Ultrasound Weldability of Al Ribbon to Cu Sheet and the Dissimilar Joint Formation Mode

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This work aims to investigate the ultrasonic weldability of Al ribbon (width 2.0 mm $\times$ thickness 0.2 mm) to Cu sheet (thickness 1.0 mm) using a WC tool of 2.0 mm $\times$ 1.0 mm (sonotrode tip size) and to understand joint formation process by examining joint microstructures and fracture behavior for different bonding times. For the selected conditions of 20 W power, 30 N clamping force, 0.1 s bonding time, it was found that sound lap joints could be readily obtained when the bonding time reached and exceeded 0.4 s, which fractured within Al ribbon, but not along interface, owing to the formation of dense and thin alloying layer of $2\sim3\mu m$ thickness with a continuous composition gradient. When such bonding has been established, the actual slipping motion shifted upwards to the top of Al ribbon. On the other hand, both microstructure and fracture surface observations indicated that in the early stage, localized adhesion occurred accompanied by the detachment of just adhered Al part from remaining Al ribbon body, leading to a cracking (called secondary interface) within weak Al ribbon. Thus, USW of Al ribbon to Cu sheet was achieved through a series of slipping at three kinds of transient interfaces: localized adhesion at original interface and alloying of the adhered Al together with detachment within Al ribbon (forming the secondary interface); re-bonding at the secondary interface together with further bonding at original interface under resisted slipping and high frictional coefficient as a result of surface roughening by previous isolated compound formation at original interface; and final upwards shifting of slipping to the third interface between top surface of Al ribbon and tool end. [doi:10.2320/matertrans.M20152511]

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1. Introduction

Ultrasonic welding (USW) is performed by clamping and driving a localized area of one of the workpieces using a tool to achieve reciprocating slipping motion at the bonding interface by applying vibration with ultrasonic frequency and micrometer scale amplitude. Owing to the direct relative scrubbing at the interface between two weldments, the surface roughness and impurities can be disrupted by vibratory energy, and then a sound interconnection or metallurgical bond can be produced within extremely short time (\textsim\,1 s),\textsuperscript{11} even without shielding gas or flux (self-cleaning and shielding) and additional heating apparatus. The unique feature of direct scrubbing at ultrasonic frequency at joint interface makes it possible to significantly reduce the requirements of other processing parameters: (i) the ultrasonic power and frictional amplitude, (ii) bonding time (a few seconds or less than 1 s), (iii) deformation (no serious damage), and (iv) bonding temperature (much lower than the melting point of base metals). Benefiting from low temperature and low deformation, the thermal and mechanical impacts on workpieces can be avoided. Thus, USW is considered as an efficient, precise and eco-friendly solid state bonding method, and then is preferentially selected to join (i) fine wire or ribbon to pad in advanced electronic packaging (from size view point), replacing resistance spot welding and brazing or soldering in some cases, especially for soft materials (e.g., Al, Cu, Ag, Au, Ni),\textsuperscript{2} and (ii) such similar or dissimilar base metals with tenacious oxide film in microjoining (from weldability view point). For a more recent example, joining of Al wire to Al pad and Al ribbon to Al pad in insulated gate bipolar transistor (IGBT) module for hybrid car were successfully achieved by Takahashi et al. with USW for Toyota Motor in 2004 and 2009, respectively.\textsuperscript{2}\textsuperscript{5}

As compared with general solid state welding methods (including deformation bonding and diffusion bonding), the joint formation mechanism during USW is not completely like that for the above solid state welding due to the great difference in heating and deformation in generation mode, degree and distribution as a result of the extremely small value of all processing parameters (e.g., bonding time, pressure and temperature). The mechanism of USW of wire to sheet (or pad) has been established, which can be described as two steps: micro-slipping at interface and side-surface folding of wire at peripheral area (especially for fine and soft Al wire).\textsuperscript{5}\textsuperscript{9} The oxide film (amorphous $Al_2O_3$) covering the surfaces of the Al wire and Al pad can be chipped off into amorphous particles by ultrasonic scrubbing motion (slipping) of the surfaces and then the amorphous $Al_2O_3$ particles roll outward the bond area driven by the gradual folding deformation, leading to expanding of direct bond area from central region and recrystallisation in the central region.\textsuperscript{7,8} By only applying the same static pressure as that in USW, deformation of wire cannot be achieved in the ambient atmosphere and temperature without applying ultrasonic vibration,\textsuperscript{9} showing that the slipping motion at interface is essential for sound USW joint. It has also been reported that the scrubbing action and compressive deformation can effectively disrupt hard oxide on a soft metal (such as 0.5--1 nm of $Al_2O_3$ on Al) rather than soft oxides on harder metal (such as NiO on Ni).\textsuperscript{2}

