Interface Microstructures and Bond Formation in Ultrasonic Consolidation

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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 ultrasonic bonding mechanism. There is a lack of information on interface microstructures in ultrasonically consolidated parts as well as a lack of consensus on the mechanism of metal ultrasonic welding, especially on matters such as plastic deformation and recrystallization. In the current work, interface microstructures of an ultrasonically consolidated multi-material Al 3003-Ni 201 sample were analyzed in detail using optical microscopy, scanning electron microscopy, energy dispersive spectroscopy, and orientation imaging microscopy. Based on the results of microstructural studies, the mechanism of metal ultrasonic welding has been discussed. The reasons for formation of defects/unbonded regions in ultrasonically consolidated parts have also been identified and discussed.

Key words: Additive manufacturing, Ultrasonic consolidation, Ultrasonic welding, Interface microstructures, Bonding mechanism.

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1. Introduction

Ultrasonic Consolidation (UC) is a novel additive manufacturing process wherein complex shaped three-dimensional metallic objects are automatically fabricated layer-by-layer without any part-specific tooling [1]. The process builds up the rough part shape by ultrasonically welding or consolidating thin metal foils (typically 150 μm thick). This ultrasonic addition is combined with 3-axis CNC milling to produce geometric details. The Solidica Formation™ UC machine (Fig.1), commercially introduced by Solidica in 2000, is an integrated machine tool which incorporates an ultrasonic welding head, 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 175°C.

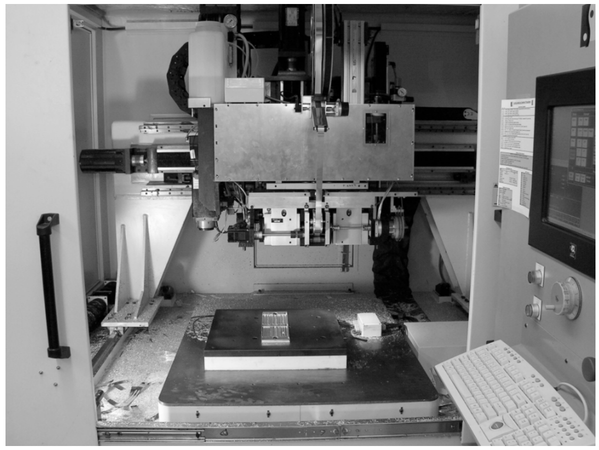


Fig.1. Solidica Formation™ UC machine.

Fig.2 illustrates the basic UC 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 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 mating surfaces [1-4]. These 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 displaced in the vicinity of the interface or along the weld zone. After depositing a strip of foil, another foil is deposited adjacent to it and this placing of foils continues until a layer is formed. 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.

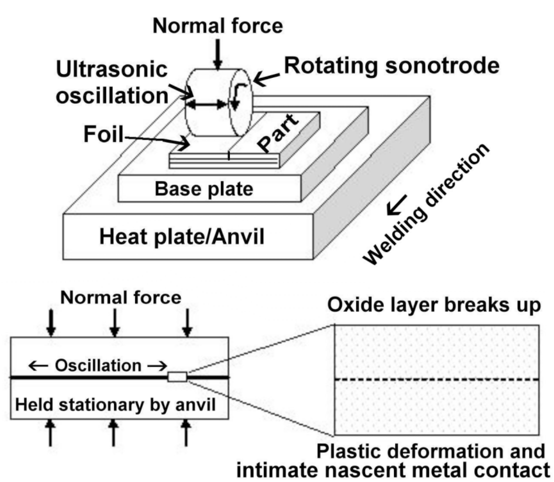


Fig.2. Schematic of the UC process.

Ultrasonically consolidated parts typically show metal-to-metal bonded regions and a few unbonded regions (physical discontinuities/defects) 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 [4,5], which directly influences, in general, the mechanical properties of ultrasonically consolidated parts. It is therefore necessary to minimize unbonded regions and maximize LWD in ultrasonically consolidated parts for use in load-bearing structural applications. This necessitates a detailed and quantitative understanding of interface microstructures and ultrasonic bonding mechanism.

While ultrasonic welding of metals has been in use for quite some time, the mechanism of bonding is still under considerable debate. So far, research results have indicated that ultrasonic welding is a complex process, involving oxide layer removal, interfacial plastic deformation, generation of heat (by friction and plastic deformation), recrystallization, diffusion, work-hardening, fatigue, and cracking, which have been categorized by Kong et al. [6] into: (i) Surface effects (ii) Volume effects, and (iii) Thermal effects. Further, bonding is generally believed to be due to one or more of the following mechanisms: (i) Mechanical interlocking, (ii) Interfacial melting, (iii) Interfacial atomic forces (nascent bonding), and (iv) Interfacial chemical reactions [7]. The intent of this paper is to discuss the mechanism of ultrasonic metal welding in light of the recent results obtained on an ultrasonically consolidated sample.

2. Experimental Work

The materials used in this study are given in Table 1. Deposition experiments were conducted on an Al 3003 base plate (dimensions: 355x355x12 mm) firmly bolted to the heat plate of the Solidica Formation™ 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 by running the ultrasonic sonotrode over it. Subsequently, another layer of Ni 201 was welded to the previously deposited Ni 201 layer. This layer arrangement was chosen to facilitate study of Ni-Al and Ni-Ni interfaces. Since the machine does not facilitate automatic feeding of multiple foil materials simultaneously, Ni layers were manually placed onto the substrate and secured with tape (Al 3003 layers were automatically fed by the machine in the usual manner).The process parameters used for all welding runs were: Oscillation amplitude – 16μm, Welding speed – 28mm/s, Normal force – 1750N, and Substrate temperature – 149°C (300°F). These parameters were found to result in a high level of LWD for Al 3003 in a previous study [8]. However, no attempts were made to optimize the process parameters for welding Ni 201 to Al 3003 and to itself. The welding direction was along the foil rolling direction in all cases.

Table 1. Materials used for UC experiments.

Material	Nominal Composition (Wt.%)	Dimensions
Al alloy 3003 (H18 condition)	Al-1.2Mn-0.12Cu	25 mm wide, 150 μm thick foil
Ni alloy 201 (Annealed condition)	Ni-0.02C-0.35Mn-0.25Si-0.25Fe-0.15Cu	25 mm wide, 75 μm thick foil

After sample fabrication, transverse sections (across the welding 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 $(NH_4)_2S_2O_8$. Interface microstructures were examined using optical and 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.

