Interfacial Phenomena and Joint Strength in Resistance Microwelding of Crossed Au-Plated Ni Wires

S. FUKUMOTO, ZHENG CHEN, and Y. ZHOU

Resistance microwelding (RMW) of crossed Au-plated Ni wires has been performed at welding currents from 250 to 800 A and welding times from 1 to 80 ms under 4-kg welding force. The interfacial phenomena and the joint breaking force were investigated using an optical microscope (OM), a scanning electron microscope (SEM), an energy-dispersive X-ray (EDX) spectroscope, and a tensile-shear test. The results showed that mechanisms of joint formation involve brazing at low welding current, brazing and solid-state bonding at medium welding current, and solid-state bonding and fusion welding at high welding current. The joint breaking force first increased with increasing welding current, and after reaching a peak value, subsequently decreased due to recrystallization and softening of the Ni wire. With Au plating on the wire surfaces, the joint breaking force was remarkably improved. Comparisons among the RMW of Au-plated Ni wires, Au-plated Ni sheets, and bare Ni wires are also discussed.

I. INTRODUCTION

RESISTANCE microwelding (RMW) is an important microjoining process used to fabricate electronic devices and components (such as batteries, capacitors, and microsensors), in which thin metal sheets or wires ($<$0.2 to 0.5 mm in thickness or diameter), mostly nonferrous metals, are welded by resistance heating.[1–4] There are many differences between RMW and the large-scale resistance welding (LSRW) that is mainly used in the automotive and appliance industries to join relatively thick sheet steels ($>$0.5 to 0.7 mm), and, to a much smaller extent, to join sheet aluminum alloys.[5–8]

Metal sheets and wires, such as Ni, Kovar, and Cu, are widely employed in the fabrication of electronic and medical devices. In addition, these base metals are frequently coated with Au, Ag, or Ni to improve corrosion resistance or to obtain a unique combination of mechanical, chemical, thermal, or electrical properties.[1,9] However, similar to the case in LSRW of Zn-coated sheet steel where the Zn significantly affects the weldability of the steels,[10] these coatings may also dramatically affect the joining processes and hence the joint quality, due to changes in chemical, physical, and mechanical properties of the base materials surface.[11] In a recent investigation of RMW of Au-plated Ni sheets by Tan *et al*,[12] it was found that three joining mechanisms (solid-state bonding, brazing, and fusion welding) occurred at different welding currents, while fusion welding was the only mechanism observed during RMW of bare Ni sheets.

The RMW of fine metal wires is often used in electronics and instrumentation fabrication, mainly for electrical interconnections.[1,11,13–15] Previous work in the authors' laboratories on RMW of crossed bare Ni wires using an alternating-current supply showed that the welding process stages included the following: (1) cold wire collapse, (2) surface melting, (3) liquid phase squeeze out, and (4) solid-state bonding.[16] These mechanisms of joint formation are significantly different from those in RMW of the Ni sheets where a fusion nugget is formed,[12] probably due to the different geometric shape of the specimens resulting in different interfacial phenomena during welding. This implies that the behaviors of Au plating on the wire surfaces during RMW would also differ from those of Au-plated Ni sheets.

The purposes of this work are to study the interfacial phenomena and the joint strength in RMW of cruciform Au-plated Ni wires and to investigate the effect of Au plating on the welding process and the joint quality.

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II. EXPERIMENTAL PROCEDURES

Both cold-worked bare Ni wires (Ni 200) and Au-plated Ni 200 wires (California Fine Wire Co., Grover Beach, CA) were used in this study. The diameter of the bare Ni wires and the thickness of electrolytic Au plating were 400 and 4 μm, respectively. The wires were bonded by resistance microwelding in the form of a cruciform joint, as shown in Figure 1. Before welding, the wires were ultrasonically cleaned in acetone for 10 minutes. The resistance microwelding system consisted of a MacGregor DC400P direct-current (DC) controller and a Unitek 80A/115 weld head (air activated) (MacGregor Welding Systems Ltd., San Diego, CA). Flat-ended, round RWMA class II (Cu-Cr) electrodes, 3.2 mm in diameter, were used. All weld tests employed the same type of welding current program, in which current was increased from zero at a constant rate of 50 A/ms until the current setpoint value (250 to 800 A) was reached. Then, current was maintained constant for a "hold time" (1 to 80 ms) before being terminated. After RMW, the joint breaking force, an indication of joint quality and strength, was measured by tensile-shear testing with a Quad Romulus IV universal mechanical strength tester (Quad Group, Spokane, WA) at a crosshead speed of 90 μm/s (Figure 1). At least three joints were tested for each run to average the joint breaking force.

