An Experimental Determination of Optimum Foil Joint Conditions for Structural Parts Fabricated by Ultrasonic Consolidation

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Abstract

This paper describes an investigation of the optimum conditions necessary to eliminate defects at foil joints in parts fabricated by ultrasonic consolidation. Tensile test specimens were fabricated with different foil joint conditions of varying degrees of overlap in the deposition layers. They were subjected to tensile tests to determine their mechanical properties. Microstructures of samples were also studied. Experimental results show correlations between foil joint condition and mechanical strength. Sample microstructures also show correlations between the bonding qualities of the foil joints and the strengths obtained. The study highlights an important process parameter to control for fabrication of defect free structural members by ultrasonic consolidation.

1. Introduction

Ultrasonic consolidation (UC) is an innovative solid-state fabrication process that combines the ultrasonic welding of metal foils and layered manufacturing methodologies to produce solid freeform objects (Kong *et al*; 2004). The UC Formation^{TM} technology developed by Solidica employs ultrasonic vibration combined with a normal force to generate static and oscillating shear forces within metal foils to produce solid-state bonds. A layer consists of one or more foils placed side-by-side such that their combined width exceeds the size of the part which is being fabricated. Foils are welded in a stack of layers to fabricate a part. A subtractive process is integrated in UC via a 3-dimensional computer numerical control (CNC) milling head for generating the layer by layer geometrical profile of the solid object. The geometry of each layer in the CAD file is replicated on the fabricated part by milling the foil layers to their desired contours. This additive and subtractive process fabricates near net shape parts, as only the substrate or base plate needs to be removed by milling to form the completed part. In the case where the base plate is integrated into the design, the process is a net shape process.

Previous work has shown the viability of this novel additive process for fabricating various multi material solid objects including metal matrix composites (Janaki Ram *et al,* 2007). Some of the applications of the UC process include fabrication of tools with conformal cooling channels, embedded electronic structures, embedded fiber optics, honeycomb structures and structures with arbitrary cavities (White, 2003; Kong *et al,* 2005; Siggard *et al,* 2006; Yang *et al,* 2007). Also, as UC is a low temperature solid freeform process, this offers a major distinction for the process when compared with other additive manufacturing processes for metals. It operates below 50% of the melting temperatures of the metals being processed. As such, thermal stresses and related problems like distortion and embrittlement in fabricated parts are minimized.

Good physical and metallurgical bonding between foil layers is of paramount importance to minimizing defects in UC fabricated parts. Each material or combinations of materials have optimum parameters required to obtain structurally sound part fabrication. Lack of good bonds between foils at the layer interface results in low-strength parts that are unsuitable for structural applications. Also, leakage can result in cases where flow channels are incorporated in the part.

Optimum process parameters have been established for the fabrication of some materials in previous studies, especially Aluminum 3003H18. Other materials for which process parameters have been established are aerospace grade aluminum such as 6061, aluminum-silicon carbide metal matrix composites, and 316L stainless steel (Kong *et al,* 2004; Yang *et al,* 2007; Tuttle, 2007). The important process parameters are vibration amplitude, normal force, welding speed, temperature, and layer surface roughness. All of these parameters have direct influence on the bond quality, and hence, the strength of the structure. It has been established that linear weld density can be greatly improved by surface machining each deposited layer. Almost 100% linear weld density has been achieved by surface machining (Janaki Ram *et al,* 2006).

Previously established process parameters largely focused on improving interlayer bonds between foils. In a typical UC fabricated part with less than 100% linear weld density, a number of interlayer bond defects, will be present. Figure 1 illustrates interlayer defects in a UC fabricated part. The process parameters mentioned above are generally optimized to eliminate or reduce the interlayer defects for a material or combinations of materials. Another area of concern for which no optimum parameter has been established is the joint between adjacent foils in each layer, that is, the edge-to-edge joint between adjacent foils within a layer. For parts with more than 24mm width (approximately one foil width); more than one foil laid side-by-side are required to create each layer. The foil joint condition in the layers, that is, whether an overlap or a gap exists, is a critical consideration. Gaps between adjacent foils are very common defects in UC deposited parts. The optimized process parameters mentioned above have not offered any solution to this problem thereby making UC fabricated parts unsuitable for some structural applications. These defects create potential stress risers that affect the load carrying capability of structures fabricated by UC. An example of such foil joint defects in an Al 3003 fabricated part is shown in the micrograph in figure 2. It reveals gaps between adjacent foils in a typical UC fabricated part. The topmost gap is about 150μm, almost the same as the thickness of the foil. This work focuses on establishing optimum process condition to minimize defects at adjacent foil joints within a layer, thereby enhancing the strength of fabricated structures.

