Improving Linear Weld Density in Ultrasonically Consolidated Parts

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Reviewed, accepted September 14, 2006

Abstract

Ultrasonic consolidation is a novel additive manufacturing process with immense potential for fabrication of complex shaped three-dimensional metallic objects from metal foils. The proportion of bonded area to unbonded area along the layer interface, termed linear weld density (LWD), is perhaps the most important quality attribute of ultrasonically consolidated parts. Part mechanical properties largely depend on LWD and a high level of LWD must be ensured in parts intended for load-bearing structural applications. It is therefore necessary to understand what factors influence LWD or defect formation and devise methods to enhance bond formation during ultrasonic consolidation. The current work examines these issues and proposes strategies to ensure near 100% LWD in ultrasonically consolidated aluminum alloy 3003 parts. The work elucidates the effects of various process parameters on LWD and a qualitative understanding of the effects of process parameters on bond formation during ultrasonic consolidation is presented. The beneficial effects of using elevated substrate temperatures and its implications on overall manufacturing flexibility are discussed. A preliminary understanding of defect morphologies and defect formation is presented, based on which a method (involving surface machining) for minimizing defect incidence during ultrasonic consolidation is proposed and demonstrated. Finally, trade-offs between part quality and build time are discussed.

1. Introduction

Ultrasonic Consolidation (UC) is a novel additive manufacturing process developed by Solidica Inc., USA, utilizing the principles of ultrasonic welding [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 Form-ation 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 the 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 350°F.

Fig.2 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 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 [1-3]. 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 displaced in the vicinity of the interface or along the weld zone. Local temperatures at the interface and the surrounding affected region (about 20 μm) can reach up to 50% of the melting point of the material being deposited [3]. 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.

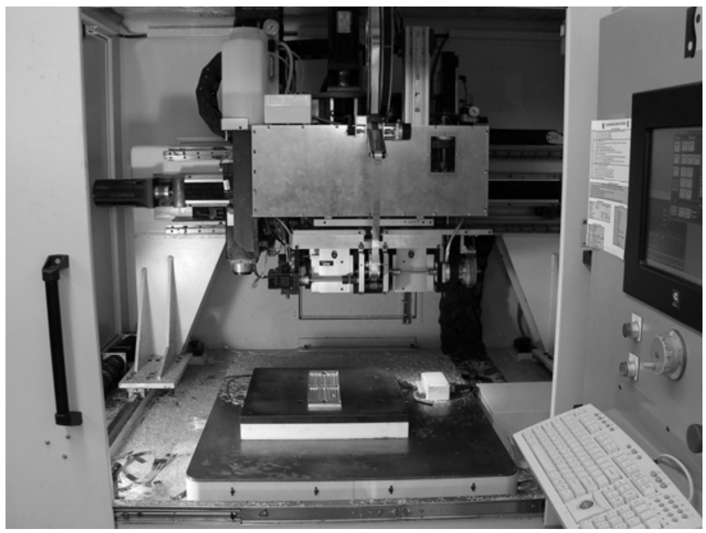


Fig.1. Solidica Form-ation ultrasonic consolidation machine.

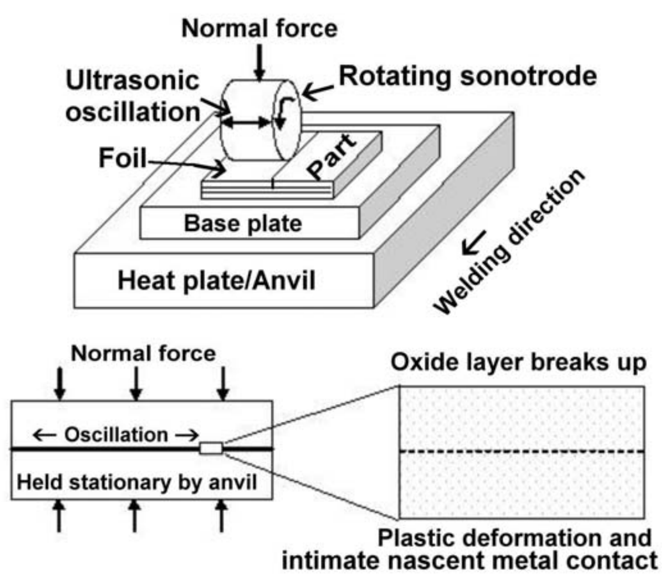


Fig.2. Schematic of the ultrasonic consolidation process.

Ultrasonically consolidated parts typically show metal-to-metal bonded regions and a few defects (oxide accumulated regions and/or physical discontinuities) along the layer interfaces, as noted by Kong et al. in their studies on UC of Al alloys [4,5]. 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], and is the most important quality attribute of ultrasonically consolidated parts. Mechanical properties of ultrasonically consolidated parts largely depend on %LWD between metal foils. 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. In this context, selection of appropriate process parameters plays a key role. In their studies on UC of alloy 3003, Kong et al. [4] 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 tests. The highest LWD reported in this study was 87%. The authors, however, did not include substrate temperature as a variable and their experiments were conducted at room temperature.

