EXPERIMENTAL DETERMINATION OF OPTIMUM PARAMETERS FOR STAINLESS STEEL 316L ANNEALED ULTRASONIC CONSOLIDATION

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Abstract

Ultrasonic consolidation is being investigated for building Stainless Steel structures. In this study, parameter optimization for ultrasonic consolidation of Stainless Steel 316L annealed is assessed by evaluating experimental factors of oscillation amplitude, welding speed, normal force and temperature. An L-16 Taguchi design was used to establish the statistical significance of these factors and identify the combination of processing parameters that maximizes linear welding density. Optical microscopy was performed to investigate bond quality.

Introduction

Ultrasonic Consolidation (UC) is an additive manufacturing process whereby layers of metal foils can be joined with a metallurgical bond by means of acoustic energy. Moreover, the UC process has the advantage of creating metal structures without high temperatures [1]. Indeed, although localized frictional heating is involved in the UC process, the mechanism for UC is not melting [1], and thus negligible shrinkage and thermal stresses result during part building [2]. In turn, ultrasonically consolidated parts have virtually no thermal degradation in material properties. Parts may be designed and built to include complex geometric features for specific applications due to the additive manufacturing nature of the process.

At its current stage of development, UC manufacturing involves ultrasonic welding and CNC milling as combined additive/subtractive manufacturing techniques for part building. As for the UC manufacturing procedures, a computer program processes a three-dimensional CAD model of the part to be built, and slices up this model into a number of horizontal layers, each layer with a thickness equal to the metal foil used. Ultrasonically deposited foil strips are placed adjacently to each other, to create a layer. After a layer (or several layers) is completed, a computer controlled milling head shapes the layer to its slice contour. Following this, milling chips are removed and foil deposition for the next layer starts [2]. As a result of continuous addition of layers, a three-dimensional part is produced from bottom to top.

A UC foil deposition schematic is shown in Figure 1. First, a thin metal foil is placed over the substrate. Following this, a rotating ultrasonic sonotrode travels along the length of the metal foil, while a normal force is applied to the metal foil through the sonotrode, keeping the foil in intimate contact with the substrate. The consolidation of the foil and the substrate is accomplished by sonotrode oscillations at an ultrasonic frequency and at user-set amplitude. The direction of the sonotrode's oscillations (direction of excitation) is along the sonotrode's rotation axis.

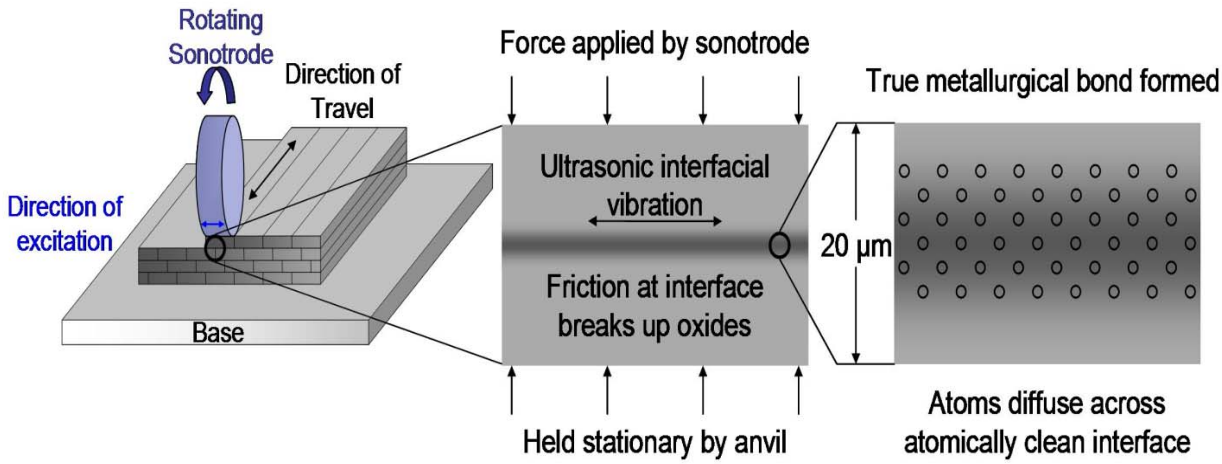

Figure 1. Schematic of the ultrasonic consolidation process

As a consequence of sonotrode dynamics, localized shear forces are generated from the combination of sonotrode pressure and oscillation, inducing interfacial stresses between the two mating surfaces and elastic-plastic deformation of surface asperities [1]. Furthermore, asperities deformations break up the oxide film, establishing a metallurgical bond between the foil and the substrate due to relatively clean metal-to-metal surface contact [2]. On a lower scale, atomic diffusion may also aid in the bonding process because 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 [1]. Although still being researched, there is evidence that ultrasonic welding mechanisms for bond formation involve: i) removal of surface oxide layers, ii) plastic deformation at the interface, and iii) to a lesser extent diffusion of metal atoms across the interface. Nonetheless, plastic deformation is considered the most important for enabling the other two mechanisms [5].

