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Investigating the effect of applied pressure on reactive multilayer foil joining

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Abstract

This paper describes the effect of applied pressure on reactive joining of stainless steel specimens and Al alloy specimens using nanostructured Al/Ni foils and AuSn and AgSn solder layers. For a given material system, higher applied joining pressure enhances the flow of the molten solder and thus improves wetting and bonding. Shear strengths of the reactive joints are shown to increase as the pressure that is applied during joining rises to a critical value. At higher applied pressures joint shear strengths remain relatively constant. The critical applied joining pressure is shown to be dependent on the foil thickness (or total heat of reaction), and the properties of the solder material and components, which determine the duration of melting of the solder and the maximum temperature at the solder/component interface. Longer durations of melting and higher interface temperatures enhance the flow of solder, improve wetting conditions and result in lower critical applied pressures.
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1. Introduction

Self-propagating formation reactions in nanostructured multilayer Al/Ni foils provide rapid bursts of energy at room temperature [1–3]. These reactive foils can act as local heat sources that can heat and melt surrounding solder or braze layers and join materials. Reactive foil soldering or brazing can be performed at room temperature and thus eliminates the need for furnaces or other external heat sources. Since heating is very localized to the interface during reactive joining, temperature sensitive components or materials can be joined without thermal damage. The localized heating offered by the reactive foils is also advantageous for joining materials with very different coefficients of thermal expansion, e.g. joining metals and ceramics. It has been shown that a wide variety of materials including Cu, Au-plated stainless steel, Au-plated Al, metallic glass, as well as SiC/Ti and Al/Al_2O_3 pairs have been successfully joined using this novel technique [4–10].

Previous research on reactive joining has suggested that under an applied pressure of 100 MPa, Au-plated stainless steel specimens can be joined successfully using Incusil coated Al/Ni reactive foils and AuSn solder layers. A tensile shear strength of 48 MPa was measured for these reactive joints. It was also observed in these initial experiments that a large fraction of the AuSn solder flows into cracks within foils and out of the joint area during joining [4,5]. The extrusion of the molten solder may limit the application of this method when joining components onto electronic boards as the extrusion of solder may damage surrounding components and circuit lines on the same board. Therefore one desires to control the movement of molten solder during joining by

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varying the pressure applied during the bonding of a given material system. Ideally one can identify applied joining pressures that ensure strong bonds but minimize the extrusion of the molten solder out of the joint area. In addition, since loading very large specimens to high pressures requires large and expensive capital equipment, identifying the minimum applied pressure that is required to form a reliable joint is useful. Such knowledge will enable one to determine the feasibility of joining large components using this novel reactive joining technique.

It has been reported that the applied pressure during both conventional joining and reactive joining affects the performance of the resulting bonds [8,11]. For conventional furnace soldering, increasing joining pressure enhances the flow of the solder and helps eliminate porosity, thus reducing the processing time and temperature [11]. Applied pressure also plays an important role in reactive multilayer joining processes. For example, when Zr-based bulk metallic glass samples were joined using reactive Al/Ni foils, the shear strength of the joints increased with larger joining pressures. It was suggested that increasing the applied pressure during joining raises the driving force for the softened glass to flow into the cracks in the reactive foils [8]. In this case, no solder or braze material is used and joints are formed by softening the components themselves. However, in a large variety of applications of reactive joining methods, solder (or braze) materials are used. Joints are formed by melting the solder (or braze) and wetting the components being bonded. The effect of applied joining pressure on reactive soldering (or brazing) has not been addressed in previous research.

This paper describes the effect of applied pressure on reactive joining of Au coated stainless steel and Al specimens using nanostructured Al/Ni foils and AuSn and AgSn solder layers. The stainless steel joints and Al joints were formed under various applied pressures in order to (1) optimize the flow of the molten solder, (2) fully wet the specimens, and (3) form strong joints while minimizing solder extrusion. The microstructure and mechanical strength of the resulting joints were characterized using scanning electron microscopy (SEM) and tensile shear lap tests, and fracture surfaces were characterized using optical stereomicroscopy. The duration of the melting of the solder layers during reactive joining and the maximum temperature at the solder/component interface were numerically predicted for both sets of samples. The applied joining pressure and the resulting shear strengths are correlated with the flow of the molten solder, duration of melting, maximum temperature at the solder/component interface, and the wetting of the components for both stainless steel samples and Al alloy samples. A critical applied pressure was identified so that a strong reactive joint can be successfully formed with minimal solder extrusion and the effect of foil thickness, solder properties, and component properties on the critical applied pressure is explained.

2. Experiments

Reactive multilayer Al/Ni foils were fabricated by magnetron sputtering from Al (Al–0.7 wt% (Si, Fe)–0.1 wt% Cu) and Ni (Ni–7 wt% V) targets onto water-cooled brass substrates that were rotated in front of the targets. The relative Al and Ni layer thicknesses were adjusted to a 3:2 ratio to produce foils with a 1:1 atomic ratio of Al to Ni–V. Three different kinds of foils were used in this study. The 40 μm thick foils contained 640 bilayers and had a bilayer thickness of 62.5 nm. The 100 μm thick foils contained 2000 bilayers and had a bilayer thickness of 50 nm. The 160 μm thick foils also contained 2000 bilayers but had a bilayer thickness of 80 nm. A 1 μm thick layer of Incusil ABA braze (59 wt% Ag–27.25 wt% Cu–12.5 wt% In–1.25 wt% Ti) was deposited on both sides of the foils, in order to enhance wetting of the foils by the AuSn or AgSn solder during joining. After sputter deposition, the Incusil coated Al/Ni multilayers were peeled from the substrates so that free-standing foils were obtained.