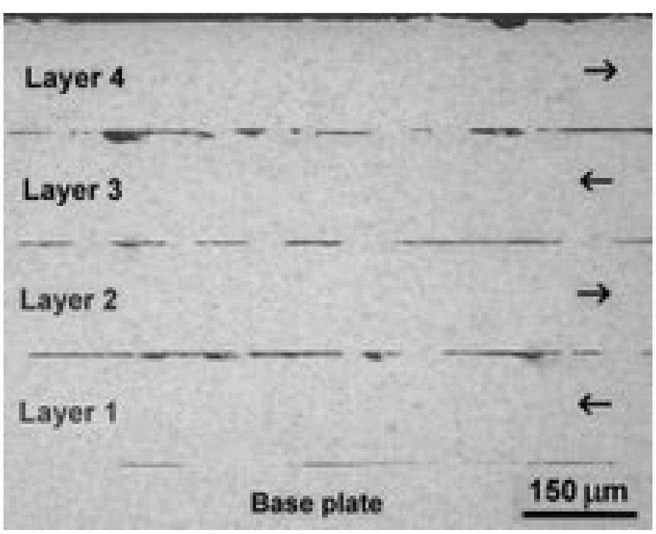


Figure 1: Micrograph showing interlayer bonding defects

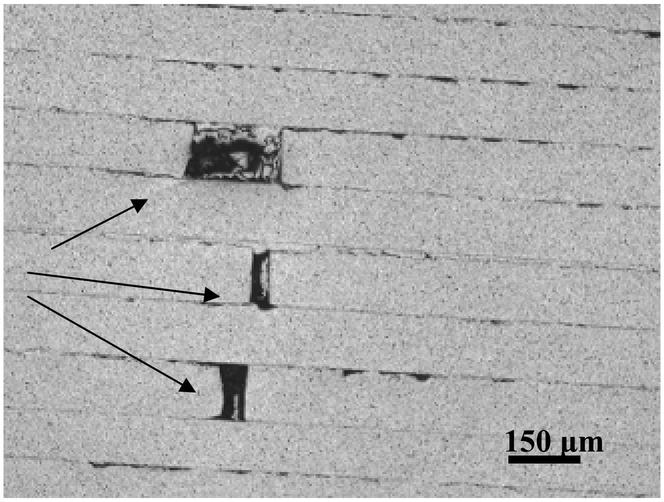


Figure 2: A micrograph with arrows showing foil joint defects

If UC fabricated parts are used in applications requiring parts to withstand dynamic loads, like in aircraft and automobiles, it becomes very important that a solution is found to foil joint defects. The weakening effects of these defects is more pronounced in complex structures that have features like ribs with transverse foil orientation to the direction of loading. Those features are more likely to fail early in comparison with other parts that have foils in the longitudinal direction to the applied load. A default foil width of 0.9411" (23.90mm) in the machine code for part fabrication is generally maintained in the UC machine. This width automatically sets the foil joint condition for Solidica supplied Al 3003 UC foil. In this work, tensile test specimens that model different foil joint conditions with varied tape width settings were fabricated and tested for strength. The fractured specimens were subjected to metallographic and fractographic studies to establish possible correlation between the quality of the foil joints, the mode of fracture and the strength of the specimens. Al 3003H-18 foil (nominal composition by wt%: Al-1.2Mn-0.12Cu, 23.90mm wide and 150µm thickness) sourced from Solidica Inc., USA was used.

2 Experimental Work

2.1 Fabrication

The experimental work was carried out with an ultrasonic consolidation machine built by Solidica, known as a Formation™ machine. Foil feed and positioning, welding and contour milling operations on the machine are computer numerically controlled. A machine code is generated for the CAD model of the part to be fabricated. This code incorporates the fabrication process parameters and directs the sequential operations of the UC machine. The foil positioning is generally randomized across the layers in the machine code automatically. This random arrangement almost always requires adjustments for good interlayer bonds and ease of fabrication. The machine has a heat plate, by which the substrate is regulated at the desired optimum temperature. Al 3003 base plate substrates (dimensions 355mm x 355mm x 12mm) bolted to the heat plate were used for the deposition of the foils. A rotating ultrasonic sonotrode of 150mm diameter vibrating at 20 KHz frequency travels on the automatically fed foil to weld it to the substrate. Figure 3 describes the Solidica ultrasonic consolidation machine. The following optimum process parameters already established in previous work for aluminum 3003 fabrication were applied in the machine code for all the specimens fabricated in this work: Temperature 300°F; Normal Force: 1750N; Amplitude16μm; Welding Speed: 12mm/s.

The tape width settings in the machine code were varied for each set of specimens fabricated; these width settings determine the distance the sonotrode is displaced to weld adjacent foils. The default tape width setting in the machine code is 0.9411" (23.90mm) with standard Al 3003 foil supplied by Solidica. Since the foils are of the same width, the distance the sonotrode moves then determines the gap between adjacent foils. This gap is critical as it determines the closeness or overlap of the foils at the joints. If the sonotrode displacement exceeds the standard tape width, adjacent foils do not touch each other and a gap is created between them. However, if the displacement is less than the standard foil width, adjacent foils overlap at the joints. The extent of the gap or overlap created at the joint is dependent upon the difference between the standard foil width and the sonotrode displacement or foil width specified in the machine code.