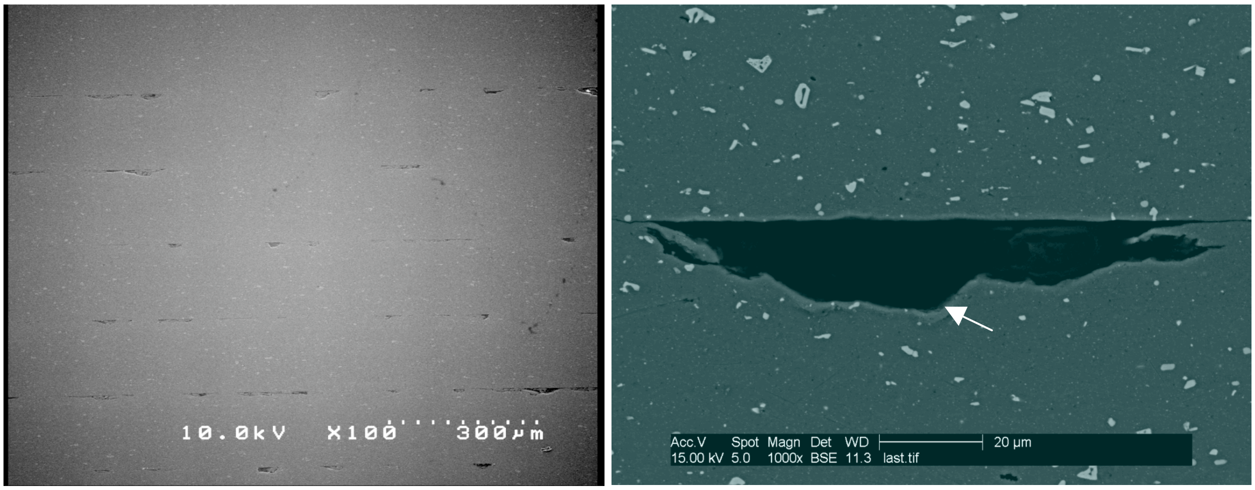
3. Results

Fig.3a shows a typical microstructure of the ultrasonically consolidated Al 3003. The dark regions seen along the layer interfaces are the unbonded regions. Examination of the defects at higher magnifications in back-scattered electron mode revealed a thin differently-contrasted layer all around the defect (Fig.3b). EDS spot analysis showed significantly higher oxygen content in this layer (Fig.4a) than in the regions adjacent to it (Fig.4b).

Fig.5 and Fig.6 show the optical and SEM microstructures of the Al 3003-Ni 201 multi-material deposit, respectively. Generally, Ni 201 seemed to bond very well to itself and to Al 3003 (Fig.5a, Fig.5b, and Fig.6a). However, as can be seen in Fig.5c, Fig.6b, and Fig.6c, there were some unbonded regions along the Ni-Ni interface. There was no evidence of melting or recrystallization at the interfaces. The interfaces appeared flat and mechanical interlocking did not seem to be in place. Further, it was observed that foil top surfaces became very rough with considerably large hills and valleys due to sonotrode motion, as can be seen on the top layer in Fig.5 (the foil stock used in this study has very fine, mirror-like surface finish).

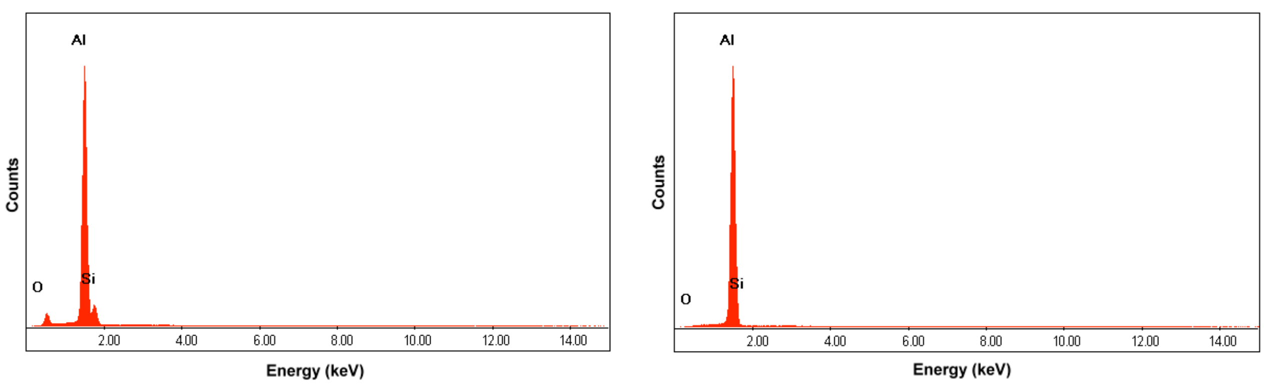
Fig.7a shows a back-scattered electron image of the Ni201-Al3003 interface at a higher magnification, showing no obvious evidence of intermetallic formation. The results of EDS line scans (for two elements, Al and Ni) performed across the Ni-Al interface (along the scan line shown in Fig.7a (100 points, 1 μm spot spacing, from Ni to Al side)) are shown in Fig.7b. As can be seen, compositions seem to change sharply across the interface, with practically no diffusion of Ni into Al and vice versa. The particles with a brighter contrast seen in Fig.7a (on Al side) have been confirmed to be manganese aluminide particles originally present in Al 3003 (Fig.7c).

Fig.8 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. A more precise tool for quantifying the extent of plastic effects is lattice curvature [9]. Fig.9 is a map of the average curvature overlaying the SEM image of the ultrasonically consolidated Ni 201 layers. Fluctuations in the curvature naturally occur in materials, as can be seen from the picture; but it is evident that there is no evidence of additional average curvature near the UC interface, relative to locations away from the interface. Thus, while there is some amount of plastic deformation at the weld interface, the amount of plastic deformation does not seem to be macroscopically significant. 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.10), indicating that the defect boundaries are covered with oxide layer and/or some kind of contamination. Such fine grains were not observed along the well-bonded portions of the Ni-Ni interface, as can be seen in Fig.8.