In order to observe the interfacial microstructure, the joints were embedded into epoxy resin, sectioned, polished, and etched in a solution containing 13 g $CuSO_4$, 60 mL HCl,

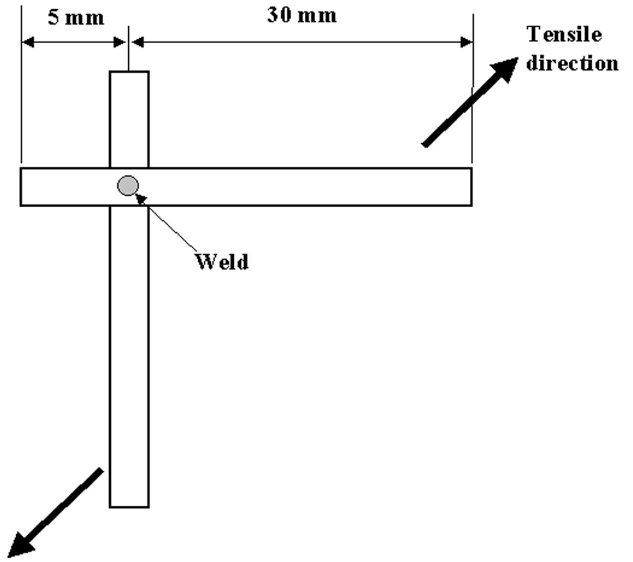

Fig. 1—Schematic illustrations of the cross-wire joint assembly and loading in tensile-shear testing.

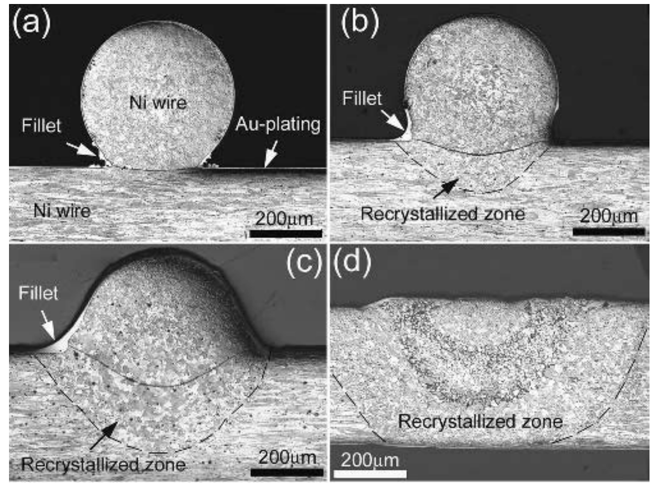

Fig. 2—OM cross-sectional micrographs of joints between Au-plated Ni wires welded at (*a*) 350 A, (*b*) 400 A, (*c*) 600 A, and (*d*) 800 A for welding time of 1 ms. (The boundaries of the recrystallized zone are indicated by dashed lines).

3 mL HF, 3 mL HNO_3, and 150 mL water for 30 seconds. The microstructure and composition of the fractured surface and cross section of joints were examined using an optical microscope (OM) and scanning electron microscope (SEM) equipped with energy-dispersive X-ray (EDX) spectroscopy.

III. RESULTS

A. *OM and SEM Observations*

Figure 2 shows OM micrographs obtained from Au-plated Ni wire joints made at various welding currents for a hold time 1 ms. It can be seen that a braze layer between the wires with braze fillet at the edge of the joint had been formed at 350 A, as shown in Figure 2(a). The braze layer was approximately 2-μm thick, which is much thinner than the initial Au plating thickness (8 μm); but the fillet was not well formed and smooth. This indicated that Au plating was melted to form a braze by the heat obtained from the contact resistance to the flow of welding current through the Au plating faying surfaces. The molten braze was then displaced from the interfacial zone to form the fillet. Increasing welding current resulted in more heat generation and hence higher temperature. As a result, the wires set down more into each other, leading to an increase in bonded area. In addition, more braze alloy was formed and squeezed out of the interfacial zone to form a larger and smoother fillet, as shown in Figures 2(b) and (c). The braze layer almost disappeared at currents above 600 A. When welding current was higher than 400 A, on the other hand, a recrystallized structure could be clearly seen around the joint interface due to increased peak temperature (Figures 2(b), (c), and (d)). As expected, the area of recrystallized zone (also termed the heat-affected zone (HAZ)) increased with increasing welding current.