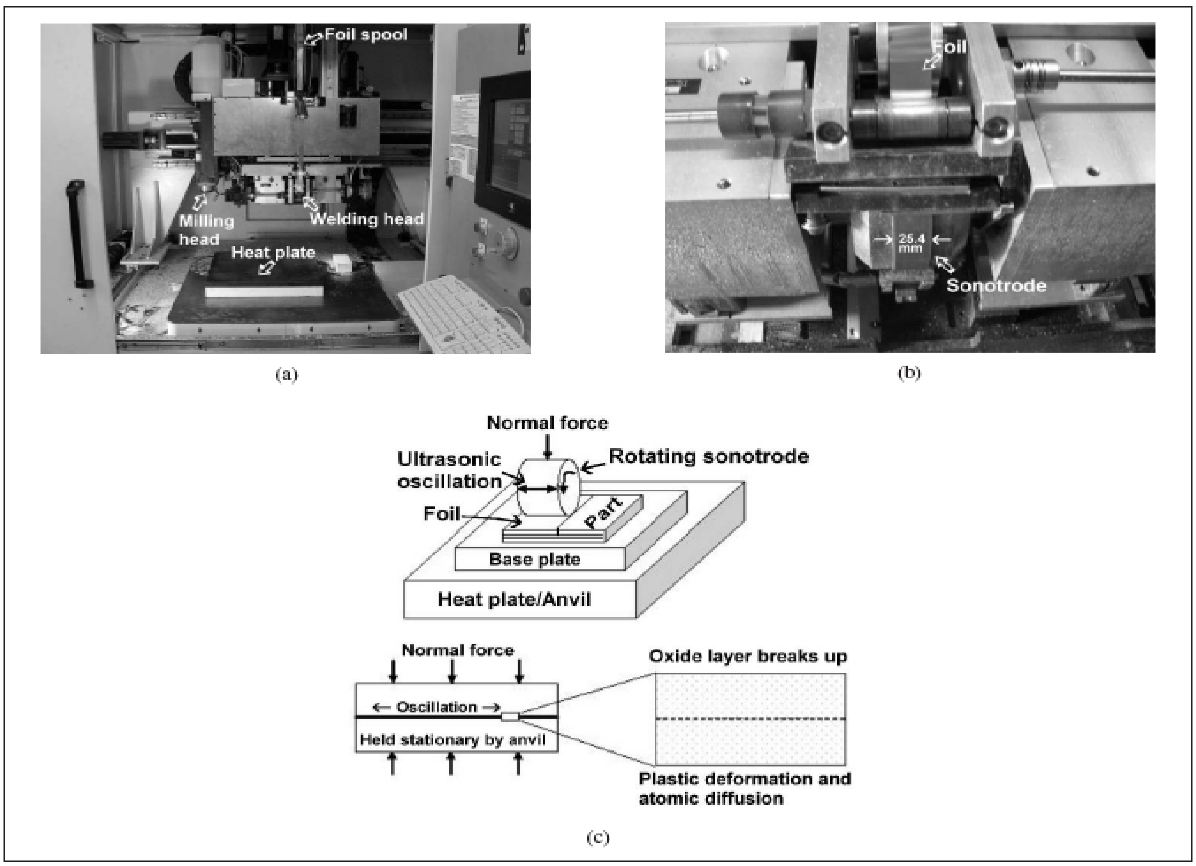


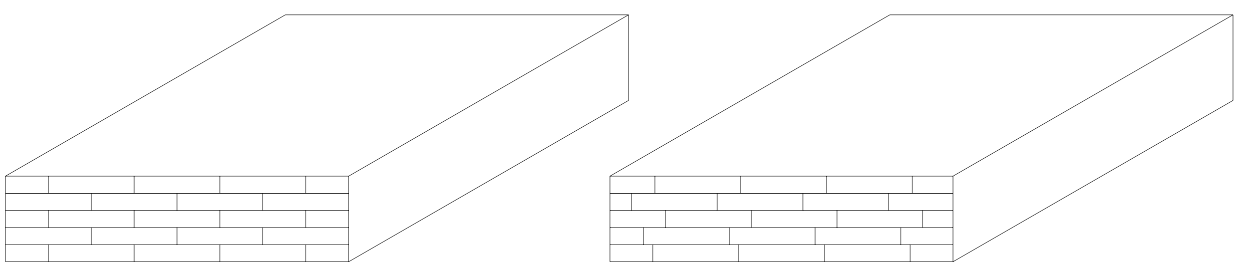
Figure 3: (a) Solidica Formation™ UC machine, (b) Close-up view of ultrasonic sonotrode from below, (c) Schematic of UC process.

Figure 4: Samples of the fabricated tensile test pieces

Standard tensile testing bars conforming to ASTM specifications were fabricated with the following dimensions: Gage length – 50.0mm; Width – 12.5mm; Thickness – 7.0mm; Radius of fillet – 12.5mm; Overall length – 200.0mm; Reduced section – 57.0mm; Length of grip section – 50.0mm; and Width of grip section – 20.0mm. Samples of the tensile specimens are shown in figure 4. Three tensile bars were fabricated for each foil joint model. Solid blocks with dimensions 210mm x 75mm x 7.2mm were first deposited, from which the tensile bar profiles were machined out with the integrated CNC facilities in reverse order from the topmost layer to the first layer in contact with the substrate. The tensile bars were removed from the substrate by machining off the substrate on a conventional milling machine. Ten different sets of three tensile bars were fabricated, each modeling a specific foil joint condition

2.2 Longitudinal Tensile bars

Out of the ten sets of specimens fabricated, one set modeled a longitudinal foil arrangement (that is, longitudinal with respect to gage length) and default tape width setting of 0.9411” (23.90mm) in the machine code. The foils were arranged with 50% overlap across layers as illustrated in figure 5a below. This is like a brick wall arrangement intended to maximize the amount of overlap with previously deposited layer. The overlap arrangement is such that the joints of foils in a previous layer were located at the middle of the foils in the immediate adjoining layer.



a: 50% overlap **b: Random overlap**

Figure 5: End view patterns of 50% and random overlap foil arrangement

2.3 Transverse Tensile Specimens

Seven sets of bars with specific foil width settings in the machine code were fabricated to model foil arrangements in the transverse direction with respect to the gage length of the fabricated tensile test specimens. The different tape width settings for the specimens with transverse foils ranged from 0.9363" (23.78mm) to 0.9435" (23.96mm) with an increment of 0.0012" (0.03mm). These seven sets utilized 50% foil overlap between the layers, as shown in figure 5a above. The 0.9423" (23.93mm) and 0.9435" (23.96mm) foil width settings were expected to produce gaps between adjacent foils. These excessive settings were purposefully included in order to evaluate the effects of differing amount of gaps on the strength of the modeled structures.

2.4 Random Transverse Tensile Bars

Two sets of bars were fabricated to model tape width settings of 0.9435" (23.96mm) and 0.9375" (23.81mm) with random overlap. An example of the random overlap is illustrated in figure 5b. These were fabricated to compare the strengths of the random overlap and 50% overlap settings.

For the purpose of identification in this work, the sets of specimens have been labeled according to their width specifications in the machine code without the "inch" and decimal notations. As an example, the 0.9363" width setting specimens are labeled 9363 specimens. For those with the random foil arrangements, their labeling is prefixed with an "R", for example, the random 0.9435" specimens are labeled R9435 specimens. The longitudinal sample set is labeled "Long."

