressed deeper into the softer metal during UC. It was also observed that the cavity due to introduction of the SiC fiber was filled only by Al 3003, and the geometry of the bottom surface of the copper foil indicated indentation by the SiC. EDS line mapping
Fig. 4.7: Inverse pole figure of an unconsolidated portion of the Ni-Ni interface. Note the extremely fine grains that are present along the defect boundaries.

Fig. 4.8: SiC fiber embedded between Al 3003 foils.
was conducted at a location close to the SiC fiber across the Al 3003/Cu interface, along the line shown in Fig 4.11(a), with 0.5\(\mu\text{m}\) point spacing (for two elements: Al and Cu, started at the Al 3003 side). As seen in Fig 4.11(b), no discernable diffusion occurred across the Al/Cu interface when considering the accuracy limitation of the EDS facility (1\(\mu\text{m}\) spot size).

4.3.2 Temperature Measurements

Temperature measurement results at the welding interface and one layer below the welding interface are shown in Fig 4.12. It was observed that the maximum processing temperature for each deposit at the welding interface changed from 68\(^\circ\text{C}\) to 98\(^\circ\text{C}\) dependent upon the processing parameter combinations used.

4.4 Discussion

4.4.1 Bond Formation Mechanism Between Metal Foils During UC

Mechanical Interlocking

Mechanical interlocking could facilitate bond formation in ultrasonic metal welding between dissimilar metals, especially combinations of materials with significant difference in hardness. Joshi [Joshi, 1971] noticed such mechanical interlocking of metals during a
Fig. 4.10: SiC fiber embedded between Al 3003/Cu foils (arrows indicating physical discontinuity at SiC/Al 3003 interface).
Fig. 4.11: (a) Al 3003/Cu interface, (b) EDS line scan results across the Al 3003/Cu interface (along scan line shown in Fig.11a, scan started on the Cu side).
study of ultrasonic welding between Al and Au. In his study, a liquid-like metal flow of Au into the Al side was observed at the welding interface. He concluded this material interlocking as the main reason for weldability between Al and Au. However in the present study of ultrasonically consolidated parts of dissimilar metals (i.e. Al 3003/Ni and Al 3003/Cu), a flat interface persisted between metal foils and no such metal interlocking was observed (Fig 4.4 and Fig 4.10). Thus, although mechanical interlocking can occur during ultrasonic metal welding between dissimilar materials, especially for material combinations with significant difference in hardness, in the current ultrasonically consolidated samples, mechanical interlocking did not appear to take place.

**Metal Melting**

Melting phenomena are related to the temperature rise at the welding interface. During ultrasonic metal welding, heat is generated primarily due to dynamic frictional effects at metal/metal interface. Some amount of heat can also be generated by acoustic heating and plastic deformation [Langenecker, 1966]. Various methods have been applied to identify
the actual processing temperature at the welding interface during UMW. Those methods include (1) embedding small thermocouples at the interface [Jones and Powers, 1956; Joshi, 1971], (2) measuring the thermoelectric electromotive forces (e.m.f) between workpieces during welding [Daniels, 1965; Jones and Powers, 1956; Weare et al., 1960], and (3) observing the interface during welding using an infrared camera [De Vries, 2004]. While there is large variation in reported interface temperatures in ultrasonic metal welding [Daniels, 1965; De Vries, 2004; Jones and Powers, 1956; Joshi, 1971; Weare et al., 1960], the measured processing temperatures are, in most cases, less than the melting point of the welded metal. A drawback of all the methods listed above is that the temperatures measured were all volume averaged temperatures of a certain volume of material at the metal/metal interface. It is possible that at some localized spots the temperature may reach or exceed the melting temperature of the metal, even if the averaged temperature at the welding interface is below the base metal melting point. Therefore microscopic analysis has also been conducted as an alternative method to investigate the possibility of material melting. In most microscopy examinations, no re-solidification microstructures were observed [Daniels, 1965; Jones and Powers, 1956; Joshi, 1971]. In some cases, however, fusion welded microstructures were observed [Gunduz et al., 2005; Weare et al., 1960]. For example, Gunduz et al. [Gunduz et al., 2005] reported localized melting of Al-Zn solid solution formed at the weld interface. Thus, while most reports confirm that ultrasonic welding is a solid-state joining process, there is at least some evidence that localized melting can occur in some instances during the process. In the present study, no evidence of melting was observed along the foil interfaces, as the measured maximum processing temperatures were significantly below the melting point of the metals and fusion welded microstructures were not observed. Therefore, occurrence of localized metal melting during ultrasonic welding is believed to be specific to certain material combinations that involve formation of low melting eutectics or solid solutions, especially when subjected to relatively severe processing conditions. In the present ultrasonically consolidated samples, metal melting is not a possible bond formation mechanism.
Diffusion

In a recent study of ultrasonic welding between aluminum and zinc, Gunduz et al. [Gunduz et al., 2005] observed significant Zn diffusion into Al. Therefore, it appeared that ultrasonic metal welding could provide necessary conditions for significant metal diffusion. However, in the current study of ultrasonically consolidated Al 3003/Ni 201 (Fig 4.5(b)), the EDS line scan results indicated practically no diffusion of Ni into Al and vice versa. No diffusion (Al into Cu or Cu into Al) was also noticed in the EDS results of ultrasonically consolidated Al 3003/Cu in Fig 4.11(b). Therefore, it appears that the mechanism of bond formation during the ultrasonic consolidation process does not significantly depend on diffusion.

Atomic Force Across Nascent Metal Interfaces

The bond formation in the current study appears to be caused by the atomic forces across the nascent metal contact points. Two necessary conditions for the occurrence of atomic level force are: i) formation of atomically clean metal contacting surfaces, and ii) intimate contact between clean metal surfaces. However, surface oxide layers exist for all metallic materials, which prevent intimate contact of nascent metal surfaces. Hence removal of surface oxide is critical for the preparation of atomically clean metal surfaces or points. During the process of ultrasonic welding, frictional effects due to ultrasonic vibration at the mating metal surfaces are generally believed to result in breaking and removal of the surface oxide layers [Daniels, 1965; De Vries, 2004]. The ease with which oxide layers can be removed during ultrasonic welding significantly determines the ultrasonic weldability of certain metals. For example, Al 3003 has a high ratio of metal oxide (Al$_2$O$_3$) hardness to metal hardness, which facilitates the breaking and removal of the oxide layer. Some materials are problematic to be ultrasonically welded due to the difficulties of oxide removal, such as for Al 6061 [Kong et al., 2003]. The surface oxide layer of Al 6061 is mainly made up of Al$_2$O$_3$ and MgO. The prevalence of MgO results in difficult oxide layer removal. Interestingly, such difficult-to-be-welded materials have been shown to be ultrasonically weldable when employing techniques for removing surface oxide layers just prior to welding.
Therefore, there is ample evidence that oxide layer removal is a crucial event in metal ultrasonic welding. Microstructural studies confirmed the presence of oxide layers along the defect boundaries (Fig 4.2, Fig 4.3 and Fig 4.7). Oxide layers were, however, absent in the fully bonded or consolidated regions (Fig 4.6). This confirmed that ultrasonic motion (and consequent frictional effects) at the welding interface helped removing the surface oxide layers. However, this occurs only at the locations wherever there is surface contact. If the mating surfaces are not in contact, there cannot be any friction to break the surface oxide layers. Therefore, the presence of oxide layers along the defect boundaries indicates that the mating surfaces across these defects had not come into contact. These non-contact regions with unremoved surface oxide layers show up as unbonded regions along the foil interfaces in the final deposit. It should be noted that unbonded regions along the foil interfaces can also be caused by cracking-related effects subsequent to bonding, especially under conditions of excessive energy input [Daniels, 1965; Kong, 2005]. However, such unbonded regions do not show oxide layers as they get removed in the process of bonding prior to cracking. Therefore, it can be deducted that the unbonded regions observed in the current study along the foil interfaces are not due to some cracking-related phenomena, but are due to a lack of complete surface contact between the mating foil surfaces as a result of excessive surface roughness prior to bonding [Janaki Ram et al., 2007b].

In addition to removal of surface oxide layer, another necessary condition for bond formation by atomic forces during UC is the plastic deformation of the materials at contacted surfaces. The occurrence of plastic deformation was confirmed in the OIM studies (Fig 4.6). Plastic deformation plays an important role in the bond formation processes of UC in several ways. First, plastic deformation facilitates the pulverization of the surface oxides. During ultrasonic welding, cracks are initiated at the brittle oxide layer under the action of dynamic interfacial stresses generated by the ultrasonic vibration and applied normal forces. These interfacial stresses also induce plastic deformation in a thin layer of metal (20µm) just beneath the oxide layer [Kong et al., 2004; White, 2003]. As a result of plastic deformation, nascent metal from beneath extrudes through the cracks, resulting in the break-up of the
oxide layers. These broken oxides are removed from the bond region by metal flow and are dispersed in the vicinity of the weld zone. Enjio [Enjio, 1986] identified such broken oxide fragments (0.05 to 0.2µm sizes) in an Al alloy diffusion weld subjected to ultrasonic vibrations. However, the dispersed oxide pieces may not be noticeable in all cases, as oxide layers can be as thin as several nanometers [Kong et al., 2003]. Second, plastic deformation is crucial for fabricating a weld with satisfactory linear weld density (LWD) [Janaki Ram et al., 2007b]. Roughness on the metal surface precludes 100% surface contact, consequently 100% joined interfaces. Metal foils are only joined at the initially contacted points if metal plastic deformation does not occur. However, several researchers have indicated nearly 100% LWD, which confirms the occurrence of metal plastic deformation [Janaki Ram et al., 2007b; Kong et al., 2004]. The situation at the mating surfaces at the beginning of ultrasonic welding can be visualized as shown in Fig 4.13. As can be seen, contact between mating surfaces occurs only at surface asperities, leaving numerous no-contact regions along the interface. Bonding across these no-contact regions will not occur unless there is a mechanism to close these voids and to bring the mating surfaces into intimate contact. Diffusion can help close these voids, but diffusion alone is unlikely to be the dominant factor, considering the short times available for diffusion during the process. This is where plastic flow is believed to play a major role. Initially, bonds are established at the existing surface contact points. As the process progresses, these bonded regions grow in size, aided by plastic deformation. Plastic deformation at the bonded regions results in squeezing of metal into the voids and the mating surfaces across the void regions approach. As this happens, new points come into contact, leading to friction, oxide layer removal and bonding. These newly bonded regions also grow with time, generating more contact points. This process can result in sound metallurgical bonding with relatively high linear weld density levels.

**Bond Formation Mechanism during UC**

The current study brings greater clarity to the mechanisms of ultrasonic consolidation. While mechanical interlocking, interfacial melting, and diffusion all can occur during ultrasonic metal welding processes, they do not seem to have universal presence; rather, they
seem to be specific to certain material combinations or processing conditions. Bonding in ultrasonic consolidation appears essentially to be solid-state caused by atomic level forces across the nascent metal contact points.

As in the case of other solid state welding processes, two conditions must be fulfilled for bond formation during ultrasonic welding: i) generation of atomically clean surfaces, and ii) intimate contact between clean metal surfaces. The bonding process in ultrasonic welding can be looked at as repeated and successive occurrence of two distinct stages: i) generation of contact points (Contact Stage), and ii) formation of bonds across the contact points (Bond Stage).

4.4.2 Fiber Embedment Mechanism During UC

The UC process has been successfully applied to sandwiching various fibers between metal foils [Janaki Ram et al., 2007a; Kong, 2005; Yang et al., 2007]. The embedded fibers are believed to be mechanically entrapped within the metal matrices, instead of chemically bonded to the matrices. Such conclusion was verified by the EDS element mapping results (Fig 4.9). In the EDS results, no evidence was observed to indicate diffusion of Al into the SiC fiber or Si into the Al matrix.

The mechanical entrapment appears caused by the plastic deformation of matrix materials. When the fiber is placed between metal foils, there are cavities created between

![Fig. 4.13: Schematic of the mating surfaces at the beginning of ultrasonic welding.](image-url)
metal foils in the vicinity of the fiber [Kong, 2005]. Under the stresses due to the ultrasonic vibration and normal force, the metals around the fiber experience more severe stresses than the materials away from the fiber, resulting in significant metal deformation and material flow into the opening around the fiber. Similar phenomena were noticed by Janaki Ram et al. [Janaki Ram et al., 2007b] during stainless steel mesh embedment between Al 3003 foils using UC, where the stainless steel mesh was found to be mechanically entrapped within the Al matrix. If the fiber is sandwiched by metal foils with similar hardness, both metal foils deform with similar magnitude, resulting in the center of the embedded fiber aligned with the metal/metal interface (Fig 4.8). When dissimilar metal foils are used, due to the differences in metal hardness the softer metal tends to deform more than the harder metal, resulting in the fiber being embedded more into the softer metal side. These phenomena are observed in Fig 4.10, where the cavities are clearly filled by the softer Al 3003, while the harder copper foil was dented during fiber embedment.

4.5 Conclusions

Samples were fabricated from similar (Al 3003/Al 3003 and Ni 201/Ni 201) and dissimilar (Al 3003/Ni 201, Al 3003/Cu) metal foils through ultrasonic consolidation processes. Interfacial microstructures indicated Ni 201 bonds well to itself and to Al 3003. High purity copper foils were ultrasonically consolidated to Al 3003 foil with desirable interfacial microstructures and bonding. There is no evidence of mechanical interlocking, localized metal melting, or diffusion at the weld interface. It appears that bonds formed during UC are essentially solid-state, which is caused by atomic level forces across the nascent metal contact surfaces or points. Two conditions were found crucial for the bond formation of UC: (i) removal of oxide layers, and (ii) intimate contact of atomically clean metal surface. These two conditions are fulfilled by the presence of dynamic interfacial stresses due to the ultrasonic vibratory motion and normal force. Bond formation during UC occurs as two distinct stages: a contact stage and a bond stage. During the contact stage, atomically clean mating metal interfaces are created. Subsequently, during the bond stage, metallurgical bonds are established across the atomically clean interface by atomic level forces, much
like forces across grain boundaries.

SiC fibers were successfully embedded within Al alloy 3003 matrices and between Al 3003 and high purity copper foils. The fibers were found mechanically entrapped between metal foils, and chemical bonding (diffusions) was not observed in the microstructure studies.

References


Chapter 5

Mechanical Properties & Microstructures of SiC Fiber Reinforced Metal Matrix Composites Made Using Ultrasonic Consolidation

This chapter is a paper submitted as a journal article to the Journal of Composite Materials.

Abstract

A study of the properties and microstructures of ultrasonically consolidated samples made from Al 3003 as the matrix material with SiC fibers embedded was undertaken. Mechanical tests were used to characterize the mechanical properties of the ultrasonically consolidated samples. During peel tests and tensile tests, embedded fibers were found to improve the strength of the parts. The mechanical properties were improved by the enhanced bonding of the matrix material in the vicinity of the embedded fibers. However, during 3-point bend tests it was found that the embedded SiC fibers caused degradation of the interlaminar shear strength of the samples. Microstructural studies of embedded SiC fiber found that fibers were mechanically entrapped between metal matrices, instead of chemically bonded to the matrix materials.

5.1 Introduction

Ultrasonic Consolidation (UC) is a novel additive manufacturing process implementing ultrasonic metal welding and CNC milling techniques for fabrication of complex three-dimensional structures from metal foils [1]. Previous research have demonstrated various

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processing capabilities of UC for fabrication of multi-functional structures with high dimensional accuracy and desirable surface finish, including objects with complex internal features, objects made up of multiple materials, and objects integrated with wiring, electronics, and fiber optics [2-4].

UC processes are conducted on a machine tool which was commercially introduced by Solidica Inc., in year 2000. The Solidica Formation™ UC machine incorporates an ultrasonic metal welding head, a 3-axis milling machine, a foil feeding apparatus, and a software program to automatically generate tool paths for material deposition and machining. In UC processes, the structure to be built is initially modeled with a CAD software package and systematically sliced into a number of horizontal layers using a customized computer program. Typically each layer is the thickness of the metal foil used in during processing, but in certain instances it is advantageous to mill the layer to a different thickness after each layer is deposited [5].