There are four general control parameters within a UC system: Amplitude of Oscillation, Contact Pressure (Normal Force between the horn and foil), Welding Speed (along direction of travel) and Temperature of the base. The first three parameters depend on sonotrode interaction with the part being built. In contrast, temperature depends on the heat applied directly to the substrate, with temperature values between room temperature and 400 °F.

Linear Welding Density (LWD) is the proportion of bonded area to total area within the weld interface [7]. Selection of this measure is better understood considering that ultrasonically consolidated parts typically show unbounded regions (defects, physical discontinuities) along the layer interfaces. Indeed, the assessment of the proportional bonded region given in a LWD measurement is also important as a quality attribute for porosity in ultrasonically consolidated parts [3]. The relevance of understanding what factors influence LWD has already been observed by Janaki Ram, Yang, and Stucker (2006) in their study of UC parts. As a matter of fact, LWD strongly affects mechanical properties in the thickness direction of a UC part and the mechanical behavior of a UC structure under load-bearing stresses [4].

However, optimum parameters for UC are not universal under general conditions. The magnitude of interfacial stresses at the mating surfaces during the UC process depends on current frictional conditions at the sonotrode/foil and substrate/foil interfaces [10] [11] [12] [13]. Furthermore, sonotrode geometry, material, and surface condition influence optimum parameter values for UC [3]. For this reason, UC optimum process parameters can vary with sonotrode wear over time, different foil material/thickness and different UC system. In general, a significant change in frictional conditions at the sonotrode/foil or substrate/foil interfaces will affect optimum UC parameter values. Therefore, it is necessary to understand that the concept of optimality of UC parameters is restricted to a reasonably consistent range of frictional conditions, whereas new optimum UC process parameters must be established if these frictional conditions change significantly.

Overall, the objective of the research effort presented here is to determine the optimum processing parameters for UC of Stainless Steel 316L annealed (SS316L annealed) foils, based on maximum linear welding density criteria. SS316L was chosen due to its commercial availability in foil form, variety of applications and greater mechanical strength than Al. Additionally, research on SS316L UC will allow comparison between previous Al UC studies and this investigation. Even though Kong, Soar and Dickens (2003) have recommended a joint approach for determining optimum UC parameters based on peel testing and LWD measurements, the criteria used in this study is minimizing part porosity and thus, maximum LWD is the benchmark used for determining the optimum.

Literature Review

In previous studies, UC of 3003/6061 Al alloy structures has been investigated using welding speed, oscillation amplitude, and contact pressure as the variable process parameters [3] [6] [7]. Evaluation of the effect the aforementioned parameters had on microstructure and mechanical properties of ultrasonically consolidated parts has been the object of active research [7] [8]. In this context, selection of appropriate process parameters plays a key role in UC bond formation of Al 3003/6061 based on LWD microscopic studies and peel-off tests [7] [9]. Although Kong, Soar and Dickens (2003) concluded that it is possible to have a low peel load response and high linear weld density with Aluminum 6061 (due to excessive strain hardening and cycling stressing of contact points at the interface); it has been verified that a high peel load response only occurs in the presence of high LWD [9]. For instance, higher oscillation amplitude values produced higher LWD in Al 3003/6061 and either higher weld strengths (in Al 3003) [8], or no significant effect on weld strength (in Al 6061)[7]. Furthermore, Janaki Ram et al. (2006) included substrate temperature as an additional factor for the Al 3003 UC process, and performed a comprehensive study of the effect of substrate temperature, welding speed, oscillation amplitude, surface machining and normal force on Al 3003 UC [3]. Among other things, Janaki Ram et al. (2006) concluded that higher normal force and higher oscillation amplitude increases LWD up to a certain level, beyond which LWD decreases. Additionally, it was observed that lower welding speeds (down to 12 mm/s) increase LWD, and higher temperatures produced higher LWD within a range from ambient to 350 °F [4].

On the other hand, previous research has demonstrated the feasibility of the UC process using Stainless Steel 316L [14]. In addition, this study explored the role played by process parameters of welding speed, amplitude, normal force, and temperature in Stainless Steel ultrasonic consolidation, while successfully achieving initial process settings identification by peel strength testing and optical microscopy of samples. The same study presented results of an analysis of variance (ANOVA) on SS316L UC, with peel strength as the response. Out of the four factor investigated, only amplitude and welding speed factors were statistically significant for peel strength (with a 90% confidence interval, p-value < 0.10), and amplitude exerted the strongest effect on peel strength [14]. Furthermore, as for the effect of process parameters on peel strength, higher oscillation amplitudes and lower welding speed increased peel strength; while temperature (up to 300°F) and normal force (up to 1600 N) were not statistically significant.