2.5 Problems Encountered

There were problems encountered during the deposition of some of the blocks for the tensile specimens. The depositions for sample sets 9363, 9375, 9387 and 9435 were more difficult to build. The level of difficulty increased as the width difference between the default 0.9411" and the desired setting increased. Thus, 9363 sample set was more difficult than 9375 sample sets in that order; also the 9435 sample set was more difficult than the 9423 sample set. Figure 6 shows a picture of one of the deposition problems that were encountered a number of times during the fabrication of the blocks. Some foils popped up without bonding to the previous layer as a result of the new width settings. This problem was typically corrected by rewelding the affected foil(s). However, in some cases the entire layer was removed by a milling recovery operation. The deposition process continued from the recovered layer.

Popped foil

Figure 6: Picture showing a layer with a popped foil. This was corrected by repeating the weld

2.6 Tensile Testing

The bars were subjected to tensile tests with an Instron tensile testing machine (model 3367) with load cell capacity of 30KN according to the ASTM standard. Also, an Instron 2630-100 Series clip-on extensometer was used for strain measurements. With the extensometer, the Young's modulus for each sample was deduced from the stress-strain relationships.

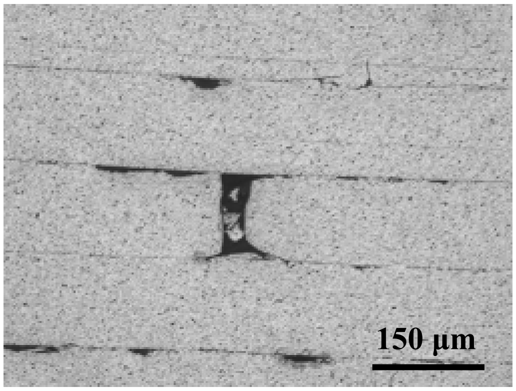
2.7 Metallographic Studies

Small samples cut from the undistorted tensile specimens' grip ends were mounted and polished according to standard metallographic preparation procedures. They were then etched with Kellers reagent (90ml H_2O, 5ml HNO_3, 3ml HCl and 2ml HF) and observed under an optical microscope for microstructural characterization. Also, fractographic studies were carried out on the fractured samples with Scanning Electron Microscopy (SEM). The fractured samples were ultrasonically cleaned with acetone in preparation for the SEM studies, such that dirt was removed effectively with the original fracture lines unaltered.

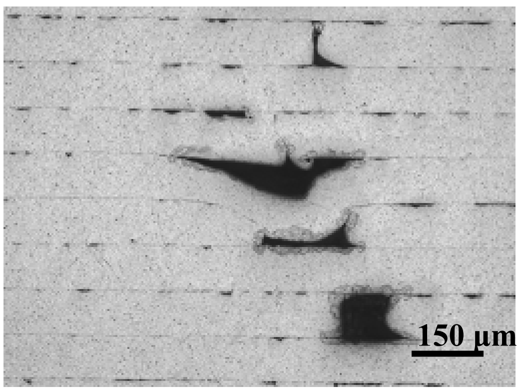
3 Results and Discussions

3.1 Microstructures

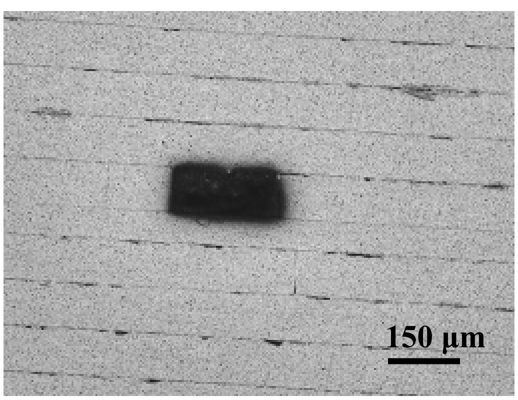
The micrographs taken from the optical microscope reveal distinctive microstructure for each set of specimens as shown in figure 7 below.