As-deposited and reacted foils were examined by X-ray diffraction (XRD) to verify the phases present. The velocities of reactions of the foils were measured using an optical method that records the intensity of light from the reaction flame as it passes through a series of optical fibers with a known spacing, as described earlier [12]. Heats of reaction for these foils were measured using a Perkin–Elmer differential scanning calorimeter (DSC). The foils were heated from room temperature to 725 °C at a rate of 40 °C/min and the heats of reaction were obtained by integrating the net heat flow with respect to time [13,14].

Tensile shear lap specimens were machined from 316L stainless steel and 6061 Al alloys. The stainless steel specimens and Al alloy specimens measure 0.5 mm × 6 mm × 25 mm and were electroplated with Ni and then Au prior to bonding to enhance wetting. The surface roughness of the Ni–Au plated stainless steel and Al specimens was characterized using a DEKTAK3 profilometer. Joints were made by stacking two 25 μm thick AuSn solder (80 wt% Au–20 wt% Sn) or two 25 μm thick AgSn solder (3.5 wt% Ag–96.5 wt% Sn) layers and one reactive Al/Ni foil between two stainless steel specimens or two Al alloy specimens under applied pressures ranging from 2 kPa to 300 MPa, as shown schematically in Fig. 1. The foils used to join stainless steel specimens were 40 and 100 μm thick, while the foils used to join Al specimens were 100 and 160 μm thick. By igniting the reactive foils with a spark, at room temperature and in air, the formation reaction of the foils can self-propagate. The heat from the reaction can melt the

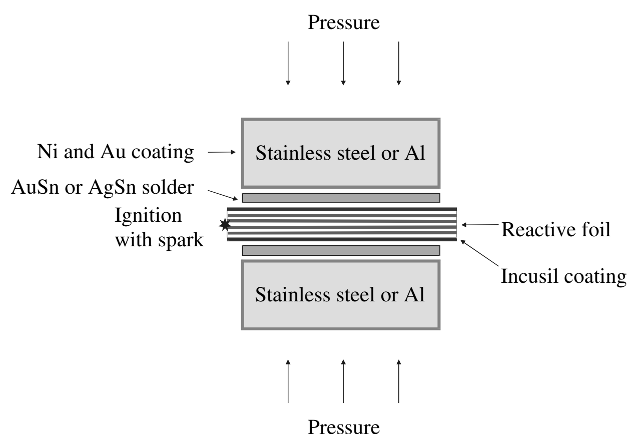

Fig. 1. Schematic showing reactive joining of Au-coated stainless steel components and Al alloy components using an Incusil coated Al/Ni foil and two AuSn or AgSn solder layers.

surrounding AuSn or AgSn solder and thereby enable bonding of the stainless steel and Al alloy specimens.

After reactive joining, the stainless steel and Al alloy shear lap joints were tested in tension at room temperature using an Instron testing machine and a crosshead speed of 0.1 mm/min. Shear strengths of these bonds were calculated by dividing the maximum failure load by the joint area, which ranged from 18 to 30 mm^2.

Fracture surfaces of the joints were observed using a stereomicroscope to study the wetting condition of the specimens, extrusion of solder, and the failure mechanism of the joints. Cross-sections of untested stainless steel joints made using Al/Ni foils and AuSn solder layers were evaluated using SEM.

3. Numerical methods

The durations of melting of the AuSn and AgSn solders and the temperatures at the solder/component interfaces in the reactive joining process were studied numerically. Properties of the foils, solders, and components, such as thermal conductivity, heat capacity, heat and velocity of reaction, and thicknesses of the foil, solders, and components were incorporated into the model. The model is based on a simplified description of self-propagating reactions that relates the nanoscale transport and kinetic phenomena within the foil, which govern the self-propagation of the reaction, with the thermal transport and phase evolution, which occur in the solder layers and components. The model assumes one-dimensional motion of the reaction front, which is described using the experimentally determined heats and velocities of the reactions. Our computation focuses on simulating heat flow into the solder layers, phase-changes within these layers, and temperature evolution within the bonded components. The temperature evolution can be obtained by integration of the energy conservation equation, which is independently solved within the reactive foil, solder layers and components:

$$\rho \frac{\partial h}{\partial t} = \Delta \cdot q + \dot{Q}, \tag{1}$$

where ρ and h are the density and enthalpy of the corresponding layer, t is time, q is the heat flux vector, and $\dot{Q}$ is the heat release rate. The enthalpy, h, is related to the temperature, T, through a relationship that involves the material's heat capacity, c_p, and the latent heat of fusion, h_f. The term $\dot{Q}$ represents the rate at which heat is released by the self-propagating front as it traverses the reactive foil. Note that $\dot{Q}$ is localized within the front that traverses the foil, and vanishes within the fusible materials and the components. A third-order finite-difference discretization of the energy equations is used in conjunction with explicit third-order time integration of the discretized evolution equations. The boundary conditions for the temperature in each layer are determined using a thermal interface model. The model accounts for thermal resistance effects at the physical interfaces between un-bounded layers and assumes that the thermal resistance exponentially decreases when melting and wetting occurs at the interface. More details of the model can be found in a previous paper [5].

4. Results

4.1. Characterization of reactive foils

For the as-deposited Al/Ni foils, all major X-ray diffraction peaks correspond to Al and Ni. After reaction, all major peaks correspond to the ordered B2 AlNi compound, which is the equilibrium compound for this composition. Since only one small peak remains unidentified, the B2 AlNi compound is expected to be the dominant product when reacting the foil during joining.

DSC curves for the Al/Ni multilayer foils used in this study, with bilayer thicknesses of 50, 62.5 and 80 nm, are shown in Fig. 2. By integrating the heat flows with respect to time, the heats of reaction, ΔH, were obtained. The calculated heats of reaction for these three bilayers are 1179, 1164, and 1199 J/g. The similarity of these values suggests that the intermixing between layers that occurs during deposition was very limited in depth, relative to the bilayer thicknesses examined [2,3,14]. The average heat of reaction for these three bilayers was determined to be 1180 J/g.