Considering these research efforts, this study addresses parameter optimization for ultrasonic consolidation of Stainless Steel 316L annealed, by evaluating experimental factors of oscillation amplitude, welding speed, normal force and temperature in order to minimize part porosity and therefore, on the basis of maximum LWD criteria.

Experimental Plan

A series of experiments with SS 316L annealed (composition by weight: 16-18 %Cr, 10-14 %Ni, 2.0-3.0 %Mo, ≤ 2 % Mn, ≤ 0.75 %Si, ≤ 0.010 %N, ≤ 0.045 %P, ≤ 0.03 %C, ≤ 0.03 %S) were performed to assess the effect of various factors in the UC process. A Solidica Formation™ machine was used to create ultrasonic consolidated samples. The Solidica Formation™ UC machine (Figure 2 and Figure 3) is an integrated UC building system that combines a rotating ultrasonic sonotrode, a heat plate, a foil-feeding spool mechanism, a three-axis milling head, and a software implementation for material deposition and machining [3]. Furthermore, the Solidica Formation™ sonotrode oscillates transversely according to a half-wave rectified sine wave at a frequency of 20 kHz and at user-set oscillation amplitude while traveling over the metal foil. The sonotrode itself is incorporated into a welding head and its position is controlled by numerical control.

Using the Solidica Formation™ system, part fabrication is performed on a firmly bolted Al 3003 H14 (composition by weight: 0.050-0.20 %Cu, ≤ 0.70 %Fe, 1.0-1.50 %Mn, ≤ 0.60 %Si, ≤ 0.10 %Zn) base plate mounted on a heat plate. Also, the heat plate maintains the substrate at a user-set temperature, between ambient and 400°F. A graphical description of the Al 3003 H14 base plate (dimensions: 355x355x12 mm) is shown in Figure 4, whereas plate/part fixture is presented in Figure 5.

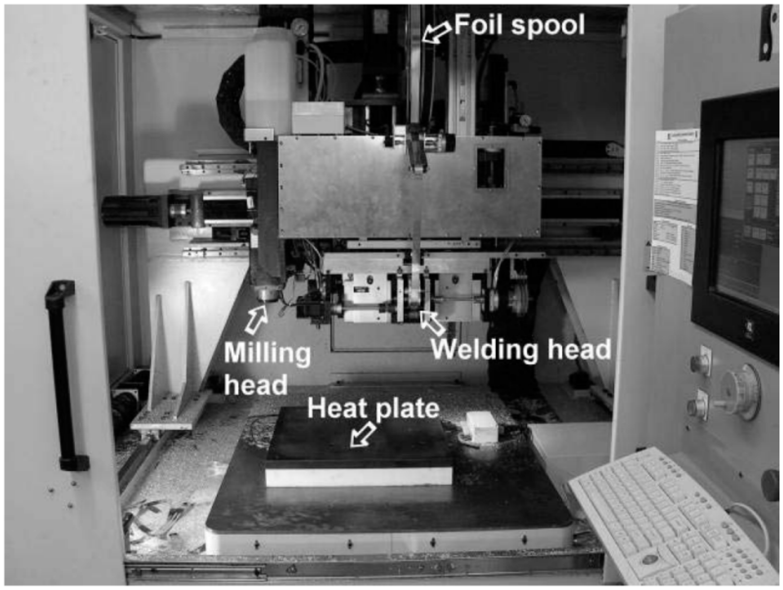

Figure 2. Solidica Formation™ machine (as shown in [3])

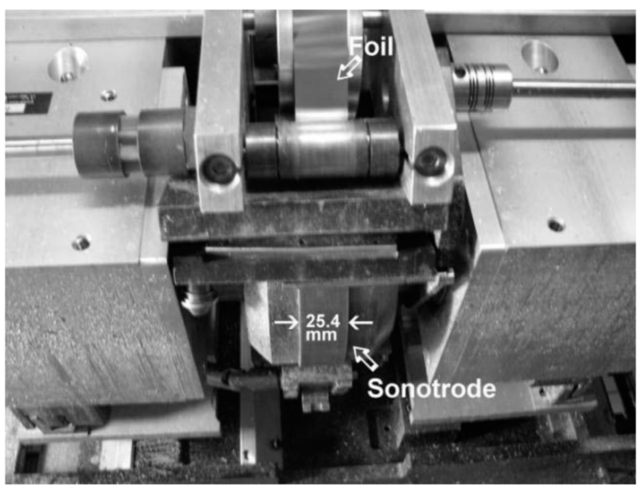

Figure 3. Close-up view of the Welding head, showing the sonotrode from below (as shown in [3])