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The folding deformation is considered to be the mechanism in expanding bonded area after elastic deformation in the initial stage of USW of wire. This deformation feature (i.e., side-surface folding accompanied by micro-slip) is different from that for rotational friction welding, where bonded area increases by radial deformation at the interface with increasing flash, primarily because deformation preferentially occurs at the regions having the minimum deformation resistance. The formation of the region easy to deform depends on the compressive stress concentration behavior,\(^4,5\) constraint condition around interface, and softening of workpieces.\(^6\) For the ultrasonic micro bump bonding (flip chip bonding, FCB) of Au bump to Al-Si-Cu pad, it is reported that the central bonded area is formed by a frictional micro-slip phenomenon, while the peripheral area is bonded mainly by side-surface folding accompanied with micro-slip.\(^9\) So, in both ultrasonic wire bonding and ultrasonic bump bonding, the mechanisms in removing oxide film and in expanding bonded area can be roughly described as the ultrasonic slipping at interface and side-surface folding at peripheral area, respectively. The folding deformation also plays an important role in initial contact period in diffusion bonding when surface void is wide.\(^10\) However, due to the absence of online remedial procedure in USW process, such as upset operation in general friction welding, excessive ultrasonic vibration should be avoided to prevent the damage to previously established adhesion.

On the other hand, the USW of ribbon is essential for packaging power electronic device operating at high frequency. One advantage of ribbon over round wire is that it has lower high-frequency impedance due to the high width-to-thickness ratio (\(w/t\)) which reduces both the inductance and the skin-effect losses.\(^2\) As such, it is often used in microwave devices and hybrids with a \(w/t\) ratio of five to ten, or even higher.\(^3\) Moreover, a transition from string metal wire interconnects to ribbon interconnects provides several advantages in avoiding interface fracture and wire heel crack at high temperature above 200°C.\(^11\) However, as compared with wire bonding, where higher compressive stress and conquassation deformation of thin wire can be easily obtained due to small contact area at initial stage, USW of ribbon does not produce high quality welds with the same ease of USW of wire. Harman has pointed out that there are two correctable problems encountered when bonding ribbon by ultrasonic vibration:\(^2\) (i) as the \(w/t\) ratio is increased (> 5), the tool and substrate must be maintained extremely parallel (within less than one degree), or one side of the ribbon will be poorly welded. Also, (ii) there is seldom a very large deformation of the ribbon during bonding, so there is little surface cleaning of oxides and contaminants from the interface.

For USW of Cu ribbon to Cu (or Ni) substrate, it was demonstrated that the exposed Cu ribbon (in air for 10 days) failed to bond with Ni even if the Ni substrates just after acid cleaning were used, and thus, to suppress the deterioration of the ultrasonic weldability of Cu caused by its surface oxide film (not passivated film on Cu), fresh Cu ribbon and tin-deposited or nickel-coated copper substrate were recommended.\(^12,13\) Soft Sn coating is preferred, and when joining as-annealed (673 K for 3600 s in a vacuum of 2 \(\times 10^{-3}\) Pa) Cu ribbon of 93 µm in thickness and 2.0 mm in width to 0.62 mm thick as-annealed Cu substrate with 0.94 µm thick deposited Sn film, bond can be achieved without intermetallic compounds (IMC) via deformation (leading to Cu-to-Cu portion) and mechanical intermixing (leading to Sn-dispersed portion).\(^12\) So, the slipping is able to remove weak Sn film by shear and trap them between substrates. For sound USW of fresh Cu ribbon to exposed Ni/Cu substrate (covered by 2 µm thick Ni film), bonding could be achieved within a smaller region where the Ni layer was bent, torn or folded.\(^13\) For sound USW of fresh-surfaced Cu ribbon to fresh Ni substrate, no included particles were observed at the interface even by high magnification observation, and the interface appeared flat.\(^13\) For sound USW of fresh Cu ribbon to exposed Ni substrate, the length of the bonded area decreased to the level of only a half of that formed with fresh Ni substrate; the peripheral part of the bond interface appeared wave, suggesting that Cu and Ni had deformed locally under a non-uniform stress during bonding.\(^13\) The microstructure observation results of the USW of fresh Cu ribbon to Cu substrate with or without coating suggested that the formed joints should belong to deformation weld in mechanism, and at least, the mechanical effect sufficiently resulting in dispersion and/or detectable deformation of coating is essential for achieving intimate contact at interface.