Fig 5.1 illustrates the basic additive manufacturing operation of UC. In this operation, a rotating sonotrode travels along the length direction of a metal foil placed over the substrate. The foil is held closely in contact with the substrate by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of travel at a frequency of 20kHz and at a user-set oscillation amplitude, while traveling over the metal foil. The combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses at the interface between the two mating surfaces [1,6]. The stresses produce elastic-plastic deformation of surface asperities, which breaks up the oxide film, producing relatively clean metal surfaces, across which metallurgical bonds are established. After depositing a strip of foil, another foil is deposited adjacent to it. This operation repeats until a complete layer is placed. After placing a certain number of layers, a computer controlled milling head shapes the layer(s) to the desired geometry. Layers of metal tapes between adjacent milling operations are called a “level” in the UC process. Four layers per level is the machine default setting for UC, meaning a milling operation occurs after depositing four layers of metal foils. Once the level is shaped to its contour by the CNC
milling head, machining chips are blown away using compressed air and foil deposition starts for the next layer.

Researchers have successfully embedded silicon carbide (SiC) fibers into Al matrices using UC [7,8], which makes UC a manufacturing technology for fiber-reinforced metal matrix composites (MMCs). Most of the research efforts were focused on the subjects of optimization of processing parameter for fiber embedding within metal matrices and characterization of interfacial microstructure between embedded fibers and matrix materials. In previously published studies, however, the mechanical properties of UC-produced MMC samples, which are critical for practical applications of MMCs, have not been reported. This necessitates the current study on the mechanical properties of UC-made samples. In this study, three mechanical property testing methods, peel tests, tensile tests and 3-point bend tests, were implemented on UC-made MMC samples. Mechanical property changes

Fig. 5.1: Schematic of ultrasonic consolidation process.
due to the presence of SiC fibers within metal matrices were characterized, and correlations between mechanical properties and the microstructures of UC-made samples were analyzed in the current study.

5.2 Experimental Procedure

In the current study, specimens without and with fibers were fabricated with identical geometries for each mechanical property test (hereafter referred as Type I and Type II specimen respectively). The Type I specimens were monolithic structures fabricated using a single Al 3003 tape (150$\mu$m thick and 24.5mm wide) for each layer. The Type II specimens were dual-material structures, which were manufactured using a single Al 3003 tape for each layer, with SiC fibers embedded periodically between layers. The SiC fibers used in the current study are 100$\mu$m in diameter, containing a Tungsten core of 10$\mu$m diameter and 1$\mu$m carbon coating on the outer surface.

5.2.1 Fabrication of Samples for Peel Tests

Type I samples for peel tests were fabricated using the following procedures (see Fig 5.2). Initially, a single Al 3003 tape was fully consolidated to the substrate and machined to 125mm in length. Subsequently, another Al 3003 tape was deposited on the first tape. The welded length was 75mm along the tape direction, purposefully leaving a 25mm offset at each end to avoid unexpected stress concentrations in these regions. For the Type II samples, there were three SiC fibers embedded between the two deposited Al tapes, but all other geometric details were identical.

The processing parameters used for fabricating both type of specimens were: oscillation amplitude of 13$\mu$m, welding speed of 32mm/s, normal force of 1450N, substrate temperature of 150$^\circ$C, and commercial UC machine with sonotrode of 147mm in diameter, under which an average linear welding density (LWD) of 60% is typically produced. The reason for using this set of processing parameters, rather than the optimum ones reported in a previous publication [5], was to examine the possible enhancement of bonding strength due to presence of SiC fibers in specimens with otherwise low LWD. Three samples were
fabricated for each type of specimen.

5.2.2 Fabrication of Samples for Tensile Tests

Geometries of Type I samples used for tensile tests followed the ASTM standard D3552-96 (design F). The samples, roughly 2.6\textit{mm} thick, were fabricated from five levels (20 layers) of metal tapes. The processing parameters used for fabricating samples for tensile tests were: oscillation amplitude of 16\textit{µm}, welding speed of 32\textit{mm/s}, normal force of 1750\textit{N}, and substrate temperature of 150\textdegree\textit{C}, under which high LWD was produced [5].

Type II samples had an identical geometry to Type I samples. During manufacturing of Type II samples, two SiC fibers were placed, parallel to the lengthwise tape direction, between the first and the second layer and between the third and the fourth layer of the second, third and fourth level. There was no fibers embedded within the first and fifth levels. The processing parameters used for fabricating samples for tensile tests were the same as the ones used for Type I samples. Three samples of each type of specimen were prepared for testing.
5.2.3 Fabrication of Samples for 3-point Bend Tests

Type I samples for 3-point bend tests were designed as small cuboids (14\(mm\) \(\times\) 10\(mm\) \(\times\) 2.6\(mm\)), according to the geometry descriptions in ASTM standard D2344-84. The samples for bend tests were fabricated from five levels (20 layers) of metal tapes. The processing parameters used for fabricating samples for bend tests were identical to those used for the tensile specimens.

Type II samples had an identical geometry to Type I. For Type II samples, SiC fibers were embedded in the same manner as for tensile testing described above. Twenty specimens of Type I and 12 Type II specimens were prepared for tests.

5.2.4 Mechanical Property Tests

Peel tests have been successfully used to evaluate bonding strength between ultrasonically consolidated metal foils [2, 7]. In the current study, peel tests were implemented to characterize the influence of embedded SiC fibers on the interfacial bonding strength between ultrasonically consolidated metal tapes. The tests were conducted on a standard tensile machine with a customized fixture, as shown in Fig 5.3. During testing, the sample to be tested was placed over the fixture, which was rigidly attached to the upper jaw of the tensile machine. The free end of metal tape on the sample was placed between the rollers of the fixture and clamped to the lower jaw of the tensile machine. The upper jaw was set to move upward at a speed of 0.05\(mm/s\). During upward motion of the fixture, the metal tape was peeled from the substrate. Loading history during peeling was recorded by the load cell attached to the lower jaw. Separate tests were conducted on each free end of the tape.

Tensile tests have been used as a universal testing method for mechanical property characterizations of various materials and structures. In this study, the ultimate tensile strength (UTS) of UC-made samples was measured. The testing speed was set to 0.017\(mm/s\) (1\(mm/min\)).

Three-point bend tests were conducted following the ASTM standard D2344-84. The tests were carried out on a standard tensile test machine. The fixture used in the tests
Fig. 5.3: Experimental setup for peel tests.
was customized according to the requirements in the ASTM standard (Fig 5.4). The span length between the supporting rollers was set to be 10\(\text{mm}\), which is approximately four times the sample thickness as required in the ASTM standard. During testing, load was applied through the upper loading roller by downward motion of the crosshead of the tensile machine. Loading history was recorded by the force sensor attached to the loading roller. For every sample, breaking load was recorded. The motion rate of the crosshead of the tensile machine was set to 0.017\(\text{mm/s}\) (1\(\text{mm/min}\)).

5.3 Results and Discussion

5.3.1 Microstructural Analysis

A typical microstructure of an embedded SiC fiber within an Al 3003 matrix is shown in Fig 5.5. As can be seen, the cavity between metal tapes introduced by placing a SiC fiber between them was fully filled by the plastic deformation of the matrix material. The metal tapes in the vicinity of the SiC fiber appears well bonded, without any observed physical
gap or discontinuity, although a few unbonded areas could be noticed in areas away from the fiber. This and other microstructural analysis indicates that metal/metal bonding in the vicinity of fibers is enhanced due to the introduction of the fiber.

Energy Dispersive Spectroscopy (EDS) studies were carried out on the SiC/Al samples (Fig 5.6). As shown, there was no evidence of significant inter-element diffusion occurring at the fiber/matrix interface. Hence, fiber embedment during UC is mainly mechanical entrapment of SiC fibers within Al matrices.

5.3.2 Peel Tests

In peel tests, the maximum load, which samples can bear before the tape begins to peel off the sample, the peeling load, is indicative of the interface bond strength. The peeling
Fig. 5.6: Element mapping results for a SiC fiber embedded within an Al 3003 matrix.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Peeling load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type I</td>
</tr>
<tr>
<td>1</td>
<td>66</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>52</td>
</tr>
</tbody>
</table>

Table 5.1: Peeling Loads for Type I and Type II Samples

load of each sample is listed in Table 5.1 and graphically shown in Fig 5.7. As depicted in Fig 5.7, the mean peeling load of Type II samples was higher than that of Type I samples, indicating enhanced bonding strength due to the presence of SiC fibers. Due to the high presence of scatter in the peel tests, a hypothesis test for the difference in the means of the peeling loads for the two types of specimens (two-sample $t$-test) was conducted. The results of this $t$-test are shown in Table 5.2. The $p$-value was 0.024, which was smaller than the chosen $\alpha$-level of 5%. Hence, the peeling loads of Type I samples were statistically lower than the peeling loads of Type II samples at a confidence level above 95%.

A representative failure surface on a metal tape which was peeled from a Type II sample, is shown in Fig 5.8. As shown, there were four zones with distinct surface features which can be observed in this figure. Zone I is an area relatively far from the embedded fiber. The placement of the fiber appeared not to influence the formation of bonds sig-
Table 5.2: Two-sample $t$-test for Peeling Loads of Two Types of Specimens

<table>
<thead>
<tr>
<th>Type</th>
<th># of samples</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Standard Error of Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6</td>
<td>48.7</td>
<td>12.6</td>
<td>5.1</td>
</tr>
<tr>
<td>II</td>
<td>6</td>
<td>67.5</td>
<td>15.7</td>
<td>6.4</td>
</tr>
</tbody>
</table>

$T$-test of difference = 0 (vs. $<$): $T$-value=-2.30, $P$-value=0.024, Degree of Freedom=9

Fig. 5.7: Results of peel tests ($\triangle$: result for an individual sample, ■: mean value for each type of specimen).
nificantly in this region, meaning the metal/metal bonds formed in this region were the same as the bonds created between metal tapes in Type I samples. There are two kinds of surface topologies which can be observed in Zone I, a rough surface and a smooth surface (Fig 5.8(a)). The rough surface corresponds to the area where bonds were created during ultrasonic consolidation and destroyed during the peel test. A view of this rough area at higher magnification is shown in Fig 5.8(b). In this figure, ductile fracture features can be seen. The smooth surfaces in Zone I are the areas where the metal tapes were not ultrasonically bonded during UC processing. Since, as mentioned previously, the processing parameters used for fabrication of samples for peel tests were intended to produce a linear welding density of 60%, it was expected that about 40% of the overall area away from the fibers would be unbonded after the manufacturing process. Both bonded areas (rough surfaces in Zone I) and unbonded areas (smooth surfaces in Zone I) can clearly be observed in the microstructure figures.

Zone II is a region where ductile fracture features are seen, in a region near to the fiber, but where the metal tapes were well bonded without any unbonded areas (as seen in Zone I). As illustrated in Figure 5.5, there is a region of enhanced bonding near fibers, and this enhanced bonding encompasses both Zones II and III. Due to the presence of SiC fibers between the metal tapes during UC processing, the materials in the vicinity of the fiber experience stress concentrations that are not experienced in regions further from the fiber. Due to the more severe stress conditions, the materials underwent enhanced plastic deformation. Janaki Ram et al. [9] found that the plastic deformation of materials is essential for producing high linear welding density within ultrasonically consolidated structures. Plastic deformation facilitates closing the micro-voids which are created when putting two metal surfaces with a certain surface roughness together. Thus, enhanced plastic deformation near the fibers means that the magnitude of unbonded areas in that region will be reduced. The reduction of unbonded areas and enhancement of bonding between metal tapes in Zones II and III is likely the reason for the improved peeling loads of Type II samples.
Zone III, as shown in Fig. 5.8(a), is a well-bonded region immediately next to the fiber that has undergone less ductile failure than Zones I and II. Since stress concentration increases during UC processing the closer to the fiber, more plastic deformation and consequently more work-hardening of materials occurs in this region. The fracture surface in Zone III appears as a brittle fracture surface compared to Zones I and II (Fig. 5.8(b)). This is due to enhanced work hardening in this region in addition to stress concentrations near the fiber during the peel test, combining to result in a transition from ductile to brittle fraction between Zones II and III.

Zone IV, as marked on the figure, corresponds to the groove created on the metal tape by the presence of the embedded fiber. The width of this groove was identical to the diameter of the embedded fiber. In Fig. 8c, the topologies of this zone are shown at higher magnification. The features in this zone were identical to the exterior surface features of the
embedded SiC fiber (which will be shown in Fig 5.11(c)). The transference of the surface pattern from the exterior of the SiC fiber to the interior surface of the groove and the fact that no tearing or other failure features were found in this region confirmed that the bonding between the fiber and matrix is mechanical entrapment rather than chemical or metallurgical bonding.

5.3.3 Tensile Tests

By definition, ultimate tensile strength (UTS) is computed as the maximum load divided by the cross section of the tested sample. The computed UTS of each sample are shown in Fig 5.9. It is interesting to note that the UTS of both types of samples are higher than the nominal UTS of Al alloy 3003 tape. During UC processing, metal tapes experience significant plastic deformation [9], thus metal tapes are work-hardened, which results in the higher UTS of ultrasonically consolidated structures. Also, it should be noted that the mean UTS of Type II samples were higher than that of Type I samples. The presence of embedded SiC fibers within Type II samples increases the tensile strength along the fiber longitudinal direction. This was expected, as the Young’s modulus and strength of SiC fibers embedded within Type II samples are much higher than those of the Al matrices.

The fracture surface of Type I sample is shown in Fig 5.10(a). As can be seen in the figure, delamination between metal tapes occurred during tensile testing. At a high magnification of the fracture surface, shown in Fig 5.10(b), ductile failure surfaces can be observed. In Fig 5.11(a), the fracture surface of a Type II sample is depicted. The embedded SiC fibers between metal tapes can be clearly seen. It is interesting to note that although delamination occurred along the metal tape interfaces, the metal/metal interface in the vicinity of the fiber did not delaminate during tensile testing, indicating the bonding strength in those regions is enhanced compared to other regions away from the fiber (Fig 5.11(b)). The average tensile strength of Type I samples was \(218.54\, MPa\). A simple rule of mixtures calculation of the enhancement in tensile strength due to the presence of SiC fibers should result in a Type II tensile strength of \(221.575\, MPa\). However, experimental results from Type II samples show a tensile strength of \(225.73\, MPa\). This increase in
tensile strength above the rule of mixtures is due to the enhanced bonding between layers of the matrix material due to the presence of the fibers.

In Fig 5.11(c), the exterior surface of an embedded SiC fiber is shown at high magnification. These features were found to be similar to the surface topologies of the groove observed in Fig 5.8(d). Since the hardness of the SiC fiber is much greater than that of the Al matrix, under the application of normal force the surface pattern of the SiC fiber was imprinted onto the surface of the softer matrix material. Because the bonding between fiber and matrices was mechanical, the transferred surface pattern was retained after the contacted surfaces between the fiber and matrix were separated during testing.

### 3-point Bend Tests

In 3-point bend tests, a factor termed interlaminar shear strength was calculated for each sample to evaluate the bonding strength between ultrasonically consolidated metal tapes under shear stresses. This factor was computed using the formula described in ASTM standard D2344-84:

![Fig. 5.9: Results of tensile tests (△: result for an individual sample, ■: mean value for each type of specimen).](image)
Fig. 5.10: (a) Fracture surface for Type I tensile tests. (b) View of fracture surface at high magnification.
Fig. 5.11: (a) Fracture surface for Type II tensile tests. (b) View of fracture surface at high magnification. (c) View of exterior surface of SiC fiber at high magnification.
Table 5.3: Two-sample t-test for 3-point Bend Test

<table>
<thead>
<tr>
<th>Type</th>
<th># of samples</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Standard Error of Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>20</td>
<td>41.92</td>
<td>2.93</td>
<td>0.66</td>
</tr>
<tr>
<td>II</td>
<td>12</td>
<td>38.77</td>
<td>2.74</td>
<td>0.79</td>
</tr>
</tbody>
</table>

T-test of difference = 0 (vs. >): T-value=3.01, P-value=0.003, Degree of Freedom=30

\[ S_H = 0.75 \times \frac{P_b}{b \times d} \] (5.1)

where \( P_b \) was the breaking load (i.e. the maximum load the sample could bear), \( b \) is the width of sample, and \( d \) is the thickness of the sample.

