ABSTRACT

Shape memory nickel-titanium (NiTi) alloys can recover up to 8% of induced strain allowing such alloys to be used in the creation of solid-state actuators. Despite the unique properties of NiTi alloys, their implementation in structural applications is expensive, complex, and in some cases unfeasible due to limitations of traditional joining techniques. This research investigates the joining of NiTi to itself, aluminum 2024, O1 tool steel, and 304 stainless steel by Ultrasonic Soldering (USS), a process that can solder difficult to wet materials without the use of flux. The USS joints were evaluated through strength testing, optical microscopy, and maximum calculated von Mises equivalent stresses developed during testing. Lap shear tests show NiTi/NiTi, NiTi/aluminum 2024, NiTi/O1 tool steel, and NiTi/304 stainless steel USS joints have average ultimate shear strengths of 30.9 MPa, 53.8 MPa, 37.2 MPa, and 40.6 MPa, respectively.

INTRODUCTION

Shape memory alloys are a class of smart materials that can be plastically deformed and then recover their original shape upon heating above the material’s austenitic finish temperature. NiTi is a particular shape memory alloy that can be strained up to 8% and fully recover all deformation [1]. The ability to recover large amounts of strain is due to the crystalline structure of the alloy transforming between martensite and austenite. Utilizing the strain recovery associated with this phase transformation, NiTi can be utilized as a solid state actuator. Since there are no moving parts, NiTi-based actuators can, in some cases, replace large, heavy motors, gear trains, and hydraulic systems. However, there are several issues in machining and joining NiTi to other structural materials which make it difficult to integrate NiTi into structural applications.

Machining of NiTi alloys has proven to be very difficult due to the high ductility, work hardening characteristics, and the non-linear stress-strain behavior of the material. These characteristics can cause poor surface finish, irregular chip breakage, and high tool wear [2]. The build-up of heat in traditional machining processes can also locally affect thermo-mechanical properties of the NiTi work piece [3]. Electric Discharge Machining (EDM) is commonly used to create NiTi parts, though this process is relatively expensive when compared to traditional machining processes. Much of the expense of using NiTi can be eliminated if a reliable and efficient way of joining it to traditional structural materials, such as aluminum or steel alloys, is found; however the concept of joining NiTi to itself and dissimilar materials presents several challenges.

Although fusion welding processes are commonly used for joining metal parts, however there are several concerns in fusion welding NiTi both to itself and to dissimilar metals. Local heating of NiTi during fusion welding nullifies the cold work in the alloy through melting and recrystallization in the weld pool or through grain growth in non-melting regions. The cold work serves to increase the magnitude and reversibility of the shape memory effect in shape memory NiTi. The loss of cold work
Solidification or “hot” cracking occurs during fusion welding of Ti-rich NiTi alloys. Since an alloy solidifies over a temperature range, solid and liquid compounds coexist as the weld is cooling. TiNi₂, a brittle compound, has a relatively low freezing point and is one of the last compounds to solidify. When the solidifying compounds begin to form grain structures, the liquid TiNi₂ can infiltrate the grain boundaries. As the weld cools, the solid lattice is put under stress as the entire work piece is thermally contracting. The stress creates cracks at the grain boundaries that then fill with more liquid alloy. As the liquid cools and solidifies the additional shrinking leaves cracks at the grain boundaries. These serve as starter cracks that can propagate through the weld and cause joint failure. In severe cases, the weld may fail completely as it cools after the initial welding process [4].

Cold cracking occurs when joining titanium alloys to ferrous alloys. The titanium and iron form brittle intermetallics, TiFe and TiFe₂, which have low strength at room temperature [3]. Fusion welding NiTi to steel readily creates these intermetallics which form along the weld line. The contracting volume of the work piece places the intermetallics phases under stress and causes cracks to propagate during cooling [5]. These cracks often result in total weld failure as the joint cools to room temperature.