In contrast, for USW of a 25 µm diameter Cu wire to a Cu substrate with 10 µm thick Sn plating using a hotplate of 373 K under the condition of 500 mW × 0.5 N × 30 ms, (i) evident impression and (ii) metallic bonding by ~1 µm thick Cu₆Sn IMC layer (with locally existing Sn) adjacent to the Cu wire were found at many areas.\(^13,14\) These reports suggested that soft Sn coating seems very effective for mechanically embedding Cu wire into soft substrate, and bonding condition and the as-received state of Sn coating can significantly influence the bonding mechanism, such as mechanical intermixing or metallurgical bonding with very thin IMC layer (e.g., less than 1 µm in thickness), especially in the vicinity of Cu wire.

For USW of Al/Cu dissimilar assembly, the most of published articles focused on the case of 1 mm thick Al sheet (but not Al ribbon), and it was reported that high power,\(^15\) high energy\(^16\) or Zn interlayer\(^17\) was required to induce interfacial reaction or eliminate interface void for the relatively thick components (1 mm). Up to now, there are few reports on the dissimilar USW of Al ribbon to Cu sheet in microelectronics. This work aims to assess the ultrasonic weldability of Al ribbon to Cu sheet at ambient temperature in air for different energy input (by varying welding time) by investigating interfacial microstructure and fracture behavior evolutions, and then to understand the joint formation process.

### 2. Experiment

Commercially pure Al ribbon (≥ 99.99%) used in the present study was supplied by Tanaka Denshi Kogyo, Japan, which was 2 mm wide and 0.2 mm thick (\(w/t = 10\)) and had an average fracture load of 23.63 N and an average elongation of 43.4%. The Al ribbon was cut into small pieces of 10 mm (for examining joint microstructure) and 20 mm
(for testing joint properties) in length to save the Al ribbon and to readily clamp Al ribbon by jig of test machine, respectively, and then the chopped Al ribbon pieces were ultrasonically cleaned in acetone for 3 min just before USW. Commercially pure Cu sheet of 1 mm thickness was cut into small pieces of 30 mm in length and 10 mm in width, which were then cleaned in 10 vol% HCl for 15 s, and followed by cleaning in water and acetone. The direction of the ultrasonic oscillation was along the longitudinal direction of the Al ribbon, and was parallel to the interface of the workpieces to be welded. The Al and Cu pieces were placed in lap configuration as top and bottom components in free and fixed states, respectively, so that the welding tool made of hard alloy can firmly clamp the soft Al ribbon to rub against the fixed Cu sheet, mechanically disrupting tenacious oxide film on Al ribbon surface. The Cu sheet piece was fixed on an anvil made of Cu plate of 40 × 40 × 5 (mm) by two screws.

A typical wedge-reed-system ultrasonic metal welder was used. The used WC-Co tool vertically fixed with the sonotrode had a flat tip with a size of 2 mm × 1 mm. Because the length of Al ribbon specimen (10 or 20 mm) was much more than the bonded size (1 mm, depending on the used WC tool end size in longitudinal direction of Al ribbon), the difference in length of the Al ribbon piece will do not affect the slipping behavior of Al ribbon piece, temperature distribution, weldability and weld properties.

Although lower clamping forces have been shown to increase the interface temperature, implying that there is increased scrubbing during some portion of the bonding cycle, failure load showed large scatter in our previous experiments under low bonding force. While excessively large clamping force seemed to generate intense friction and suppress the relative motion at the faying interface, resulting in decrease in the joint strength. Therefore, this work was carried out in air with the following moderate parameters: 75 kHz, 20 W, 30 N (30 N/(2 × 1)mm² = 15 MPa), except time (or energy input) varying from 0.2 to 0.8 s (or 4 to 16 J). For each energy input, three samples were prepared and evaluated by lap tensile shear tests (Fig. 1) with a constant crosshead speed of 1 mm/min to evaluate joint reliability. The samples for microstructure examination were grinded with silicon carbide abrasive paper to No. 1500, and then buffed by a metallographic polishing cloth with 2.5 µm diamond spray polish agent for 10 min. The interfacial microstructure evolution on cross section and fracture behaviors were examined by a scanning electron microscope (SEM) equipped with back-scattered electron (BSE) image and energy-dispersive X-ray spectroscopy (EDS) analysis systems.

For comparison, the USW of a chopped Cu foil of 0.2 mm thickness (as top and free piece) and the Al ribbon (as bottom and fixed piece) was also performed to ensure the component assembly mode. In the contrast experiment, Cu foil, rather than Cu plate, was preferred to facilitate deformation of top piece for clamping and contacting at joint interface under the limited bonding load.