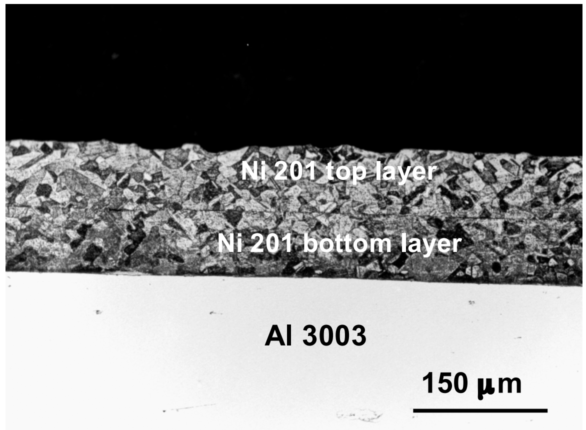
(a) (b)

Fig.3. Defects/unbonded regions in ultrasonically consolidated Al 3003: (a) Low magnification, Secondary electron image; (b) High magnification, Back-scattered electron image (note the thin layer with a different contrast all around the defect (shown by arrow)).

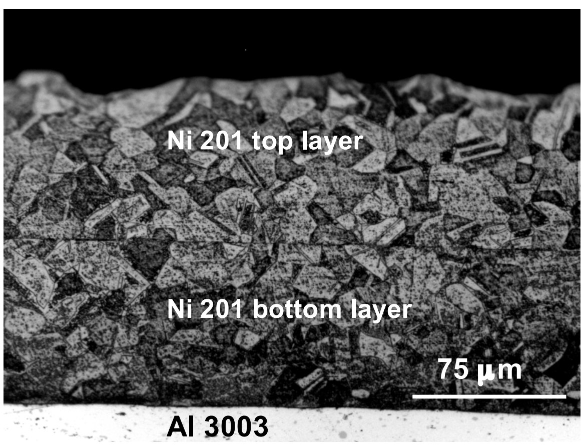


(a) (b)

Fig.4. (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.



(a)



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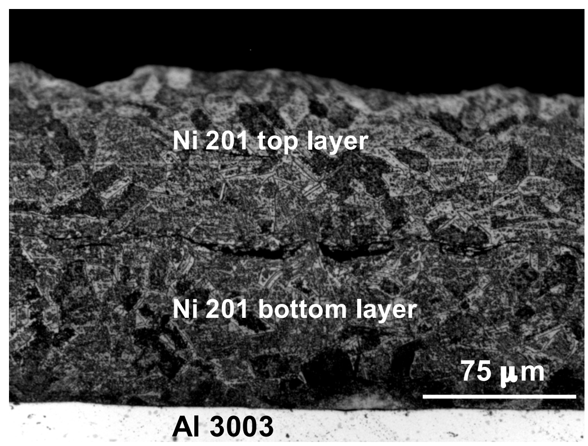
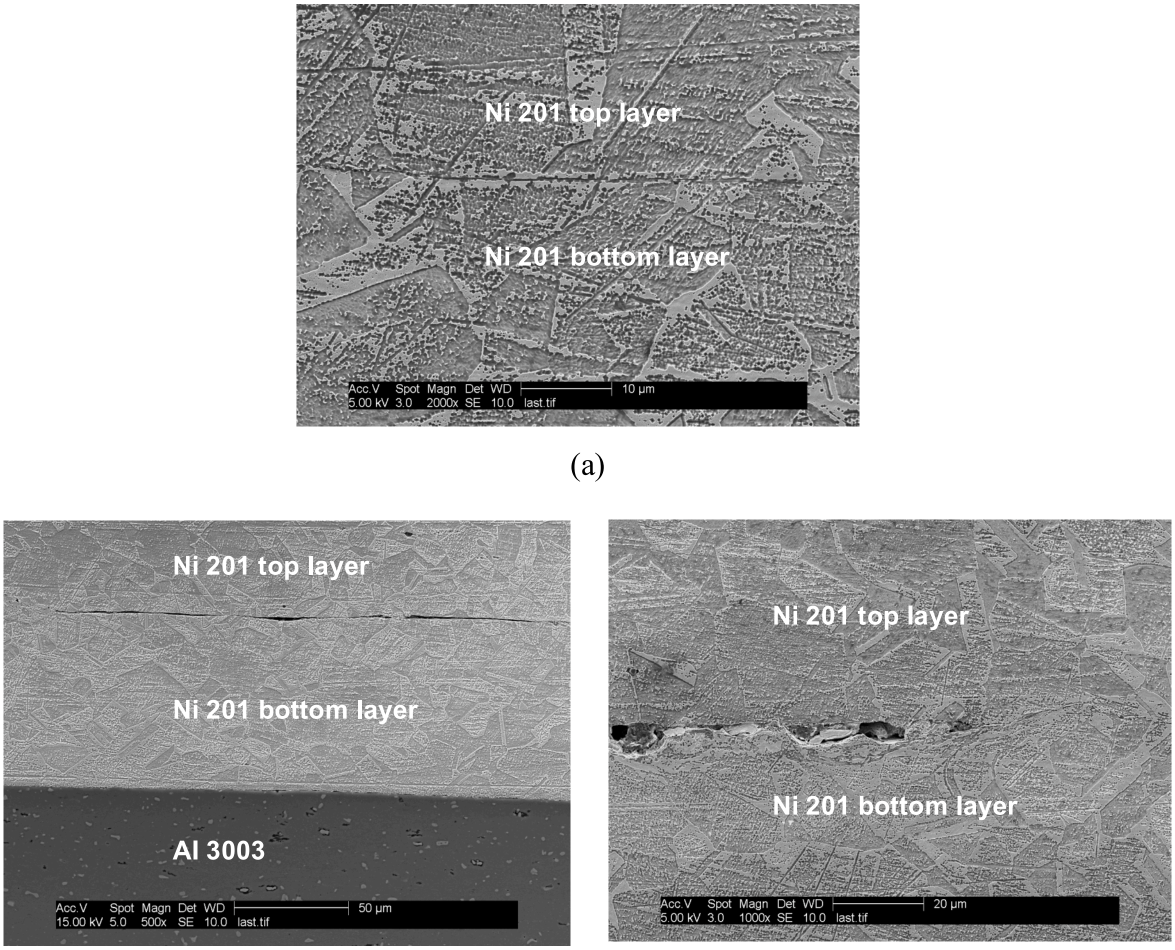