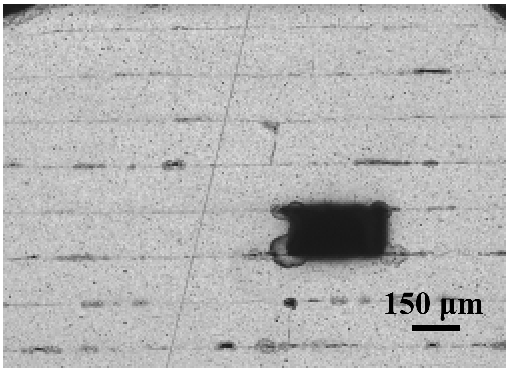
a: A Longitudinal sample



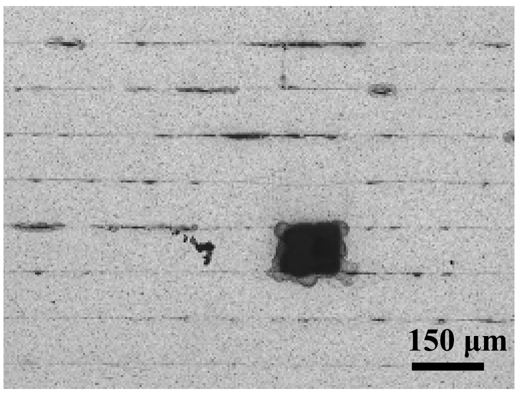
b: A 9435 sample



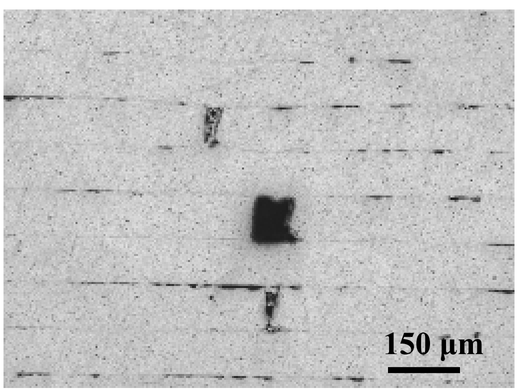
c: An R35 sample



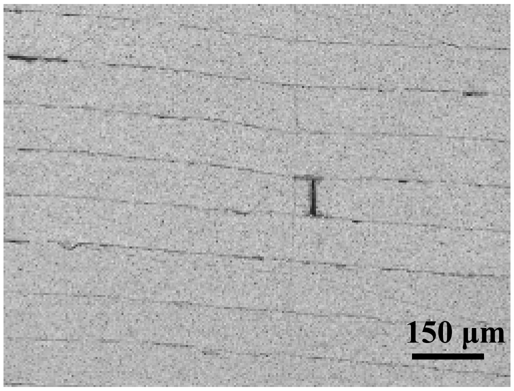
d: A 9423 sample



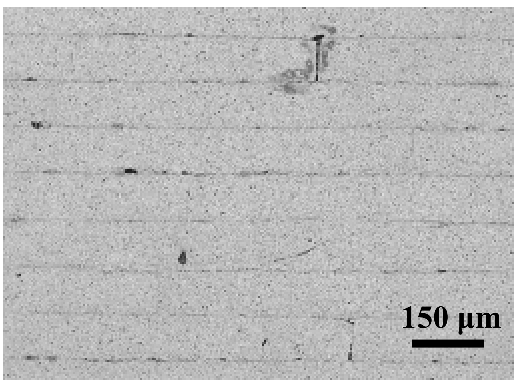
e: A 9411 sample



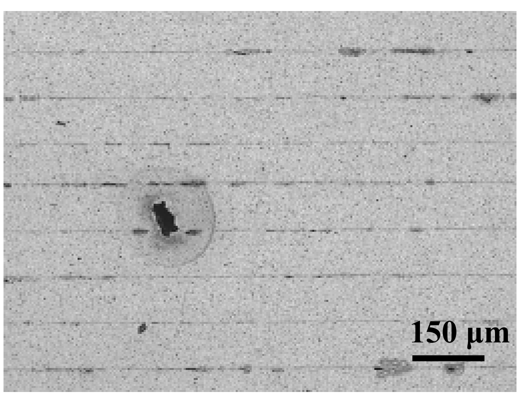
f: A 9399 sample



g: A 9387 sample



h: A 9375 sample



i: A 9363 sample

Figure 7: **Representative micrographs of each set of tensile specimens**

The micrographs in figure 7 above reveal the bonding conditions at the foil joints of the respective sample sets of the specimens. It is evident that the frequency and size of defects at the joints is proportional to the foil width specified in the machine code for the respective specimens. The 9435 sample in figure 7b, a sample of the specimens with the widest foil width setting, shows the widest gaps between the foils to the extent that a foil bent over into the gap in a lower layer can be observed. Virtually all alternate layers have sizable gaps in the sample. A trend can be observed in the size of defects from figures 7b to 7i representing a decrease in the foil width setting from 0.9435” (23.96mm) to 0.9363” (23.78mm). The foil joint defects progressively reduce down to the 9375 sample where the smallest defect occurrence is observed, and then slightly larger defects in the 9363 sample. It is noteworthy that the 9411 sample representing the most commonly used foil width setting for UC fabrications with the Solidica supplied Al 3003 alloys has joint defects. This can also be confirmed in the longitudinal sample represented in figure 7a that was also fabricated with a width setting of 0.9411”. It therefore means that the default foil width setting of 0.9411” for Al 3003 can not fabricate defect-free parts. It can also be observed in the micrographs that the foil edge-to-edge joints are not in perfect alignment across the layers for the 50% overlap condition, there is up to 150µm displacement between them. It shows that the UC machine does not precisely deposit foils in the location prescribed by the machine code. The precision of the machine is thus a limitation, as 150µm error is relatively high for a process that is sensitive to gap width differences of this magnitude. From observations made on the feeding and guiding mechanism of the machine, there is more clearance than required to precisely locate the foils in the tacking positions on the substrate. Also, when the foils are not properly tacked, sometimes they slide out of position during the welding operation, thereby creating gaps between adjacent foils. In addition to these, the translation precision of the gantry on the axes of the machine can also be a contributing factor.

3.2 Tensile Strengths

Table 1 shows the tensile strength data obtained from the specimens. The table contains the average strength and standard deviation. Figure 8 shows the same data in table 1 in the form of a bar chart for better comparison. Each of the bars in the figure represent the average tensile strength of each set of specimens, while the error bars show the range of tensile strengths in the respective set.

Table 1: Strength (MPa) Comparison for Tensile Test Specimens

Sample	1	2	3	Average	St. Dev.	St. Dev (%)
9435	137	123	129	129.7	7.0	5.42
R9435	166	153	157	158.7	6.7	4.20
9423	152	159	164	158.3	6.0	3.81
9411	166	185	188	179.7	11.9	6.64
9399	185	187	183	185.0	2.0	1.08
R9375	145	208	206	186	35.8	19.2
9387	189	188	201	192.7	7.2	3.75
9375	202	195	207	201.3	6.0	2.99
9363	186	199	206	197.0	10.1	5.15
Long	234	239	226	233.0	6.6	2.81