3. Results and Discussion

3.1 Clamping effect and resultant joint appearance evolution

In USW, vibrating tool end cannot directly touch the interface to be bonded in disrupting surface roughness and impurities, so firmly clamping top piece of Al ribbon by tool end is essential for inducing relative motion at initial Al/Cu interface. Considering that the required driving effect of the tool on the scrubbing of Al ribbon along initial Al/Cu interface depends on (i) the initial surface roughness of the pieces and (ii) the clamping and surficial deformation behavior of Al ribbon, the initial roughness of the pieces and the evolution of joint appearances were firstly investigated.

Figure 2 shows the measured results of the initial surface roughness of the two pieces. On the Cu sheet surface, there were many small peaks of 0.1–0.2 µm in height (especially along transverse direction) and some pits (~0.5 µm in depth or peak-height, and ~6 µm in width) at somewhere due to etching in HCl solution. While Al ribbon showed waviness of ~1.5 µm in width. The presence of peaks and waviness would result in partial contact and significant frictional coefficient in the early stage. The surface roughness must be disrupted by vibratory energy coming from Al ribbon, which contacts with tool end.
Figures 3(a)–(d) shows the evolution of top surface appearance of Al ribbon after USW for different welding time showing transverse deformation and clamping mark, (a) 0.25 s; (b) 0.3 s, and the presence of Al fragments (c) and (d) 0.5 s.

Fig. 3 Evolution of top surface appearance of Al ribbon after USW for different welding time showing transverse deformation and clamping mark, (a) 0.25 s; (b) 0.3 s, and the presence of Al fragments (c) and (d) 0.5 s.

When vibration time reached 0.5 s, it should be noted that the friction slip mark became evident on the top surface of Al ribbon, and numerous small fragments of Al were present at the boundary of tool end mark. The results indicated that the scrubbing action of tool tip was so strong that the Al ribbon surface could be broken, and especially, at the moment, the slipping motion at Al/Cu interface had ceased and then the actual slipping motion had shifted to the top interface between tool end and Al ribbon surface after Al/Cu interfacial bonding had been established. Ultrasonic energy was then absorbed into the entire weldment area.22)

On the other hand, for Cu/Al (top/bottom) configuration even for 1 s bonding time, joint could not be formed. When 0.2 mm thick Cu foil (free) was placed on the top of the Al ribbon (fixed), the joint could be manually separated with extremely small force. When 1 mm thick Cu sheet and the same Al ribbon were placed at top and bottom respectively, the weldments separated after USW. In particular, no Al was attached on Cu foil or sheet. The lack of relative motion at the Cu/Al interface, resulting from the lack of clamping effect should be responsible for the failure for the Cu/Al in top/bottom assembly. Therefore, to enhance clamping and driving effect of tool on top piece, soft material should be set as top component. Moreover, the smaller hardness is more efficient for transfer of the welding energy.20)

3.2 Joint properties and isolated adhesion on fracture surface

Figure 4 shows the effect of bonding time on the fracture load for Al/Cu in top/bottom assembly. Sound joint can be readily obtained when welding time reached 0.4 s, which fractured within Al ribbon under a tensile shear facture load of ~23 N (equivalent to the nominal tensile load of the Al ribbon) with a significant elongation of Al ribbon during tensile shear test. When vibration time was less than 0.4 s, most joints fractured along interface. However, even for short vibration time of 0.2, 0.25, 0.3 s, a little amount of Al could be adhered on the central region of Cu sheet surface (Fig. 5(a) and (b)), forming isolated adhesion. Moreover, the friction mark could also be seen on the surface of the
adhered Al (Fig. 5(c)). Based on the observation of the fracture surface of USW joint of Al/Cu foils of the same thickness of 0.3 mm, Watanabe et al. also demonstrated that weak Al could adhere to strong Cu, while Cu was not found on the fracture surface of Al side.21) The presence of isolated adhesion can be attributed to high actual compressive stress at several contacting areas (higher than nominal pressure of 15 MPa), initial roughness of the surfaces (Fig. 2, e.g., peaks or pits on Cu sheet and long waviness surface profile of Al ribbon), and the stronger reciprocating slipping motion with unsuppressed amplitude in the early stage. The presence of friction mark on the surface of the locally adhered Al of the failed joint produced for short time of 0.25 s indicated that (i) the adhesion of weak Al onto strong Cu surface can be readily achieved at several contacting areas by mechanical surface cleaning and further ultrasonic scrubbing motion in the early stage; (ii) simultaneously, with the localized adhesion in the early stage, the detachment of the just adhered Al from the Al ribbon body occurred due to shear force and relative displacement at interface caused by initially unsuppressed amplitude; (iii) the actual friction interface at the regions with adhesion would shift from initial Al/Cu interface (called first interface) to the adhered Al/Al body interface (called secondary interface), leading to additional resistance and inhibition to subsequent vibration; and (iv) sound joint could not be achieved for short time due to insufficient bonding not only at the first interface, but also at the secondary interface.