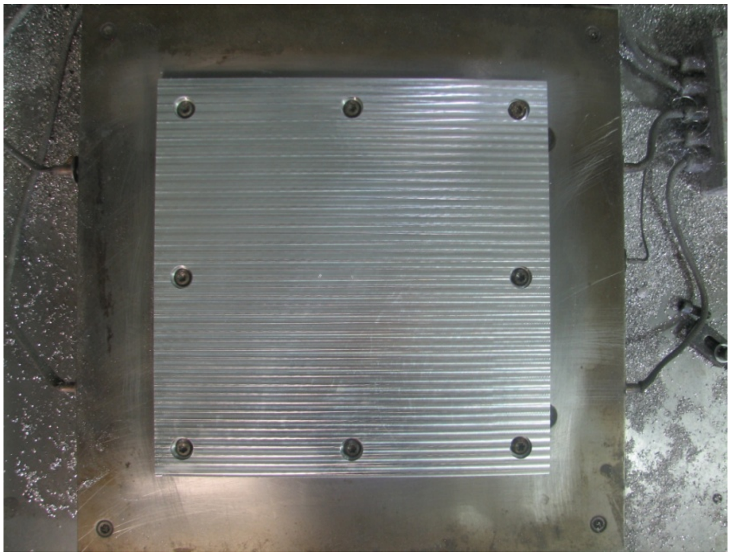

Figure 4. Geometry of the base plate used within the Solidica Formation™ machine and bolt locations just before deposition

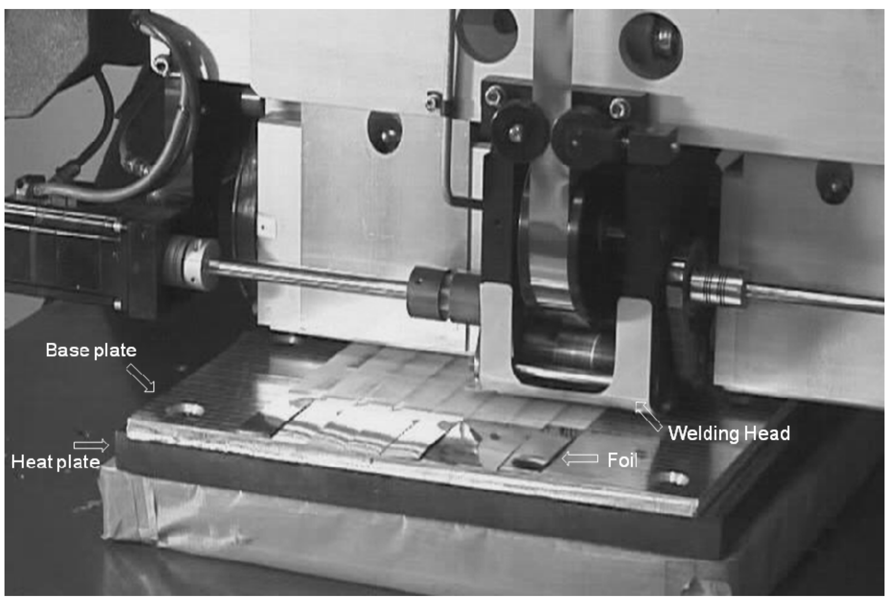

Figure 5. Base plate and part fixture in the Solidica Formation™ machine

A 146.75 mm diameter Titanium sonotrode was employed for UC depositions. Sonotrode roughness was measured using a Mitutoyo Surftest SV-602 stylus profilometer, at three evenly spaced angular locations (0°, 120°, 240°). The arithmetic average of absolute values (Ra) was calculated respectively in the sonotrode direction of excitation and around the sonotrode midplane circumference (a one inch long arc centered at each angle location). Results for Ra calculations are presented in Table 1.

Table 1. Schematics of the SS316L annealed UC samples

	Sonotrode angular location		
Measurement Type	**0 degrees**	**120 degrees**	**240 degrees**
Ra (μm) in the direction of oscilations	6.06	4.74	4.81
Ra (μm) around the circumference	5.01	3.96	6.59

Furthermore a Design of Experiment (DOE) approach was chosen for evaluating UC SS316L annealed process parameters of oscillation amplitude, welding speed, normal force and temperature and performing further parameter optimization. Four different levels for each parameter were adopted in order to evaluate any non-linear effects (Table 2). Also, specific levels for each of the parameters were selected based on Solidica Formation™ machine setting limits.

Table 2. Parameters and levels for UC experiments

Factors	Levels			
Temperature	85 F	190 F	295 F	400 F
Contact Normal Force	500 N	1000 N	1500 N	1800 N
Welding Speed	26 ipm	38 ipm	50 ipm	62 ipm
Amplitude	16 μm	20 μm	24 μm	27 μm

A special Taguchi L-16 orthogonal array, namely the L'16 (4^5 L-16) Taguchi orthogonal array, was utilized to determine the effects of individual process parameters. The L'16 array comprises 5 different experimental factors, 4 levels each. As only 4 process parameters are being considered in this study, the fifth factor of the L'16 orthogonal array was discarded, obtaining the experimental matrix shown in Table 3.