The calculated interlaminar shear strength of each sample is graphically shown in Fig 5.12. The mean of interlaminar shear strength of Type II samples was found to be lower than that of Type I samples, indicating a degradation in shear strength due to the presence of SiC fibers. A hypothesis test for the difference in means of peeling loads for two types of samples (two-sample t-test) was conducted on the interlaminar shear strength results. The t-test results are shown in Table 5.3. The \( p \)-value for this t-test is 0.003, which is smaller than the chosen \( \alpha \)-level of 5%. Hence, the interlaminar shear strength of Type II samples is lower than the interlaminar shear strength of Type I samples at a confidence level of 95%.

The reasons for the degradation in interlaminar shear strength are likely due to the failure mode which occurs in 3-point bend tests, as contrasted with tensile and peel tests. Since the bonding between the embedded fibers and the matrix materials is simply mechanical entrapment, there is no resistance to shear loading (other than friction due to surface roughness) between the fibers and the matrix. As the presence of fibers introduces stress concentrations it is likely that the decreased interlaminar shear strength due to the combination of stress concentrations and lack of resistance to shear loading at the interface is more significant than any enhanced shear strength due to the more well-bonded region near the fiber, resulting in an overall decrease in interlaminar shear strength.
Fig. 5.12: Results of 3-point bend tests (△: results for an individual sample, ■: mean value for each type of specimen).
5.4 Conclusions

In the current study, peel tests, tensile tests and 3-point bend tests were used to characterize the difference between mechanical properties of ultrasonically consolidated Al 3003 with and without embedded SiC fibers. Microstructural studies indicated the SiC fiber were mechanically entrapped within the metal matrix, and not chemically or otherwise bonded to the matrix materials. The presence of embedded SiC fibers enhanced the peeling resistance and UTS of the specimens in the peel tests and tensile tests respectively. This enhancement is due to the increased presence of well-bonded regions in the vicinity of the embedded fiber. However, in 3-point bend test, it was found that the presence of embedded SiC fibers degraded the interlaminar shear strength of the samples. This degradation is likely due to the lack of bonding between the fiber and the matrix and the stress concentrations which occur during shear loading.

References


Chapter 6

Conclusions and Future Work

6.1 Conclusions

In the current study on the fabrication of long-fiber-reinforced metal matrix composites using ultrasonic consolidation, three research goals have been achieved. Bond formation mechanisms and fiber embedment mechanisms were studied and discussed. The effects of processing parameters on bond formation and fiber embedment were experimentally and analytically investigated. The mechanical properties of UC-fabricated MMC structures were characterized. The knowledge and understanding achieved in the current study gave a clear understanding of the issues involved in the application of UC to the fabrication of long-fiber-reinforced MMC structures.

6.1.1 Bond Formation and Fiber Embedment Mechanisms During UC

Various bond formation mechanisms dominate for different ultrasonic metal welding processes, depending on material combinations and processing conditions. For ultrasonic consolidation, it was found that bond formation is primarily due to atomic forces across nascent metal surfaces, and not other mechanisms such as metal mechanical interlocking, metal melting or diffusion. During the formation of bonds due to atomic force, two necessary conditions are essential, which are: (i) generation of atomically clean metal surfaces by removing surface oxide layers, and (ii) intimate contact of the nascent metal surfaces.

Since bonds due to atomic forces can only be established across atomically clean metal surfaces, the generation of atomically clean surfaces is important for the bond formation during UC. However, for all engineering metallic materials, oxide layers are contained on the exterior surface, which prevent establishment of bonds by atomic forces. The ease
with which the oxide layer is removed during the UC process will determine the ultrasonic-weldabilities of metals to some extent. Generally speaking, the metallic materials with an oxide layer which is easily damaged and removed by interfacial frictional effects and material deformation during UC, exhibit good ultrasonic-weldabilities, such as Al 3003. For some other metallic materials of poor ultrasonic-weldabilities, such as Al 6061, it was found that the presence of a difficult to remove oxide layer at the metal/metal welding interface prevented bond formation. Interestingly, the Al 6061 metal tapes were successfully ultrasonically welded when the surface oxide layer were removed by chemical etching just prior to welding.

Besides removal of surface oxide layers, it is crucial to initiate intimate contact at the nascent metal surfaces so that the bonds can be established by the atomic forces. Thus the bonds can be formed at the atomically clean metal contact surface under the application of normal force during UC processing. But, there is no perfectly flat metal surface; all surfaces are characterized by asperities at a small scale as a pattern of hills-and-valleys. Consequently, when two metal surfaces are brought together, there are always some voids (no-contact areas) existing at the metal/metal interface. Bonds can only be formed at the initially contacted surfaces, whereas bonds are not formed in the voids areas. But, in the experimental studies, high linear welding densities up to 98% have been achieved, indicating the no-contact areas are brought into contact and the voids are eliminated during UC processing. The elimination of voids must then be caused by the plastic deformation of the surface. Material plastic deformation is observed in the orientation imaging microscopic study results on ultrasonically consolidated Ni parts.

The bond formation process during UC occurs as a result of two repetitive distinct stages: a Contact Stage and a Bond Stage. During the first Contact Stage, mating surfaces are brought into contact under the influence of applied normal force. It is at these oxide-covered contact points that bonding initially occurs in the next stage of the process. As the sonotrode travels over the layer to be deposited, simultaneous application of normal and oscillating shear forces results in generation of dynamic interfacial stresses between
the two mating surfaces at the contact points. The stresses produce cracks in the surface oxide layers as well as induce plastic deformation in a thin layer of metal just beneath the oxide layer. As this happens, nascent metal deformation forms cracks in the oxide layer, causing disintegration of the oxide layers into smaller pieces, which are dispersed in the vicinity of the bond zone by metal flow. This process generates atomically clean metal surfaces and brings them into intimate contact, establishing a metallurgical bond. This completes the first Bond Stage of the overall process. After the first Bond Stage, there may be numerous “no-bond” regions (corresponding to the original “no-contact or void” regions) along the interface, still covered with oxide layer. As the process progresses, the bonded regions (formed in the first Bond Stage) grow in size, aided by plastic deformation and diffusion. Plastic deformation at the bonded regions results in flow of metal into the voids and the mating surfaces across the void regions approach. As this happens, new points come into contact. This marks the completion of a second Contact Stage of the process. Continued application of ultrasonic energy results in friction, oxide layer break-up and bonding across these new contact points (in the same manner as described in the first Bond Stage) in what can be called a second Bond Stage of the process. This will be followed by another Contact Stage, and subsequently by another Bond Stage and so on. Thus ultrasonic welding involves repeated and successive occurrence of Contact and Bond Stages at every region along the weld deposit. It should be noted that fatigue mechanisms due to excessive vibrational amplitude, stress or vibration repetitions may cause portions of the interface which had been bonded to fail and become a no-bond region. The generation of no-bond regions due to this mechanism is material dependent, and further studies are required to more fully understand how significant this might be. In our studies of Al 3003, the fact that LWD increased with decreasing welding speed in all tests, means a repetition-related fatigue threshold had not been reached.

Fiber embedment during UC was found to be due to mechanical entrapment of fibers within the matrix materials, and no evidence of chemical bonding was observed. In element mapping studies on the microstructure of embedded SiC fibers within Al 3003 matrices using
UC, no diffusion of Al into SiC fibers and diffusion of Si into Al matrices were observed. Additionally, in the studies of fracture surfaces for fiber-embedded samples, it was found that the exterior surface features of SiC fibers were identical to the interior topologies of metal surfaces which contacted the fiber, and no tearing or other failure features were observed. This suggests that SiC fibers are mechanically indented into the matrix materials and not bonded to the matrix. Mechanical entrapment of the fiber is facilitated by plastic deformation of the matrix materials. When the fiber is embedded between similar metals, both metal tapes deform at a similar magnitude. When the fiber is embedded between dissimilar metals, especially metals with significant hardness differences, the softer metal tends to deforms more than the harder metal, resulting in the fiber being embedded more into the softer metal side.

6.1.2 Effects of Processing Parameters on Bond Formation and Fiber Embedment During UC

For UC processes (as discussed in the papers included in Appendices A and B), there are four machine-related processing parameters: vibration amplitude, welding speed, normal force and heating temperature. The chosen levels of these parameters can strongly influence the welding quality of UC-made parts, i.e. linear welding density (LWD). It has been found that parameters of vibration amplitude, normal force and heating temperature have non-linear effects on LWD of UC-made parts. An optimum level is required for each of these three parameters to achieve a high level of LWD. The parameter of welding speed was found to affect LWD in an opposite manner. The higher the welding speed, the smaller the LWD produced. Parts with nearly 100% LWD were produced with the following optimum process parameter combination: oscillation amplitude - 16µm, welding speed - 12 mm/s, normal force - 1750 N, and substrate temperature - 149°C.

Operations of surface machining were applied on the ultrasonically consolidated metal tape before another metal tape was to be deposited on it. It was found that the surface machining was significantly beneficial to the LWD of ultrasonically consolidated parts. Nearly 100% LWDs were achieved in surface-machined UC-made parts with both the optimum
processing parameters and a set of non-optimum process parameters (oscillation amplitude - 16µm, welding speed - 32 mm/s, normal force - 1750 N, and substrate temperature - 25°C). As stated earlier, there are two prerequisite conditions for bond formation during UC. The operations of surface machining were expected to benefit both the necessary conditions. Firstly, the surface oxide layers of the metal tapes are removed by the surface machining operation, which prepares atomically clean metal surfaces for bond formation (the oxide layer formed immediately after machining would be very thin and thus easily removed during UC). In addition, the roughened surface created by the sonotrode on the top surface of previously deposited metal tapes is removed by the surface machining operations. Consequently, the no-contact areas and voids along the welding interface created by the hill-and-valley surface pattern are eliminated after the surface machining operations. As a result, both conditions for bond formation during UC processing are facilitated. In the microscopic results, the improved LWD reflects the enhanced bond formation. However, the means of using surface machining operations to improve LWD are not always desirable for UC processing from a practical point of view, as the time required for surface machining negatively impacts the efficiency and productivity of UC.

6.1.3 Analytical Energy Model for the Effects of Process Parameters on Bond Formation

A simplified energy-based model has been developed to analytically investigate the effects of the processing parameters, including vibration amplitude, welding speed and normal force, on bond formation during UC processing. Two factors, energy input within a single cycle of ultrasonic motion \( E_0 \) and total energy delivered \( E_t \), were defined in this model. It was found that linear weld density, \( E_0 \) and \( E_t \) were typically affected by processing parameters in a similar manner, and linear weld density was found strongly correlated to \( E_0 \) and \( E_t \). In the correlation between LWD and \( E_0 \), it was found the best LWD was produced at a medium level of \( E_0 \). Excess energy input per cycle was found not beneficial to bond formation during UC, which agreed with the experimental observations of LWD degradation at high vibration amplitude and/or high normal force. It was found that lin-
ear welding density asymptotically approached 100% with increased $E_t$ when operating at optimum parameter levels with respect to $E_0$. In experimental studies, it was noted that a reduction in welding speed increased LWD, if other parameters are held constant. At a low welding speed level of 12mm/s, the LWD was as high as 98%. Using the current model, it was found that LWD asymptotically approaches 100% at low welding speeds (e.g. high levels of $E_t$).

6.1.4 Process Parameter Optimization of MMC Fabrication Using UC

For manufacturing of SiC fiber reinforced MMCs using the UC process, besides the four machine-related parameters listed above, there is one additional process-related parameter to be considered, which is the parameter of fiber orientation with respect to the sonotrode traveling direction. Thus five processing parameters must be optimized for the fabrication of fiber-reinforced MMCs using UC. A "push-out test" was developed and implemented to characterize the bond strength between embedded SiC fibers and matrix materials. Variations in vibration amplitude, welding speed, normal force, heating temperature, and fiber orientation contributed to statistically significant variations in bond strength between fibers/matrices. The best bond strength was found to be achieved with the following processing parameters: oscillation amplitude - 20$\mu$m, welding speed - 34 mm/s, normal force - 1700 N, substrate temperature - 149$^\circ$C, and fiber orientation - 45$^\circ$.

6.1.5 Mechanical Properties of UC-fabricated MMC Structures

Peel tests, tensile tests and 3-point bend tests were used to characterize the differences between mechanical properties of ultrasonically consolidated Al 3003 with and without embedded SiC fibers. Various stress conditions were created in these three types of tests, during which the effects of embedded SiC fibers on the mechanical properties of ultrasonically consolidated MMC structures were characterized.

In peel tests, load was applied on the metal tape to detach it from the metal base plate, to which the tape was ultrasonically consolidated. During testing, the maximum load which samples could bear before the tape begins to peel off the sample, the peeling
load, was indicative of the interface bond strength. The peeling loads of the samples with SiC fibers embedded between metal tapes were found higher than the peeling loads of samples without embedded fibers. Four distinct zones with various failure surface features were observed on the fracture surface of the samples for peel tests. In Zone I, roughened areas, at which bonds were formed during sample fabrication and destroyed during testing, were present along with a number of smooth areas, where bonds were not created during sample fabrication. In Zone II and III, it was found that the smooth areas corresponding to unbonded areas were not observed, and the 100% roughened surface confirmed excellent bond formation in the vicinity of embedded fiber. Bond formation in these areas were enhanced due to the presence of a fiber. Zone IV was a groove created on the metal tapes by the presence of SiC fibers. In this zone, it was found that the interior surface of the groove was identical to the exterior of the SiC fiber and no tearing or other failure features were found in this region. The fractographic observations confirmed the SiC fibers embedment mechanisms are due to mechanical entrapment rather than chemical bonding. Thus, the enhanced bonding in Zones II and III (compared to Zone I) were more significant than the lack of bonding of the matrix to the fiber in Zone VI, resulting in a greater overall peel strength.

During tensile tests, ultimate tensile strength (UTS) was identified for samples with and without embedded fibers. By definition, ultimate tensile strength (UTS) is computed as the maximum load divided by the cross section of the tested sample. The mean UTS of samples with embedded fibers was higher than that of samples without fibers. For the fiber-reinforced MMC parts prepared for tensile tests, the fiber volume fraction was small, about 0.785%. From a mechanics of composite materials point of view, the embedded fibers could improve the tensile strength when the fiber volume fraction is beyond a critical level. Otherwise, the embedded fibers would not act as reinforcements but holes (or defects) within the parts. The computed critical fiber volume fraction for the material combination of Al 3003 and SiC fibers is 0.302%, which is smaller than the fiber volume fraction of the samples for tensile tests. Thus, the embedded SiC fibers within the Al 3003 matrix could improve the
tensile strength of UC-made MMC parts. In the experimental results of tensile tests, it was shown that the average tensile strength of samples without fibers was 218.54MPa, whereas the average tensile strength of samples with fibers was 225.73MPa, confirming the enhanced tensile strength due to the presence of SiC fibers. The calculated tensile strength of the samples with fibers was 221.57MPa using a simple rule of mixtures method. The results obtained in experiments were higher than the computed value. The increment above the rule of mixtures result (which is typically considered an upper bound) was likely due to the enhanced bonding between layers of the matrix material in the vicinity of the embedded fibers as well as strain hardening of the matrix due to the plastic deformation required for material to flow around a fiber. Enhanced bonding was observed in the fractographic analysis of the tensile samples. It was noted that although delamination occurred along the metal tape interfaces, the metal/metal interface in the vicinity of the fiber did not delaminate during tensile tests.