(c)

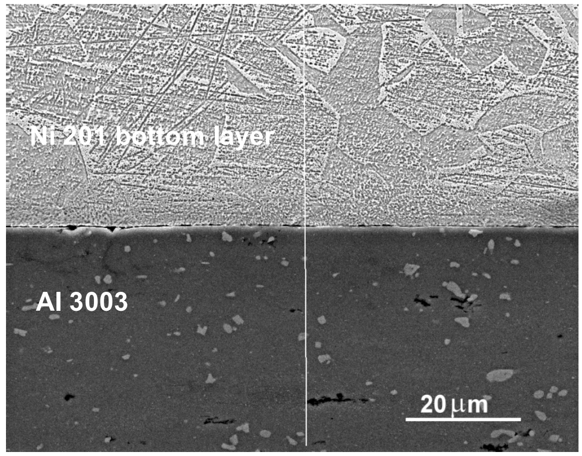
Fig.5. Optical micrographs of the Al 3003-Ni 201 multi-material deposit.
Ni 201 bonded well to itself to the Al 3003 substrate ((a) and (b)). A few Ni-Ni unbonded regions were, however, present (c). Note the roughness on the top layer induced by sonotrode motion.



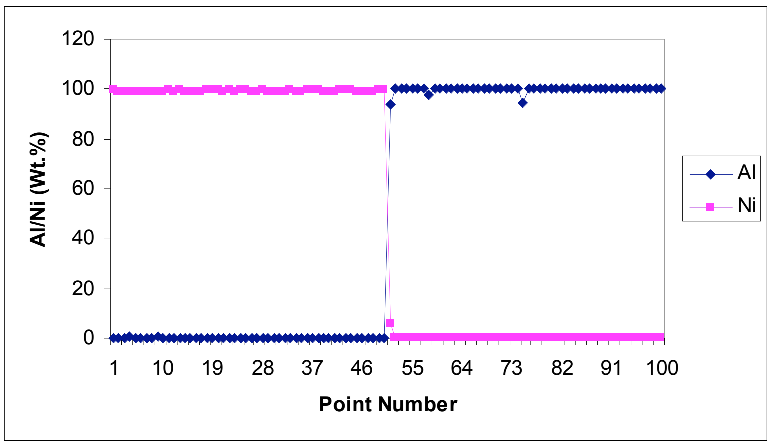
(a)

(b) (c)

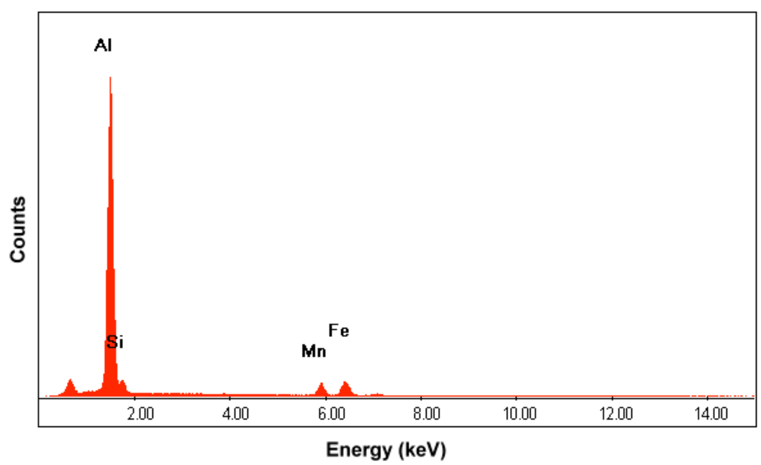
Fig.6. SEM micrographs of the Al 3003-Ni 201 multi-material deposit. (a) shows a well-bonded Ni-Ni region, (b) and (c) show a few Ni-Ni unbonded regions.



(a)



(b)



(c)

Fig.7. (a) Back-scattered electron image of the Ni 201-Al 3003 interface, (b) EDS line scan results across the Ni 201-Al 3003 interface (along scan line shown in Fig.7a, scan started on the Ni side), (c) EDS spectrum obtained on the bright particles present in Al 3003.

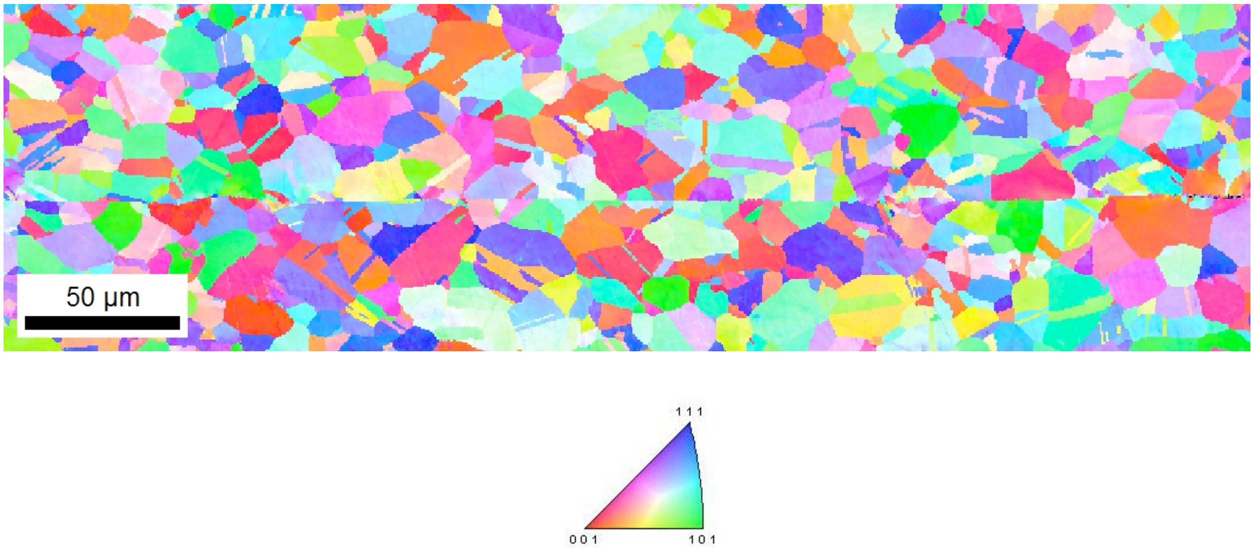


Fig.8. An image of several inverse pole figures of contiguous areas along a well-bonded Ni-Ni interface stitched together. The grains in the image are color coded to reflect their orientation. The line across the center of the image defines the Ni-Ni weld interface.