Table 3. Taguchi L'16 experiment matrix

Experiment run	Temperature	N. Force	W. Speed	Amplitude
1	85 F	500 N	26 ipm	16 µm
2	85 F	1000 N	38 ipm	20 µm
3	85 F	1500 N	50 ipm	24 µm
4	85 F	1800 N	62 ipm	27 µm
5	190 F	500 N	38 ipm	24 µm
6	190 F	1000 N	26 ipm	27 µm
7	190 F	1500 N	62 ipm	16 µm
8	190 F	1800 N	50 ipm	20 µm
9	295 F	500 N	50 ipm	27 µm
10	295 F	1000 N	62 ipm	24 µm
11	295 F	1500 N	26 ipm	20 µm
12	295 F	1800 N	38 ipm	16 µm
13	400 F	500 N	62 ipm	20 µm
14	400 F	1000 N	50 ipm	16 µm
15	400 F	1500 N	38 ipm	27 µm
16	400 F	1800 N	26 ipm	24 µm

The experimental units were randomized and each of the 16 runs consisted of depositing four rectangular layers of SS316L annealed foil one over another using a constant welding direction (Figure 7) and manual placement of foils. Therefore, each layer comprises a single foil 63.5 mm long, 25.4 mm wide and 0.1016 mm thick, and one experimental sample resulted from each experimental run.

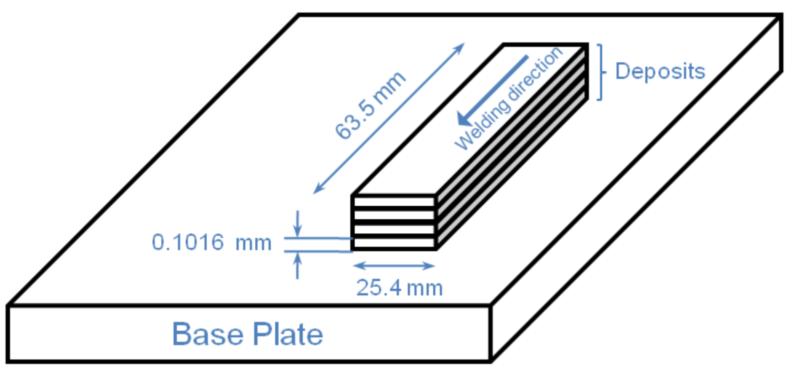

Figure 7. Schematics of the SS316L annealed UC sample

All 16 samples were built on a single base plate and high temperature tape was used to keep the foils in place before deposition. Completed samples on the base plate are shown in Figure 8.