3.3 Interfacial microstructure and formation and elimination of the secondary interface

Figure 6(a)–(d) shows secondary electron images of the joints produced for 0.2, 0.25, 0.5 and 0.8 s, respectively. As the oscillation time increased, the presence and elimination of a crack (secondary interface) and the extension of alloying layer were observed. The microstructure evolution behavior is useful for examining joint formation process, types of transient interface and defect, and final resultant microstructure.

Overall, the intimate contact over the entire interface can be well achieved with increasing bonding time, indicating that this couple has good ultrasonic weldability. While for short time, although isolated adhesion could be presented at several areas, it should be noted that a detectable crack
parallel to initial interface was simultaneously present between the adhered Al and the remaining Al ribbon body, leading to the formation of the secondary interface within weak Al ribbon (Fig. 6(a)). The presence of unbounded Al/Al secondary interface should be responsible for the separation of the joints under extremely small force after USW for short vibration time (less than 0.3 s).

The microstructure observation for the joint produced for short time (Fig. 6(a)) agreed well with the fracture surface profile (Fig. 5), clearly indicating that in the early stage, isolated adhesion occurred accompanied by the detachment within weak parent Al ribbon, leading to the secondary interface. This was a very important microstructural feature for understanding the joint formation process. The newly formed secondary interface within weak Al piece was also found in friction stud welding of Al/steel dissimilar combination without upset operation, and it was considered as a result of the difference in load-bearing capacity between strongly bonded interface and weak parent Al.22) With the presence of strong isolated adhesion and the resultant secondary interface within weak Al ribbon at several regions, the actual slipping motion at these regions would shift from the initial interface upwards to the secondary interface. Because the transient interface of each piece became remarkably uneven due to local adhesion (for Cu piece) and local detachment (for Al piece), the actual rubbing motion would occur simultaneously at the two kinds of interfaces (including the Al/Cu initial interface and the secondary interface within Al ribbon) at different regions depending on the initial interfacial bonding behavior. Since the newly formed secondary interface within the weak Al ribbon must be re-bonded to eliminate the crack within weak Al ribbon, it can be deduced that in the late stage, the major function for ultrasonic slipping should be to re-bond the secondary interface, rather than the initial interface.

The detachment of just locally adhered superficial Al from Al ribbon body in the early stage should mainly result from locally excessive shearing deformation within the surficial portion of the Al ribbon as a result of the competition between low total adhesion force at the small adhered areas (depending on Al/Cu interfacial bonded area and bonding strength) and high interfacial shear force (depending on tool driving behavior). The detailed reasons for the local detachment can be further summarized as follows: (i) both large vibration amplitude and interfacial shear force in the initial stage, which were demonstrated by Ando et al.,23) (ii) too small bonded area at initial interface, which was unable to suppress or stop relative motion of Al ribbon even if the isolated adhesion was strong, (iii) enhanced shear effect of strong Cu on weak Al by some detectable peaks on Cu surface (Fig. 2), and (iv) lower shear strength of the weak Al base metal. Of the four reasons above, (ii) should be the key reason for the crack formation in the early stage, while (iv) should be the key reason in the middle stage due to the extension of the actual bonded areas and enhancement of these areas by scrubbing and alloying. Although the presence of the newly formed detachment interface within Al ribbon (secondary interface) in the dissimilar USW can be considered as a symbol of local consolidation at initial interface, the bonding at both initial and secondary interfaces should be further enhanced by simultaneous slipping at both of the interfaces to resist interfacial shear force, to eliminate any previous crack and unbounded (or debonded) regions, and to prevent new crack formation again by compelling the slipping action to shift to the top surface.

The alloying element distribution and interfacial reaction were investigated by BSE image and EDS point analysis and line scanning analysis. Figures 7–9 show the EDS analysis position and corresponding results for the joints produced for 0.2, 0.5 and 0.8 s, respectively. The SEM observation level and EDS line scanning results showed the thickness of the alloyed layer (with a composition gradient) was about 1, 2 and 3 µm for 0.2, 0.5 and 0.8 s, respectively. At the most interface for all sound joint produced above 0.4 s (Figs. 8 and 9), both (i) the achievement of intimate contact (except small boundary region, Fig. 9(c)) without the defects (e.g., void and crack) and (ii) the presence of the detectable diffusion layer with a thickness of 2–3 µm can be considered as an indirect evidence for removing oxide film, because (i) the achievement of contact at most interface can enable
friction action at the interface and then mechanically disrupt oxide film, and (ii) the presence of the alloying layer suggested that the oxide film, which acts as a barrier layer for atom diffusion, was removed well by slipping action. The thickness of the unstable IMC with a composition gradient did not further increase so rapidly as initial stage less than 0.3 s due to the limitation in temperature. No flat step was found in the composition profile based on the level of examination, thus the interfacial microstructure can be characterized by the established metallurgical bonding of very thin layer-like unstable compound (~2 µm) with a composition gradient.