In 3-point bend tests, interlaminar shear strength was calculated for each sample to evaluate the bonding strength between ultrasonically consolidated metal tapes under in-plane shear stresses. It was found that the mean of interlaminar shear strength of samples with embedded fibers was lower than that of samples without fibers, indicating degradation in shear strength due to the presence of SiC fibers. The reasons for the degradation in interlaminar shear strength are likely due to the failure mode which occurs in 3-point bend tests, as contrasted with tensile and peel tests. Since the bonding between the embedded fibers and the matrix materials is simply mechanical entrapment, there is no resistance to shear loading between the fibers and the matrix. As the presence of fibers introduce stress concentrations, it is likely that the decreased interlaminar shear strength due to the combination of stress concentrations and lack of resistance to shear loading at the interface is more significant than any enhanced shear strength due to the presence of the more well-bonded region near the fiber, resulting in an overall decrease in interlaminar shear strength.

6.2 Future work

Several areas of needed research have been identified as a result of the current study.
These areas are classified into materials development, UC process development, and MMC mechanical property testing methodologies development recommendations for future work.

6.2.1 Materials Development

In the current study, the MMC structures were ultrasonically consolidated from Al 3003 as matrix materials with SiC fibers as reinforcements. As stated earlier, the UC process is capable of fabricating structures with a large variety of materials, including multi-material structures. Therefore a wide range of metallic materials could be considered as candidates for matrix materials for UC-made MMCs, such as Ti-6Al-4V for many diverse applications. The reinforcements, as well, could be selected from other ceramic fibers, shape memory fibers, optical fibers and more, according to various application requirements. In addition, it is expected that the presence of high hardness reinforcing fibers will improve bond formation in the vicinity of the fibers for other matrix materials as well. This may enable the fabrication of MMCs from matrix materials which are difficult to produce as monolithic structures from UC.

MetPreg tapes, which are pre-fabricated metal matrix composites, have been successfully joined to Al 3003 using the UC process. Therefore, besides the consolidation methodology used in the current study, MMC structures can be manufactured by consolidation of pre-fabricated metal matrix composite tapes.

6.2.2 UC Process Development

As numerous metals and fibers could be the candidate matrix materials and reinforcements for MMCs in UC processing, processing parameter optimization studies are highly beneficial for successful fiber embedment. For some materials with bad ultrasonic-weldability, pre-process operations could be conducted to assist bond formation, such as mechanical cleaning, chemical etching, surface deposition of ultrasonically weldable metal by CVD, or other methods.

In the current studies, Al 3003 tapes used for fabrication of MMC structures were automatically fed by the tape feeding mechanisms in the commercial UC machine, whereas
the embedded fibers were manually introduced. The manual introduction of fibers is undesirable for practical applications of UC to the production of MMCs. From a manufacturing point of view, it will be necessary to integrate automatic fiber feeding mechanisms into a commercial UC machine to enable cost-competitive fabrication of long-fiber-reinforced MMCs using UC.

6.2.3 Mechanical Property Testing Methodologies Development

Several mechanical property testing methods have been successfully adopted in the current study for characterizing the mechanical performance of UC-made MMC parts. The push-out test has been demonstrated as a useful testing method for interfacial bonding strength comparisons between embedded fibers and matrix materials for metal matrix composites. The macro mechanical properties of UC-made MMCs can be identified using peel tests, tensile tests and 3-point bend tests. Besides the testing methods used, there are other testing methods available for mechanical property testing of UC-made MMCs, among which 4-point bend tests is one desired method to be implemented in future research work. Fixture used in 4-point bend test is similar to the one for 3-point bend test, except two loading rollers are designed compared one loading roller in 3-point bend test. In 3-point bend test, bending moment increases from zero at supporting position to the maximum value at middle of span length where load is applied. In 4-point bend test, however, bending moment increases from zero at supporting position to the maximum value at each of loading point; and the bending moment between two loading points hold constant, whose value is determined by the load applied and the position of loading points. Therefore in 4-point bend tests, a stress condition of pure bending is prepared for the MMC samples made by UC.

In conclusion, the manufacture of long-fiber-reinforced MMC structures with desirable mechanical properties has been demonstrated using ultrasonic consolidation. As a result, UC has the potential to be used for commercial fabrication of MMC structures. Further studies are recommended to develop the process for practical utilization of UC in the production of components from engineering materials with optimum fiber volume fractions.
Appendices
Appendix A

Effect of Process Parameters on Bond Formation During Ultrasonic Consolidation of Aluminum Alloy 3003

G. D. Janaki Ram, Y. Yang, and B. E. Stucker

This appendix is a paper published as a journal article in the Journal of Manufacturing Systems (Vol.25/No.3, page 221-238, 2006). All permissions to using this paper as a part of this dissertation are contained in Appendix C.

Abstract

Ultrasonic consolidation (UC) is a novel additive manufacturing process wherein three-dimensional metallic objects are fabricated layer-by-layer in an automated fashion from thin metal foils. The process has immense potential for fabrication of injection molding tooling with conformal cooling channels, fiber-reinforced composites, multi-material structures, smart structures, and others. The proportion of bonded area in relation to the total interface length, termed linear weld density (LWD), is perhaps the most important quality attribute of UC parts. A high level of LWD is desirable in parts intended for load-bearing structural applications. It is therefore necessary to understand what factors influence LWD and devise methods to enhance bond formation during ultrasonic consolidation. The current work elucidates the effects of process parameters on LWD in Al alloy 3003 UC parts. A set of optimum parameters for Al 3003 part fabrication using UC has been obtained, which may vary, however, for different foil materials and sonotrode/foil frictional conditions. The beneficial effects of using elevated substrate temperatures and its implications on overall manufacturing flexibility and the trade-offs between part quality and build time
are discussed. The mechanism of ultrasonic welding is discussed based on oxide layer removal and plastic deformation at the weld interface. A preliminary understanding of defect formation during UC is presented, based on which a method (involving surface machining) for obtaining near 100% LWD is demonstrated. The findings of the current work encourage wider utilization of the UC process and could stimulate further research in the areas of UC process development and modeling.

**Key words:** Ultrasonic consolidation, ultrasonic welding, additive manufacturing, linear weld density.
A.1 Introduction

Ultrasonic Consolidation (UC) is a novel additive manufacturing process developed by Solidica Inc., USA, utilizing the principles of ultrasonic welding for fabricating complex three-dimensional (3D) structures from metal foils [White 2003]. The process uses a high frequency ultrasonic energy source to induce combined static and oscillating shear forces within metal foils to produce solid-state bonds and build up the rough part shape. This ultrasonic addition is combined with 3-axis CNC milling to produce geometric details. The Solidica Formation™ UC machine (Figure A.1(a)), commercially introduced by Solidica in 2000, is an integrated machine tool which incorporates a rotating ultrasonic sonotrode (Figure A.1(b)), a foil feeding mechanism, a 3-axis milling machine, and software to automatically generate tool paths for material deposition and machining. Part fabrication takes place on a firmly bolted base plate (typically of the same material as the foil being deposited) on top of a heat plate. The heat plate maintains the substrate at a set temperature allowing the deposition process to be carried out at temperatures ranging from ambient to $177^\circ C$ ($350^\circ F$).

In additive manufacturing, a 3D CAD model of the component to be built is generated initially and a computer program slices the model into a number of horizontal cross-sections or layers. These cross-sections are systematically created from bottom to top producing a 3D object. Figure 1c illustrates the basic UC additive manufacturing process. In this process a rotating ultrasonic sonotrode travels along the length of a thin metal foil placed over the substrate. The thin foil is held closely in contact with the substrate by applying a normal force via the rotating sonotrode. The sonotrode oscillates transversely to the direction of welding at a frequency of $20kHz$ and at a user-set oscillation amplitude, while traveling over the metal foil. The combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses between the two mating surfaces [White 2003; Daniels 1965; O’Brien 1991]. The stresses produce elastic-plastic deformation of surface asperities, which breaks up the oxide film, producing relatively clean metal surfaces under intimate contact, establishing a metallurgical bond. Oxide films, broken up during the process, are generally
Fig. A.1: (a) Solidica Formation™ UC machine, (b) Close-up view of the ultrasonic sonotrode from below, (c) Schematic of the UC process.
believed to be displaced in the vicinity of the weld zone (mechanical alloying with nascent metal is another possibility). Local temperatures at the interface and the surrounding affected region (about 20\(\mu\)m) can reach up to 50\% of the melting point of the material being deposited [O’Brien 1991]. After depositing a strip of foil, another foil is deposited adjacent to it. This process repeats until a complete layer is placed. After placing a layer, a computer controlled milling head shapes the layer to its slice contour. This milling can occur after each layer or, for certain geometries, after several layers have been deposited. Once the layer is shaped to its contour, the chips are blown away using compressed air and foil deposition starts for the next layer.

UC combines the advantages of additive and subtractive fabrication approaches allowing complex 3D parts to be formed with high dimensional accuracy and surface finish, including objects with complex internal passageways, honeycomb structures, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors and other electronic instruments [White 2003; Hu et al. 2006; George and Stucker 2006; Yang, Janaki Ram, and Stucker 2007; Kong, Soar, and Dickens 2004a; Janaki Ram et al. 2007; Siggard et al. 2006]. These benefits make the process very attractive for a variety of applications in tooling, automotive, aerospace, electronics, and defense industries. Because the process does not involve melting, dimensional errors due to shrinkage, residual stresses, and distortion in the finished parts are not as significant as they are with other metal additive manufacturing techniques. One unique aspect of UC is that highly localized plastic flow around embedded structures is possible, resulting in sound physical/mechanical bonding between the embedded material and matrix material. This ability to embed materials within the matrix can be utilized in a number of ways, including manufacture of fiber-reinforced metal matrix composites with structural fibers for localized stiffening [Yang, Janaki Ram, and Stucker 2007], optical fibers for communication and sensing, shape memory fibers for actuation [Kong, Soar, and Dickens 2004a], or wire meshes for planar or area stiffening [Janaki Ram et al. 2007]. It is possible to simply insert pre-fabricated components (such as thermal management devices, computational devices, sensors, etc.) into machined cavi-
ties of the part under construction prior to encapsulation by subsequent material addition [Siggard et al. 2006].

Ultrasonically consolidated parts typically show metal-to-metal bonded regions and a few unbonded regions (defects/physical discontinuities) along the layer interfaces. A parameter called “linear weld density” (LWD) is generally used to represent the proportion of bonded area in relation to the total interface length [Kong, Soar, and Dickens 2003, 2004b], which strongly influences the mechanical properties of ultrasonically consolidated parts (particularly in the thickness direction). In addition, LWD strongly affects the overall porosity of a part and thus the leakage which may occur from internal channels and which are filled with fluid. It is therefore necessary to minimize defects and ensure a high level of LWD in ultrasonically consolidated parts for use in load-bearing structural applications and applications with fluid channels. In this context, selection of appropriate process parameters plays a key role. In their studies on UC of Al 3003 using a conventional ultrasonic seam welder with some modifications, Kong et al. [2004b] have presented a preliminary understanding of the effects of oscillation amplitude, welding speed and normal force on bond formation and identified a general process window for successful part fabrication based on microscopic studies and peel-off tests. The highest linear weld density reported in this study was 87%. The authors, however, conducted their experiments at room temperature and did not include substrate temperature or substrate surface roughness as variables. While substrate temperature and surface roughness can significantly influence bond formation during UC, little published information is available in this regard.

Frictional conditions at the sonotrode/foil and substrate/foil interfaces play an important role in the UC process as they fundamentally influence the magnitude of interfacial stresses at the mating surfaces [Doumanidis and Gao 2004; Zhang, Zhu, and Li 2006a,b; Zhang and Li 2006]. Therefore, the combination of optimum process parameters can vary not only from material to material, but also from machine to machine, depending on the geometry, material, and surface condition of the ultrasonic sonotrode employed. Further, even for a given machine, since the sonotrode surface condition is bound to degrade with service
(leading to variations in frictional conditions at the sonotrode/foil interface), the combination of optimum process parameters must be verified from time to time. It is, therefore, necessary to experimentally establish the optimum process parameters whenever there is a significant change in foil material/thickness or sonotrode geometry/surface condition.

One important issue with UC is the mechanism behind the origin of defects at layer interfaces, about which very little is known. When one understands the mechanism behind the origin of defects, one can devise suitable techniques to minimize the incidence of defects. This paper describes our efforts to improve LWD in ultrasonically consolidated parts focusing on i) process parameters effects, including substrate temperature, and optimization, and ii) origin of defects and defect elimination through substrate (e.g. previously deposited foil) surface roughness reduction. The trade-offs among part quality, build time and manufacturing flexibility are discussed in the context of proposed strategies for improving LWD in ultrasonically consolidated parts.

A.2 Experimental Work

Machine and Materials

All deposition experiments were conducted using a commercially available Solidica Formation™ UC machine. The machine consisted of a 147 mm diameter titanium sonotrode. The material used for these UC experiments was Al alloy 3003 (nominal composition by wt. %: Al-1.2Mn-0.12Cu) foil, 150 μm thick and 25 mm wide with an H18 temper, obtained from Solidica, Inc., USA. Deposition experiments were conducted on an Al 3003 base plate (dimensions: 355x355x12 mm) firmly bolted to the heat plate of the machine at 8 locations around its exterior.

Process Parameter Optimization Experiments

A design of experiments (DOE) approach was adopted to systematically evaluate the
Table A.1: Parameters and Levels Selected for UC Experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillation amplitude (mm)</td>
<td>10</td>
<td>13</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Welding speed (mm/s)</td>
<td>28</td>
<td>32</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Normal Force (N)</td>
<td>1450</td>
<td>1600</td>
<td>1750</td>
<td>1900</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>24</td>
<td>66</td>
<td>107</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>150</td>
<td>225</td>
<td>300</td>
</tr>
</tbody>
</table>

effects of process parameters and to identify the optimum parameter combination. The process parameters and the levels selected for evaluation in this study are shown in Table A.1. Variation of each parameter at four different levels was considered necessary to assess any non-linear effects. Specific levels for each of the parameters were selected based on preliminary experiments, machine setting limits, and available published information. A Taguchi L16 orthogonal array was utilized in the present study to determine the effects of individual process parameters [Ross 1988]. Interacting influences between two or more process parameters are not possible with a Taguchi L16 experimental design and were not assessed. Table A.2 lists all the parameter combinations used for deposition experiments. The experimental runs were randomized and each of the 16 runs was repeated twice. Although it is typical to use three replicates, two replicates were considered adequate for obtaining statistically meaningful data in the present case as each run consisted of depositing four layers of foil one over another (Figure A.2), which is equivalent to testing each parameter combination eight times. Subsequent to deposition, each deposit was slightly machined along the foil edges. The welding direction was along the foil rolling direction in all cases and was reversed for each layer. The ultrasonic oscillation frequency was maintained constant at 20kHz for all the experimental runs (the UC machine used in the current study does not facilitate variation of oscillation frequency).

Metallography

Two longitudinal sections (one from the center and one from an end portion of the deposit, about 20mm long each) and one transverse section (from the center, about 25mm long) were extracted from each of the deposits (locations shown in Figure A.2) and were
Table A.2: Taguchi L16 Experimental Matrix

<table>
<thead>
<tr>
<th>Run #</th>
<th>Amplitude (mm)</th>
<th>Speed (mm/s)</th>
<th>Force (N)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>28</td>
<td>1450</td>
<td>24</td>
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<tr>
<td>2</td>
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<td>11</td>
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<tr>
<td>16</td>
<td>10</td>
<td>40</td>
<td>1900</td>
<td>149</td>
</tr>
</tbody>
</table>

Fig. A.2: Schematic of the experimental UC deposit consisting of four layers. Welding occurred along the 100mm direction. Metallographic sample locations are shown in the picture.
prepared for microstructural study following standard metallographic practices. Studies on both deposit center and edge portions were considered necessary to assess variations in bond formation across the foil width. Microstructural observations were conducted using an inverted light microscope (Zeiss Axiovert 100A) on as-polished samples. Pictures were taken at a number of locations on each sample and were used to measure the average LWD in each deposit. The LWD on a picture frame was measured using the following formula:

\[ \%LWD = \left( \frac{\text{Bonded interface length}}{\text{Total interface length}} \right) \times 100 \]  
(A.1)

At least 12 picture frames taken on both longitudinal and transverse sections were utilized for estimating the average LWD in each of the deposits. The interface between the base plate and the first layer was not considered in LWD measurement for reasons described in Section A3.3. The micrographs presented in this paper were taken at representative sample locations and show average LWD levels and typical defects.