The mechanism of bond formation during ultrasonic welding of metals has long been investigated, although considerable debate still exists in this matter [2,3]. According to the current understanding, bond formation during ultrasonic welding of metals involves three mechanisms: i) removal of surface oxide layers, ii) plastic deformation at the interface, and iii) diffusion of metal atoms across the interface. Plastic deformation aids in bond formation in three ways i) it helps break the surface oxide layers causing metal flow through the cracks generated in the oxide layer by the action of ultrasonic energy and, perhaps more importantly, remove the broken oxide scales away from the bonding region, ii) it helps increase interfacial contact area by causing metal flow into the gaps existing at the interface due to surface roughness, iii) it helps bring nascent metal surfaces in intimate contact across which bonding sets in (diffusion of metal atoms across the interface helps, but bonding can occur without it). Therefore, plastic deformation at the interface, in a way, can be considered the enabling mechanism for the other two mechanisms. Having noted the importance of plastic deformation, use of elevated substrate temperatures is potentially beneficial in promoting bond formation However, practically no published information is available on the effect of substrate temperature during UC.

Another important aspect is the origin of defects that show up at the layer interfaces, on which very little is known. It is important to gain greater insights into this aspect and precisely identify the origin of defects, based on which one can devise suitable techniques to minimize the incidence of defects. This paper describes our ongoing 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 process improvements. 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.

2. Experimental Work

2.1 Materials

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, obtained from Solidica, Inc., USA. Deposition experiments were conducted on an Al 3003 base plate (dimensions: 355x355x12 mm) firmly bolted to the heated platen in the machine.

2.2 Parameter optimization experiments

A design of experiments (DOE) approach was adopted to systematically evaluate the 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 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, and machine setting limits. A Taguchi L16 orthogonal array was utilized in the present study to determine the effects of individual process parameters. Interacting influences between two or more process parameters were not assessed. Table 2 lists all the parameter combinations used for deposition experiments. The experimental runs were randomized and each of the 16 runs was repeated twice. Each run consisted of depositing four layers of foil one over another (Fig.3). The welding direction was reversed for each layer. The ultrasonic oscillation frequency was maintained constant at 20 kHz for all the experimental runs.

The response parameter employed in the present study was %LWD. Analysis of Variance (ANOVA) was performed taking LWD as the response parameter, following standard statistical procedures [6]. Following the initial round of experiments, 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. These experiments were considered necessary to unambiguously assess the effect of welding speed on LWD.

Table 1. Parameters and levels selected for UC experiments.

Parameter	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Oscillation amplitude (μm)	10	13	16	19
Welding speed (mm/s)	28	32	36	40
Normal Force (N)	1450	1600	1750	1900
Temperature (°F)	75	150	225	300

2.3 Metallography

All the deposits were metallographically examined to estimate %LWD. Samples corresponding to longitudinal and transverse sections were extracted from each of the deposits and were prepared for microstructural study following standard metallographic practices. Studies on both deposit center and end portions were considered necessary to assess any local variations in bond formation. 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 (at least 12 picture frames) and were used to measure the average LWD in each deposit. The interface between the base plate and the first layer was not considered in LWD measurement for reasons described in the next section. The LWD on a picture frame was measured using the following formula:

$$\%LWD = \left[\frac{\text{Bonded interface length}}{\text{Total interface length}}\right] \times 100$$

Table 2. Taguchi L16 experimental matrix and the results of linear weld density measurements.

Run #	Amplitude (μm)	Speed (mm/s)	Force (N)	Temperature (°F)	LWD (%)		
					Deposit 1	Deposit 2	Average
1	10	28	1450	75	17	19	18
2	16	40	1600	75	50	60	55
3	19	32	1750	75	69	65	67
4	13	36	1900	75	24	26	25
5	13	40	1750	150	31	33	32
6	19	28	1900	150	78	74	76
7	10	32	1600	150	22	26	24
8	16	36	1450	150	58	52	55
9	13	28	1600	225	62	58	60
10	10	36	1750	225	46	54	50
11	19	40	1450	225	35	37	36
12	16	32	1900	225	55	59	57
13	19	36	1600	300	72	68	70
14	16	28	1750	300	92	88	90
15	13	32	1450	300	58	62	60
16	10	40	1900	300	44	40	42

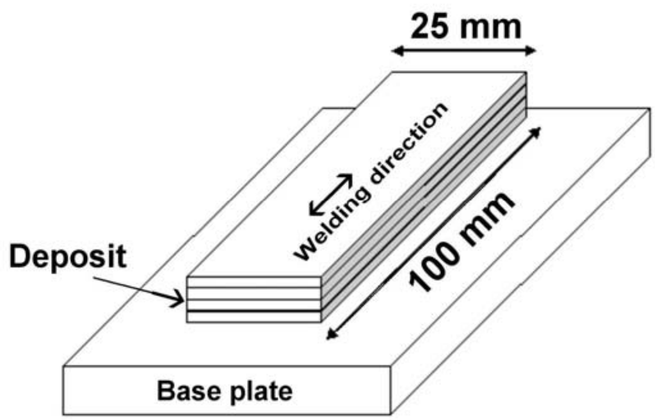


Fig.3. Schematic of the UC deposits.