Fig. 7 Interfacial microstructure for short welding time of 0.2 s showing the adhesion with detachment from Al ribbon body, (a) SEM image and thin alloyed layer less than 2 µm, (b) BSE image.

Fig. 8 Microstructure (BSE image) of the joint produced for 0.5 s showing intimate contact at the Al/Cu interface with detectable alloying layer (~2 µm) with a composition gradient.

Fig. 9 Microstructure (BSE image) of the joint produced for 0.8 s showing intimate contact at most of the Al/Cu interface (a) with a detectable alloying layer of (~3 µm) having a composition gradient (b), except small unbonded region at periphery part (c).
Table 1 EDS point analysis results on Fig. 7(b) (at%).

<table>
<thead>
<tr>
<th>Position</th>
<th>Al (%)</th>
<th>Cu (%)</th>
<th>Possible Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Below the initial interface</td>
<td></td>
<td></td>
<td>Cu</td>
</tr>
<tr>
<td>1</td>
<td>0.54</td>
<td>99.46</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
<td>99.12</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.37</td>
<td>99.63</td>
<td></td>
</tr>
<tr>
<td>Below the crack</td>
<td></td>
<td></td>
<td>Cu rich IMC</td>
</tr>
<tr>
<td>4</td>
<td>65.43</td>
<td>34.67</td>
<td>$\theta + \eta_2$</td>
</tr>
<tr>
<td>5</td>
<td>49.44</td>
<td>50.46</td>
<td>$\eta_2$</td>
</tr>
<tr>
<td>6</td>
<td>52.36</td>
<td>47.64</td>
<td>$\eta_2$</td>
</tr>
<tr>
<td>7</td>
<td>14.30</td>
<td>85.70</td>
<td>(Cu)</td>
</tr>
<tr>
<td>Above the crack</td>
<td></td>
<td></td>
<td>Al rich IMC</td>
</tr>
<tr>
<td>8</td>
<td>79.84</td>
<td>20.16</td>
<td>(Al) + $\theta$</td>
</tr>
<tr>
<td>9</td>
<td>67.33</td>
<td>32.67</td>
<td>$\theta$</td>
</tr>
<tr>
<td>10</td>
<td>74.28</td>
<td>25.72</td>
<td>(Al) + $\theta$</td>
</tr>
</tbody>
</table>

Even for the joint produced for short vibration time of 0.2 s, EDS point analysis results across the secondary interface (Table 1) showed that both the adhered Al and the edge of the remaining Al ribbon body have been alloyed. The continuous layer-like morphology feature of the interfacial phase was quite different from that in typical rotary and linear friction welded Al/Cu joints. For a sound rotary friction welded Al/Cu joint of 14 mm diameter produced under high pressure (40 MPa) for short time (1 s), Cu and IMC fragments were incorporated into weak Al piece adjacent to the interface by intense stripping and embroiling resulting from extremely high upset pressure (160 MPa), forming a mixing layer over a few tens of microns, and then no IMC layer was present at the Al/Cu interface.24) For a sound linear friction welding of aluminum to copper of commercially pure grades (AA 1050 to C101) with a weld interface of 50 mm × 12 mm under the condition of 75 MPa friction/forge pressure, 50 Hz frequency, 2 mm oscillation amplitude and 2 mm burn-off distance, a large amount of copper particles and thin intermetallic (CuAl2 phase) films around these Cu particles were incorporated into weak Al over 100 µm wide strip region, while the thickness of IMC layer at the weld line was calculated to be only 0.7 µm.25) In linear friction welding of Cu/6063Al of 13 mm × 26 mm area to be welded, the Al and Cu remained contact but distinct, and Cu particles were entrained in the thermo-mechanically affected zone (TMAZ) on 6063Al side, especially for lower power input for relatively long friction time.26) In contrast to the mixing layer or turbulent zones mainly consisting of Cu particle and deformed Al matrix formed by very high pressure (40–75 MPa) in general rotary and linear friction welded joint, the continuous layer-like morphology of interfacial microstructure formed in the Al/Cu USW joint suggested that the layer-shaped interfacial phase should be finally formed by an surficial alloying activated by high shear deformation rate (and/or degree) under ultrasonic slipping at lower temperature (called ultrasonic mechanical alloying), rather than only or major mechanical mixing. Moreover, a high affinity for Al/Cu assembly at temperatures >120°C is also beneficial to interfacial alloying.26)