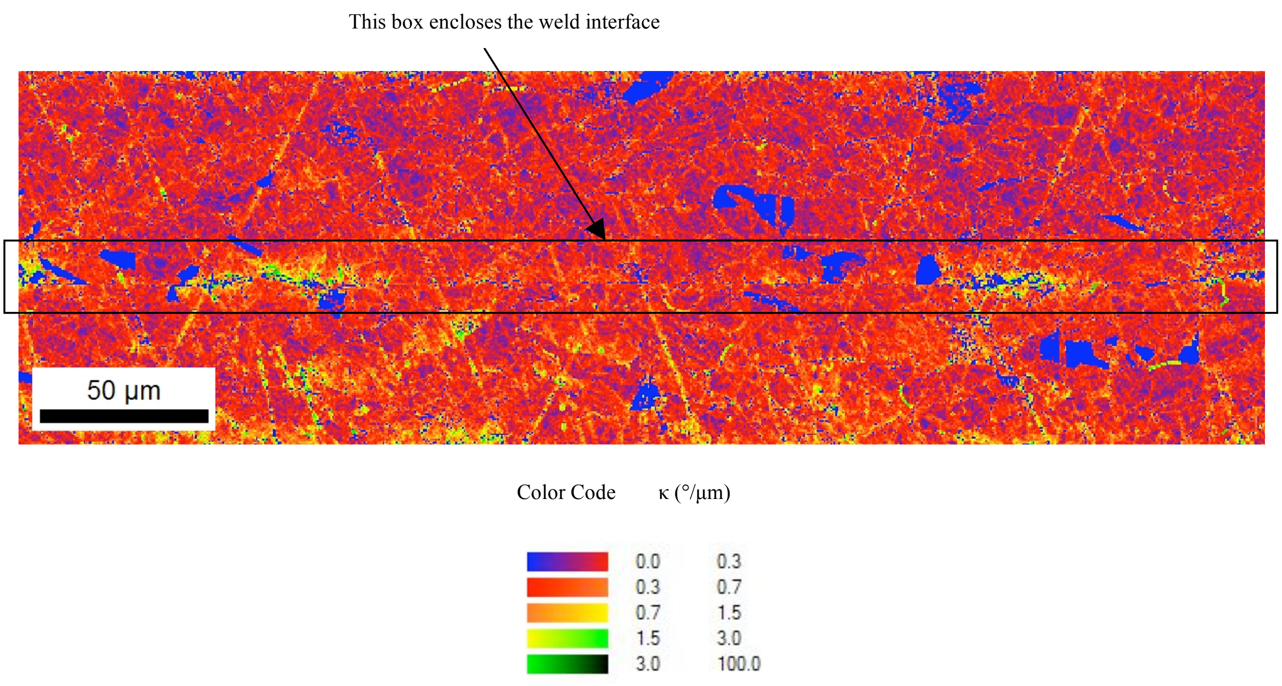


Fig.9. Average curvature map overlaying the SEM image of the ultrasonically consolidated Ni 201 layers.

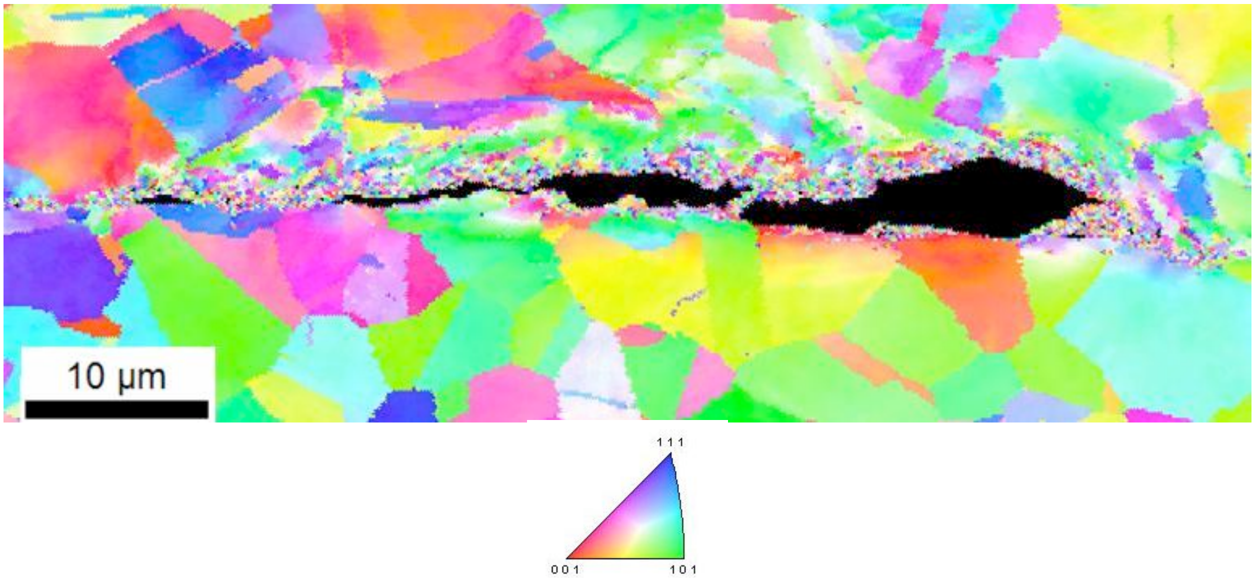


Fig.10. Inverse pole figure of an unconsolidated portion of the Ni-Ni interface. Note the extremely fine grains that are present along the defect boundaries.