Reaction velocities for foils with bilayer thicknesses of 50, 62.5 and 80 nm were measured to be 5, 4 and 3.5 m/s, respectively. As bilayer thickness decreases from 80 to 50 nm, the diffusion distance between layers becomes smaller and atoms can mix more rapidly so that

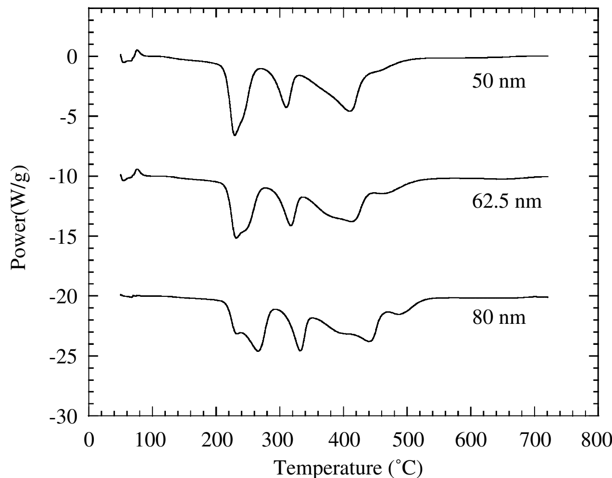

Fig. 2. Net DSC curves of Al/Ni multilayer foils with bilayer thicknesses of 50, 62.5 and 80 nm, measured at a heating rate of 40 °C/min. The curves plotted here were obtained by running two scans to 725 °C and subtracting the second (baseline) scan from the first scan.

heat is released at a higher rate and the reactions travel faster through the foils. These measured heats and velocities were used as inputs for the numerical predictions of thermal transport during the joining process.

4.2. Numerical results

The duration of melting of the AuSn and AgSn solder layers and the temperatures at the solder/component interfaces during reactive joining of stainless steel and Al alloy are numerically predicted and the results are shown in Table 1. When the stainless steel specimens are joined using 40 μm thick Al/Ni foils and 25 μm thick AuSn solder layers, the duration of melting of the AuSn solder layer is 0.5 ms and the maximum temperature at the solder/stainless steel interface is 455 °C. As the foil thickness increases to 100 μm, the duration of melting rises to 5 ms and the maximum temperature rises to 680 °C.

Compared with stainless steel joining, when the Al alloy specimens are joined using 100 μm thick Al/Ni foils and 25 μm thick AuSn solder, the duration of melting of the AuSn solder layer is only 1 ms and the maximum temperature at the solder/Al interface decreases to 481 °C. The shorter duration of melting and the lower temperature at solder/Al interface are due to the much higher thermal conductivity of the Al alloy (167 W/mK) compared with that of the stainless steel alloy (16.2 W/mK). When joining components with higher thermal conductivity, heat released from the reactive foils is transferred to the components more rapidly, resulting in quicker cooling and a shorter duration of melting of the solder layer [10]. The duration of melting of the AuSn solder rises to 5 ms as the foil thickness increases to 160 μm, and the maximum temperature at the solder/Al interface increases to 567 °C.

When 25 μm thick AgSn solder layers, instead of AuSn solder layers, are used to join stainless steel specimens with 40 μm thick Al/Ni foils, the duration of melting of the AgSn solder and the temperature at the AgSn solder/component interface are numerically calculated to be 1 ms and 471 °C, respectively, compared to 0.5 ms and 455 °C for the AuSn solder.

4.3. Characterization of the reactive joints

4.3.1. Cross-sectional microstructure

Cross-sectional SEM photographs of two sets of stainless steel specimens that were joined under different pressures, 10 kPa and 60 MPa, are shown in Fig. 3. In both cases a 100 μm thick Al/Ni reactive foil and two free-standing 25 μm thick AuSn solder layers were used. When the specimens were joined under a lower applied pressure (10 kPa), the thickness of the AuSn solder layers remained constant at approximately 25 μm, before and after joining (Fig. 3(a)). However when the specimens were joined under a much higher applied pressure (60 MPa), the majority of the solder flowed out of the joining area, and the AuSn solder layers decreased in thickness from 25 to 5 μm (Fig. 3(b)). These results show that increasing applied joining pressure will facilitate the flow of molten solder and will result in thinner solder layers as expected.

4.3.2. Shear strength

Shear strengths of stainless steel joints made with Al/Ni foils (40 and 100 μm thick) and AuSn solder layers (25 μm thick) were measured and plotted as a function of applied joining pressure in Fig. 4. For the joints made with 100 μm thick foils, as the applied joining pressure increases from 2 to 10 kPa, shear strengths increase from 8 to 50 MPa. Further increases in the applied joining

Table 1
Numerical predictions of the duration of melting of AuSn and AgSn solder layers and the maximum temperatures at the solder/component interfaces

Component	Foil thickness (μm)	Solder	Duration of melting (ms)	Maximum temperature at interface (°C)
Stainless steel	40	AuSn	0.5	455
Stainless steel	40	AgSn	1	471
Stainless steel	100	AuSn	5	680
Al	100	AuSn	1	481
Al	160	AuSn	5	567

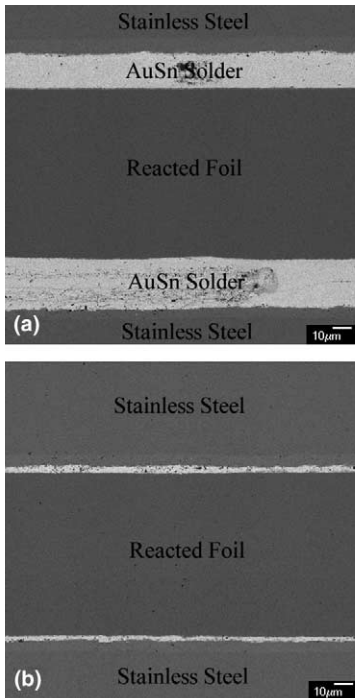

Fig. 3. SEM micrographs of stainless steel components joined using one reactive Al/Ni foil (100 μm thick) and two free-standing AuSn solder (25 μm thick) layers under an applied joining pressure of (a) 10 kPa. Here the thickness of the solder layer remains constant at approximately 25 μm before and after reactive joining. (b) At 60 MPa, note that most of the AuSn solder flows out of the joint and the thickness of the solder layer is approximately 5 μm.