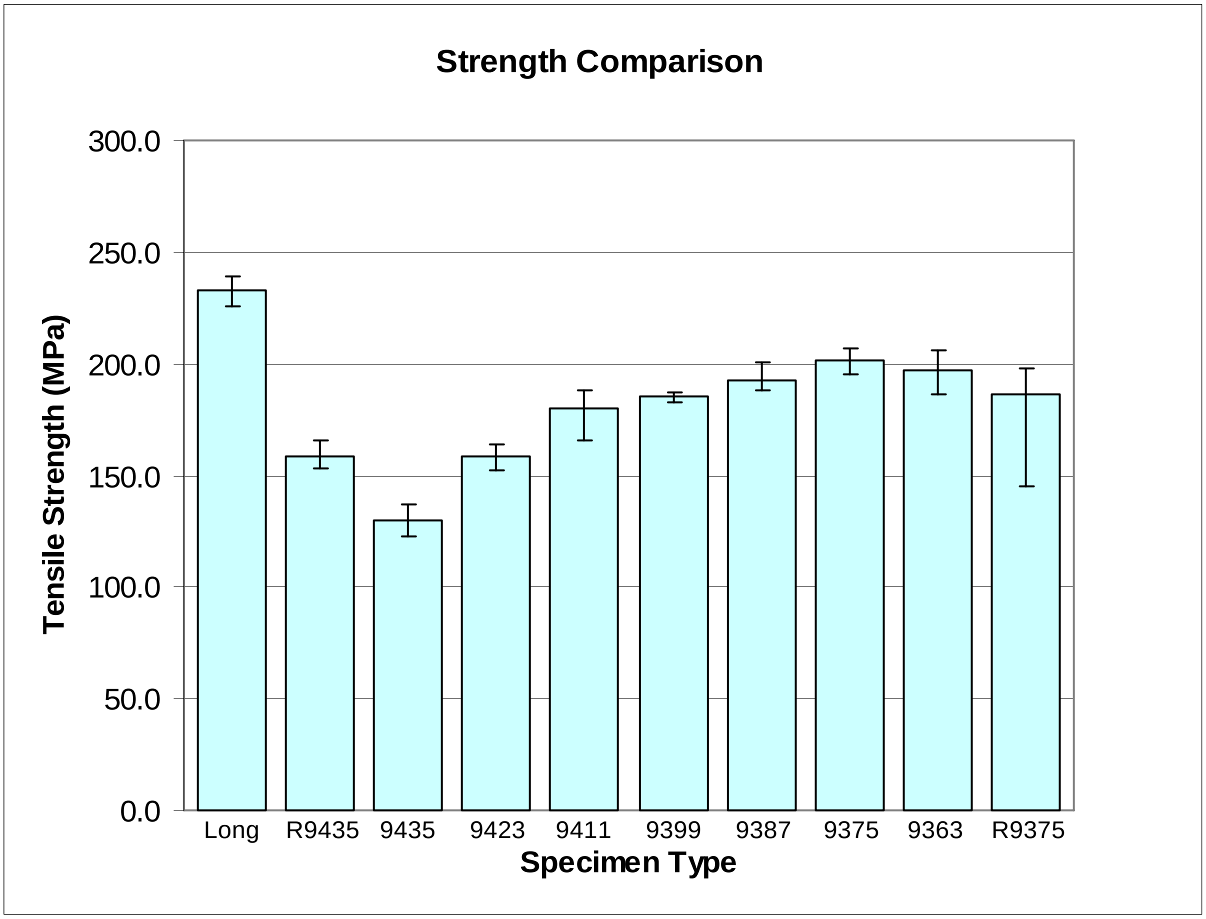
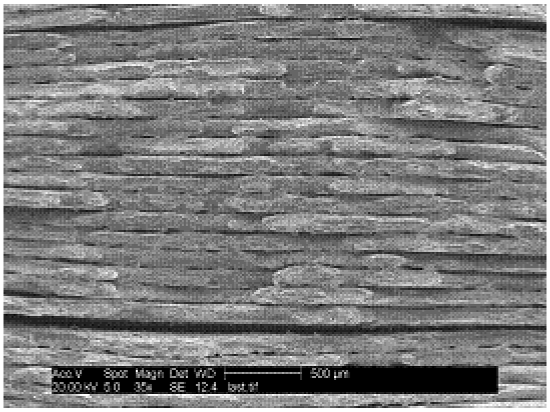


Figure 8: Bar chart with error bars showing strength comparison for samples fabricated with different width settings.

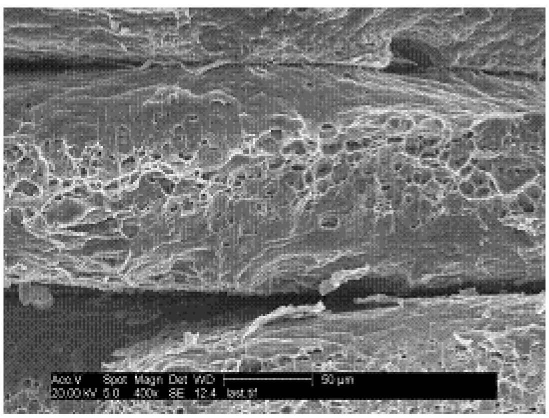
In the tensile test results, the 9435 samples have the lowest strength among the 50% overlap transverse tensile specimens. A trend similar to the one in the microstructure studies in 3.1 can be observed in the tensile results. From table 1 and figure 8, it can be seen that strength increases as foil width decreases. It means that as the bond quality at the foil joints improve, the strength increases. Since stresses are magnified at points of defects or voids, and the magnitude of amplified stress is proportional to the size of the voids, it means the increase in strength is a result of the decrease in defects at the joints. Therefore, it can be reasonably stated that the foil width specified determines the foil joint integrity, and hence the strength of a UC fabricated part. The tensile strengths peaked for the width settings of 0.9375" (23.81mm) at an average strength of 201.3 MPa as shown in table 1. The lower width value of 0.9363" (23.78mm) resulted in a smaller average strength of 197MPa. The difficulty encountered in welding the 9363 samples as a result of the reduced foil width values may have caused this reduction in strength. It can be said that the 0.9375" (23.81mm) width setting is the optimum width, beyond which the part begins to degrade in strength due to an accumulation of fabrication errors. This optimum width setting is more difficult to fabricate than the default 0.9411" setting. However, if strength is an important factor in the application of the fabricated part, it would be best to apply this optimum value.