4. Discussion
4.1 Oxide Layer Removal

All engineering metals contain surface oxide layers. Removal of these surface oxide layers is considered to be a necessary conditions for bond formation during ultrasonic welding. Removal of surface oxide layers is important because it facilitates intimate nascent metal contact, which is a further necessary condition for metallurgical bonding. During the process of ultrasonic welding, frictional effects at the mating base metal surfaces are generally believed result in break-up of the surface oxide layers [2,10,11]. 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 alloys, with a very high oxide-to-metal hardness ratio, are one of the well-suited materials for ultrasonic welding. Noble metals such as gold which do not have a surface oxide layers have been reported to be quite amenable for ultrasonic welding as well [12]. Materials that present difficulties with oxide layer removal have been reported to be problematic for ultrasonically welding. For example, Al-Mg-Si 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 [5]. Similarly, recent attempts to ultrasonically consolidate commercially pure Ti by the authors were unsuccessful due to difficulties with oxide layer removal [13]. Interestingly, such difficult-to-weld materials have been shown to be ultrasonically weldable when employing techniques like acid stripping for removing surface oxide layers just prior to welding [5,13]. Therefore, there is ample evidence that oxide layer removal is a crucial event in metal ultrasonic welding. Further, ultrasonic weldability of metals appears to be essentially governed by the ease with which the oxide layers can be removed.

Microstructural studies confirm the presence of oxide layers along the defect boundaries (Fig.3b and Fig.10). Oxide layers were, however, absent in the fully bonded or consolidated regions (Fig.8). This confirms that ultrasonic action (and consequent frictional effects) at the weld interface helps remove the surface oxide layers. However, this occurs only wherever there is surface contact. If the mating surfaces are not in contact, there cannot be any friction to break-up 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 defects/unbonded regions along the foil interfaces in the final deposit. It should be noted that unbonded regions/defects along the foil interfaces can also be caused by cracking-related effects subsequent to bonding, especially under conditions of excessive energy input [2,14,15]. However, such defects do not show oxide layers as they get removed in the process of bonding prior to cracking. Therefore, it can be inferred that the defects/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.

Based on the above, it appears that 100% surface contact is a necessary condition for achieving 100% LWD. However, all real surfaces exhibit at least some level of microscopic roughness, precluding 100% surface contact. Further, as seen in Fig.5, sonotrode motion on a just deposited foil surface makes it very rough. This sonotrode-induced surface roughness significantly increases the number and size of non-contact regions during subsequent layer deposition. Therefore, the authors believe that sonotrode-induced surface roughness is a major source of defects in ultrasonically consolidated parts. Further, from this standpoint, it does not seem possible to achieve 100% LWD in ultrasonic welds. However, experience shows that near 100% LWD levels can be achieved with proper process parameter optimization in ultrasonically consolidated parts [8]. Therefore, it is surmised that 100% surface contact is something that occurs progressively during the bonding process. How this occurs is discussed in the next section.

4.2 Plastic Deformation

OIM studies indicate that some amount of plastic deformation occurs at the weld interface, which is, however, not macroscopically significant. Nevertheless, the authors believe that plastic deformation, however small it may be, is the key for ultrasonic metal welding, as discussed below.

The first question that rises is "Are there conditions severe enough to cause plastic deformation?" To answer this question we need to consider the effect of ultrasonic excitation on deformation behaviour 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 "Blaha effect" or "acoustic softening." Following early work by Blaha and Langenecker [16,17], acoustic softening has been noticed by several other researchers in their experiments involving tube and wire drawing [18,19]. Although similar, it appears that ultrasonic energy is more effective than thermal energy in reducing the flow stress of a metallic material. For example, Eaves et al. [20] 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 [17]. Langenecker [17] explained this difference as "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 (more on this will be covered in the next section). Thus, although the forces involved in a typical ultrasonic welding operation are generally modest, there seem to be conditions enough for causing plastic deformation and metal flow, when considering the combined acoustic and thermal softening effects.

The role of plastic deformation in bond formation is often underestimated. As noted earlier, removal of surface oxide layers and generation of atomically clean surfaces is essential for ultrasonic welding. We believe that plastic deformation plays an important role in this process. During ultrasonic welding, cracks are generated in the surface oxide layers (oxides are usually brittle) due to the action of dynamic interfacial stresses generated by the ultrasonic vibrations and applied normal force. These stresses also induce plastic deformation in a thin layer of metal (~ 20 μm) just beneath the oxide layer [1,4], which can also generate cracks in the oxide layer. As a result of plastic deformation nascent metal from beneath extrudes through the cracks. This process results in the break-up of surface 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 [21] identified such broken oxide fragments (0.05 to 0.2 μm size) 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 very thin. Thus, plastic deformation at the interface plays a critical role in displacing surface oxides and generating atomically clean surfaces at the interface. In fact, it is because of the role played by plastic deformation that the ease with which oxide layers can be removed is dependent on the ratio of oxide layer hardness to nascent metal hardness.

The effects of plastic deformation go beyond this and are even more crucial in producing a weld with satisfactory LWD. As noted in the previous section, roughness on the foil surfaces precludes 100% surface contact. The situation at the mating surfaces at the beginning of ultrasonic welding can be visualized as shown in Fig.11. 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 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, 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. Further, plastic deformation at the bonded regions is also important for 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 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 three ways: i) it helps break up surface oxides and remove the broken oxide scales away from the bonding region, ii) it helps the bonded regions grow in size, and brings mating surfaces into intimate contact, and iii) it generates new contact points across which bonding can occur.

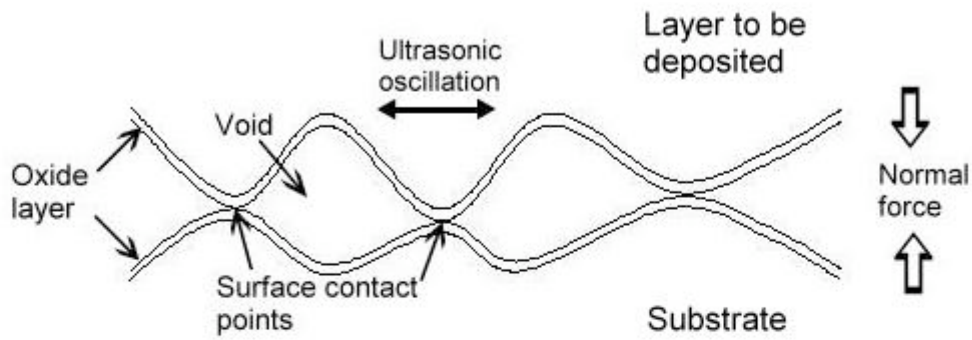


Fig.11. Schematic of the mating surfaces at the beginning of ultrasonic welding.