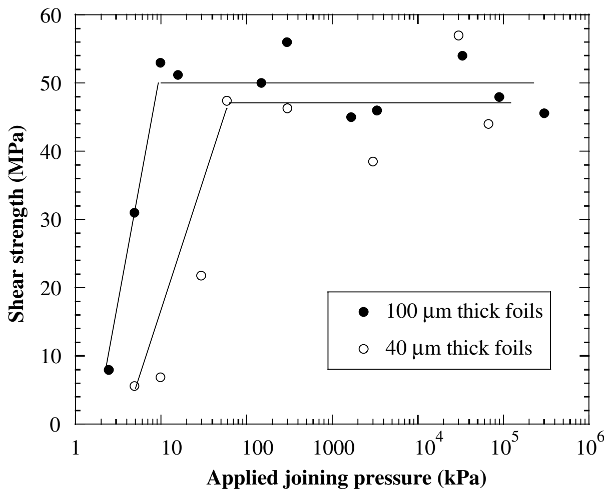

Fig. 4. Tensile shear strength of stainless steel joints made with reactive Al/Ni foils (40 and 100 μm thick) and AuSn solder (25 μm thick) layers, as a function of applied joining pressure.

pressure do not raise the shear strength of the joints. The strengths remain constant at approximately 50 MPa for pressures ranging from 10 kPa to 300 MPa. Shear strengths of the joints made with 40 μm thick Al/Ni foils vary with applied joining pressure in a similar way. The strengths increase with increasing applied pressure until pressure reaches a critical value of 50 kPa. Afterwards strengths are almost constant, as shown in Fig. 4, near 50 MPa. Failure sites shift from the solder/sample interfaces to the solder layers as applied pressure increases.

The shear strengths of Al alloy joints made with 100 μm thick Al/Ni foils and 25 μm thick AuSn solder layers were plotted as a function of the applied joining pressure in Fig. 5 and are compared with strengths for stainless steel joints. Shear strengths increase until the applied joining pressure reaches a critical value for both the stainless steel joining and Al alloy joining. The same trend in failure location occurs as well. However, the critical applied pressure for stainless steel joints and Al joints are different. Under an applied joining pressure of 10 kPa, stainless steel specimens can be joined successfully, and offer a shear strength of approximately 50 MPa. The Al alloy joints though, are still quite weak at this pressure with a shear strength less than 10 MPa. The applied joining pressure needs to reach at least 10 MPa to form a strong Al joint with an average maximum shear strength of 35 MPa. Thus, the critical applied pressure is 1000 times larger for Al specimens than for stainless steel specimens when using a 100 μm thick foil. As the foil thickness increases to 160 μm, the critical applied pressure for Al joining decreases slightly to 5 MPa, yet is still much higher than that for stainless steel joining, as shown in Figs. 6 and 7.

The effect of applied pressure on reactive joining was also explored using AgSn solder instead of AuSn solder. 40 μm thick Al/Ni foils and stainless steel specimens were used. Similar to the joints made with AuSn solder, the shear strengths of these joints increase from 18 to 35 MPa as the applied joining pressure rises from 2 to 10 kPa. For the joints made under applied pressures higher than 10 kPa, shear strengths were constant at

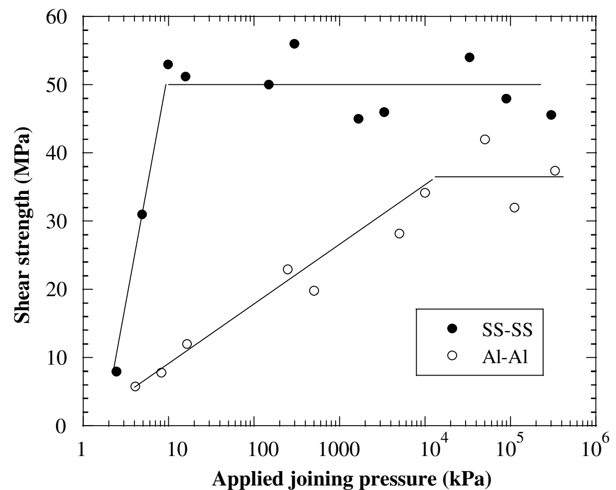

Fig. 5. Tensile shear strength of stainless steel joints and Al alloy joints made with reactive Al/Ni foils (100 μm thick) and AuSn solder (25 μm thick) layers, as a function of applied joining pressure.