2.4. Surface machining experiments

Based on metallographic observations, sonotrode-induced surface roughness on the deposited foil surface was identified as the major source of defects in ultrasonically consolidated parts. This led us 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 just deposited layer/foil surface. Experiments were conducted to demonstrate this idea at various welding speeds (at both ambient and elevated substrate temperatures) by removing about 30 microns thick of material (based on observations of the scale of sonotrode-induced surface roughness, which is about 10-15 microns) on the foil surface after depositing each layer using the CNC mill that is part of the Solidica Form-ation machine. Table 3 lists all the parameter combinations used for deposition experiments with surface machining (no replication). The surface machining step was incorporated into the machine code so that the process proceeds from one step to the next automatically. No modifications to the regular part building sequence utilized by the UC process were made except the introduction of an intermediate surface machining step.

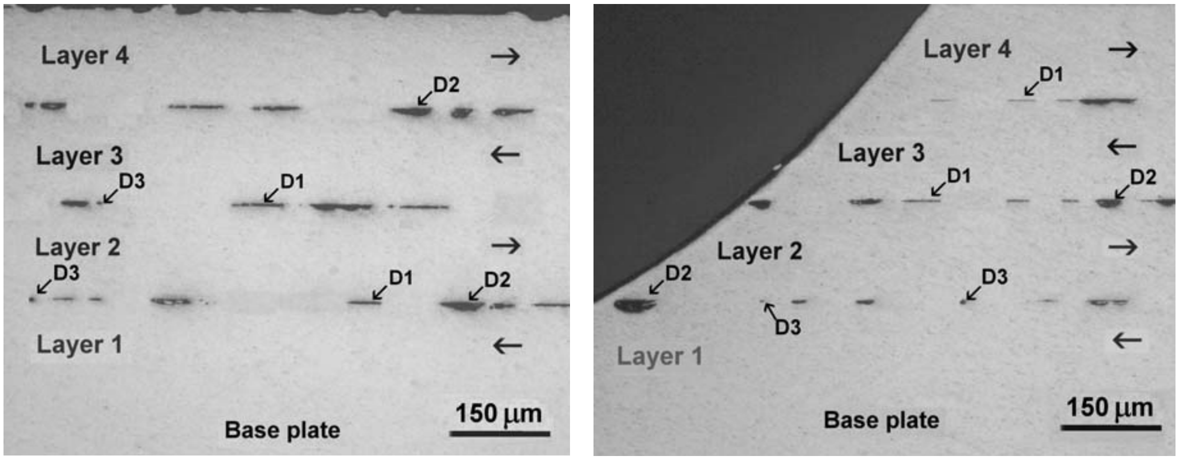
Table 3. Welding speeds and substrate temperatures used in deposition experiments with surface machining and corresponding LWD results. Other parameters were kept constant at their optimum levels (oscillation amplitude: 16 μm, Normal force: 1750 N).

Welding speed (mm/s)	**Substrate Temperature (°F)**	**LWD (%)**
28	75	100
	300	100
32	75	100
	300	100
36	75	90
	300	100
40	75	80
	300	90

3. Results and Discussion
3.1 Effect of process parameters
3.1.1 Linear weld density

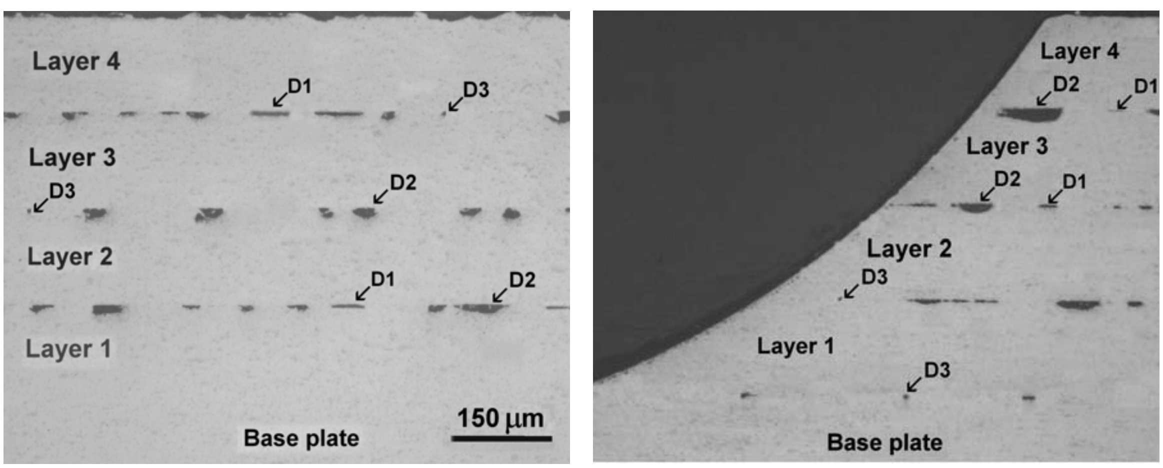
No significant differences in LWD were noticed between center and end (start/stop) portions of a deposit, as can be seen, for example, in the microstructures (longitudinal section) of Run # 6 shown in Fig.4. The dark regions seen along the layer interfaces are the unbonded regions. No specific relationship 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 Fig.5. However, considerable differences in LWD across the deposit width were noticed in higher aspect ratio deposits made in a subsequent study [7].