Soldering NiTi work pieces is a more desirable option for creating joints containing NiTi. There is no melting of the base metal and the filler metal melts at or below 450°C [6, 7]. With relatively low temperatures, soldering avoids the loss of cold work that must be recovered when using fusion welding processes. The main obstacle in creating NiTi-containing solder joints is in wetting the surface of the NiTi with the solder. Tenacious surface oxides that form on the surface of Ti and its alloys usually require the use of harsh surface treatments and aggressive fluxes [8, 9]. The use of flux raises concerns including the increased complexity of an additional process step, waste disposal, health concerns for those working with fluxes, as well as issues with corrosion if flux residue is not completely cleaned from finished joints [7].

This research investigates the use of Ultrasonic Soldering (USS), a fluxless process, for creating joints between NiTi, aluminum 2024 (Al 2024), O1 tool steel, and 304 stainless steel (304 SS). The filler metal used in this research is a Sn-based Pb-free solder that has been developed for use with USS [10]. The solder contains an active element, Al, which allows the solder alloy to react with the base metal and improve adhesion [8]. When tinning the faying surfaces, a piezoelectric transducer creates ultrasonic vibrations at the tip of a soldering iron to create cavitations in the liquid solder resting on the base metal. As the cavitations implode they impinge upon the surface of the base metal breaking up surface oxide layers and cleaning the faying surface, Figure 1. The removal of surface oxides increases the wetting of the faying surface by the solder [7] and allows the solder to wet otherwise not-wetting materials such as ceramics, glass, titanium, and aluminum without the use of flux. [8].

This paper is organized as follows. The first part discusses the methods used to characterize the USS joints including lap shear testing and methods for microscopic analysis. The second section presents the results obtained from shear testing and microscopic analysis while the results are interpreted and failure modes are analyzed based upon the calculation of von Mises equivalent stresses in the discussion section.

EXPERIMENTAL METHODS

Sample Construction.

A lap shear joint is the typical geometry used for load-bearing solder, braze, and adhesive joints [6, 7, 11]. In this geometry, the joint area can be easily increased to augment joint strength. Also, unlike a solder joint in tension, the strength of a soldered lap shear joint is not strongly dependent on the thickness of the solder layer [12].

In order to test the USS joint shear strength when joined to typical structural materials, joints between two pieces of Al 2024, O1 tool steel, and 304 SS were created and tested. These baseline tests were performed in two groups, one with no surface treatment of the faying surfaces and the second using a 50 μm SiC grit blast of all faying surfaces followed by a methanol rinse to remove any SiC particles and other surface contaminants. Al 2024 was chosen because it is a common aerospace alloys noted for its fatigue strength and moderately high yield strength [13]. O1 tool steel is a common oil hardenable steel that is frequently used for tools, dies, and fixtures [14]. 304 SS was chosen because it is one of the most common stainless steel alloys noted for its corrosion resistance, formability, and good weldability [15].

During soldering, base metal pieces were placed on a hot plate and preheated to 250°C, approximately 20°C above the melting point of the filler metal, SonicSolder™ [10], to ensure that the solder was fully melted and to allow for cavitation.

Figure 1. SCHEMATIC REPRESENTATION OF THE ULTRASONIC SOLDERING PROCESS (COURTESY EDISON WELDING INSTITUTE).
The faying surfaces were next tinned using the USS iron. Once tinned, the base metals were placed on a soldering jig, which was designed to maintain a nominal solder thickness of 0.076 mm. Additional solder was placed at the joint interface in order to fill any voids by capillary action and to ensure a consistent, void-free, solder joint. The jig and sample were then taken from the hot plate and allowed to cool.

USS lap shear specimens were constructed using work pieces 9.52 mm thick, 17.15 mm wide and 38.10 mm long. The work pieces were soldered such that a joint area of 17.15 mm X 12.70 mm was created. Figure 2 shows a typical shear test specimen with nominal thickness dimensions. After soldering, samples were then machined to remove solder flash.

The Al 2024, O1 tool steel, and 304 SS shear samples are shown in Figure 3 (a), (b), and (c), respectively. The samples pictured have gone through the post soldering flash removal processes. During the final machining process, two samples, O1/O1 tool steel sample 1 and 304 SS/304 SS sample 4, broke. Both samples were from the set of joints that had no surface preparation prior to soldering.