Further insight was obtained from the cross-sectional micrographs of joints made at different welding currents for the hold time 80 ms, as illustrated in Figure 3. A brazed joint had been formed at the welding current as low as 250 A with extensive recrystallization of the Ni wires (Figures 3(a1) and (a2)), indicating that the temperature reached the Au-Ni minimum melting temperature. It is worth noting that in Figure 3(b2), Au plating was melted on the wire surface where there was a recrystallized zone. With an increase of welding current to 350 A, a continuous and dense braze layer of about 1.2-μm thickness measured at higher magnification was clearly observed at the interface between the Ni wires (Figure 3(c2)). At the welding current of 400 A, consistent with the formation of a smooth fillet (indicating more molten braze was formed and squeezed out of interface) (Figure 3(d1)), a solid-state bonded region was produced at the interface, as shown in Figure 3(d2). However, a very thin braze layer was still present at part of the interface (Figure 3(d2)). A complete solid-state bonded joint was formed between the wires with disappearance of the interface at higher current (for example at 600 A, Figures 3(e1) and (e2)). Finally, a weld nugget in the center of the joint was produced when the welding current reached 800 A (Figure 3(f1)). In addition, Figure 3(f2) revealed that the solid-state bonded interface was maintained around the central fusion nugget. Electrode-wire sticking started to occur at the welding currents of 800 A or more because excessive heat generation produced locally melted areas at the electrode-wire interface, as shown in Figure 3(f1).

Figure 4 shows the micrographs obtained from the joints welded at 350 A for different hold times. Once more, both deformation of wires and the area of the recrystallization zone increased with prolonging of the hold time. However, the effect of the hold time was not as significant as increasing the welding current (comparison of Figure 4 with Figures 2 and 3). In addition, at welding current as low as 350 A, bonding between the wires was achieved only by a brazing process, and the braze layer thickness showed little variation even with long hold time.

Further SEM observation and EDX analysis were carried out to investigate the interfacial zone. Figures 5(a) and (b) show the interfacial region and fillet formed in the joint welded at 250 A for 80 ms. The average thickness of the braze layer was estimated to be about 2 μm. The EDX analysis indicated that the braze layer and fillet were a Ni-Au alloy with 85 at