Three distinct types of defect morphologies were observed, as can be seen in Fig.4 and Fig.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. These observations, however, were not statistically verified during this study, and further studies are planned to further understand defect morphologies and correlate their occurrence to bond formation mechanisms and process parameter effects.



(a) (b)

Fig.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.



(a) (b)

Fig.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.

During ultrasonic welding, the mating surfaces come in contact with each other at surface asperities under the influence of an applied normal force. As noted earlier, the combination of normal and oscillating shear forces results in generation of dynamic interfacial stresses between the two mating surfaces. The stresses produce elastic-plastic deformation of surface contact points, which breaks up the oxide film, producing relatively clean metal surfaces under intimate contact, establishing a metallurgical bond. However, this process leaves some unbonded regions along the interface. Probable causes for these unbonded areas include: (i) lack of complete contact between mating surfaces due to surface roughness and/or entrapped air, (ii) persistence of surface oxide layers preventing intimate nascent metal contact, and (iii) accumulation of removed surface oxides at localized regions along the interface. For these reasons, 100% bonding is difficult to achieve in ultrasonic welding. 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 Fig. 4a and Fig.5a (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 tops and curved bottoms, whose size closely matches with 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.

The results of linear weld density measurements are presented in Table 2. 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 Fig.6. The first layer was found to be bonded to the base plate at a considerably higher LWD than the second, third and forth 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 analysis are summarized in Table 4. All the four parameters contributed to statistically significant variations in LWD at a 90% confidence 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.

Table 4. Results of ANOVA analysis.

Source	**Sums of squares (SS)**	**Degrees of freedom (ν)**	**Variance (V)**	**F**
Amplitude	5232	3	1744	11.40
Speed	1577	3	526	3.43
Force	1247	3	416	2.71
Temperature	1527	3	509	3.32
Error	2907	19	153	
Total	12490	31		
$F_{(table, 3,19)}$ at 90% confidence = 2.40				