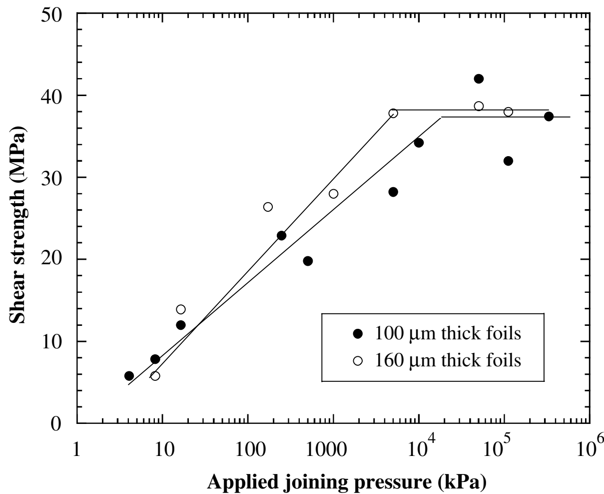

Fig. 6. Tensile shear strength of Al alloy joints made with reactive Al/Ni foils (100 and 160 μm thick) and AuSn solder (25 μm thick) layers, as a function of applied joining pressure.

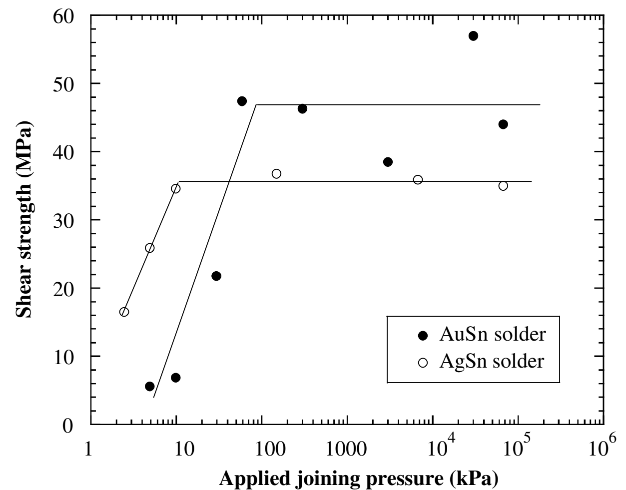

Fig. 8. Tensile shear strength of stainless steel joints made with 40 μm thick Al/Ni foils and 25 μm thick solder (AuSn and AgSn) layers, as a function of applied joining pressure.

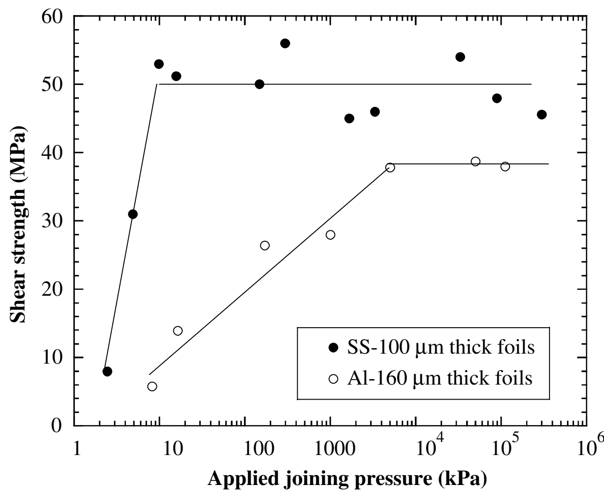

Fig. 7. Tensile shear strength of stainless steel joints made with 100 μm thick Al/Ni foils and 25 μm thick AuSn solder layers, and Al alloy joints made with 160 μm thick Al/Ni foils and 25 μm thick AuSn solder layers, as a function of applied joining pressure.

35 MPa, as shown in Fig. 8. The lower maximum strength was expected for the joints made with the AgSn solder, given the inherent differences in strength between the two solders.

4.3.3. Fracture surfaces

Optical photographs of fracture surfaces of three stainless steel joints made with 100 μm thick Al/Ni foils and 25 μm thick AuSn solder layers are shown in Fig. 9, revealing trends with applied joining pressure. As shown in Fig. 9(a), for a joint formed under an applied pressure of 2 kPa, there was partial wetting of the Au-coated stainless steel specimens and no solder extrusion was observed. This very limited wetting results in a low shear strength, i.e. 8 MPa and failure occurred at the solder/sample interfaces. As the applied pressure increases from 2 to 10 kPa, failure location gradually shifts from the solder/sample interfaces to within the solder layers. For a joint formed under an applied pressure of 10 kPa, there was full wetting of the Au-coated stainless steel specimens, yet all the AuSn solder still remained in the joining area (Fig. 9(b)). The shear strength of this joint was 50 MPa, due to the full wetting, and failure occurred predominantly within the solder layers. The very low pressure (10 kPa) needed to form strong joints will enable the application of reactive multilayer joining to the bonding of components over large surface areas. Under a much higher applied pressure, such as 30 MPa, there was also full wetting of the Au-coated stainless steel specimens but there was also significant flow of the AuSn solder out of the joining area, as shown in Fig. 9(c). This is consistent with the very thin solder layers seen in the stainless steel joints formed under high applied joining pressure (Fig. 3(b)). The joint formed under an applied pressure of 30 MPa also showed a high shear strength of about 50 MPa with full wetting of the sample even though the AuSn solder layer is significantly thinner compared with the joint formed under an applied pressure of 10 kPa. Failure continues to occur within the solder layers.

For stainless steel joints made with 40 μm thick foils and AuSn solder layers, as applied joining pressure increases, failure sites also shift from the solder/sample interfaces to within the solder layers, and consequently shear strength increases gradually to the maximum value of 50 MPa.