Once baseline USS shear strength results were obtained for structural materials, a third set of lap shear joints was made to measure the shear strength of NiTi containing USS joints. NiTi pieces (55% wt. Ni) were jointed to NiTi, Al 2024, O1 tool steel, and 304 SS pieces. Dimensions of the NiTi lap shear joints are slightly different than the previous lap shear joints. The NiTi pieces used were 6.35 mm thick; shims were used in construction to ensure proper solder joint thickness was maintained. In creating NiTi containing joints, all samples were first surface treated with a 50 µm SiC grit blast and rinsed with methanol prior to being soldered. The joining process for NiTi containing lap shear joints was identical to the process for the previous USS joint sets. Figure 4 (a)-(d) shows NiTi/NiTi, NiTi/Al 2024, NiTi/O1, and NiTi/304 SS solder joints. These pictures show the joints before solder flash removal.

**Sample Testing.**

Shear tests of the lap joints utilized a testing jig that supported one half of the specimen while applying a direct shear load to the other half as shown in Figure 5. This loading scheme causes all resulting shear stress to be transmitted through the shear plane. Test specimens were loaded in compression under displacement control until failure. Displacement was controlled by a ramp of 0.254 mm/s. During testing, ram displacement was measured by an LVDT (linear variable differential transformer) integrated in the load frame and applied force was measured using a load cell placed in series with the load train.

**USS Sample Sectioning**

Two NiTi/Al 2024 USS joint were constructed for the purpose of mounting, sectioning, and polishing to observe the interface between the NiTi and Al 2024 with the filler metal. Al 2024 samples were machined with a 0.076 mm recess to control solder thickness. Faying surfaces of the NiTi and Al 2024 pieces were treated with a 50 µm SiC grit blast and methanol rinse prior to joining. One of the resulting joints was hot mounted in a polymer matrix while the second was cold mounted in an epoxy matrix.

**EXPERIMENTAL RESULTS**

**USS Lap Shear Joints**

The results for the USS lap shear tests for Al 2024/Al 2024 pairs, O1/O1 tool steel pairs, and 304 SS/304 SS pairs are presented in Tables 1, 2, and 3, respectively.

Without surface treatment, Al 2024/Al 2024 lap shear joints have an average ultimate shear strength of 67.2 MPa with a coefficient of variance ($C_v$), standard deviation relative to average shear strength, of 5.5%. With surface treatment, the average ultimate shear strength is 76.0 MPa with a $C_v$ of 2.0%. Force data for Al 2024/Al 2024 joint 1 with no surface treatment was not acquired due to an error in testing. Al 2024/Al 2024 joint 4 with no surface preparation was discarded as an outlier because the fracture surface shows a large void was present in the solder joint (Figure 6). This void was due to an error in manufacturing the sample and is therefore not representative of the strength of an Al 2024 USS joint.

The O1/O1 tool steel lap shear joints have an average ultimate shear strength of 13.0 MPa and a $C_v$ of 67.2% without surface treatment. With the application of surface treatment, the
average ultimate shear strength is 36.0 MPa with a \( C_v \) of 5.1%.

Similarly, 304 SS USS lap shear joints have an average ultimate shear strength of 3.9 MPa with a \( C_v \) of 82.0% when soldered with no surface treatment. With surface treatment the average ultimate shear strength is 31.2 MPa with a \( C_v \) of 34.6%.

Table 4 shows the ultimate shear stress for all NiTi-containing USS lap shear joints. The average ultimate shear strength is 30.9 MPa for NiTi/NiTi joints with a \( C_v \) of 8.9%, 53.8 MPa for NiTi/Al 2024 joints with a \( C_v \) of 6.3%, 37.2 MPa for NiTi/O1 tool steel with a \( C_v \) of 17.4%, and 40.6 MPa for NiTi/304 SS joints with a \( C_v \) of 13.7%.