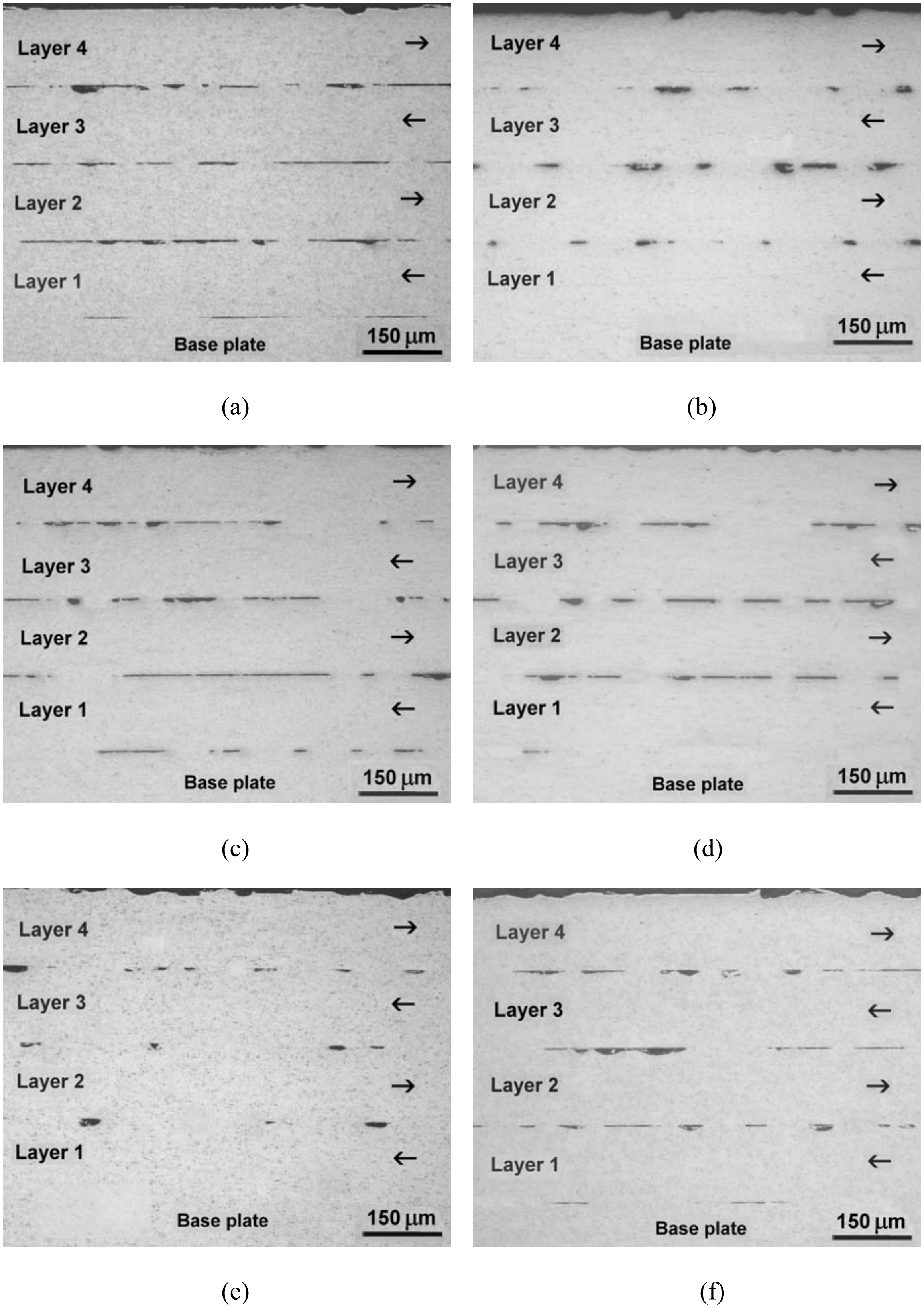


Fig.6. Microstructures of UC deposits (longitudinal section): (a) Run # 1, (b) Run # 3, (c) Run # 5, (d) Run # 9, (e) Run # 14, (f) Run # 16. Arrows indicate welding direction for each layer.

The effects of individual process parameters on LWD are graphically shown in Fig.7. It should be noted that the LWD for each level of a particular parameter in Fig.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 Fig.7 represents at least 96 observations of LWD microstructures.

3.1.2 Effect of process parameters

The effects of individual process parameters are discussed in detail elsewhere [8]. A summary of observations is presented here.

Effect of oscillation amplitude: The LWD increased with increase in oscillation amplitude from 10 to 16 μm (Fig.7a). 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. This would enhance the elastic-plastic deformation at the surface contact points and facilitate easier removal of surface oxide layers and plastic flow. It is likely for these reasons the deposits showed an increase in LWD 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 (Fig.7a). The reasons for this are unclear, but 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, which can affect the sonotrode operational performance.

Effect of welding speed: The LWD increased with decrease in welding speed from 40 to 28 mm/s (Fig.7b). Welding speed determines amount of energy input/unit length or, in other words, the time over which energy is applied at any particular point during ultrasonic welding [2]. 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. This explains why the deposits showed decrease in LWD with 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. It is thus 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 speed levels below 28 mm/s, keeping all other parameters constant at their optimum levels. Observations from these follow-up experiments are discussed in Section 3.1.3.

Effect of normal force: The LWD increased with increase in normal force from 1450 to 1750 N (Fig.7c). 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 increase in normal force from 1450 to 1750 N. Further increase in normal force to 1900 N, however, resulted in considerable drop in LWD (Fig.7c). While the exact reason for this behaviour is not clear at present, there are several potential explanations. 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 and LWD.

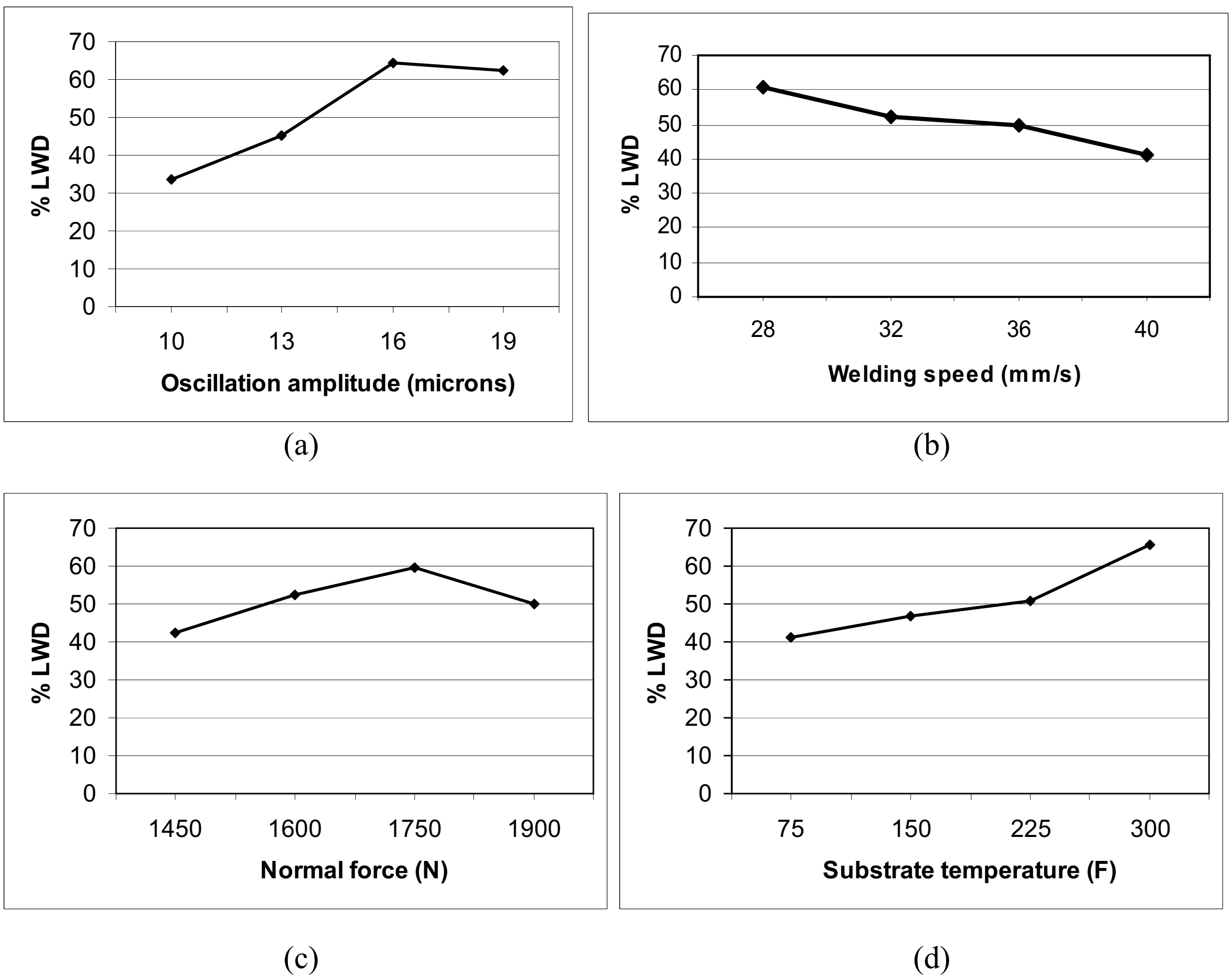
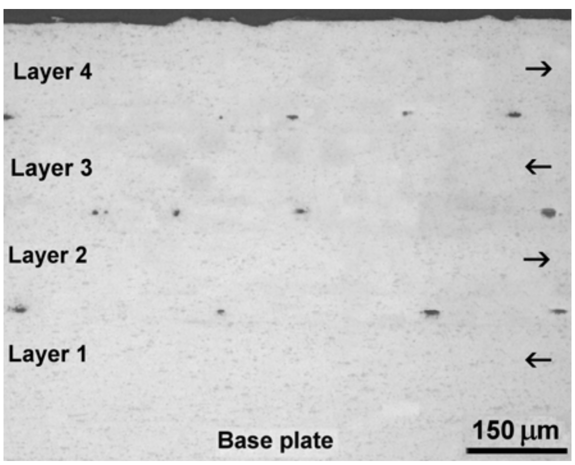