With increasing the time for scrubbing along the new actual interface, no gap or cracking was found (Fig. 6(c) and (d)), and both initial interface and secondary interface could be sequentially bonded well by alloying via detectable diffusion over ~2 µm. The re-bonding at the secondary interface can be attributed to the following factors which are able to resist the shear force and amplitude in the late stages: (i) the roughening of the actual slipping surface by already adhered Al, (ii) the improvement in both plasticity and strength of surficial portion of the Al ribbon, caused by sufficient energy input (e.g., recrystallization)36) and gradient alloying, respectively, and (iii) the resultant increase in the total bonded area mainly at the secondary interface to a critical value being able to prevent re-damage within the Al ribbon. Finally, shifting of actual slipping upwards to the third interface between top Al/tool occurred spontaneously after consolidation at both initial and secondary interfaces was established. Owing to the intimate contact at both initial interface and the secondary interface, the joints fractured within weak Al ribbon during tensile shear test. However, excessive slipping at the Al ribbon top surface will roughen the top surface of the Al ribbon, thin the actual thickness of Al ribbon, and re-damage the bonded region again, after firmly clamping Al ribbon and excessive diffusion.

3.4 USW joint formation mechanisms

Based on some previous studies, the final mechanisms of USW can be summarized as limited deformation in micrometer scale (small extent in absolute value but high extent in relative value for very small pieces of micron scale) and/or limited diffusion with the aid of thermo-mechanical effect of ultrasonic vibration. In detail, depending on base metal assemblies and bonding conditions, USW can be achieved by the following possible mechanisms: (i) sweeping aside brittle surface oxides and contaminants,\(^8,12\) intimate contact, intermixing or interlocking under considerable stress by shearing, bending, tearing and/or folding (e.g., in the case of using Cu substrate electroplated by very thin Sn or Ni film),\(^8,12,13\) (ii) ultrasonic softening (by ultrasonic energy), subsequent deformation\(^2\) and recrystallization at very thin region with the presence of submicrometre sized equiaxial grains,\(^3\) and (iii) metallurgical bonding with the presence of IMC even for short bonding time.\(^15,16\) It should be noted that with the aid of ultrasonic vibration, since recrystallization can occur by atomic migration, interdiffusion may be possible to occur to some extent even for short time at lower temperature. For general wire bonding, according to the works by Takahashi and Maeda,\(^3\) the mechanisms can be described as follows: elastic deformation only by pressure, plastic deformation by ultrasonic vibration, adhesion and expansion in bonded area \textit{via} folding. For USW of Cu ribbon to tin-deposited Cu plate, Maeda \textit{et al.} proposed a schematic illustration showing that the weak Sn film was mechanically dispersed in the vicinity of the interface without IMC.\(^12\) For USW of Al ribbon to SiO\(_2\) substrate, Ando \textit{et al.} proposed that the joining process can be divided into three stages: in the initial stage, the interfacial shear force increases rapidly and the vibration amplitude is high; in the middle stage, the shear force increases slowly and the vibration amplitude is suppressed; in the final stage, the shear force and the vibration amplitude become steady.\(^23\)
USW can be considered as a special friction welding process, in which the small amplitude (several micrometers) requires ultrahigh frequency to rapidly accumulate thermal-mechanical effect on joining interface and then to achieve oxide film removal and intimate contact at interface. But the conditions of USW are quite different from general friction welding in clamping and driving modes, bonding pressure level, temperature and deformation and relative displacement (in tangential direction) levels at interface, leading to different interfacial macrostructure feature and its forming mechanism. This work shows that using soft base metal as top workpiece is more effective for clamping and driving effect via compressive and static friction deformation in dissimilar metal USW. While in rotary friction welding of dissimilar metals, the selection of rotary workpiece does not affect the welding quality due to the consistent and firm clamping mode.