3.3 Fracture features

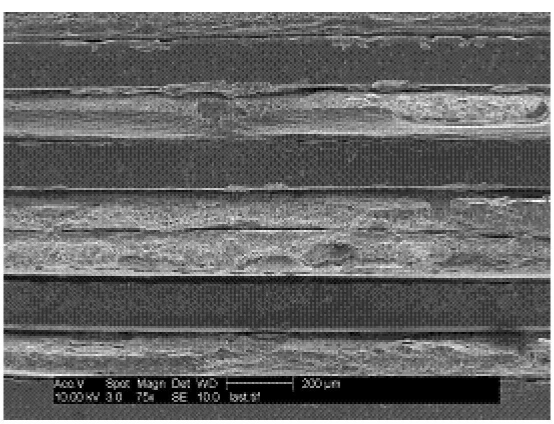
Some of the distinctive features of the fracture surfaces of the specimens as revealed by SEM are shown in figure 9.



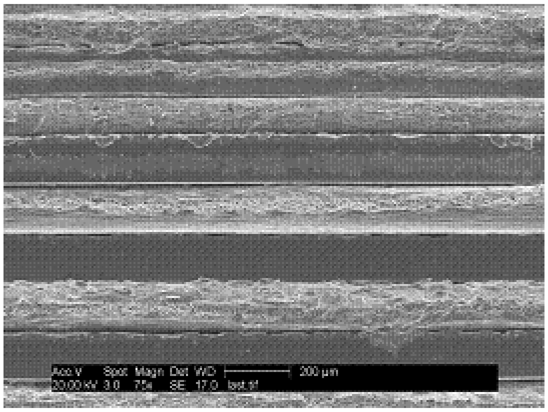
a: A view of the fractured surface of a longitudinal sample



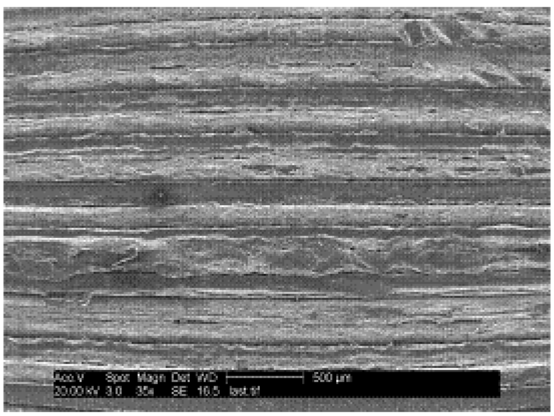
b: Lower magnification of the longitudinal sample



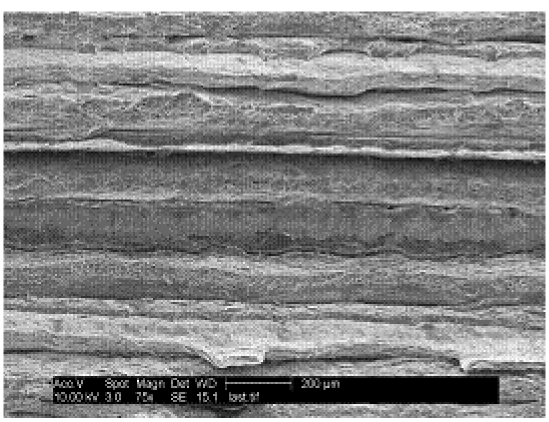
c: A view of the fractured surface of an R9435 sample



d: A view of the fractured surface of a 9411 sample

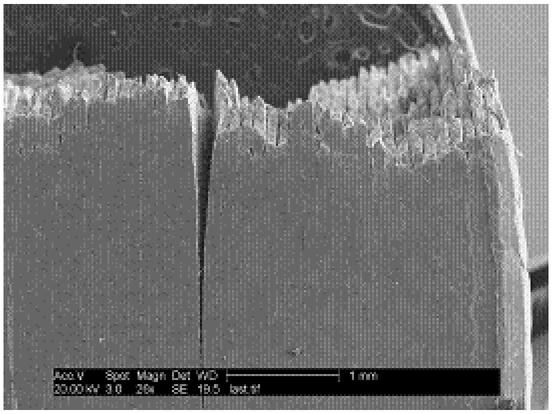


e: A view of the fractured surface of a 9387 sample

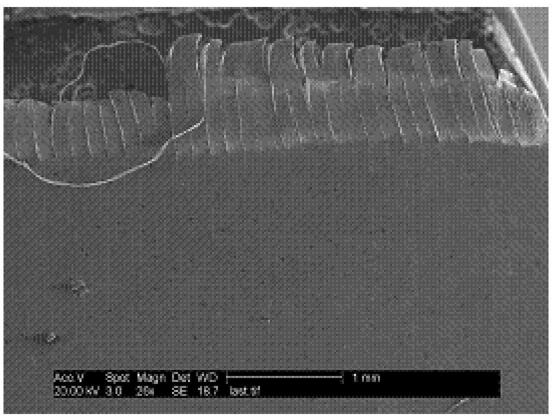


f: A view of the fractured surface of a 9375 sample

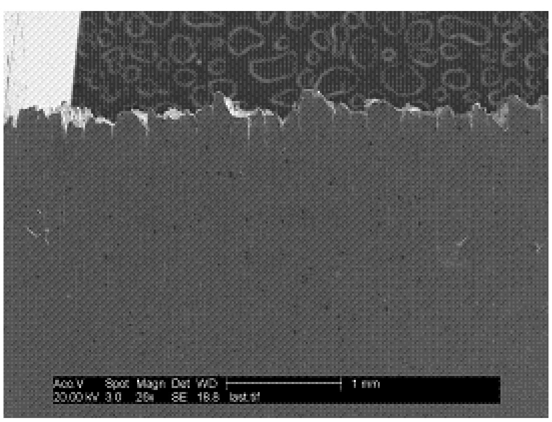
Figure 9: Fractured surface of selected sample specimens