Fig.7. Effect of process parameters on linear weld density: (a) Oscillation amplitude vs. LWD, (b) Welding speed vs. LWD, (c) Normal force vs. LWD, (d) Substrate temperature vs. LWD.

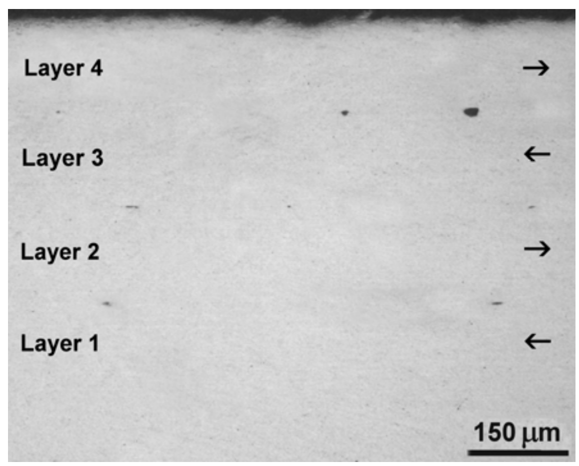
Effect of substrate temperature: LWD increased with increase in substrate temperature from 75 to 300°F (Fig.7d). During ultrasonic welding, the in-situ raise in interface temperature as a result of friction plays a key role in bond formation by (i) reducing the flow stress of the material, (ii) enhancing atomic diffusion, and (iii) increasing the driving force for recrystallization [3]. 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.

3.1.3 Further experiments at lower welding speeds

Following the initial round of experiments, additional experiments were conducted at four different speeds below 28 mm/s keeping all other parameters constant at their optimum levels. Table 5 shows the parameters used in these experiments along with the results of linear weld density measurements. Representative microstructures of the deposits made at 24 mm/s and 12 mm/s are shown in Fig.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 the 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 is 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.



(a)



(b)

Fig.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 µm, Normal force: 1750 N, and Temperature: 300°F). Arrows indicate welding direction for each layer.

3.1.4 Optimum process parameters

Based on the observations made in the present study, the following was identified as the optimum parameter combination for alloy 3003: oscillation frequency – 16 µm, welding speed – 16 mm/s, normal force – 1750 N, substrate temperature – 300°F. A welding speed of 16 mm/s was chosen as a likely 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.

Table 5. Welding speeds used in follow-up experiments and corresponding LWD results. Other parameters were kept constant at their optimum levels (oscillation amplitude: 16 μm, Normal force: 1750 N, and Temperature: 300°F).

Welding speed (mm/s)	LWD(%)
24	94
20	96
16	98
12	98

The experiments conducted in the present study do not facilitate statistical assessment of the optimum process parameters at room temperature. 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 weld density levels in the deposits than those observed in this study at room temperature, although not likely as high as those achievable at 300°F.