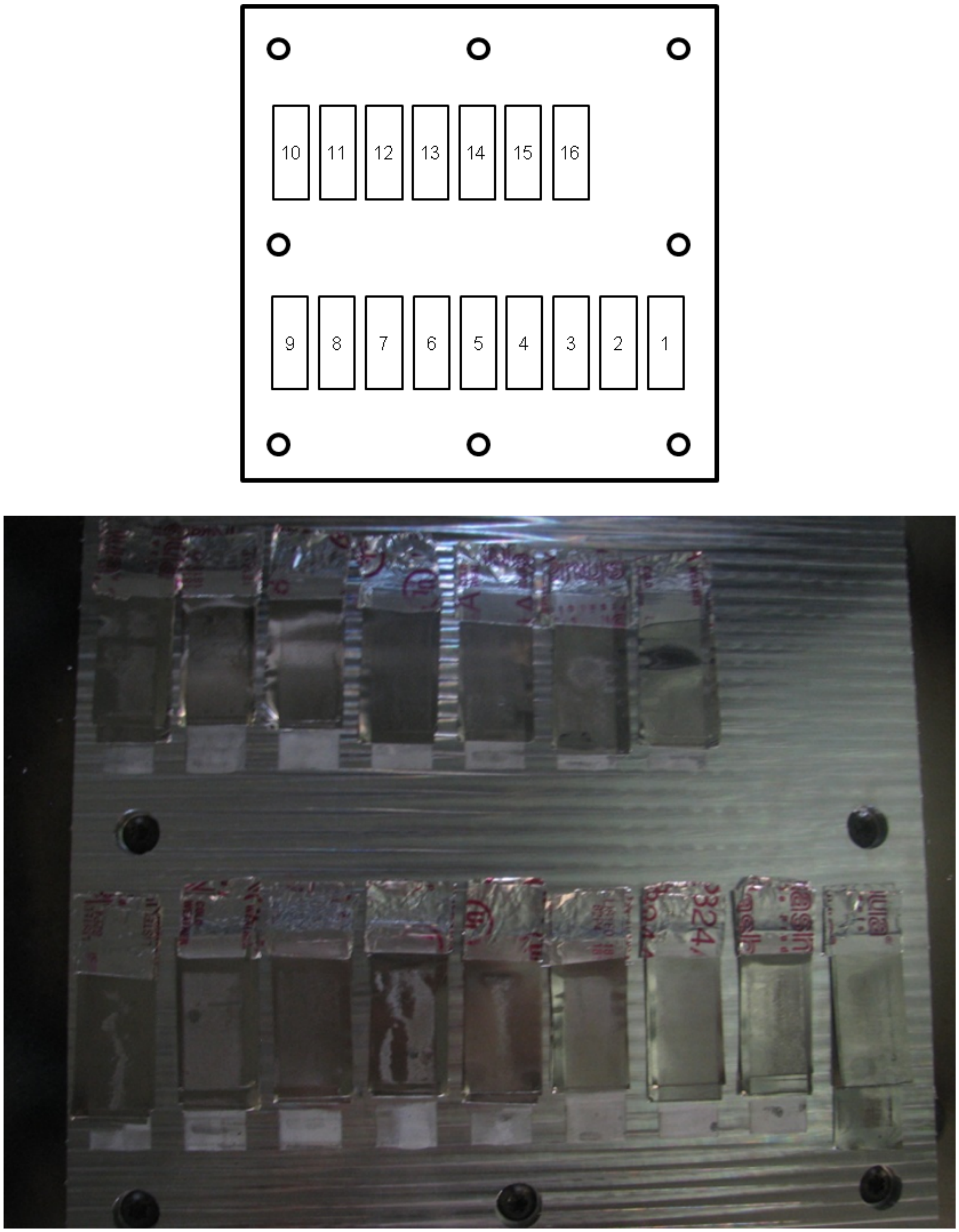

Figure 8. Actual experiment samples and layout of experiment runs on base plate

Following sample deposition, a microstructural analysis of the weld interface was conducted by sectioning weld samples along the width of the foil. The samples were mounted, polished to a 0.05 μm finish and cleaned in isopropyl alcohol using an ultrasonic bath. Both interface characterization and LWD were assessed from micrograph images of samples taken from weld cross-sections. LWD was estimated by microstructural observations using a Zeiss Axiovert 100A inverted light microscope, considering only the interface between foils.

As Linear Welding Density was the response measurement in this experiment, LWD was calculated for picture frames using the following formula:

$$\%LWD = \frac{\text{Bonded interface length}}{\text{Total interface length}} \times 100$$

Results

Most parameter combinations resulted in insufficient energy to bond SS316L. In two cases significant bonding occurred but excess strain hardening energy resulted in delamination of previously formed bonds. In one case bonding was observed without delamination. In order to select successfully bonded samples a LWD threshold was set at 50%. Those samples with an average LWD greater than 50% were considered welded. Consequently, out of 16 experiment runs performed, 3 successfully bonded samples resulted from using the process parameters combinations in the experimental matrix (Table 4). Micrographs of the 3 successfully bonded samples are shown in figures 10 through 12.