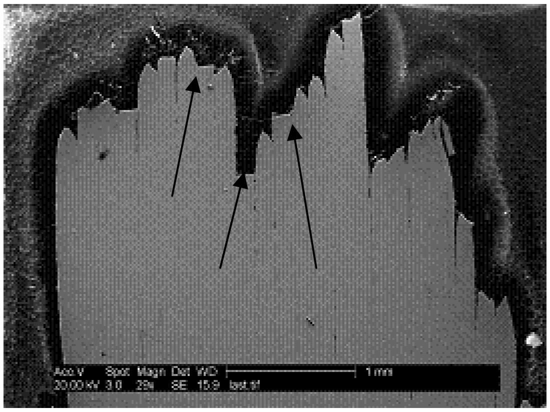
a: Side view of the fracture surface of a longitudinal sample



b: Side view of the fracture surface a 9411 sample



c: Side view of the fracture surface a 9387 sample



d: Fracture line of a polished R9435 sample

Figure 10: Fracture lines of some of the specimens

The SEM pictures for R9435 and 9411 samples in figures 9c and 9d show the mode of fracture propagation in parts with width settings above the optimum value. The figures show some foils with clean, unaltered surfaces at alternate layers for the 50% overlap settings and at random locations for the random overlap samples. The clean surfaces are the fracture paths through gaps created by foil joint defects, where no bonding occurred between adjacent foils. At those locations, there were no fractures in the material. The other foil surfaces with dimples are evidence of fracture at locations within continuous foils or at locations where good bonding occurred between adjoining foils.

Figure 10 show the fracture lines at the side view of some of the samples. In figure 10a, there is evidence of necking before final fracture in the longitudinal samples, a characteristic of ductile failure. This is understandable since all the foils run through the length of the samples, and all of them were fractured. In contrast, all the 50% overlap samples exhibit a somewhat flat fracture surface, which is characteristic of brittle materials. The flatness is due to the arrangements of the foils that have the foil joint lines almost directly above one another in alternate layers. Also, because perfect bonding was not achieved in all the joints, the weakest points in the specimens were at those un-bonded and partially bonded joints. The fracture lines therefore pass through them, and in the case of 50% overlap samples, this result in a near straight fracture line. In the case of random overlap samples, represented by an R9435 sample in figure 10d, the fracture line can be seen passing through un-bonded and partially bonded foil joints. The arrowed foils in figure 10d are some of the un-bonded foils in alternate layers, the fracture line in this case follow the random pattern of the foil arrangements.

Conclusions

In this work, it has been shown that the default foil width setting of 0.9411" (23.90mm) in UC fabrication with Solidica supplied Al 3003H-18 foil does not produce structures with optimal strength. Also, the quality of foil joints in terms of defects is directly correlated to the foil width setting in UC fabricated structures for transversely oriented foils with respect to loading direction. The higher the width set in the UC machine code, the poorer the foil joint quality for the fabricated part. The effects of the feeding and guiding mechanism for foil positioning with respect to joint defects have been highlighted. Improved feeding and guiding mechanisms will result in reduced defects, and also enhanced repeatability in foil placement.

Bonding quality at the joints has been found to be directly related to the strength of fabricated structures. Data generated through tensile tests, optical metallographic and fractographic studies shows that a width setting of 0.9375" (23.81mm) for the Al 3003 standard foils yields optimal strength for UC fabricated structures with transversely oriented foils to the direction of loading.

The longitudinal samples recorded better strength values than the transverse samples, in part because the foil used was manufactured by rolling, which inherently have anisotropic properties and also because of the defects at the edge-to-edge joints of the of the foils in each layer. The drop in strength for the specimens with widths above the optimum setting of 0.9375" are considerably less than 50% of the longitudinal samples, as might be expected if no load were carried across these joints. The bonding pattern observed in the micrographs for those samples show that some of the layers have well bonded foil joints, which means the frequency of the foil edge-to-edge defects is less than the number of joints in those specimens. This reasonably explains the reason for the higher strength than expected in those set of specimens.

The data generated from the randomly arranged foils i.e., R9435 and R9375 does not show general evidence of improvement over their counterparts with 50% overlap. While the R9435 show evidence of little improvement in strength over 9435 specimens, the R9375 recorded a lower average strength value when compared to 9375. It therefore, can be concluded that the randomly arranged foils do not have reliable or predictable strength values when compared to the trend observed with the 50% overlap specimens.

Acknowlegement

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References

Dawn R. Wright, (2003), "Ultrasonic consolidation of aluminum tooling", Advanced materials and processes, pp. 64-65.

Kong, C.Y.; Soar, R.C.; and Dickens, P.M. (2004), "Optimum process parameters for ultrasonic consolidation of 3003 aluminium." *Journal of Materials Processing Technology* (v146), pp181-187.

C. Y. Kong, 2005, "Investigation of Ultrasonic Consolidation for Embedding Active/Passive Fibers in Aluminum Matrices," Doctoral thesis, Loughborough University, Loughborough, United Kingdom.

G.D Janaki Ram, Y. Yang, and B.E. Stucker, (2006), "Effect of process parameters on bond formation during ultrasonic consolidation of Aluminum alloy 3003", Journal of manufacturing systems; Vol. 25, No. 3.

E.J. Siggard, A.S. Madhusoodanan, B Stucker,. and B. Eames, (2006), "Structurally embedded electrical systems using ultrasonic consolidation (UC)." *Proc.* of 17th Solid Freeform Fabrication Symp., Aug. 14-16, 2006, Austin, TX.

Y. Yang, G.D. Janaki Ram and B.E. Stucker, (2007), "An experimental determination of optimum processing parameters for Al/SiC metal matrix composite made using ultrasonic consolidation", Journal of engineering materials and technology – transactions of the ASME, 129(4) pp.538-549.

R.B. Tuttle (2007), "Feasibility study of 316L stainless steel for the ultrasonic consolidation process", Journal of manufacturing processes, July 2007.