Another aspect that was not addressed in this study is interacting influences between two or more process parameters. 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 slower welding speeds and/or higher normal forces at a given oscillation amplitude may be seen to result in relatively higher weld density levels. Further work is necessary to precisely identify the interactions between various process parameters.

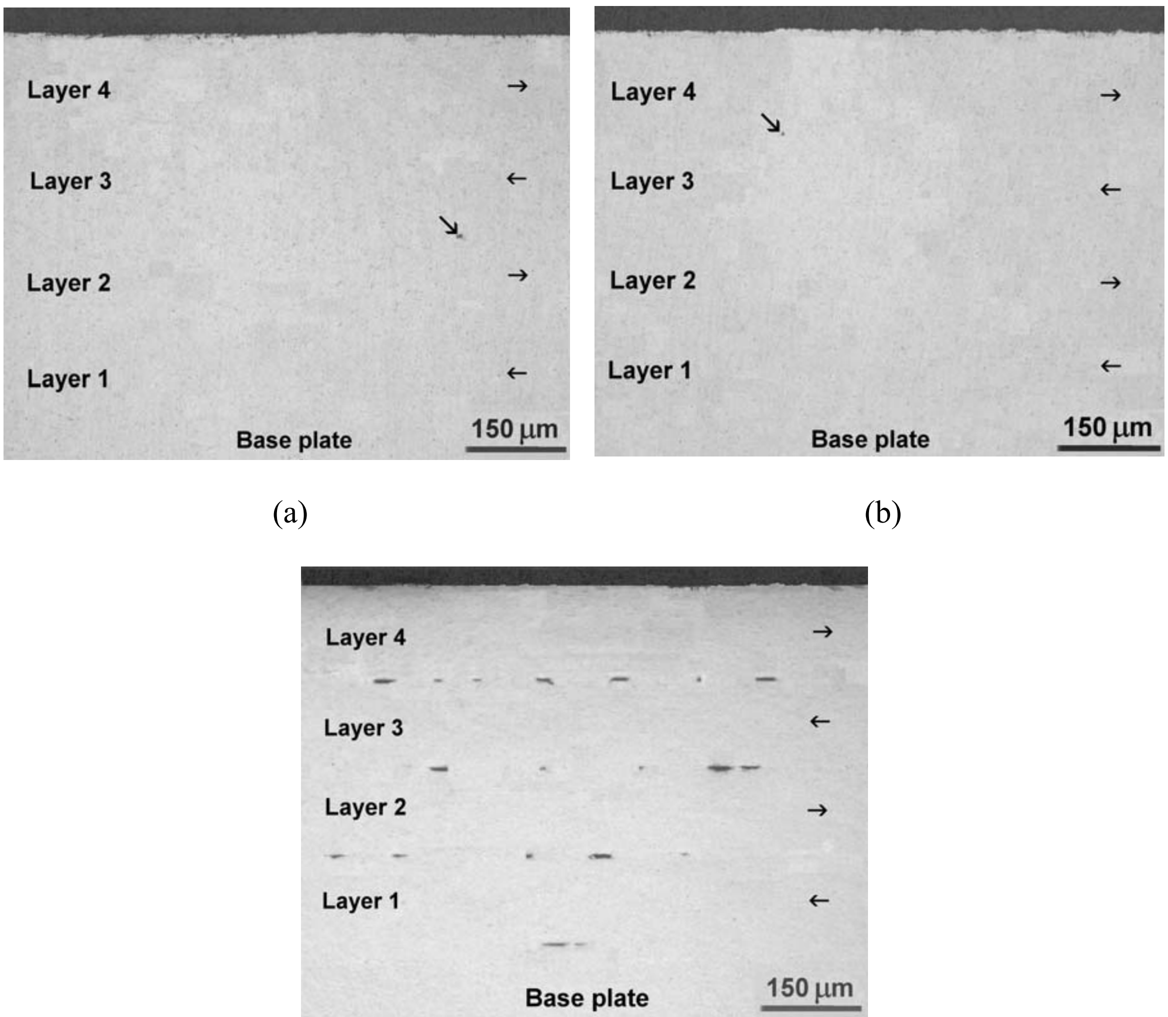
Thus, while a high level of LWD can be achieved by appropriately choosing process parameters, this approach has certain limitations:

- While parameter optimization certainly helps minimize defect formation, defects cannot be eliminated altogether. Thus, use of optimum parameters is not a complete solution.
- Low welding speeds significantly increase build time and overall cost of part fabrication.
- Elevated substrate temperatures put severe limitations on process capabilities. For example, parts with embedded electronics or other temperature-sensitive devices cannot be fabricated employing elevated substrate temperatures. 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 [2,3]. This may necessitate frequent sonotrode cleaning or replacement. More importantly, the 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 [4,5].

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.