4.3 Melting and Recrystallization

Melting and recrystallization phenomena are related to the temperature rise at the weld interface. During ultrasonic welding, heat is generated primarily due to friction. Some amount of heat can also be generated by acoustic heating and plastic deformation [17]. Several methods have been applied to measure the actual temperature at the weld interface during ultrasonic welding [2,7,10,22,23]. While there is large variation in reported interface temperatures in metal ultrasonic welding, they are, in most cases, less than the melting point of the base materials, with peak temperatures generally in the range of 40-50% of the melting point of the base materials. For example, using an infrared camera with an accuracy of ±10°C for temperature measurement, de Vries [10] recently reported a temperature of 314°C during ultrasonic welding of Al 6061. Microscopic analyses were also conducted to investigate interfacial melting. In most microscopy examinations, no fusion welded microstructures were observed [2, 22,23]. However, Weare [23] observed molten Cu during ultrasonic welding of Cu-Monel at high oscillation amplitudes. Kreye [24] found some evidence of metal melting during ultrasonic welding of Cu_2Co. More recently, Gunduz et al. [25] reported localized melting of Al-Zn solid solution formed at the weld interface due to Zn diffusion into Al. Thus, while most reports confirm that ultrasonic welding is a solid-state welding 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. We believe that occurrence of localized melting during ultrasonic welding is specific to certain material combinations that involve formation of low melting eutectics or solid solutions, especially when subjected to relatively severe processing conditions.

Plastic deformation and temperature rise at the interface can provide the necessary driving force for recrystallization during ultrasonic welding (whether there is adequate time for recrystallization or not is still unknown). Recrystallization is desirable as it brings in necessary readjustments to the grain structure at the interface and replaces the strained grain structure on both sides of the interface with a set of freshly formed strain-free, fine grains. It facilitates grain continuity across the interface and a smooth transition of weld zone microstructure from the rest of the material. However, no conclusive evidence exists on whether recrystallization takes place during ultrasonic welding. Both unrecrystallized and partially or fully recrystallized grain structures have been reported in the literature, although satisfactory bonding was demonstrated in all cases [26-28]. In the current work, no recrystallization was observed at the foil interfaces. It appears that specific processing conditions and the material systems in questions govern the recrystallization process.

4.4 Diffusion and Interfacial Chemical Reactions

Once atomically clean surfaces are generated and are brought into intimate contact, interatomic forces can set in across the interface, establishing solid-state bonds. Although diffusion is not a prerequisite for establishing these atomic level bonds (otherwise cold welding would not be possible), diffusion of metal atoms across the interface helps the overall process. Diffusion allows for mass transfer across the interface and, as a result, bonded regions can grow in size. As noted earlier, this can also help close the voids/non-contact regions present at the interface. Although temperature rise at the interface can facilitate diffusion, the times available for diffusion are extremely short (owing to the short residence of the sonotrode over any particular area). Thus, from this standpoint, significant diffusion appears unlikely. However, there are indications that diffusivities can increase significantly under the conditions of ultrasonic welding. Ultrasonic welding can produce plastic deformation at very high strain rates, as reported by Langenecker [17] and, more recently, by Gunduz et al. [25]. Consequently, dislocation densities and vacancy concentrations in the bond region can be significantly higher, which enhance diffusion. For example, Gunduz et al. [25], in their studies on ultrasonically welded Al-Zn, found that a strain rate up to $10^3 s^{-1}$ can be produced during ultrasonic welding, which increased the vacancy concentration to around 10^{-1}. As a consequence, they observed significant Zn diffusion into Al, nearly five orders of magnitude higher than the calculated diffusivity of Zn under normal conditions at the measured interface temperature. Therefore, it appears that ultrasonic welding can provide conditions for significant diffusion. However, in the current study EDS line scan results indicated practically no diffusion of Ni into Al and vice versa. Therefore, it appears that the mechanism of bond formation during ultrasonic welding does not depend heavily on diffusion. However, diffusion can occur during ultrasonic welding and if it occurs, it helps the overall bonding process.

It should be noted that diffusion is not a beneficial phenomenon in all cases, especially while dealing with metallurgically incompatible dissimilar material combinations. Diffusion often leads to chemical reactions, which can be detrimental to the bonding process/part mechanical properties. For example, formation of brittle intermetallics or low melting eutectics/solid solutions is not generally desirable. However, interfacial chemical reactions can be beneficial in some cases with a positive influence on the bond strength. In the present case, ultrasonic welding did not result in formation of nickel aluminide intermetallics at the Ni-Al interface. Overall, it appears that interfacial chemical reactions are not essential for bond formation during ultrasonic welding.

4.5 Mechanical Interlocking

A few investigators indicated mechanical interlocking as a possible bonding mechanism in ultrasonic welding. For example, ultrasonically welded Al and Au were found to be mechanically interlocked with a kind of liquid-like flow of Au into Al [12]. Interestingly, most of the reports that hinted upon mechanical interlocking dealt with dissimilar material combinations. In the current study, no evidence of mechanical interlocking was observed along the Ni-Al and Ni-Ni interfaces. Therefore, while mechanical interlocking can occur during ultrasonic consolidation, it appears to be specific to certain hard and soft material combinations. We believe that mechanical interlocking might assume greater significance while dealing with metal-polymer or metal-ceramic combinations, such as during the embedding of fibers into a matrix using ultrasonic consolidation.

4.6. Mechanism of Ultrasonic Metal Welding

The current study brings greater clarity into the mechanisms of ultrasonic welding. While interfacial melting, diffusion, interfacial chemical reactions, and mechanical interlocking all can occur during ultrasonic welding, they do not seem to have universal presence; rather, they seem to be specific to certain material combinations or processing conditions. Bonding in ultrasonic welding 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). These stages are discussed below.

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 (see Fig. 11). 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 magnitude of which is a function of the process parameters used and the frictional conditions at the sonotrode/foil and substrate/foil interfaces. 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 (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. 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.