**USS Sample Sectioning**

Figure 7 shows a micrograph of the hot mounted NiTi/Al 2024 USS joint section. The solder joint shows a uniform thickness of 0.127 mm and maintains intimate contact with both base metals throughout the joint. The joint did not show external signs of cracking, though in some regions long cracks have developed (Figure 8). These cracks are found at both the periphery of the joint as well as within the main joint area. The cold mounted joint shows no cracking in the main joint area but does exhibit cracking at the periphery of the sample.
Table 2. O1/O1 USS LAP SHEAR TEST RESULTS.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>36.1</td>
</tr>
<tr>
<td>2</td>
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<td>34.1</td>
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<td>37.8</td>
</tr>
<tr>
<td>4</td>
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<tr>
<td>Avg.</td>
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</tr>
<tr>
<td>S.D.</td>
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<td>1.8</td>
</tr>
<tr>
<td>$C_v$</td>
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<td>5.1%</td>
</tr>
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</table>

Table 3. 304 SS/304 SS USS LAP SHEAR TEST RESULTS.

<table>
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<td>20.1</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td></td>
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<tr>
<td>Avg.</td>
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</tr>
<tr>
<td>S.D.</td>
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<tr>
<td>$C_v$</td>
<td>82.1%</td>
<td>34.6%</td>
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</table>

Table 4. NiTi USS LAP SHEAR TEST RESULTS.

<table>
<thead>
<tr>
<th>Sample</th>
<th>NiTi</th>
<th>Al 2024</th>
<th>O1</th>
<th>304 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>51.9</td>
<td>40.4</td>
<td>46.9</td>
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<td>2</td>
<td>28.4</td>
<td>57.7</td>
<td>29.7</td>
<td>36.4</td>
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<tr>
<td>3</td>
<td>33.9</td>
<td>51.8</td>
<td>41.4</td>
<td>38.6</td>
</tr>
<tr>
<td>Avg.</td>
<td>30.9</td>
<td>53.8</td>
<td>37.2</td>
<td>40.6</td>
</tr>
<tr>
<td>S.D.</td>
<td>2.8</td>
<td>3.4</td>
<td>6.5</td>
<td>5.6</td>
</tr>
<tr>
<td>$C_v$</td>
<td>8.9%</td>
<td>6.3%</td>
<td>17.4%</td>
<td>13.7%</td>
</tr>
</tbody>
</table>

DISCUSSION

USS Lap Shear Joints

The results for USS lap shear tests on Al 2024, O1 tool steel, and 304 SS show that surface treatment is a necessary step even though the ultrasonic cavitation of the solder is meant to break up and disperses surface oxides and contaminants. All three passive material pairs show an increase in ultimate shear strength and a decrease in their respective coefficients of variance when
soldered after being grit blasted with 50 µm SiC and a methanol rinse. This shows that the additional surface preparation yields stronger and more consistent joints.

To investigate the nature of the USS joints, ultimate shear strengths were used to calculate the maximum equivalent von Mises stress for each lap shear sample. The von Mises stress was calculated using equation 1 by considering a differential solder element subject to only pure shear stresses (Figure 9). When subjected to only shear stresses, $\sigma_1, \sigma_2 = \pm \tau_{xy}, \sigma_3 = 0$, and the equivalent stress is given by

$$\sigma_{eq} = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]}.$$

The equivalent stresses in Al 2024, O1 tool steel, and 304 SS lap shear joints are calculated by

$$\sigma_{eq} = \sqrt{3} \tau_{xy}.$$

These stresses are summarized in Table 5.

Using the equivalent stresses and qualitative observation of fracture surfaces, a determination can be made as to how the solder joint failed: in an adhesive or cohesive mode. If the calculated equivalent stress is significantly less than the bulk ultimate tensile strength of SonicSolder$^{TM}$, 53.8 MPa as found from bulk solder tensile tests, it indicates that the failure did not occur within the solder itself but rather at the interface of the solder and base metal (adhesive failure). This can be corroborated if a fracture surface shows a significant amount of bare base metal. If both base metal pieces still have solder on the faying surfaces after testing and have an equivalent stress equal to or greater than the bulk solder tensile strength, this indicates that the joint failed cohesively, a failure of the bulk solder between the base metal pieces.

In considering surface preparation, the Al 2024 joints show a marginal increase in maximum equivalent stress. Both joint sets indicate a cohesive failure mode with equivalent stresses in excess of the solder ultimate tensile stress and solder covered fracture surfaces. For O1 tool steel and 304 SS samples, the difference between the strengths of joints with and without surface treatments is clearly delineated between adhesive and cohesive failures. Without surface treatment, the equivalent stresses are significantly lower than the strength of the bulk solder and fracture surfaces show large areas of bare base metal. However, with surface treatment, both steel base metals have an average equivalent stress greater than the ultimate tensile strength of the solder and show greater adhesion to the base metal.