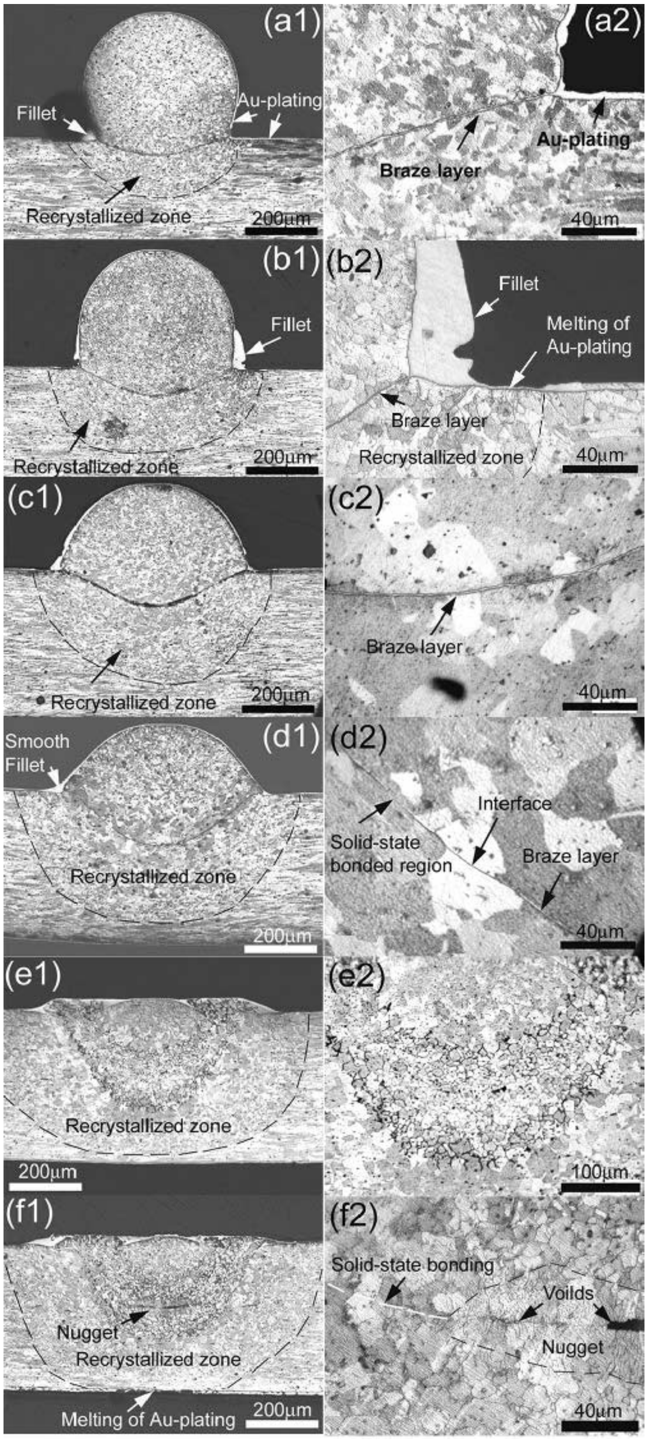

Fig. 3—OM cross-sectional micrographs of joints between Au-plated Ni wires welded at (*a*1) and (*a*2) 250 A, (*b*1) and (*b*2) 300 A, (*c*1) and (*c*2) 350 A, (*d*1) and (*d*2) 400 A, (*e*1) and (*e*2) 600 A, and (*f*1) and (*f*2) 800 A for the welding time of 80 ms. ((a2) through (f2) show detailed regions of either the fillet or the interface in (a1) through (f1), respectively).

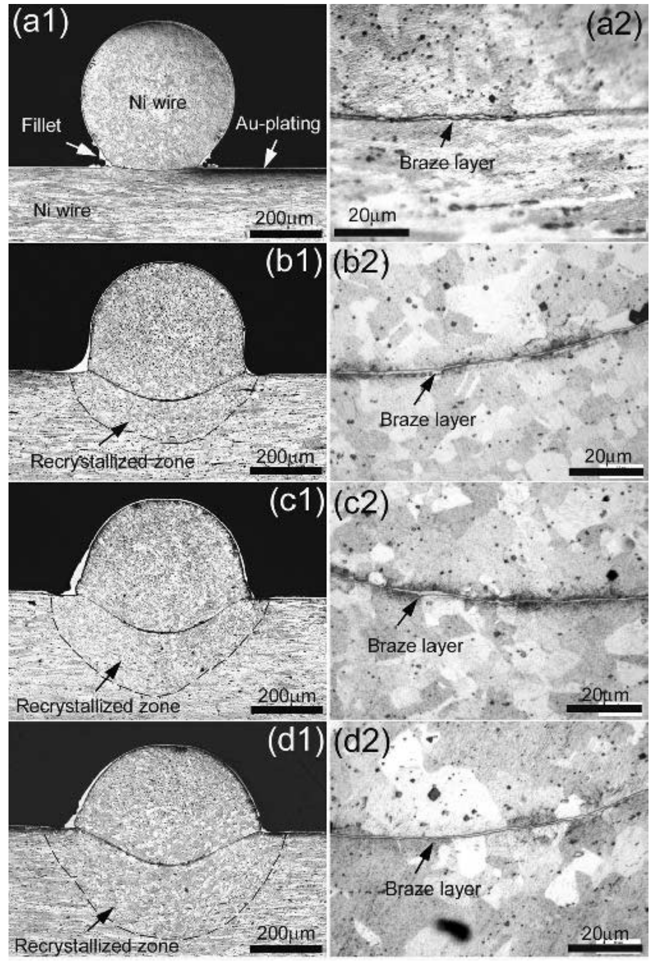

Fig. 4—OM cross-sectional micrographs of joints between Au-plated Ni wires welded at 350 A for (*a*1) and (*a*2) 1 ms, (*b*1) and (*b*2) 10 ms, (*c*1) and (*c*2) 40 ms, and (*d*1) and (*d*2) 80 ms. ((a2) through (d2) show detailed center interfacial regions in (a1) through (d1), respectively).