5. Summary

Interface microstructures of an ultrasonically consolidated Al 3003-Ni 201 multi-materials sample were presented. Ni 201 bonded very well to itself and to Al 3003 and it appeared to be a promising material for ultrasonic consolidation. There was no evidence of localized melting or recrystallization at the weld interfaces. Ni and Al did not interdiffuse and there was no obvious evidence of intermetallic formation at the interface. Studies indicate that some amount of plastic deformation occurs at the weld interface, which, however, is not macroscopically significant. While interfacial melting, diffusion, interfacial chemical reactions, and mechanical interlocking all can occur during ultrasonic welding, they do not seem to have universal presence; rather, they seem to be specific to certain material combinations and/or processing conditions. Bonding in ultrasonic welding essentially appears to be solid-state caused by atomic level forces across the nascent metal contact points. Two conditions must be fulfilled for this: (i) generation of atomically clean surfaces, and (ii) intimate contact between clean metal surfaces. Plastic deformation plays a crucial role in metal ultrasonic welding in three ways: (i) it helps break up surface oxides and remove the broken oxide scales away from the bonding region, (ii) it helps the bonded regions grow in size, and brings mating surfaces into intimate contact, and (iii) it generates new contact points across which bonding can occur. 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). Sonotrode-induced surface roughness appears to be a major source of defects in ultrasonically consolidated parts. The current work lends greater insights into the mechanism of metal ultrasonic welding. The role of microscopic plastic deformation at the weld interface has been clearly brought out. Conditions for achieving 100% LWD in UC parts have been clearly identified.

References

1. D.R. White, Ultrasonic consolidation of aluminium tooling." *Advanced Materials and Processes*, Vol.161, 2003, 64-65.
2. H.P.C. Daniels, Ultrasonic welding, *Ultrasonics*, 1965, 190-196.
3. R.L. O'Brien, *Welding Processes*, in: Welding Handbook (Vol.2, 8th ed.), American Welding Society, Miami, 1991.
4. C.Y. Kong, R.C. Soar, and P.M. Dickens, Optimum process parameters for ultrasonic consolidation of 3003 aluminium, *Journal of Materials Processing Technology*, Vol. 146, 2004, 181-187.
5. C.Y. Kong, R.C. Soar, and P.M. Dickens, Characterization of aluminium alloy 6061 for the ultrasonic consolidation process, *Materials Science and Engineering A, Vol.* A363, 2003, 99-106.
6. C.Y. Kong, R.C. Soar, and P.M. Dickens, A model for weld strength in ultrasonically consolidated components, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, Vol.219, 2005, 83-91.
7. T. H. Hazlett and S.M. Ambekar, Additional studies on interface temperatures and bonding mechanisms of ultrasonic welds, *Welding Journal*, Vol. 49, 1970, 196s-200s.
8. G.D. Janaki Ram, Y. Yang, J. George, C. Robinson, and B.E. Stucker, Improving linear weld density in ultrasonically consolidated parts, *17th Solid Freeform Fabrication Symposium*, Aug. 14-16, 2006, University of Texas at Austin, USA.
9. B.L. Adams, C. Landon, C. Nylander, B. Aydelotte, B.E. Stucker and G.D. Janaki Ram, Accessing the Properties Closure by Rotation and Lamination, submitted to *Acta Materialia*, July 2007.
10. E. de Vries, Mechanics and mechanisms of ultrasonic metal welding, Doctoral Dissertation, Ohio State University, 2004.
11. M. Hiraishi, Ultrasonic welding of aluminum-magnesium alloy, *THERMEC 2003: International Conference on Processing & Manufacturing of Advanced Materials*, Vol. 426-432, 2003, 315-320.
12. K.C. Joshi, The formation of ultrasonic bonds between metals, *Welding Journal*, Vol. 50, 1971, 840-848.
13. Unpublished work by authors
14. U.I. Chang and J. Frisch, On optimization of some parameters in ultrasonic metal welding, *Welding Journal*, Vol. 53, 1974, 24s-35s.

15. C.Y. Kong, Investigation of ultrasonic consolidation for embedding active/passive fibers in aluminum matrices, Doctoral Dessertation, Loughborough University, 2005.
16. F. Blaha and B. Langenecker, Plasticity test on metal crystals in an ultrasonic field, *Acta Metallurgica*, Vol. 7, 1959, 93-100.
17. B. Langenecker, Effects of ultrasound on deformation characteristics of metals, *IEEE Transactions on Sonic and Ultrasonic*, Vol. 13, 1966, 1-8.
18. I. Hassen and A. Tholen, Plasticity due to superimposed macrosonic and static strains, *Ultrasonics*, Vol. 16, 1978, 57-64.
19. G.R. Dawson, C.E. Winsper, D.H. Sansome, Application of high- and low-frequency oscillation to the plastic deformation of metals-II, *Metal Forming*, Vol. 37, 1970, 254-261.
20. A.E. Eaves, A.W. Smith, W.J. Waterhouse, D.H. Sansome, Review of the application of ultrasonic vibrations to deforming metals, *Ultrasonics*, Vol. 13, 1975, 162-170.
21. T. Enjio, Effects of ultrasonic vibration on diffusion welding of aluminum, *Transactions of JWRI*, Vol. 15, 1986, 289-296.
22. J. B. Jones and J. J. Powers, Ultrasonic welding, *Welding Journal*, Vol. 35, 1956, 761-766.
23. N.E. Weare, J.N. Antonevich, and R.E. Monroe, Fundamental studies of ultrasonic welding, *Welding Journal,* Vol. 39, 1960, 331s-341s.
24. H. Kreye, Melting phenomena in solid state welding processes, W*elding Journal*, May, Vol. 56, 1977, 154s-158s.
25. I.E. Gunduz, T. Ando, E. Shattuck, P.Y. Wong, and C.C. Doumanidis, Enhanced diffusion and phase transformations during ultrasonic welding of zinc and aluminum, *Scripta Mterialia*, Vol. 52(9), 2005, 939-943.
26. V. Prieb, Structural aspects of metal joining, stretching and stamping using ultrasonics, 1st Memory Alloys GmbH, 2002 (http://www.materialforschungsservice-dr-prieb.de/Publikationen.htm).
27. E. Kenik and R. Jahn, Microstructure of ultrasonic welded aluminum by orientation imaging microscopy, *Microscopy and Microanalysis*, Vol. 9, 2003, 720-721.
28. S.M. Allameh, C. Mercer, D. Popoola, and W.O. Soboyejo, Microstructural characterization of ultrasonically welded aluminum, *Journal of Engineering Materials and Technology*, Vol.127 (1), 2005, 65-74.