**Analysis of Variance (ANOVA)**

The response parameter employed in the present study was %LWD, determined based on metallographic observations of the deposits. A high level of LWD is desirable, as part mechanical properties, especially in thickness direction, and as leakage of internal fluid channels would directly relate to it. However, some combinations of parameters, while ensuring a high level of LWD, may lead to deterioration in properties due to strain hardening and fatigue related effects [Kong, Soar, and Dickens 2004b]. Therefore, a comprehensive strategy for assessing the quality of ultrasonically consolidated deposits should include both metallographic observations and actual bond strength/bulk mechanical property measurements. However, in the current work, LWD was employed as the response parameter as it is a more fundamental bond quality attribute. Also, LWD is relatively simple to measure, which allows for statistically meaningful data to be generated rapidly. Analysis of Variance (ANOVA) was performed taking LWD as the response parameter, following standard sta-
tistical procedures [Ross 1988]. All the parameters were assessed for their significance at a 90\% confidence level.

**Further Experiments at Lower Welding Speeds**

Following the initial DOE studies, additional experiments were conducted at relatively lower welding speeds (24, 20, 16 and 12 mm/s) keeping all other parameters constant at their optimum levels, following the same deposition procedure as previously described. These experiments were considered necessary to unambiguously assess the effect of welding speed on LWD. No replicates were made during these experiments.

**Surface Machining Experiments**

Based on metallographic observations and analysis of the deposits made in the DOE studies, sonotrode-induced surface roughness on the deposited foil surface (which becomes the substrate for subsequent layer deposition) was identified as a major source of defects in ultrasonically consolidated parts. This led to the idea of employing an intermediate surface machining step after depositing each layer and prior to subsequent layer deposition to remove the sonotrode-induced surface roughness on the substrate. Experiments were conducted to investigate this idea using various welding speeds (28, 32, 36, and 40 mm/s) by removing approximately 30\(\mu m\) of material (sonotrode-induced surface roughness is about 10 – 15\(\mu m\)) from the foil surface after depositing each layer using the CNC mill that is part of the UC machine. These experiments were conducted at both ambient (24\(^\circ\)C) and elevated (149\(^\circ\)C) substrate temperatures, keeping the oscillation amplitude and normal force at identical levels in all cases (no replication). The surface machining step was incorporated into the machine code so that the process proceeded from one step to the next automatically. No modifications to the traditional part building sequence utilized by the UC process were made except the introduction of an intermediate surface machining step.
A.3 Results and Discussion

Ultrasonic Bonding Mechanism

In order to properly understand the effects of process parameters on bond formation, a brief explanation of the dominant bonding mechanisms in ultrasonic welding, which are still a matter of considerable debate, is in order. As in the case of any other solid-state welding process, two conditions must be fulfilled for bond formation during ultrasonic welding: i) generation of atomically clean surfaces, and ii) intimate contact between clean metal surfaces. The bonding process in ultrasonic welding can be looked at as repeated and successive occurrences of two distinct stages: i) generation of contact points (Contact Stage), and ii) formation of bonds across the contact points (Bond Stage). These stages are briefly discussed below, but are discussed in greater length elsewhere [Janaki Ram et al. 2007].

The situation at the mating surfaces at the beginning of ultrasonic welding can be visualized as shown in Figure A.3. All surfaces are characterized by some surface roughness at the microscopic level and the first Contact Stage is accomplished as the mating surfaces are brought into contact under the influence of applied normal force. As the sonotrode travels over the layer to be deposited, simultaneous application of normal and oscillating shear forces results in generation of dynamic interfacial stresses. The stresses produce cracks in the surface oxide layers (oxides are usually brittle) as well as induce plastic deformation in a thin layer of metal (up to 20 microns) just beneath the oxide layer (plastic deformation can itself cause further cracking in the oxide layer). As this happens, nascent metal is extrudes between the cracks in the oxide layer, causing disintegration of oxide layers into smaller pieces, which are displaced in the vicinity of the bond zone by metal flow. This process generates atomically clean metal surfaces, establishing a metallurgical bond. This completes the first Bond Stage of the overall process. After the first Bond Stage, there may be numerous “no-bond” regions (corresponding to the original “no-contact or void” regions) along the interface, still covered with oxide layer.

As the process progresses, the bonded regions (formed in the first Bond Stage) grow in size, aided by plastic deformation and diffusion, and new points come into contact. Con-
Fig. A.3: Schematic of the mating surfaces at the beginning of ultrasonic welding.

tinued application of ultrasonic energy results in friction, oxide layer break-up and bonding across new contact points. Thus ultrasonic welding involves repeated and successive occurrence of Contact and Bond Stages at every region along the weld deposit. In general, the higher the number of these stage repetitions during ultrasonic welding, the better the bonding between the mating surfaces and the higher the LWD. The number of stage repetitions that occur during the bonding process depends on process parameters, in particular the welding speed employed. If the material is prone to work hardening under these conditions, a threshold can be reached, above which the bonding between the mating surfaces will begin to degrade.

Plastic deformation plays a crucial role in both the Contact and Bond Stages of the ultrasonic welding process. In essence, we believe that plastic deformation acts in four important ways: i) it helps break up surface oxides and ii) remove the broken oxide scales away from the bond region; iii) it helps in establishing intimate nascent metal contact; and iv) it generates new contact points across which bonding can occur.

**General Microstructural Observations and Defect Morphologies**

No significant differences in LWD were noticed between center and end (start/stop) portions of a deposit, as can be seen, for example, in the microstructures (longitudinal
section) of Run # 6 shown in Figure A.4. The dark regions seen along the layer interfaces are the unbonded regions. No specific relationship was found to exist between the occurrence of defects and the welding direction. Similarly, no significant differences in LWD were observed across the deposit width as can be seen, for example, in the microstructures (transverse section) of Run # 8 shown in Figure A.5. In experiments described elsewhere [(Robinson et al. 2006)] deposits with significantly more than 4 layers did show a significant difference in LWD across the deposit as the height to width ratio approached 1:1. For these experiments, however, the height to width ratio was significantly below 1:1 and no significant difference across the specimen width was observed. These pictures also show that defects/unbonded regions in UC parts exclusively occur along the layer interfaces in a random fashion. An idea of how these defects are distributed in the part can be obtained when longitudinal and transverse section microstructures are visualized together.

Three distinct types of defect morphologies were observed, as can be seen in Figure A.4 and Figure A.5: (i) line-like defects, (ii) parabola-like defects, and (iii) point-like defects. While all the three types of defects were present to some extent in all the deposits, certain broad trends were observed. The occurrence of line-like defects was found to be more frequent in samples exhibiting a very low %LWD, deposited using a low level of oscillation amplitude and/or normal force. The parabola-like defects were always observed to be pointed downwards with flat tops and curved bottoms. Parabola-like defects were found to be more frequent in samples exhibiting medium or medium to high weld density levels, while samples exhibiting very high weld density levels usually showed only point-like defects. From a fracture mechanics standpoint, line-like defects will likely be more detrimental to mechanical properties than parabola-like or point-like defects. These observations, however, were not statistically verified during this study, and further studies are planned to gain greater insights into defect morphologies and correlate their occurrence to bond formation mechanisms and process parameters effects.

Based on the mechanism of ultrasonic welding discussed in Section A3.1, these defects or unbonded areas arise due to: (i) lack of complete contact between mating surfaces due
Fig. A.4: Microstructures of Run # 6 deposit (longitudinal section): (a) center, (b) end (start/stop) portion. Horizontal arrow show welding direction for each layer. D1, D2 and D3 show line-like, parabola-like, and point-like defects, respectively.
Fig. A.5: Microstructures of Run # 8 deposit (transverse section): (a) center, (b) edge. D1, D2 and D3 show line-like, parabola-like, and point-like defects, respectively.
to surface roughness, (ii) persistence of surface oxide layers preventing intimate nascent metal contact, and (iii) accumulation of removed surface oxides or contaminants at localized regions along the interface. Further, while depositing a layer, sonotrode motion on the foil can result in a very rough surface with hills and valleys, as can be seen on the top layer in Figure A.4(a) and Figure A.5(a) (the foil stock used in this study has a very fine, mirror-like surface finish). This sonotrode-induced roughness on the deposit surface can prevent effective surface contact during subsequent layer deposition and the regions corresponding to valleys can manifest into defects. This hypothesis is supported by the occurrence of parabola-like defects with flat top and curved bottom, whose size closely match the roughness scale induced on the foil surface due to sonotrode motion. Therefore, it is our belief that this sonotrode-induced roughness is a major source of defects in ultrasonically consolidated parts.

**Linear Weld Density and ANOVA**

The results of linear weld density measurements are presented in Table A.3. Variation in LWD within a deposit and from one deposit to another deposit of any one experimental run was found to be generally less than 15%. Representative microstructures of some of the deposits (longitudinal sections) are shown in Figure A.6. The first layer was found to be bonded to the base plate at a considerably higher LWD than the second, third and fourth layers in all the deposits. This is mainly attributable to a combination of the absence of an oxide layer on the base plate and a lower surface roughness (absence of sonotrode-induced roughness), as the machine performs surface milling on the base plate just prior to depositing the first layer. For this reason, the interface between the first layer and the base plate was not considered in LWD measurements.

The LWD was found to change considerably among the 16 experimental runs ranging from 18% (Run # 1) to 90% (Run # 14) indicating that bond formation is strongly dependent on process parameters. The results of ANOVA are summarized in Table A.4. All four parameters contributed to statistically significant variations in LWD at a 90% confidence
Fig. A.6: Microstructures of UC deposits (longitudinal section): (a) Run # 1, (b) Run # 3, (c) Run # 5, (d) Run # 9, (e) Run # 14, (f) Run # 16. Arrows indicate welding direction for each layer.
Table A.3: Results of Linear Weld Density Measurements on Experimental Runs

<table>
<thead>
<tr>
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<th>Deposit 1 (LWD%)</th>
<th>Deposit 2 (LWD%)</th>
<th>Average LWD%</th>
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<td>1</td>
<td>17</td>
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</tr>
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Table A.4: Results of ANOVA Analysis

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<td>12490</td>
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</table>

\( F_{(table,3,19)} \) at 90% confidence = 2.40

level. Oscillation amplitude was found to exert the strongest influence among the four parameters studied. Welding speed and substrate temperature were found to have a similar level of influence on LWD. The normal force was found to have the weakest influence on LWD within the parameter range used in this investigation.

The effects of individual process parameters on LWD are graphically shown in Figure A.7. It should be noted that the LWD for each level of a particular parameter in Figure 7 corresponds to the average of four experimental runs for that level, with 2 replicates. In addition, at least 12 picture frames of a particular deposit in question were used to find an average LWD for each deposit. Thus each data point in Figure A.7 represents at least
Effect of Oscillation Amplitude

Oscillation amplitude was found to have a non-linear effect on LWD as can be seen in Figure A.7(a). The LWD increased with increase in oscillation amplitude from 10 to 16 µm. Further increase in oscillation amplitude to 19 µm resulted in a small drop in LWD. At a particular oscillation frequency, the higher the oscillation amplitude the higher would be the amount of applied ultrasonic energy into the system. This energy together with the static
applied normal force determines the total energy available for weld formation. Therefore, an increase in oscillation amplitude increases the magnitude of oscillating shear forces and, hence, the magnitude of dynamic interfacial stresses between the two mating surfaces. This would enhance the elastic-plastic deformation at the surface contact points and facilitate easier removal of surface oxide layers and plastic flow. Both these factors provide favorable conditions for intimate nascent metal and formation of strong metallurgical bonds. It is likely for these reasons the deposits showed an increase in LWD with increase in oscillation amplitude from 10 to 16µm. Further increase in oscillation amplitude to 19µm resulted in a small drop in LWD. Kong et al. [2004b] have also noticed a similar drop in LWD with increase in oscillation amplitude beyond a certain level at high contact pressure. The reasons for this are unclear, but it may be due to one or more of the following reasons. When the amplitude is too high, excessive stresses developed at the interface may break up already formed bonds just behind the moving sonotrode, particularly if these higher stresses also resulted in excessive strain hardening, resulting in a lower weld density. Also, at a fixed ultrasonic oscillation frequency, the time available for completing a cycle is fixed. Thus when the amplitude is set at a higher level, the sonotrode must accelerate and decelerate more rapidly in order to complete a cycle. It could be that the acceleration and deceleration forces necessary to oscillate at the higher amplitude are at the upper limit of the sonotrode’s capabilities, and we may not be achieving the desired operational performance. While further studies are necessary to fully assess the effect of oscillation amplitude, the present study shows that an amplitude of 16 m produces the best results.

**Effect of Welding Speed**

In contrast to oscillation amplitude, welding speed was found to have a relatively linear effect on LWD over the parameter range, as can be seen in Figure A.7(b). The LWD increased with a decrease in welding speed from 40 to 28 mm/s. Welding speed determines amount of energy input per unit length or, in other words, the time over which energy is applied at any particular point during ultrasonic welding [Daniels 1965]. Use of higher
welding speeds minimizes sonotrode resident times and hence does not facilitate transfer of sufficient welding energy. Consequently, the magnitude of stresses generated at the interface would be insufficient to cause complete oxide layer removal and to induce adequate plastic deformation at surface contact points. As discussed in Section A3.1, lower welding speeds (i.e., longer sonotrode resident times) allow more stage repetitions, and hence can help produce UC deposits with high weld density levels. This explains why the deposits showed a decrease in LWD with an increase in welding speed. Use of 28 mm/s, the lowest speed within the range selected in this study, was found to produce the best results. Therefore, it was considered necessary to study the effect of welding speed at still lower levels in order to see if a further decrease in welding speed contributes to any further increase in LWD. To address this issue, experiments were conducted at four different levels below 28 mm/s, keeping all other parameters constant at their optimum levels. Observations from these follow-up experiments are discussed in Section A3.8.

**Effect of Normal Force**

As with the oscillation amplitude, normal force was found to have a non-linear effect on LWD (Figure A.7(c)). As can be seen, the LWD increased with an increase in normal force from 1450 to 1750 N. However, further increase in normal force to 1900 N was found to result in considerable decrease in LWD. The applied normal force in ultrasonic welding not only serves to bring the mating surfaces in close contact with each other, but also determines the magnitude of dynamic interfacial stresses in combination with the oscillating shear forces due to ultrasonic vibration. An increase in applied normal force increases the magnitude of the resultant interfacial stresses, and hence aids in bond formation. This explains why the LWD increased with an increase in normal force from 1450 to 1750 N. Further increase in normal force to 1900 N, however, resulted in considerable drop in LWD. Kong et al. [2004b] have also noticed a similar effect in their studies on Al alloy 3003. While the exact reason for this behavior is not clear at present, there are several potential explanations. As discussed previously, use of too high of a normal force might result in excessive interfacial
stresses leading to breakage of already formed bonds. Also, an increase in normal force will necessitate an increased sonotrode oscillatory force to maintain the same frequency. Excessive normal force might reduce the ability of the sonotrode to vibrate at its resonant frequency or set amplitude, thus leading to an overall reduction in operational performance and LWD. While further studies are necessary to fully assess the role of normal force during bond formation, the best results were obtained at an applied normal force of 1750 N in the present investigation.