Both the O1 tool steel and 304 SS lap shear samples are significantly weaker than Al 2024 lap shear samples. The lower strengths seen in the O1 tool steel and 304 SS lap shear speci-
mens without surface treatment may be due to the nature of the surface oxides and hardness of the underlying base metal. When cavitations implode and impinge on Al 2024, the impingements cause deformation of the Al 2024 under the aluminum oxide layer. The deformation of the supporting base material causes the brittle oxide layer to crack and exposes nascent surfaces of the base metal. Steel alloys typically have elastic moduli three times larger than aluminum alloys. It follows that the O1 and 304 SS samples would not deform as much as Al 2024 while being impinged by the solder cavitations. With less deformation there would likely be less disruption of the oxide surface revealing less nascent metal surface area with which the solder can alloy.

Even with surface treatment, O1 tool steel and 304 SS lap shear joints are still significantly weaker than Al 2024 joints. This is likely due to the nature of the alloying between the filler metal and different base metals. Filler metal-base metal alloying is a key component in the strength of solder and braze joints [6, 7]. The Al 2024 lap shear joints are likely the strongest of the three base metal joints because the composition of SonicSolder™ contains a percentage of aluminum [10]. With O1 tool steel and 304 SS, base metal alloying may increase adhesive strength, but the composition of each material may allow for the formation of intermetallic compounds at or near filler metal-base metal interfaces. Where Al in the solder may have made the Al 2024 lap joints stronger, Al-Fe intermetallics such as FeAl₃ and FeAl₄.

Of all NiTi-containing joints, the NiTi/NiTi lap shear joint have the lowest average ultimate shear strength but also have the second lowest coefficient of variance. Furthermore, the calculated equivalent stresses for NiTi/NiTi lap shear joints are near the ultimate tensile strength of bulk SonicSolder™, as shown in Table 6. This may indicate that the solder is not alloying with the NiTi or may be forming adverse intermetallic compounds in the solder joint. The other NiTi/base metal pairs show an increase in equivalent stress over the NiTi/NiTi joints.

In joining NiTi to Al 2024, the average shear strength decreased relative to the Al 2024/Al 2024 joints but increased relative to the NiTi/NiTi joints (Table 4). A similar comparison for joints containing O1 tool steel and 304 SS suggests that the NiTi/steel joints have a higher strength than the like base metal joints, O1/O1 tool steel, 304 SS/304 SS, and NiTi/NiTi joints. The coefficients of variance for the steel-containing pairs are again the highest of all material pairs. The large coefficients of variance indicate that the strengths for any steel-containing lap shear joints are statistically equivalent. The inconsistency of the steel-containing joints also indicates that the joining system used, USS and the specific filler metal, is not a good candidate for creating solder joints with steel base metals.

One aspect that concerns the NiTi/passive metal USS joints is the residual stresses due to differential thermal expansion and contraction of the different base metals. Evidence of the residual stresses is seen in the section of a NiTi/Al 224 USS joint showing cracks in the solder (Figure 8). The NiTi/Al 2024 sectioned joints both showed cracks at various parts of the solder joint. These cracks likely occur due to differential contraction of the NiTi and Al 2024 pieces as they cooled below the melting point of the solder. It is expected that similar cracks appear in the lap shear samples with dissimilar base metals. These cracks can act as stress concentrators and fracture initiation points resulting in premature failure of the joint.

These findings are applied to the lap shear USS joints containing NiTi and a passive metal in order to estimate the residual stresses in the solder. Stress in the outer fiber of the passive metal, denoted \( \tau_p \), is calculated by

\[
\sigma_p = -\frac{(\alpha_{NiTi} - \alpha_p) (\Delta T) E_p}{K_1} \left[ \frac{t_p}{t_{NiTi}} + 2 \left( \frac{t_p}{t_{NiTi}} \right) + \frac{E_{NiTi} t_{NiTi}}{E_p t_p} \right],
\]