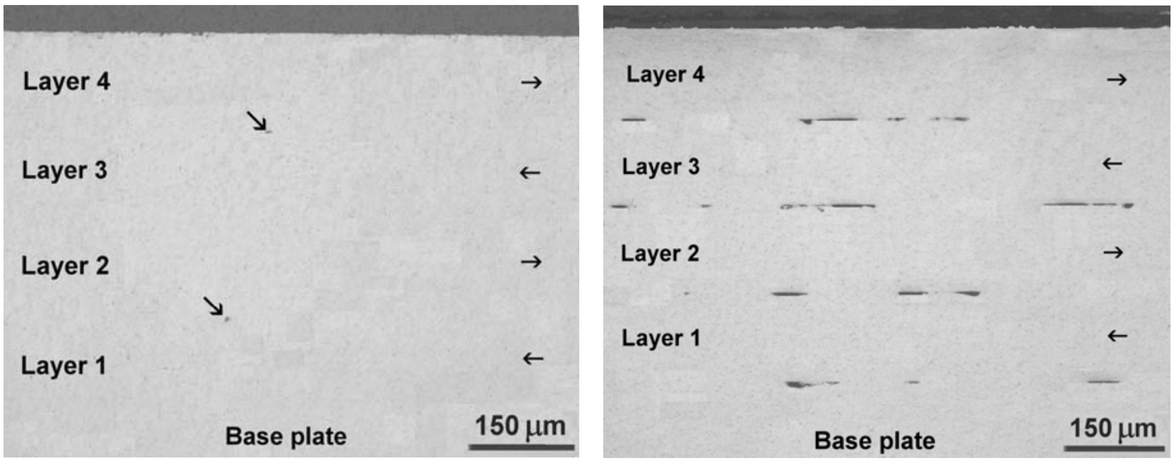
3.2 Effect of surface machining

As noted earlier, sonotrode-induced surface roughness was identified as the major source of defects in ultrasonically consolidated parts. In order to minimize the incidence of defects due to 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. Fig.9 shows the microstructures of deposits made employing the surface machining technique at various welding speeds at 300°F. Similarly, Fig.10 shows the microstructures of deposits made employing the surface machining technique at various welding speeds at 75°F. These microstructures conclusively demonstrate the effectiveness of surface machining for improving the LWD of ultrasonically consolidated parts.



(c)

Fig.9. 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:16 µm, Normal force: 1750 N, and Temperature: 300°F).



(a) (b)

Fig.10. 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:16 µm, Normal force: 1750 N, and Temperature: 75°F).

One major benefit of surface machining is that high-quality deposits can be made at welding speeds that are significantly higher than those which results in high-quality deposits without surface machining. Welding speeds up to 36 mm/s at 300°F and up to 32 mm/s at 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 welding speed is too high, as illustrated in Fig.9c and Fig.10c, although LWD levels are considerably higher than those achievable with regular UC processing (without surface machining) under similar processing conditions.

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

i) 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.
ii) Surface machining removes the hills and valley pattern on the foil surface caused by the sonotrode motion, which would otherwise manifest into defects and entrapped air.
iii) Surface machining completely removes the oxide layer on one of the mating surfaces during ultrasonic welding, thus all problems associated with oxide layers are reduced to half.
iv) Surface machining removes any work hardened layer either completely or partially on the deposited foil surface. This would facilitate easier plastic flow at the interface when the subsequent layer is deposited, which is one of the important conditions for bond formation during ultrasonic welding.

The current work shows that the surface machining technique satisfactorily solves 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 on 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 current method is extremely simple and can be implemented without any modification to the commercial UC equipment.
- The current work shows that, with proper choice of process parameters and surface machining, the ultrasonic consolidation process is quite capable of producing high quality parts on par with established wrought or cast processing techniques.

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 can result in delamination of previously deposited layers. However, when appropriate milling parameters are used, the gains in part quality, welding speed and manufacturing flexibility may more than compensate for the extra machining time. Further, it is possible to significantly reduce intermediate machining times when a surface machining set-up is developed specifically suited to intermediate surface machining (as 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.

4. Conclusions

Bond formation during ultrasonic consolidation of Al alloy 3003 is strongly dependent on process parameters. Variations in oscillation amplitude, welding speed, normal force and substrate temperature contribute to statistically significant variations in linear weld density. Oscillation amplitude exerts the strongest effect. Linear weld density increases with increase in oscillation amplitude and normal force up to a certain level. Further increase in either oscillation amplitude or normal force results in a drop in linear weld density. Linear weld density asymptotically approaches 100% with decrease in welding speed. Welding speed presents a clear trade-off between linear weld density and part build time. Use of elevated substrate temperatures promotes bond formation during ultrasonic consolidation. Linear weld density increases with increase in substrate temperature. The following combination of parameters produced the best results (98% linear weld density) during ultrasonic consolidation of Al alloy 3003 based on the parameter range studied: oscillation frequency – 16 μm, welding speed – 16 mm/s, normal force – 1750 N, substrate temperature – 300°F.

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 employing an intermediate surface machining step. An intermediate surface machining technique facilitates part fabrication with nearly 100% LWD at significantly higher welding speeds and/or at ambient temperature.

Acknowledgements

Support for this project was provided by the National Science Foundation (DMI 0522908), by an NSF STTR grant through MicroSat Systems, Inc. (OII 0512641) and by the State of Utah Centers of Excellence Program (Center for Advanced Satellite Manufacturing).

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