Effect of Substrate Temperature

As with welding speed, substrate temperature was found to have a linear effect on LWD over the experimental parameter range, as can be seen in Figure A.7(d). LWD increased with increase in substrate temperature from 24 to 149°C (75 to 300°F). During ultrasonic welding, the in-situ rise in interface temperature as a result of friction plays a key role in bond formation by (i) reducing the flow stress of the material, (ii) enhancing atomic diffusion, and (iii) increasing the driving force for recrystallization [(O’Brien 1991]. In addition, any strain hardening effect during plastic deformation would be reduced at elevated temperatures. Use of external thermal energy input in the form of elevated substrate temperature would further enhance these effects and thus promote bond formation during ultrasonic welding. Use of a substrate temperature of 149°C (300°F), the highest temperature in the range selected, was found to produce the best results. In studies involving the embedding of SiC fibers into an Al matrix using UC, the debonding load between the fiber and matrix decreased at temperatures above 149°C [Yang, Janaki Ram, and Stucker 2007]. Thus, although a further increase in substrate temperature may contribute to a further increase in LWD, it could be that increased oxidation above this temperature may counteract these beneficial effects and actually impede bond formation. This is an area that merits further investigation.
Table A.5: Welding Speed Levels Used in Follow-up Experiments and Corresponding LWD Results (Other Parameters were Kept Constant at Their Optimum Levels (Oscillation Amplitude: 16µm, Normal Force: 1750N, and Temperature: 149°C))

<table>
<thead>
<tr>
<th>Welding speed (mm/s)</th>
<th>LWD(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>94</td>
</tr>
<tr>
<td>20</td>
<td>96</td>
</tr>
<tr>
<td>16</td>
<td>98</td>
</tr>
<tr>
<td>12</td>
<td>98</td>
</tr>
</tbody>
</table>

**Further Experiments at Lower Welding Speeds**

Following the DOE studies, additional experiments were conducted at four different speeds below 28 mm/s keeping all other parameters constant at the optimum levels found above. Table A.5 shows the parameters used in these experiments along with the results of LWD measurements. Representative microstructures of the deposits made at 24 mm/s and 12 mm/s are shown in Figure A.8. Microstructures of 20 mm/s and 16 mm/s deposits were quite similar to those of 24 mm/s and 12 mm/s deposits, respectively. All four deposits showed only a few defects, mostly belonging to the point-like defect category. As can be seen, use of lower welding speeds resulted in further increase in %LWD, up to 98%, which compared favorably to Run # 14, the best run in the initial round of experiments, with 90% LWD. Among the four deposits made in the follow-up experiments, samples made at 16 mm/s and 12 mm/s were found to be slightly better compared to the other two. Thus the results show that LWD appears to asymptotically approach 100% as welding speed decreases.

It should be noted that use of very low welding speeds is undesirable for a number of reasons. Very low welding speeds could roughen the foil surfaces (which affects deposition of the subsequent layer), lead to cracking at the weld interface, and cause damage to the sonotrode, as reported by other investigators [(Daniels 1965; O’Brien 1991]. However, none of these effects were observed within the parameter ranges used in this study. In addition, very low welding speeds could result in unacceptable levels of strain hardening and/or fatigue-related effects at the interface leading to property deterioration. Further studies involving peel-off tests and/or transverse tensile tests are necessary to determine whether
Fig. A.8: Microstructures of UC deposits (longitudinal section): (a) Welding speed: 24\,mm/s (b) Welding speed: 12\,mm/s. Other parameters were kept constant at their optimum levels (oscillation amplitude: 16\,\mu m, Normal force: 1750\,N, and Temperature: 149^\circ C). Arrows indicate welding direction for each layer.
these potential detrimental effects occur. Lastly, welding speed directly affects part build time. A decrease in welding speed would result in a proportional increase in fabrication time.

**Applicability of the Optimum Process Parameters Identified in this Study**

Based on the observations made in the present study, the following was identified as the optimum parameter combination for alloy 3003: oscillation frequency - 16µm, welding speed - 16mm/s, normal force - 1750N, substrate temperature - 149°C (300°F). A welding speed of 16 mm/s was chosen as a practical optimum condition, as further reduction in welding speed does not contribute to an increase in LWD sufficient to justify the increase in fabrication time. Use of these parameters, barring other geometry-induced effects, should result in 98% linear weld density in Al alloy 3003 deposits.

Operation at room temperature is important for the embedding of some temperature-sensitive components, such as electronics. When, in a future study, the process parameters are optimized for room temperature, it should be possible to achieve significantly higher LWD levels in the deposits than those observed in this study at room temperature, although not likely as high as those achievable at 149°C (300°F).

While the experimental matrix utilized in the present study does not facilitate precise identification of interactions, certain general trends may be noted. For example, use of low oscillation amplitude in combination with high welding speed and/or with low contact force may be seen to result in low weld density levels. Similarly, use of lower welding speeds and/or higher normal forces at a given oscillation amplitude may be seen to result in relatively higher LWD levels. Further work is necessary to identify the interactions between various process parameters with statistical precision.

The optimum parameters reported in this study are more or less specific to the machine configuration and the foil material used in this study. It is necessary to verify the optimum parameter combination in the case of significant variation in either foil material or sonotrode-related parameters. While this situation calls for a more generalized approach for evaluation and optimization of UC process parameters, it requires precise knowledge
of (i) effects of sonotrode/foil and substrate/foil friction, (ii) in-process variations in frictional conditions, including the effects of surface plastic deformation, temperature rise and increase in build height, and (iii) effects of foil material properties on bond formation (such as crystal structure, elastic modulus, yield strength, ductility, etc.). Some work has already been done to model the UC process along these lines, although much remains to be done [Doumanidis and Gao 2004; Zhang, Zhu, and Li 2006a,b; Zhang and Li 2006].

Despite the above limitations, the findings of the current study are of great practical significance to the users of UC and ultrasonic welding (ultrasonic welding has been in use for welding Al alloys for some time, particularly in the automotive industry). The current work clearly identifies the effects of individual process parameters, including the effect of substrate temperature, and the importance of process parameter optimization. Since the current work was performed using the Solidica Formation™UC machine, which is the only commercially available UC machine model to date, the results are useful to all UC users. The optimum parameter combination reported in this study serves as a useful starting point for further optimization efforts. Also, the current study provides a satisfactory methodology for evaluation and optimization of UC process parameters.

While sonotrode surface condition is certainly important, service-bound variations in sonotrode surface condition may not significantly influence the process as long as a “no slippage” condition exists at the sonotrode/foil interface. The authors have obtained preliminary experimental evidence to this effect. Figure 9 shows the microstructure of an Al 3003 UC deposit (referred to hereafter as the confirmation deposit), which was made a year after the original process parameter optimization experiments using the same parameter combination as Run # 14 (Table A.2). The average sonotrode surface roughness measured across the width and along the circumference of the sonotrode when this deposit was made are Ra 5.19µm and Ra 2.99µm, respectively (surface roughness across the sonotrode width is more relevant to a “no slip” condition as the sonotrode vibrates transversely). The sonotrode may have had a different surface roughness at the time of original process parameter optimization experiments, however, the microstructure of the confirmation deposit
was comparable to that of Run # 14, as can be seen from Figure A.9 and Figure A.6(e). Thus, in view of the insights gained in this study, it appears that variations in sonotrode surface condition with regular use over the period of one year did not significantly affect the process (at least as long as a “no slippage” condition exists at the sonotrode/foil interface). These results also serve to validate the findings for the reported sonotrode roughness data. Further studies, spread over longer time intervals, are necessary to fully assess the effect of service-induced variations in sonotrode surface condition on the process.

Thus, while a high level of LWD can be achieved by appropriately choosing process parameters, this approach has certain limitations:

- Even with optimum process parameters, defects cannot be eliminated altogether.

Thus, use of optimum parameters is not a complete solution.
• Low welding speeds result in better LWD, but significantly increase build time and overall cost of part fabrication, in addition to the potential for fatigue hardening and embrittlement.

• Elevated substrate temperatures put limitations on process capabilities. For example, parts with embedded electronics or other temperature-sensitive devices cannot be fabricated employing elevated substrate temperatures. Further, use of elevated substrate temperature can cause excessive oxidation of the substrate/foil materials in certain cases during the building process, which can severely limit bond formation. For example, attempts by the authors to ultrasonically consolidate pure Cu using elevated substrate temperatures were unsuccessful due to excessive oxidation of the previously deposited Cu layers [Janaki Ram, Johnson, and Stucker 2007]. In addition, alloys which age-harden at modest temperatures would see a change in bulk properties if processed at elevated temperatures.

• Use of high oscillation amplitude and/or normal force in combination with low welding speed can be damaging to the sonotrode [Daniels 1965; O’Brien 1991]. This may necessitate frequent sonotrode cleaning or replacement. More importantly, severe processing conditions can lead to unacceptable levels of strain hardening and/or fatigue-related effects at the interface, which could hamper bond strength and overall part mechanical properties, as shown in a previous investigation [Kong, Soar, and Dickens 2003, 2004b].

Therefore, one cannot rely entirely on process parameters for ensuring a high LWD in ultrasonically consolidated parts. It is thus necessary to look for alternative strategies which can result in 100% bonding even when processing at higher welding speeds and at ambient substrate temperature. Towards this end, a simple technique was devised, as described below.
Table A.6: Welding Speeds and Substrate Temperatures Used in Deposition Experiments with Surface Machining and Corresponding LWD Results (Other Parameters were Kept Constant at Their Optimum Levels (Oscillation Amplitude: 16μm, Normal force: 1750 N))

<table>
<thead>
<tr>
<th>Welding Speed (mm/s)</th>
<th>Substrate Temperature (°C)</th>
<th>LWD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>24</td>
<td>100</td>
</tr>
<tr>
<td>28</td>
<td>149</td>
<td>100</td>
</tr>
<tr>
<td>32</td>
<td>24</td>
<td>100</td>
</tr>
<tr>
<td>32</td>
<td>149</td>
<td>100</td>
</tr>
<tr>
<td>36</td>
<td>24</td>
<td>90</td>
</tr>
<tr>
<td>36</td>
<td>149</td>
<td>100</td>
</tr>
<tr>
<td>40</td>
<td>24</td>
<td>80</td>
</tr>
<tr>
<td>40</td>
<td>149</td>
<td>90</td>
</tr>
</tbody>
</table>

Effect of Surface Machining

As noted in Section A3.2, sonotrode-induced surface roughness was identified as a potentially major source of defects in ultrasonically consolidated parts. In order to minimize the incidence of defects due to sonotrode-induced surface roughness, a simple technique was devised incorporating an intermediate surface machining step after depositing each layer. Experiments were conducted at various welding speeds at both ambient and elevated substrate temperatures, as listed in Table A.6 along with corresponding LWD results. Figure A.10 shows the microstructures of deposits made employing the surface machining technique at various welding speeds at 149°C (300°F). Similarly, Figure A.11 shows the microstructures of deposits made employing the surface machining technique at various welding speeds at 24°C (75°F). These microstructures conclusively demonstrate the effectiveness of surface machining for improving the LWD of ultrasonically consolidated parts.

One major benefit of surface machining is that high-quality deposits can be made at welding speeds that are significantly higher than those which result in high-quality deposits without surface machining. Welding speeds up to 36 mm/s at 149°C (300°F) and up to 32 mm/s at 24°C (75°F) showed nearly 100% LWD, with just a few isolated point-like defects. Thus, with surface machining it is possible to achieve nearly 100% LWD even when processing at significantly higher welding speeds and even when processing at ambient temperature. However, defects can occur even with surface machining when the
Fig. A.10: Microstructures of Al alloy 3003 UC deposits with surface machining (longitudinal section). (a) Welding speed: 28 mm/s, (b) Welding speed: 36 mm/s, and (c) Welding speed: 40 mm/s (Oscillation amplitude:16µm, Normal force: 1750 N, and Temperature: 149°C (300°F)). Horizontal arrows indicate welding direction for each layer.
Fig. A.11: Microstructures of an Al alloy 3003 UC deposit produced with surface machining (longitudinal section) (a) Welding speed: 32 mm/s, (b) Welding speed: 40 mm/s (Oscillation amplitude:16µm, Normal force: 1750 N, and Temperature: 24°C (75°F)). Horizontal arrows indicate welding direction for each layer and other arrows indicate location of defects.
welding speed is too high, as illustrated in Figure A.10(c) and Figure A.11(b), although LWD levels are considerably higher than those achievable without surface machining under similar processing conditions.

The observed improvement in bond formation utilizing the surface machining technique can be attributed to the following:

1. Removal of sonotrode-induced surface roughness facilitates intimate contact between mating surfaces, leading to a significant increase in number of surface contact points at which bonding occurs.

2. Surface machining removes the hills and valleys on the foil surface caused by the sonotrode motion, which would otherwise lead to defects.

3. Surface machining completely removes the oxide layer and any surface contaminants on one of the mating surfaces immediately prior to welding, thus problems associated with oxide layers are reduced.

4. Surface machining removes any work hardened layer either completely or partially on the deposited foil surface. This facilitates easier plastic flow at the interface when the subsequent layer is deposited, which is important for bond formation during ultrasonic welding.

The current work shows that the surface machining technique satisfactorily addresses the problem of defects in ultrasonically consolidated parts, with the following benefits:

- The technique widens the process window for satisfactory part fabrication.

- It facilitates part fabrication at significantly higher welding speeds and/or at ambient temperatures without compromising LWD.

- With surface machining, one can avoid the use of such process parameter selections that lead to excessive work hardening and/or fatigue-related effects at the interface.

- The surface machining method is extremely simple and can be implemented without any modification to commercial UC equipment.
The current work shows that, with proper choice of process parameters and with a surface machining technique, the UC process is quite capable of producing parts with high quality bonds, which should encourage wider utilization of the process for applications in defense, aerospace, automotive, and other industries. It should be noted that the introduction of an intermediate surface machining step adds to the overall build time. In addition, if milling parameters are not optimized, an intermediate surface machining step may result in delamination of or damage to previously deposited layers. However, when appropriate milling parameters are used, the gains in part quality, welding speed and manufacturing flexibility will likely more than compensate for the extra machining time. Further, it should be possible to significantly reduce intermediate machining times if a new machine architecture which supports rapid surface machining is developed (the current UC apparatus was not designed with this in mind).

Alternatively, one may envision the use of other means of removing the surface roughness that could be more time-effective than machining, such as surface rolling, planishing, or acid or chemical etching.

Finally, the current work raises important questions about ultrasonic sonotrode design strategies. Sonotrode designers, apart from other considerations, should pay greater attention to the problem of sonotrode-induced surface roughness. With improved sonotrode designs, this problem can be significantly reduced, possibly eliminating the need for surface machining altogether. A sonotrode surface finish which results in a “no slip” condition at the sonotrode/foil interface without inducing significant surface roughness in the deposited foil may significantly improve UC performance and is thus an important area for further investigation.

A.4 Conclusions

Mechanical properties of ultrasonically consolidated parts depend on how well the individual layers are bonded. It is thus necessary to understand what factors influence bonding and to devise methods to enhance bond formation during ultrasonic consolidation. The
The current work investigated the effect of process parameters on LWD and demonstrates a method to almost completely eliminate interfacial defects in ultrasonically consolidated Al alloy 3003 parts. The following conclusions can be drawn from the current work:

- Process parameters strongly influence bond formation during ultrasonic consolidation. Generally, it is beneficial to select process parameters which result in enhanced plastic flow (e.g. higher oscillation amplitudes, higher magnitudes of normal force, higher substrate temperatures and lower welding speeds) but at a level below that which will result in material oxidation and/or fatigue-related embrittlement. With optimum process parameters, LWD levels as high as 98% can be achieved in Al alloy 3003.

- The optimum process parameter combination can vary from material to material and from machine to machine. Even for a given machine it should be verified from time to time since any variations in foil material properties and sonotrode-related parameters may affect the results significantly. While the findings of the current work are specific to the materials and sonotrode used, the current work adds insight into the effects of process parameters on bond formation and provides a satisfactory methodology for process parameter optimization.