According to the above brief summarization for previous studies and the observation of macrostructure, microstructure and fracture surface in the present study, a mode of the dissimilar USW joint formation was proposed and illustrated in Fig. 10. The dissimilar USW joint can be formed by the following stages: (i) partial contact and mechanical cleaning, initially isolated adhesion together with detachment of the just adhered Al part from remaining Al body, and forming the secondary interface at several contacting areas, due to uneven faying surface, nonuniform pressure distribution, and excessive shear deformation caused by unsuppressed amplitude and shear force in the early stage for small bonded area; (ii) extending of both the adhered area at initial interface and the secondary interface area, isolated compound formation by rapid alloying of the just adhered Al activated by shear deformation at low temperature by superficial Cu, and especially, local shifting of actual slipping interface upwards to the newly formed secondary interface; (iii) re-bonding at the secondary interface as major part of the actual slipping interface and further bonding at remaining initial interface (as minor part) with the aid of (a) the resisting of shear force and amplitude by the roughening of the actual slipping surfaces by already adhered Al, and (b) possible improvement in both plasticity (with sufficient energy input under high frictional coefficient and recrystallization) and strength (with a gradient of alloying) of the surfacial portion of the Al ribbon adjacent to secondary interface; and (iv) spontaneously shifting of the actual slipping interface upwards to the third interface between tool end and top surface of Al ribbon after strong bonding at both initial and secondary interfaces was established, resulting in the presence of Al fragments on Al surface (even further fracture within the weakest region of joint region). Because the vibration in horizontal direction is hard to induce vertical mixing between the top and bottom metals, the interfacial phase with a composition gradient and continuous layer-like morphology may be formed by ultrasonic mechanical alloying with limited mixing.

According to this illustration, the actual slipping action tends to be present at the weakest interface of the three kinds of transient interfaces in different stages, and the presence of a small number of fragments of Al on its top surface should be a symbol that strong bonding has been established at both initial and secondary interfaces, compelling the additional slipping to shift to the top surface. However, excessive vibration will evidently roughen the Al ribbon surface and thin the actual thickness of Al ribbon, even results in a crack again in bonded region or obvious damage to weak top Al ribbon. The fact that the disruption of Al foil during USW of Al to stainless steel when welding time was too long (more than 1 s) may be explained by the spontaneously shifting of actual slipping interface, namely, the presence of ultrasonic vibration at the third interface between tool/Al. Moreover, according to this illustration, excessive ultrasonic power may be unsuitable for sound USW because the re-bonding of the secondary interface is hard due to the miss match between too strong vibration and limited roughing by isolated adhesion.

Additionally, interfacial void shrinkage mechanisms in USW (cleaning, smoothing and adhering by mechanical scrubbing) should be quite different from general diffusion welding where interface diffusion is the primary mechanism for eliminating interfacial void. While in USW, diffusion occurs after mechanical adhesion in the early stage to further enhance interfacial bonding.

4. Conclusions

(1) Both microstructure and fracture surface observations indicated that in the early stage, isolated adhesion occurred accompanied by the detachment of just adhered Al from remaining Al ribbon body, leading to a cracking (called secondary interface) to be bonded within weak parent Al ribbon. For the welding time less than 0.4 s, the combination failed to form a joint due to small bonded area at the initial interface and the presence of the secondary interface.

(2) The dissimilar assembly of Al ribbon and Cu sheet showed good USW applicability, even without any coating on Cu sheet surface, because (i) weak Al ribbon can be readily clamped, driven and finally adhered to strong Cu sheet, and (ii) a defect-free metallurgical
bond of unstable alloying layer of 2–3 μm thickness with a composition gradient was produced when the welding time reached 0.4~0.8 s. Owing to the sound metallurgical bond, the joints fractured within Al ribbon after significant elongation during tensile shear test.

(3) The mechanism of USW of Al/Cu can be summarized as follow: (i) isolated adhesion together with detachment of the just adhered Al part from remaining Al body (forming the secondary interface) under unsupported slipping; (ii) extending of both the adhered area at initial interface and the secondary interface area and isolated unstable compound formation by rapid alloying; (iii) re-bonding at the secondary interface (as major part) with the aid of resisted slipping, high frictional coefficient (due to previous adhesion), and possible improvement in both plasticity and strength of the surficial portion of the Al ribbon; and (iv) spontaneously shifting of actual slipping upwards to the third interface between top Al/tool after consolidation at both initial and secondary interfaces was established.

(4) During the dissimilar USW, the actual slipping interface, frictional coefficient and amplitude would change with time (or bonding evolution). The actual slipping action tends to be present at the weakest interface of the three kinds of transient interfaces in different stages, not always at initial interface; and the presence of a small number of fragments of Al on its top surface symbolizes that strong bonding has been established at both initial and secondary interfaces. However, excessive vibration has the risk of roughening the Al ribbon surface and further damaging the bonded region again.

(5) Soft base metal should be placed as top component to enable the clamping and driving of the top base metal (via static friction and/or compressive deformation) to perform relative motion against hard bottom base metal.

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