(3)

and the stress in the outer fiber of the NiTi piece, \( \sigma_{NiTi} \), is given by

\[
\sigma_{NiTi} = \frac{-\alpha_{NiTi} - \alpha_p (\Delta T) E_p}{K_1} \left[ \frac{3 t_p}{t_{NiTi}} + 2 - \frac{E_{NiTi}}{E_p} \left( \frac{t_p}{t_{NiTi}} \right)^3 \right],
\]

(4)

where

\[
K_1 = 4 + 6 \frac{t_p}{t_{NiTi}} + 4 \left( \frac{t_p}{t_{NiTi}} \right) + \frac{E_p}{E_{NiTi}} \left( \frac{t_p}{t_{NiTi}} \right)^3 + \frac{E_{NiTi} t_{NiTi}}{E_p t_p}.
\]

(5)

These calculations [16] consider bimetal systems but they do not take into account the non-linear stress-strain curve of the NiTi material. For this initial analysis, the NiTi is instead treated as a linear elastic material with an elastic modulus equal to its martensitic elastic modulus, \( E_M \). Material properties used for calculation of residual stresses are shown in Table 7. The stresses are considered to develop when the joint cools from 231°C, the melting point of SonicSolder™ [10], to 20°C.

By assuming a linear stress gradient from the outer fiber of the passive material and outer fiber of the NiTi in each joint, the

<table>
<thead>
<tr>
<th>Sample</th>
<th>NiTi</th>
<th>Al 2024</th>
<th>O1</th>
<th>304 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.9</td>
<td>89.9</td>
<td>70.0</td>
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</tr>
<tr>
<td>2</td>
<td>49.3</td>
<td>99.9</td>
<td>51.5</td>
<td>63.0</td>
</tr>
<tr>
<td>3</td>
<td>58.7</td>
<td>89.6</td>
<td>71.7</td>
<td>66.8</td>
</tr>
<tr>
<td>Avg.</td>
<td>53.6</td>
<td>93.1</td>
<td>64.4</td>
<td>70.3</td>
</tr>
</tbody>
</table>
stress at the middle of the solder joint was calculated by interpolating the stress at 9.563 mm from the outer fiber, \((t_p + t_{solder}/2)\), of the passive material:

\[
\sigma_{solder} = \left( \frac{\sigma_{NiTi} - \sigma_p}{t_p + t_{NiTi} + t_{solder}} \right) (t_p + t_{solder}/2) + \sigma_p. \tag{6}
\]

The resulting estimated residual stresses are presented in Table 8. If the shape memory properties of the NiTi were considered the resulting residual stresses would be less than the stresses calculated using linear elastic NiTi due to the detwinning stress plateau in the NiTi stress-strain curve [17].

The resulting compressive stresses for the NiTi/passive material USS lap shear joints would increase the equivalent stresses experienced in the solder joint, though due to the linear estimation of NiTi portion of the joints, this calculation is reserved until further modeling of the system is accomplished.

### USS Sample Sectioning

The difference in the amount of cracking between the hot and cold mounted USS sections indicates that the mounting process may exacerbate the cracking present due to differential thermal expansion. In the hot mounting process, the sample is heated to a substantial fraction of the melting point of the solder and then is cooled using cold water. This thermal shock likely causes crack growth in the sample, but as observed in the cold mounted sample, cracking is still evident when the hot mounting process is not used. These indicates that the differential thermal expansion of the base metal pieces is causing initial cracking in the solder joint as it cools, though the extent of the cracking requires further investigation.

### CONCLUSION

The lap shear testing suggests that USS is best suited to joining NiTi to Al 2024. This material pair has the highest ultimate shear strength of all NiTi-containing joints and the lowest coefficient of variance indicating that it is the strongest and most repeatable NiTi-containing joint created through USS. In addition, USS can be used to create consistent joints between NiTi and itself. For all USS joints, proper surface preparation is paramount in creating strong, consistent bonds.

Additional modeling is also required to estimate the stresses in the solder joints due to differential thermal expansion of the NiTi and structural materials. Also, current joints can be further analyzed to observe what types of compounds form as the result of alloying between the base metal and solder as well as investigating the extent of crack initiation based upon different coefficients of thermal expansion of the joined base metals.

### ACKNOWLEDGMENT

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