- Use of process parameters, especially welding speed and substrate temperature, optimized for high LWD levels may not be desirable in all manufacturing situations. The current work reflects on the various issues that must be considered when choosing the appropriate process parameters.

- Sonotrode-induced surface roughness on the foil surface is a major source of defects in ultrasonically consolidated parts. Significant improvement in LWD can be achieved by removing the sonotrode-induced surface roughness in the substrate prior to depositing additional foils by employing an intermediate surface machining step. This technique facilitates part fabrication with nearly 100% LWD at significantly higher welding speeds and/or at lower temperatures than is possible without surface machining.
The findings of the current work are primarily useful to users of ultrasonic consolidation and ultrasonic welding equipment. This work clearly illustrated the effects of process parameter variation on LWD and the importance of process parameter optimization. It identified and demonstrated a simple method to almost completely eliminate defects in ultrasonically consolidated parts, which can be exploited on a commercial basis. The findings of the current work encourage wider and more confident utilization of the UC process in defense, aerospace, automotive, and other industries and have identified significant areas for further research related to UC process development, improvement, and modeling.

Acknowledgments

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References


Appendix B

Use of Ultrasonic Consolidation for Fabrication of Multi-material Structures

G. D. Janaki Ram, C. Robinson, Y. Yang, and B. E. Stucker

This chapter is a paper published as a journal article in the Rapid Prototyping Journal. All permissions to using this paper as a part of this dissertation are contained in Appendix C.

Abstract

Purpose - Ultrasonic consolidation (UC) is a novel additive manufacturing process developed for fabrication of metallic parts from foils. While the process has been well-demonstrated for part fabrication in Al alloy 3003, some of the potential strengths of the process have not been fully explored. One of them is its suitability for fabrication of parts in multi-materials. This work aims to examine this aspect.

Methodology/approach - Multi-material UC experiments were conducted using Al alloy 3003 foils as the bulk part material together with a number of engineering materials (foils of Al-Cu alloy 2024, Ni-base alloy Inconel 600®, AISI 347 stainless steel, and others). Deposit microstructures were studied to evaluate bonding between various materials.

Findings - It was found that most of the materials investigated can be successfully bonded to alloy Al 3003 and vice versa. SiC fibers and stainless wire meshes were successfully embedded in an Al 3003 matrix. The results suggest that the UC process is quite suitable for fabrication of multi-material structures, including fiber-reinforced metal matrix composites.

Originality/value - This work systematically examines the multi-material capability of the UC process. The findings of this work lay a strong foundation for a wider and more
efficient commercial utilization of the process.

**Key words**: Additives, manufacturing systems, ultrasonic, welding, fiber testing.

**Paper type**: Research paper.

### B.1 Introduction

Ultrasonic Consolidation (UC) is a novel additive manufacturing process developed for fabrication of metallic parts from foils. The process uses a high frequency ultrasonic energy source to induce combined static and oscillating shear forces within metal foils to produce solid-state bonds and build up a near-net shape part, which is then machined to its final dimensions using an integrated, 3-axis CNC milling machine (White, 2003). UC combines the advantages of additive and subtractive fabrication approaches allowing complex parts to be formed with high dimensional accuracy and surface finish, including objects with complex internal passageways, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors, and instruments. Because the process does not involve melting, one need not worry about dimensional errors due to shrinkage, residual stresses and distortion in the finished parts. This will also help in dealing with metallurgically incompatible dissimilar material combinations.

One unique aspect of UC is that highly localized plastic flow around embedded structures is possible, resulting in sound physical/mechanical bonding between the embedded material and matrix material, although the exact mechanism by which it is made possible is not yet fully understood (Doumanidis and Gao, 2004; Kong et al., 2005). This ability can be utilized in a number of ways, including manufacture of fiber-reinforced metal matrix composites with structural fibers for localized stiffening, optical fibers for communication and sensing, shape memory fibers for actuation, or wire meshes for planar or area stiffening (Yang et al., 2006). It is possible to simply insert pre-fabricated components (such as thermal management devices, sensors, computational devices, etc.) into machined cavities of the part under construction prior to encapsulation by subsequent material addition (Siggard et al., 2006).
While, in principle, the UC process can be utilized for manufacturing of multi-material structures (White, 2003; Wohlers, 2003; Hu et al., 2006), the capabilities of the process are yet to be fully explored. Practically no published information is available on multi-material UC, with most of the work being carried out on Al alloy 3003 (Kong et al., 2004). Successful extension of the process to widely used engineering materials like Fe, Ni, and Cu, and to dissimilar combinations like Al/brass, Al/stainless steel, and Al/Ni, will significantly expand commercial opportunities for ultrasonic consolidation.

In view of the above, in the current work an attempt has been made to explore multi-material UC. A number of engineering materials in the form of foils (hereafter referred to as dissimilar or second materials) were tried in combination with Al alloy 3003 foils (as the bulk part material). In addition, the possibility of embedding SiC fibers and a stainless steel wire mesh in an alloy 3003 matrix were examined. Multi-material UC deposit microstructures were examined to evaluate bonding or embedding characteristics between various second materials and Al alloy 3003. The main aim of this study is to broadly assess the UC process for fabrication of multi-material structures, including fiber-reinforced metal matrix composites.

B.2 Experimental work

Materials

Al-Mn alloy 3003 (nominal composition by wt.%: Al-1.2Mn-0.12Cu) foil (150μm thick and 25mm wide) obtained from Solidica, Inc., USA, was used as the bulk part material for all experiments. Deposition experiments were conducted on an Al 3003 base plate (dimensions: 355x355x12mm) firmly bolted to the heat plate of the Solidica Formation UC machine. The materials used for multi-material UC experiments are listed in Table B.1. All these second materials were in the form of foil (except SiC (fiber) and stainless steel 304 (wire mesh)). Since the machine does not facilitate automatic feeding of multiple foil materials simultaneously, the second materials used in this study were not fed through the
Table B.1: Materials Used for Multi-material UC and Their Forms

<table>
<thead>
<tr>
<th>Material</th>
<th>Nominal Composition (Wt.%)/Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al alloy 3003 (Al 3003) (H18 condition)</td>
<td>Al-1.2Mn-0.12Cu, 150µm thick foil</td>
</tr>
<tr>
<td>Al alloy 2024 (Al 2024)</td>
<td>Al-4.5Cu-1.5Mg, 225µm thick foil</td>
</tr>
<tr>
<td>SiC fiber</td>
<td>100µm diameter</td>
</tr>
<tr>
<td>MetPreg</td>
<td>Al$_2$O$_3$ short fiber reinforced Al matrix composite tape, 325µm thick</td>
</tr>
<tr>
<td>Inconel 600 (IN 600)</td>
<td>Ni-15Cr-8Fe-0.15C, 200µm thick foil</td>
</tr>
<tr>
<td>Brass</td>
<td>Cu-30Zn, 75µm thick foil</td>
</tr>
<tr>
<td>Stainless steel AISI 347 (SS 347)</td>
<td>Fe-18Cr-11Ni-1Nb-0.08C, 150µm thick foil</td>
</tr>
<tr>
<td>Stainless steel AISI 304 wire mess (SS mesh)</td>
<td>Fe-18Cr-8Ni-0.08C, 25µm diameter wire</td>
</tr>
</tbody>
</table>

Deposition experiments were conducted in such a way that they facilitate study of bonding Al 3003 to a second material, and vice versa, following one or both of the following methods:

**Method 1 (direct welding):** Method 1 deposition procedure consisted of depositing a few layers of Al alloy 3003 (on an Al alloy 3003 base plate) and then placing a layer of a given second material on the Al 3003 deposit, and running the ultrasonic head directly over the second material layer. After depositing the second layer, a layer of Al 3003 was deposited on the second material in some cases. This method was used to bond a single layer of second material or as many as three layers of second material, with each layer individually being welded to the previous layer.

**Method 2 (indirect welding):** Method 2 deposition procedure consisted of depositing a few layers of Al alloy 3003 foil (on an Al alloy 3003 base plate) and then placing a given second material layer on top of the previously deposited layer, and then using the automatic machine’s foil feeding mechanism, but were manually placed, while the bulk part material Al alloy 3003 foil was automatically fed by the machine in the usual manner.
Table B.2: Process Parameters Used for Multi-material UC Experiments

<table>
<thead>
<tr>
<th>Material combination</th>
<th>Amplitude ($\mu m$)</th>
<th>Speed (mm/s)</th>
<th>Force (N)</th>
<th>Temperature ($^\circ F$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All combinations except Al 3003/SiC fiber</td>
<td>16</td>
<td>28</td>
<td>1750</td>
<td>300</td>
</tr>
<tr>
<td>SiC fiber</td>
<td>20</td>
<td>34</td>
<td>1700</td>
<td>300</td>
</tr>
</tbody>
</table>

Fiber was oriented at 45° to the welding direction.

tape feeder to lay Al 3003 over the second material while running the ultrasonic head over the layers, thus simultaneously bonding the top Al 3003 layer to the second material, as well as the second material layer to the Al 3003 substrate in one pass.

In the case of SiC fibers, the experimental procedure consisted of: i) depositing a layer of Al 3003 on top of an Al alloy 3003 base plate, ii) placing a SiC fiber on the top of the deposited Al 3003 layer and holding it in place using a custom-designed fixture, and iii) depositing a layer of Al alloy 3003 on the pre-placed fiber. More details on fiber embedment experiments are presented elsewhere (Yang et al., 2006).

The process parameters used for all the deposition experiments are listed in Table B.2. These parameters were found to ensure good bonding between Al alloy 3003 foils (Janaki Ram et al., 2006). However, no attempts were made in this study to optimize process parameters for maximizing bond quality between Al 3003 and any of the second materials, except in the case of SiC. For SiC fiber embedment, a comprehensive process parameter optimization exercise was undertaken using statistically designed experiments involving use of oscillation amplitude, normal force, welding speed, fiber orientation, and substrate temperature at five different levels. Deposits produced using various process parameter combinations were evaluated for fiber/matrix bond strength using “push-out” testing, based on which optimum process parameters were identified (shown in Table B.2). More details on this process parameter optimization exercise are presented elsewhere (Yang et al., 2006).

**Metallography**

All the deposits were metallographically examined to assess bonding or embedding
characteristics between various second materials and Al alloy 3003. Samples corresponding to longitudinal and/or transverse sections were extracted from each of the deposits and were prepared for microstructural study following standard metallographic practices. Microstructural observations were conducted on as-polished samples using optical and scanning electron microscopes.

### B.3 Results and discussion

**Mechanism of bond formation**

Before discussing multi-material UC deposits, a brief explanation of the dominant bonding mechanisms in ultrasonic welding, which are still a matter of considerable debate, is necessary. As in the case of any other solid state welding process, two conditions must be fulfilled for bond formation during ultrasonic welding: i) generation of atomically clean surfaces, and ii) intimate contact between clean metal surfaces. The bonding process in ultrasonic welding can be looked at as repeated and successive occurrence of two distinct stages: i) generation of contact points (Contact Stage), and ii) formation of bonds across the contact points (Bond Stage). These stages are discussed below.

The situation at the mating surfaces at the beginning of ultrasonic welding can be visualized as shown in Fig B.1. All surfaces are characterized by some surface roughness at the microscopic level. The hills and valleys pattern on the mating surfaces does not allow 100% surface contact at the interface; instead, the mating surfaces contact only at surface asperities. Thus, in a way, the first Contact Stage is immediately accomplished as the mating surfaces are brought into contact under the influence of applied normal force. It is at these oxide-covered contact points that bonding initially occurs in the next stage of the process, as described below.

As the sonotrode travels over the layer to be deposited, simultaneous application of normal and oscillating shear forces results in generation of dynamic interfacial stresses between the two mating surfaces at the contact points. The stresses produce cracks in the
surface oxide layers (oxides are usually brittle) as well as induce plastic deformation in a thin layer of metal (up to 20 microns) just beneath the oxide layer (plastic deformation can itself cause further cracking in the oxide layer). As this happens, nascent metal from beneath extrudes through the cracks in the oxide layer causing disintegration of oxide layers into smaller pieces, which are dispersed in the vicinity of the bond zone by metal flow. This process generates atomically clean metal surfaces and brings them into intimate contact, establishing a metallurgical bond. This completes the first Bond Stage of the overall process.

After the first Bond Stage, there may be numerous “no-bond” regions (corresponding to the original “no-contact or void” regions) along the interface, still covered with oxide layer.

As the process progresses, the bonded regions (formed in the first Bond Stage) grow in size, aided by plastic deformation and diffusion. Plastic deformation at the bonded regions results in squeezing of metal into the voids and the mating surfaces across the void regions approach. As this happens, new points come into contact. This marks the completion of the second Contact Stage of the process. Continued application of ultrasonic energy results in friction, oxide layer break-up and bonding across these new contact points (in the same manner as described in the first Bond Stage) in what can be called the second Bond Stage of the process. This will be followed by another Contact Stage, and subsequently by another Bond Stage and so on. Thus ultrasonic welding involves repeated and successive occurrence of Contact and Bond Stages at every region along the weld deposit. In general,
the higher the number of these stage repetitions during ultrasonic welding, the better the bonding between the mating surfaces. If the material is prone to work hardening under these conditions, a threshold can be reached, above which the bonding between the mating surfaces will begin to degrade.

Macroscopically, the bonding process at a given region along the weld deposit begins as the traveling sonotrode approaches that region and completes as the sonotrode travels past that region after a very brief resident time. The number of stage repetitions that occur during the bonding process depends on process parameters, in particular the welding speed employed. For example, slower welding speeds (i.e., longer sonotrode resident times) allow more stage repetitions and hence, can help produce UC deposits with high weld density levels. This is illustrated in Fig B.2, which shows the microstructures of two ultrasonically consolidated Al alloy 3003 deposits, produced at different welding speeds. The deposit shown in Fig B.2(a) was produced using a welding speed of 28 mm/s, whereas the deposit shown in Fig B.2(b) was produced at a lower welding speed of 12 mm/s (other parameters being the same in both cases as listed in Table B.2). The dark regions seen along the layer interfaces are the unbonded regions. These unbonded regions arise due to lack of bonding between the mating surfaces due to surface roughness. As can be seen, use of a lower welding speed resulted in significantly fewer and smaller unbonded regions and thus a higher linear weld density in the deposit (98% for 12 mm/s welding speed versus 90% for 28 mm/s welding speed). This is attributed to a longer sonotrode resident time allowing more number of Contact and Bond Stage repetitions during the bonding process. Alternatively, if one can increase the number of contact points along the mating surfaces by reducing surface roughness, it may be possible to achieve high weld density levels even at relatively high welding speeds. This idea has been demonstrated in another work by the authors (Janaki Ram et al., 2006). It should be noted that other process parameters, such as oscillation amplitude, and build height also exert a strong influence on linear weld density (Janaki Ram et al., 2006; Robinson et al., 2006).

As can be seen, plastic deformation is a crucial player in both Contact and Bond
Stages of the ultrasonic welding process. In the Contact Stage, plastic deformation of the bonded regions not only serves to generate more contact points, but also helps in the survival of already formed bonds. If the bonded regions are incapable of repeated deformation, continued ultrasonic oscillations will result in breakage of bonds. Although repeated breakage and rebonding can occur under specific processing conditions (e.g., too high an oscillation amplitude), we believe that bonded regions likely do not break in most cases, but experience plastic deformation. In essence, we believe that plastic deformation at the interface plays a crucial role in metal ultrasonic welding in four ways: i) it helps break up surface oxides and ii) remove the broken oxide scales away from the bonding region, iii) it helps in establishing intimate nascent metal contact, and iv) it generates new contact points across which bonding can occur.