Fracture surfaces of a stainless steel joint and an Al alloy joint, both made with 100 μm thick Al/Ni foils and 25 μm thick AuSn solder layers under an applied

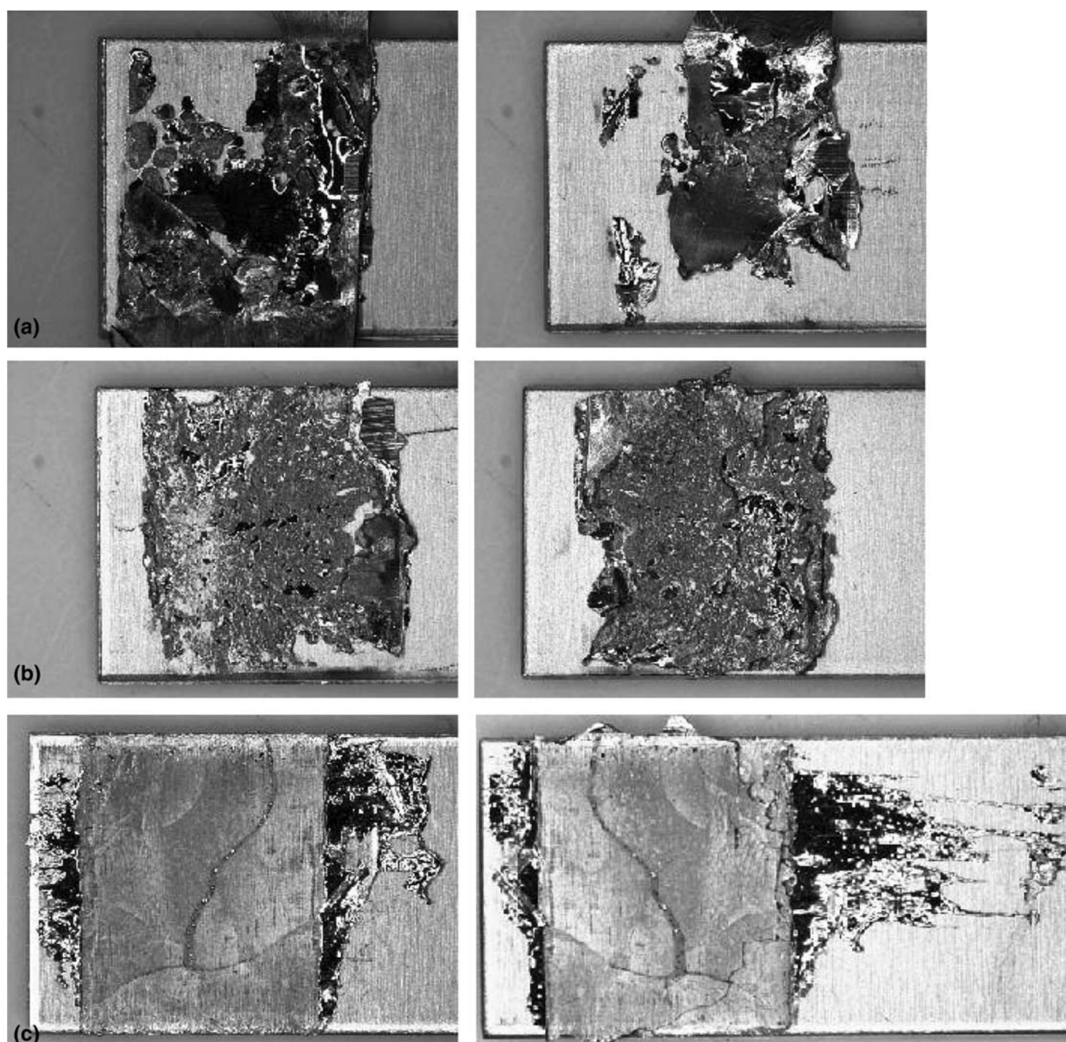

Fig. 9. Fracture surfaces of the stainless steel joints made with reactive Al/Ni foils (100 μm thick) and AuSn solder layers (25 μm thick), obtained by optical stereomicroscopy. (a) Joint was formed under an applied pressure of 2 kPa and shows partial wetting of the Au-coated stainless steel specimens and a shear strength of 8 MPa. No solder extrusion was observed. (b) Joint was formed under an applied pressure of 10 kPa and shows full wetting of the Au-coated stainless steel specimens and a shear strength of 50 MPa. All the solder material remained in the joining area. (c) Joint was formed under an applied pressure of 30 MPa and shows full wetting of the Au-coated stainless steel specimens and a shear strength of 50 MPa. There was a large amount of solder that flowed out of the joining area.

pressure of 10 kPa, are shown in Fig. 10. For the stainless steel joint, there was full wetting of the AuSn solder onto the stainless steel specimens (Fig. 10(a)). This joint had a shear strength of 50 MPa and failure occurred within the solder layer. However for the Al alloy joint, only partial wetting onto the Al alloy specimens was observed (Fig. 10(b)). The shear strength of this Al alloy joint is only 8 MPa and failure occurred at the solder/sample interface. Fracture surfaces of an Al joint made with 100 μm thick Al/Ni foil and 25 μm thick AuSn solder layers under an applied pressure of 10 MPa are shown in Fig. 10(c). There was good wetting of the Al specimens by the AuSn solder. However failure did not occur within the AuSn solder. The joint failed at the interface between Al and Ni undercoat layer. The weaker Al/Ni undercoat interface might be due to poor wetting of the Al surface during Ni electroplating or due to the formation of an Al–Ni intermetallic layer at the Al–Ni interface during reactive bonding, thus embrittling the interface [10].