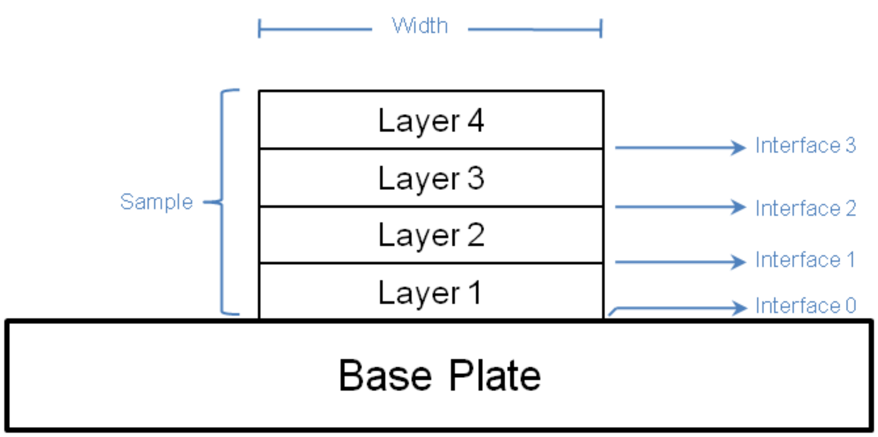

Figure 9. Sample welding interfaces

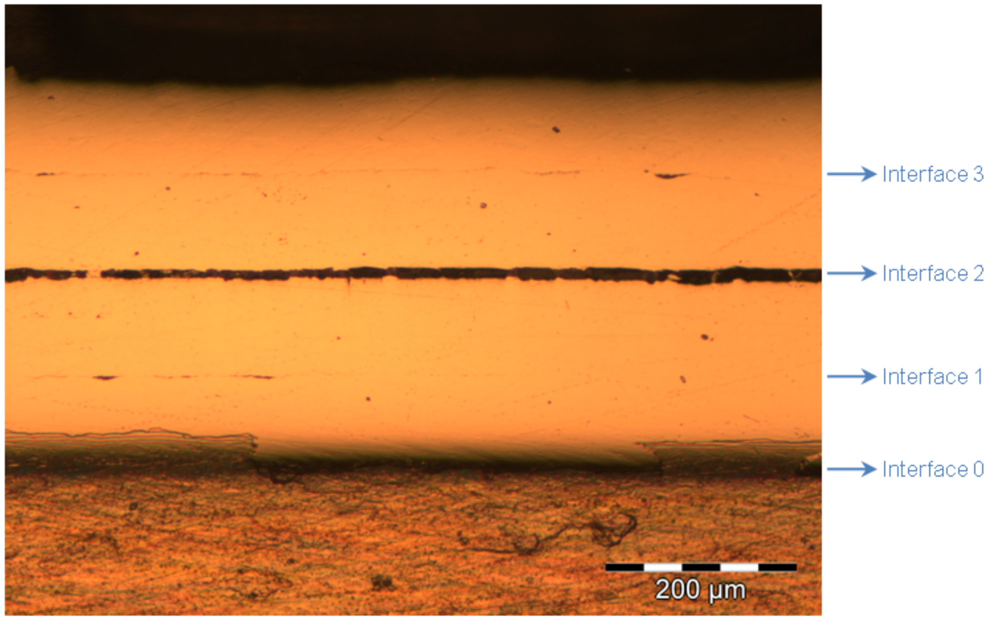

Figure 10. Micrograph of sample corresponding to experiment run 6

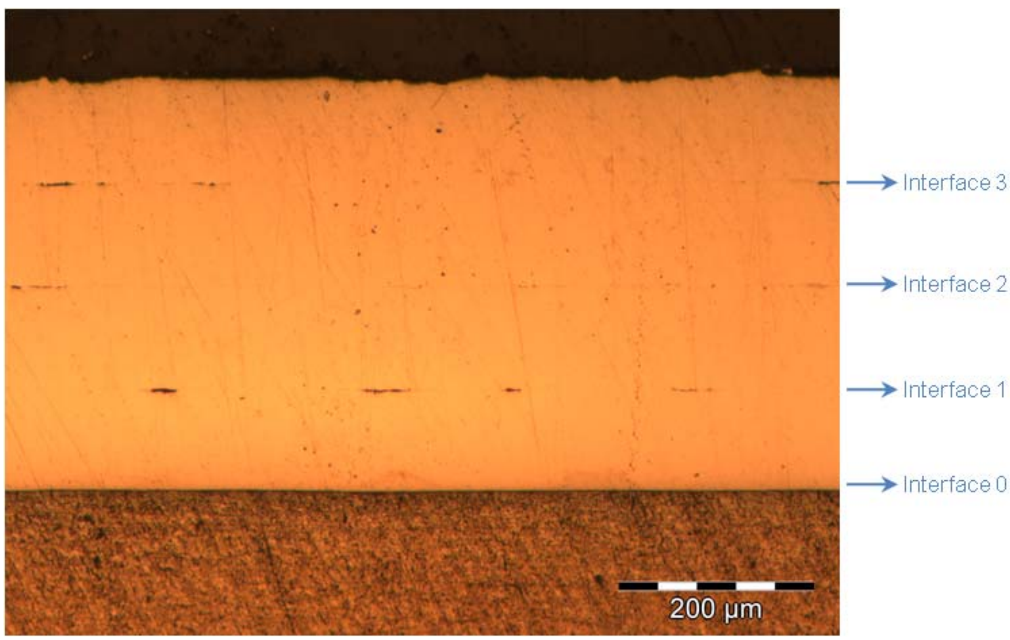

Figure 11. Micrograph of sample corresponding to experiment run 15

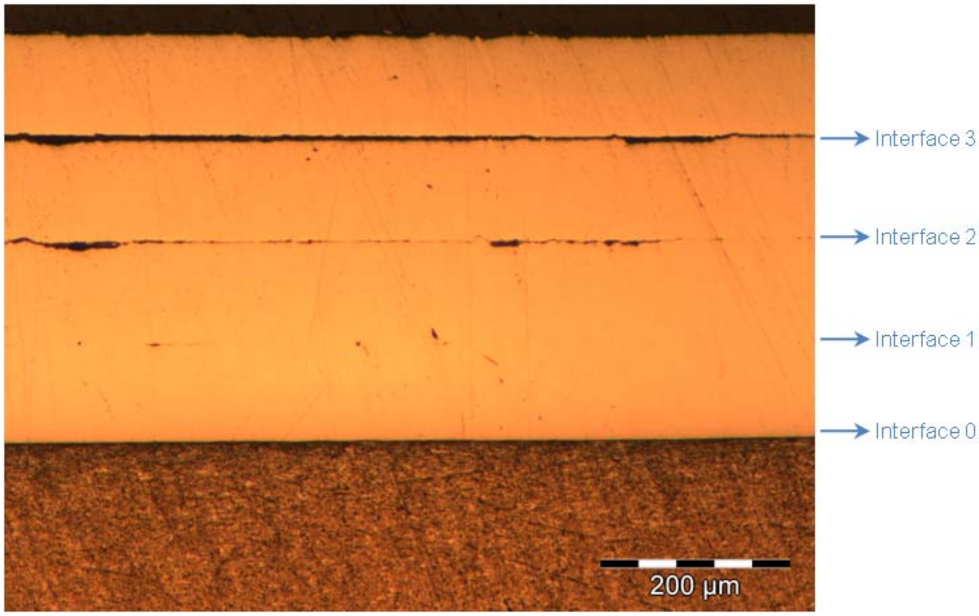

Figure 12. Micrograph of sample corresponding to experiment run 16

Individual LWD measurements were carried out on successfully bonded sample interfaces. The interface between the first layer and the base plate (see Figure 9) was not considered in LWD measurements because it does not constitute a Stainless Steel to Stainless Steel bond and, in contrast with the other depositions, there is no initial sonotrode-induced roughness on the substrate. Results of LWD measurements are included in Table 4.

Table 4. Successful experimental runs and respective LWD results

					% LWD			
Experiment run	Temperature	N. Force	W. Speed	Amplitude	Interface 1	Interface 2	Interface 3	Average
6	190 F	1000 N	26 ipm	27 µm	90.49%	0.54%	83.62%	58.22%
15	400 F	1500 N	38 ipm	27 µm	84.47%	87.69%	76.01%	82.73%
16	400 F	1800 N	26 ipm	24 µm	95.96%	62.85%	0.00%	52.94%

Based on the findings presented in this work, the following was identified as the optimum process parameter combination for SS316L annealed UC: oscillation amplitude=27 µm, welding speed=38 mm/s, normal force=1500 N, substrate temperature= 400 °F. Therefore, evidence suggests that, apart from geometry-induced effects, employing this process parameter combination should result in nearly 83% linear weld density in SS316 annealed deposits.

Discussion

The present work independently verified the feasibility of UC of SS316L annealed, obtaining 3 parameter combinations where bonding occurred. The fact that only 3 out of 16 samples had above a 50% average LWD is strong evidence that bond formation during ultrasonic consolidation of SS316L annealed is highly dependent on process parameters.

Many aspects make this research effort unique. Even though SS316L UC feasibility studies have been performed before [14], LWD has not been the experimental response in any previous study of SS316L UC. In addition, this UC study includes specific sonotrode surface roughness data for better assessment of the existing frictional conditions.