With this background, it may be expected that successful fabrication of multi-material structures using UC requires that at least one of the materials involved in a dissimilar combination should be capable of plastic deformation. Secondly, oxide layers on both the mating metal surfaces should be amenable for removal during the bonding process. The ease with which an oxide layer is removed is a function of its hardness in relation to the nascent metal hardness. In fact, the ratio of oxide layer hardness to nascent metal hardness is regarded as a good rule of thumb for determining the ultrasonic weldability of metallic materials (O’Brien, 1991). The higher the difference in the hardness levels of the oxide and nascent metal, the easier it is to break up the oxide layer and therefore, the better the ultrasonic weldability.

Preliminary microstructural results pertaining to each of the dissimilar combinations examined in the present work are discussed below under separate headings.

**Al 3003/Al 2024**

Al 3003/Al 2024 deposits were made using both the direct and the indirect welding methods detailed in Section B.2.2. Fig B.3 shows the optical microstructures of these deposits. These pictures show that Al 3003 can be very well bonded to Al 2024 and vice
Fig. B.2: Optical microstructures of Al alloy 3003 UC deposits: (a) 28 mm/s welding speed (90% linear weld density), and (b) 12 mm/s welding speed (98% linear weld density).
versa. It is interesting to note that Al 2024 was well bonded to Al 3003, even when indirectly welded (Fig B.3(b)). Further, Al 3003/Al 2024 bonding appeared to be as good as that of Al 3003/Al 3003. Thus the current work shows that multi-material parts can be successfully fabricated out of Al-Mn and Al-Cu alloys employing the UC process, allowing one to take advantage of the superior strength characteristics of Al-Cu alloys and the superior corrosion resistance of Al-Mn alloys. It is expected that various other Al alloys can be similarly combined for multi-material part fabrication using the UC process.

Al 2024 to Al 2024 bonding was not examined in the current work. In an earlier study Kong et al. (2003) reported inferior weld quality in ultrasonically consolidated Al-Mg alloy 6061, which was attributed to difficulties in oxide layer removal due to the presence of MgO in the oxide layer of alloy 6061. Alloy 2024 also contains a considerable amount of Mg (1.5 wt.%). Therefore, Mg might present similar difficulties during ultrasonic welding of alloy 2024 to itself. The presence of Mg, however, did not result in any problems during ultrasonic welding of alloy 2024 to alloy 3003, which contained very little Mg (0.05 wt.% max.).

**Al 3003/SiC**

Fig B.4 shows the SEM microstructures of Al 3003/SiC deposits. The SiC fiber used in this study has a tungsten core (about 10µm dia.). For successful embedment of fibers, there must be adequate plastic flow of the matrix material to close the gaps that were created by placing the fiber between the layers. As can be seen in Fig B.4, these gaps were completely eliminated by plastic metal flow during UC processing, leading to excellent fiber embedment. The circular flow lines around the fiber evident on Fig B.4(b) may have been caused during sample polishing because of a large difference in hardness between matrix and fiber materials. Similar success was reported by Kong et al. (2005) with shape memory alloy fibers in an Al 3003 matrix. Kong, through detailed elemental mapping studies, concluded that the matrix and the embedded fiber were not chemically or metallurgically bonded. Similarly in the present case, bonding between SiC fiber and Al 3003 matrix is expected to be physical/mechanical, rather than chemical/metallurgical.
Fig. B.3: Optical microstructures of Al 3003/Al 2024 deposits: (a) Al 2024 layer directly welded to Al 3003, (b) Al 2024 layer sandwiched between Al 3003 layers (indirectly welded).
Studies thus show that SiC fibers can be successfully embedded in an Al 3003 matrix, making UC a viable process for fabrication of intricate parts out of continuous fiber reinforced metal matrix composites.

**Al 3003/MetPreg®**

Fig B.5 shows the SEM microstructures of directly welded Al 3003/MetPreg® deposits. As mentioned earlier, MetPreg® is a commercially available Al₂O₃ short fiber reinforced aluminum matrix composite. As can be seen, the MetPreg® layer was very well bonded to the Al 3003 substrate with a featureless interface. On the other hand, when the MetPreg layer was indirectly welded, the Al 3003 top layer was bonded well with the MetPreg® layer, but the MetPreg® layer was not well bonded to the Al 3003 bottom layer. These observations are shown in Fig B.6.

The discrepancy can be explained as follows. When the ultrasonic sonotrode is passed over the Al 3003 top layer during indirect welding, much of the available ultrasonic energy acts at the Al 3003 top layer/MetPreg® interface (therefore producing good bonding), as it is located directly beneath the sonotrode. Compared to this, the amount of ultrasonic energy that reaches or acts at the MetPreg®/Al 3003 bottom layer interface would be much less. This makes oxide layer removal and/or plastic deformation difficult at the MetPreg®/Al 3003 bottom layer interface, leading to poor bonding. In this context, one might argue that the same should be the case with indirectly welded Al 3003/Al 2024. However, indirect welding did not result in poor bonding at the Al 2024/Al 3003 bottom layer interface (Fig B.3(b)). This is understandable when we consider that: i) Al 2024 foil (225µm) is considerably thinner than the MetPreg® foil (325µm), and ii) MetPreg® is significantly stiffer and stronger than Al 2024. Further, the composite nature of the MetPreg, which contained hard and stiff Al₂O₃ fibers in a soft Al matrix, can result in greater absorption or attenuation of the input ultrasonic energy.

The present work thus shows that it is possible to ultrasonically consolidate Al metal matrix composite layers and Al 3003 layers in any combination with excellent interface char-
Fig. B.4: SEM microstructures of Al 3003/SiC: (a) SiC fiber embedded between Al 3003 layers, (b) SiC fiber at a higher magnification showing intimate contact with the matrix. Arrow shows tungsten core.
Fig. B.5: SEM microstructures of directly welded Al 3003/MetPreg®: (a) MetPreg® layer bonded to Al 3003 substrate, (b) Al 3003/MetPreg® interface at a higher magnification.
Fig. B.6: SEM microstructures of indirectly welded Al 3003/MetPreg®: (a) MetPreg® layer sandwiched between Al 3003, (b) Al 3003 bottom layer/MetPreg® interface at a higher magnification.
acteristics adopting the direct welding methodology. This capability can be utilized in many ways. For example, lighter, stronger, and stiffer Al parts can be produced by embedding metal matrix composite laminates. Further, fabrication of functionally graded Al matrix composite parts is a possibility. Fabrication of composite parts using metal matrix composite tapes is yet another possibility. Although bonding between MetPreg® /MetPreg® was not examined in the current work, it is expected that this material combination can be ultrasonically welded, at least up to a certain volume fraction of the reinforcing phase. Plastic deformation due to ultrasonic excitation of the softer Al matrix of the mating composite surfaces is expected to result in necessary readjustments at the interface, producing sound matrix/matrix metallurgical bonding.

**Al 3003/IN 600®**

The interface microstructure of the directly welded Al 3003/IN 600® deposit is shown in Fig B.7. As can be seen, IN 600® was well bonded to Al 3003, without any physical discontinuities at the interface. The indirect welding method also produced good bonding between an Al 3003 top layer/IN 600® (Fig B.8(a)). The interface microstructure is quite similar to that shown in Fig B.7. However, numerous unbonded regions were observed at the IN 600® /Al 3003 bottom layer interface (Fig B.8(b)). As explained in Section B.3.4, insufficient ultrasonic energy is the reason for this, rather than intrinsic difficulties in bond formation.

While IN 600® appears to be well bonded to Al 3003, it is necessary to examine the interface in greater detail since Ni and Al can form a nickel aluminide intermetallic, which can affect the deposit properties. Nevertheless, the current work shows that IN 600® can be ultrasonically bonded to Al 3003 and vice versa, proving the combination viable for multi-material part fabrication using ultrasonic consolidation. It is expected that other Ni-based alloys can be similarly combined with Al 3003 for multi-material part fabrication.
Fig. B.7: SEM microstructure of directly welded Al 3003/IN 600®.
Fig. B.8: SEM microstructures of indirectly welded Al 3003/IN 600®: (a) IN 600® layer sandwiched between Al 3003 layers, (b) Al 3003 bottom layer/IN 600® interface at a higher magnification showing the interfacial defects.
**Al 3003/Brass**

Experiments with Al 3003/brass combinations were conducted using both the direct and the indirect welding methods. The interface microstructures of the indirectly welded Al 3003/brass deposit are shown in Fig B.9. As can be seen, the brass layer was not well bonded to the Al 3003 layers. The Al 3003 top layer/brass interface (Fig B.9(b)) looked better compared to the brass/Al 3003 bottom layer interface (Fig B.9(c)), although both interfaces were not tight and contained numerous interfacial defects.

In another method, a brass layer was initially directly welded to Al 3003. Following this, two more brass layers were deposited with each of them being directly welded to a previously deposited brass layer. The microstructures of this deposit are shown in Fig B.10. Again, the brass layer was not well-bonded to the Al 3003 substrate (Fig B.10(b)). However, there was reasonable bonding between the brass layers, as can be seen in Fig B.10.

It may be noted that both Cu and Zn, the main constituent elements in brass, were reported to be ultrasonically weldable to Al (Daniels, 1965; O'Brien, 1991). Therefore, one might expect that brass can be ultrasonically weldable to alloy 3003. The current work, however, indicates that brass is not easily weldable to Al 3003, although it is not clear whether the lack of bonding is due to improper process parameters or due to intrinsic difficulties in bonding. Thus the Al 3003/brass combination requires further examination using careful process parameter optimization in order to more clearly assess the situation. On another note, the current work shows that brass can be ultrasonically welded very well to itself, and therefore can be used for part fabrication using the UC process.

**Al 3003/SS 347**

Fig B.11 shows the interface microstructures of indirectly welded Al 3003/SS 347 deposit. The Al 3003 top layer/SS 347 interface (Fig B.11(b)) appeared tight without any large physical discontinuities; however, further microstructural studies are required to assess the bond quality. In contrast, the SS 347/Al 3003 bottom layer interface (Fig B.11(c)) showed wide gaps and a total absence of bonding, which is attributable again to a lack of
Fig. B.9: SEM microstructures of Al 3003/brass: (a) Brass layer sandwiched (indirectly welded) between Al 3003 layers, (b) Al 3003 top layer/brass interfaces at a higher magnification, (c) Brass/Al 3003 bottom layer interfaces at a higher magnification.
Fig. B.10: SEM microstructures of directly welded Al 3003/brass: (a) Three layers of brass over Al 3003, (b) Al 3003/brass interface at a higher magnification.
sufficient ultrasonic energy at the interface.

In another method, a layer of SS 347 was initially directly welded to Al 3003. Following this, two more SS 347 layers were deposited with each of them being directly welded to previously deposited SS 347 layer. The first SS 347 layer appeared to bond well to the Al 3003 substrate, but subsequent microstructural examination showed that these materials did not bond quite satisfactorily (Fig. B.12) but merely deformed to produce relatively intimate contact. The top two SS 347 layers completely came off the deposit indicating inadequate bonding between the SS 347 layers.

While Fe-base alloys were reported to be ultrasonically weldable to themselves and to Al alloys (O’Brien, 1991), the current study indicates that the bonding achievable between SS 347 and Al 3003 is not good enough for fabrication of functional multi-material parts. Further, fabrication of SS 347 parts using ultrasonic consolidation looks even more challenging considering the lack of bonding between SS 347 layers. Further deposition experiments after careful process parameter optimization and detailed microstructural studies are necessary to assess the bonding potential between SS 347 to itself and to Al 3003.

Al 3003/SS Mesh

Experiments with an Al 3003/SS mesh combination were conducted using the direct welding method. The method consisted of depositing a few layers of Al alloy 3003 and then placing a layer of SS mesh on the Al 3003 deposit, and running the ultrasonic head directly over the SS mesh. Following this, a layer of Al 3003 was deposited on the SS mesh. The SEM microstructures of the deposit thus made are shown in Fig B.13. As in the case for fiber embedment, plastic flow of the matrix material is critical for successful embedment of the mesh. Microstructural observation revealed excellent metal flow into the gaps of the SS mesh between the Al 3003 layers, resulting in good physical/mechanical bonding between the Al 3003 matrix and SS mesh. Also, passage of the ultrasonic head over the mesh even at a relatively high normal force level (1750 N) did not damage the original wire weaving arrangement of the mesh (Fig B.13(a)). However, the SS mesh was not metallurgically
Fig. B.11: SEM microstructures of indirectly welded Al 3003/SS 304: (a) SS 304 layer sandwiched between Al 3003 layers, (b) Al 3003 top layer/SS 304 interface at a higher magnification, and (c) SS 304/Al 3003 bottom layer interface at a higher magnification.
Fig. B.12: SEM microstructure at the interface of directly welded SS 347(first layer)/Al 3003.
bonded to the Al 3003 matrix, as evidenced by a clearly discernible narrow physical gap that existed between Al 3003 and the SS mesh (shown by white arrows in Fig B.13(b)).

It was observed that the wire elements of the mesh became metallurgically bonded to their neighbors during the deposition process. This can be seen in Fig B.13(b) (black arrows), where the circular wire cross-sections present a featureless interface with the sine wave-like horizontal wire. This indicates that SS 304 can be ultrasonically bonded to itself, making it a candidate material for part fabrication using ultrasonic consolidation. Further deposition experiments using SS 304 foils are necessary to confirm this.

**Multi-material ultrasonic consolidation**

Although further work is considered necessary, the deposition and characterization procedures adopted in this study are appropriate for a preliminary assessment of the potential for multi-material part fabrication. Of the dissimilar material combinations studied, only two, Al 3003/brass and Al 3003/SS 347, appeared to be problematic. The lack of bonding in these cases is not entirely understood, but may be improved through more effective deposition techniques. Further, more detailed microstructural and microchemical characterization of the interfaces is necessary for comprehensively assessing the bond quality in most cases.

Another important aspect for future work is process parameter optimization. In the current work, process parameters were not fine-tuned to maximize bonding between Al 3003 and the second materials. Each material combination requires a unique set of process parameters for achieving optimal bonding because of the varying physical, chemical and mechanical characteristics of the materials and their surface oxides. Determination of such process parameter combinations necessitates rigorous experimentation with parameter variations, which is a time-consuming task. When the right combination of process parameters is chosen for each material combination, it may be possible to achieve better results than the ones presented in this work.

The current work amply demonstrates that multi-material parts, including fiber-reinforced metal matrix composites, can be successfully fabricated using the UC process. It shows that
Fig. B.13: SEM microstructures of Al 3003/SS mesh: (a) SS mesh embedded between Al 3003 layers, (b) Al 3003/SS mesh interface at a higher magnification. The featureless interface between SS 304 wire elements is shown by black arrows, and the interfacial defects between Al 3003/SS mesh are shown by white arrows.
the process can be successfully extended to a wide range of engineering materials. This flex-
ibility in terms of part material in combination with the multi-material capabilities opens
tremendous opportunities for the UC process. While this is so, the current commercially
available UC machines need to be modified to facilitate fully automated fabrication of multi-
material structures. For example, a suitable mechanism for simultaneous automated tape
feeding of multiple materials must be in place. In addition, further developments in the
areas of computer aided design and data representation methods are necessary for efficiently
handling multi-material situations in UC as well as in other additive manufacturing pro-
cesses (Liu et al., 2004).

B.4 Summary

Fabrication of multi-material parts presents a significant challenge. In this context,
the UC process, by virtue of its inherent process characteristics, is quite promising. The
current work examined the capacities of the process for fabrication of multi-material parts.
A number of engineering materials were utilized in combination with Al alloy 3003, used as
the bulk part material. Studies show that Al-Cu alloys, Al matrix composites, and Ni-based
alloys can be ultrasonically welded to Al alloy 3003 and vice versa with excellent interfacial
characteristics. Successful embedment of SiC fibers and a stainless steel wire mesh in Al
alloy 3003 matrix was also demonstrated. AISI 347 stainless steel and brass did not weld
well to Al alloy 3003 using the parameters chosen for this study. However, better results
may be possible with the right process parameters. Overall, the current work shows that
multi-material part fabrication out of materials with widely differing physical, chemical and
mechanical characteristics is more than a mere possibility with UC.

References


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