5. Discussions

The shear strength results for stainless steel and Al joints made with AuSn or AgSn solder and Al/Ni foils (Figs. 4–8), together with the optical photographs of the fracture surfaces (Figs. 9 and 10) suggest that for a given material system as the applied joining pressure increases, the flow of the molten AuSn solder is enhanced, resulting in better wetting of the specimens and the formation of stronger joints. Shear

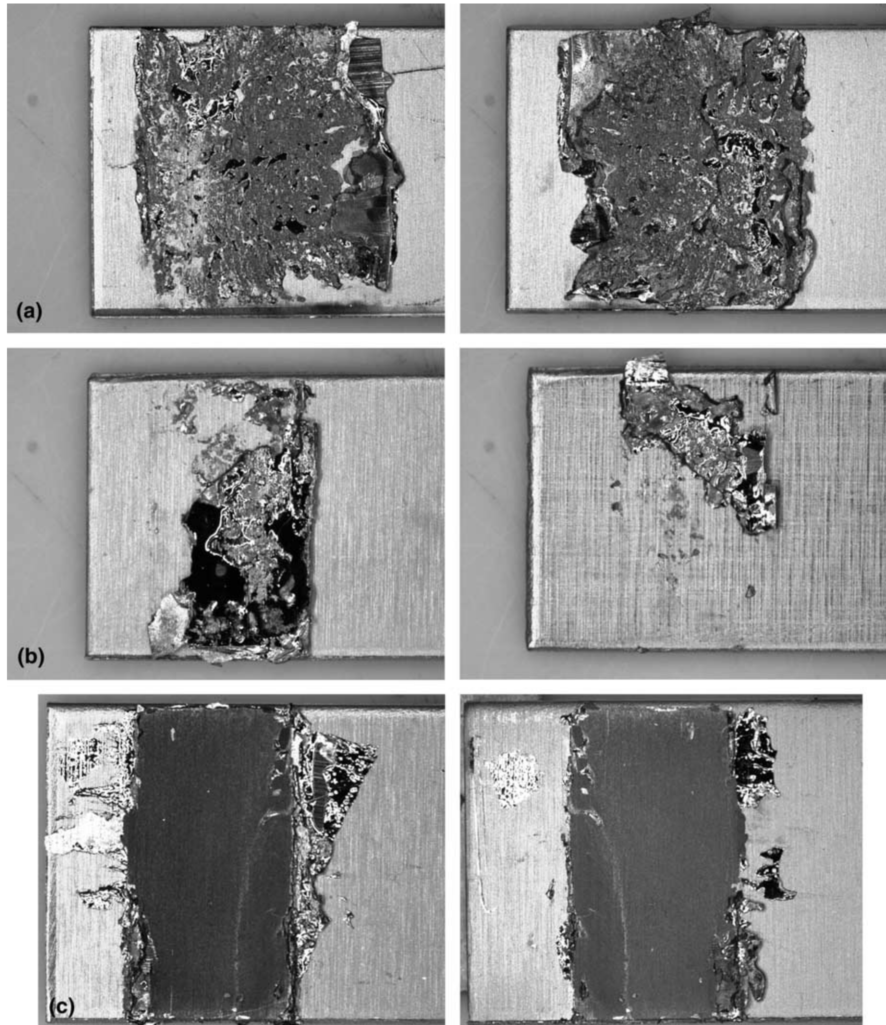

Fig. 10. Fracture surfaces of stainless steel and Al joints, made with reactive Al/Ni foils (100 μm thick) and AuSn solder layers (25 μm thick). Images were obtained by optical stereomicroscopy. (a) A stainless steel joint, made under an applied pressure of 10 kPa. There was full wetting of the stainless steel samples and shear strength is 50 MPa. (b) An Al joint, made under an applied pressure of 10 kPa. There was partial wetting of the Al samples and shear strength is 8 MPa. (c) An Al joint, made under an applied pressure of 10 MPa. There was full wetting of the Al samples and shear strength is 34 MPa.

strengths increase as the applied joining pressure rises until it reaches a critical value. At higher applied joining pressures, shear strengths remain almost constant and failure occurs within one of the two solder layers. It is expected that the variation of shear strength with applied pressure will also be seen when joining other materials or components using different reactive foils or different solder or braze materials. When components are joined using reactive foils and free-standing solder or braze materials, increasing the applied pressure is likely to improve the shear strength of the resulting joints, up to some maximum value. For higher applied pressures, the measured shear strengths will remain relatively constant. In other words, the applied joining pressure needs to reach a critical value to form a strong joint.

Figs. 3 and 9 also show that the extrusion of AuSn solder out of the joining area increases with increasing applied joining pressure, resulting in thinner solder layers in the reactive joints. Solder extrusion due to high applied joining pressure can damage other components nearby as mentioned earlier. In addition, joints with thinner solder layers may be more susceptible to thermal fatigue and mechanical fatigue [15]. Thus the applied pressure should be maintained at or slightly above the critical pressure to enable enough solder flow and component wetting to form strong joints while minimizing solder or braze extrusion.

The values of the critical applied joining pressure will vary from system to system, as can be seen in Figs. 4–8, due to variation in the physical properties and geometries of the foil, solder, and components. Here we explore foil thickness (or total heat of reaction), solder properties, and components properties, which will affect the flow of the molten solder and the wetting condition.

5.1. Foil thickness

As shown in Figs. 4 and 6, the critical applied joining pressure required to form strong joints decreases with increasing foil thickness (or total heat of reaction) for both stainless steel joining and Al joining. Numerical results in Table 1 reveal that both the duration of melting of the AuSn solder and the maximum temperature at the solder/component interface increase as the foil thickness rises. Longer durations of melting and higher interface temperatures will enhance flow of the molten solder for filling gaps and will enhance wetting of the component surfaces, thus improving bonding. These results suggest that specimens can be joined successfully under lower applied pressures as the foil thickness and total heat of reaction are increased, meaning that the critical applied joining pressure decreases with increases in the foil thickness.