Moreover, these experimental results reveal some important trends for SS316L annealed UC. Regarding microscopy analysis, LWD measurements across layers show well-bonded and delaminated layers for samples 6 and 16. This suggests that there is a slight degree of excess energy, and that additional experimentation may result in optimum process parameter settings which give higher LWD without delamination. A future full factorial study centered around parameter combinations similar to samples 6, 15 and 16 will be performed to more adequately search the parameter space in this region of settings.

In similitude with the Al 3003 case [8], oscillation amplitude proved influential in SS316L annealed UC. Indeed, 2 of 3 successfully bonded samples occurred at 27 microns of amplitude (the highest evaluated level of this process parameter). In addition, LWD tends to increase with higher amplitudes, confirming previous results obtained with SS316L [14].

Normal force values above 1000 N of force appear to contribute favorably to obtaining full width foil welds (Figure 8). Additionally, successful depositions were obtained at welding speeds below 50 ipm, thus limiting potential build speed. With respect to substrate temperature, evidence suggests that SS316L annealed UC may be aided by higher temperatures, as samples with good bonding occurred at 190 °F and 400 °F.

Unfortunately the ability to further increase oscillation amplitude and temperature is limited by the capabilities of the Solidica Formation™ machine settings. Further machine improvements that enable larger oscillation amplitudes and higher temperatures may enable more effective UC of SS316L annealed foils. Even with these machine limitations, UC of SS316L was confirmed with LWD values comparable to those found for Al 3003/6061 previously [4] [7].

Conclusion

This study confirms the feasibility of the UC process with SS316L annealed foils to obtain a high degree of Linear Welding Density. Although more experimentation is needed to obtain final conclusions and to investigate geometry-induced effects, an optimum parameter set was identified, producing approximately 83% average linear welding density by using the following combination of parameters: oscillation amplitude=27 µm, welding speed=38 mm/s, normal force=1500 N, and substrate temperature=400 °F.

Acknowledgements

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