5.2. Properties of components

Fig. 5 shows the effect of applied joining pressure on shear strength of both stainless steel and Al joints made with 100 μm thick Al/Ni foil and 25 μm thick AuSn solder layers. As shown above, the critical applied pressure for joining of stainless steel specimens is 10 kPa. Fracture surfaces of specimens bonded at 10 kPa or higher showed full wetting of the specimens and the joints had shear strengths of approximately 50 MPa. However when Al alloy specimens were joined using the same foils and solder layers at an applied pressure of 10 kPa, only partial wetting of the Al alloy specimens was observed and the joint was very weak with a shear strength less than 10 MPa. The critical applied joining pressure for Al joints is 1000 times higher than that for stainless steel joints. This significant difference can be explained in part by the much higher conductivity of the Al samples. The numerical model predicted that the duration of melting of the AuSn solder in an Al alloy joint is only 1 ms compared to 5 ms in stainless steel joints, for a 100 μm thick Al/Ni foil and 25 μm thick AuSn solder layers. The maximum temperature at the solder/Al interface was also predicted to be lower than that at the solder/stainless steel interface. These differences are due to the much higher thermal conductivity of the Al specimens. With more conductive components, the rate of heat removal from the solder layers during joining is increased, thereby reducing solder flow and wetting. Consequently, higher applied joining pressures are required to reach maximum joint strength for components with larger thermal conductivities.

To pursue this line of reasoning a bit further and compare the effect of duration versus the effect of maximum temperature, the stainless steel joints made with 100 μm thick foils and AuSn solder layers were compared with the Al joints made with 160 μm thick foils and AuSn solder layers in Fig. 7. Numerical predictions show that the durations of melting for these two systems are identical, i.e. 5 ms, while the maximum temperature at the solder/stainless steel interface (680 °C) is slightly higher than that at the solder/Al interface (567 °C). Given the critical applied pressure for the Al joints is still 500× higher than that for the stainless steel joints, differences in maximum interface temperatures appear to account for 500× of the 1000× difference. Thus potentially little of the 1000× difference may be attributed to the original difference in the duration of melting: 1 versus 5 ms. However other factors besides the duration of melting and the maximum temperature are also likely to play a role.

One additional factor that we explored is surface roughness. The roughness of solid surfaces affects wetting due to the fact that the actual surface area is increased with greater roughness. The relationship between an increased surface area and wettability is given as [16],

$$\cos\theta' = S_r \cos\theta, \qquad (2)$$

where S_r is the ratio of the actual area to the planar area, which is related to surface roughness. θ is the contact wetting angle to the substrate, and θ' is the apparent macroscopic contact angle. This equation predicts that rougher surfaces will result in smaller contact angles and thus better wetting. Yet the RMS roughness of the stainless steel specimens was measured to be 0.4 μm while that of the Al specimens was 0.5 μm. Given the very similar surface roughnesses, other factors are likely to be affecting the different critical applied pressures in these two systems and will be investigated in the future.

5.3. Solder material

Shear strengths of the stainless steel joints made with 40 μm thick foils and AuSn solder layers and AgSn solder layers (Fig. 8) indicate that the critical applied joining pressure is also dependent on the properties of the solder materials. The critical pressure is approximately eight times lower when AgSn solder is used. Numerical results of heat transfer (Table 1) show that duration of melting of the AgSn solder is longer than that of the AuSn solder and that the maximum temperature at the AgSn solder/stainless steel interface is higher than the maximum temperature at the AuSn solder/stainless steel interface. Thus changing the physical properties of the solder layers or the components can increase the duration of melting and the maximum interface temperature and consequently is likely to enhance solder flow and wetting and thereby lower the critical applied pressure. However, these limited comparisons cannot determine which solder properties (T_m, melting temperature, h_f, latent heat of fusion, c_p, heat capacity, or k, thermal

conductivity) are most important. Additional numerical studies will be undertaken to explore the impact of each component and solder property.

In addition to T_m, h_f, c_p, and k impacting duration of melting and maximum temperature, the viscosity and the chemistry of the solder and its ability to wet the component surface may also affect the critical applied pressure. Molten solder with low viscosity can flow more easily over component surfaces and fill gaps or voids between components better. Thus, the critical applied pressure is expected to decrease when a solder with a lower viscosity in its molten state is used. A solder's chemistry can also affect its ability to wet a component and can be explored through surface energies. Classically wetting can be described by the contact wetting angle, θ, given as [17],

$$\cos\theta = \frac{\sigma_{SV} - \sigma_{SL}}{\sigma_{LV}}, \quad (3)$$

where σ_{SV}, σ_{SL}, σ_{LV} are surface tensions of the solid–vapor, solid–liquid and liquid–vapor interfaces. The smaller the contact angle, the better the wettability. According to Eq. (3), a large σ_{SV} and small σ_{SL} and σ_{LV} enhance wetting and should result in a lower critical applied joining pressure. The use of solders that contain reactive elements such as Ti, could offer lower values for σ_{SL} and σ_{LV} and thereby enhance wetting and lower critical pressure. Conversely, using stainless steel or Al specimens that are not coated with Au would raise σ_{SL} and σ_{LV}, thereby degrading wetting and raising the critical applied pressure.

6. Conclusions

To summarize, we investigated the effect of applied pressure on reactive multilayer foil joining. Higher applied joining pressure can enhance the flow of solder or braze material, improve the wetting of the specimens, and thereby form stronger joints. Meanwhile the extrusion of molten solder or braze out of the joining area also increases with increasing applied joining pressure, resulting in thinner solder or braze layers in the reactive joints. The shear strength of the reactive joints increases as the applied joining pressure increases until a critical value is reached. At higher applied pressures, the shear strength of the joints remains constant and is determined by failure within the solder layers. The critical applied pressure can be as low as 10 kPa, so joining large components using this new reactive joining technique is practical. The critical applied joining pressure is shown to be dependent on the foil thickness (or total heat of reaction), solder properties, and components properties that determine the duration of melting of the solder material and the maximum temperature at the solder/component interface. Longer durations of melting and higher interface temperatures enhance the flow of solder, improve wetting and result in lower critical applied pressures.

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