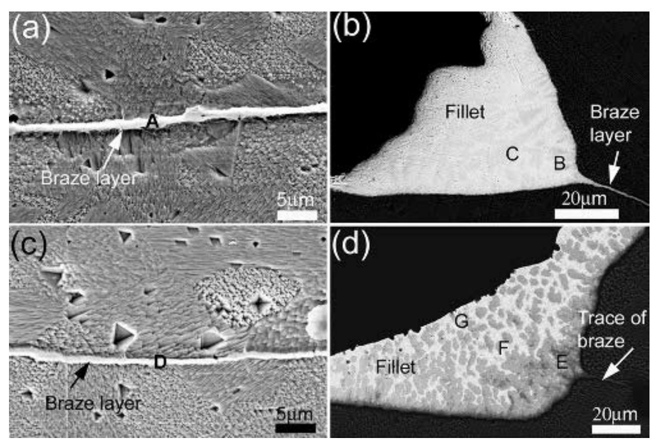

Fig. 5—SEM cross-sectional images of the (*a*) interface and (*b*) fillet in the joint welded at 250 A for 80 ms as well as the (*c*) interface and (*d*) fillet in the joint welded at 400 A for 80 ms. (The compositions of different regions are listed in Table I).

pct Ni and about 60 at pct Ni, respectively, which are much higher than the Ni concentration of the lowest melting point Au-Ni alloy (45.5 at. pct).[17] The thickness of the braze layer was reduced to 1 μm and much more Ni was alloyed into the braze layer and fillet (Figures 5(c) and (d) and Table I), as the welding current increased to 400 A. Based upon the EDX analysis results that the Au content decreased progressively on going from the edge of fillet toward the region adjacent

Table I. EDX Analysis Results of Points A through G in Figure 5 (Atomic Percent)

Position	Au	Ni	Notes
A	14.5	85.5	braze
B	34.4	65.6	fillet
C	45.4	54.6	fillet
D	2.6	97.4	braze
E	15.3	84.7	fillet
F	23.2	76.8	fillet
G	48.3	51.7	fillet

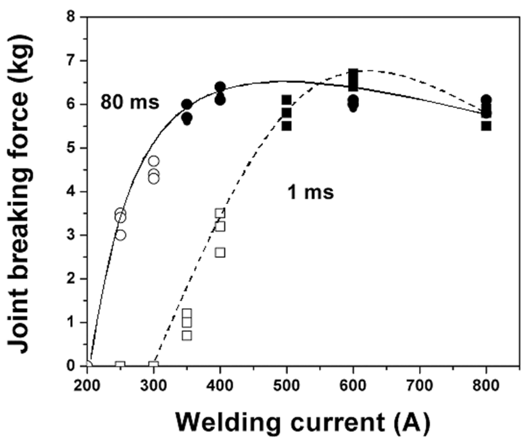

Fig. 6—Effect of welding current on the breaking force for 1 and 80 ms weld times (open and closed symbols indicate fracture at interface between wires and in the HAZ of Ni wire, respectively).

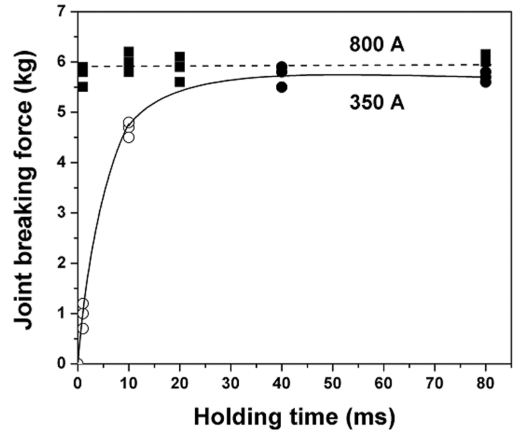

Fig. 7—Effect of the hold time on the breaking force of joints welded at 350 and 800 A (open and closed symbols indicate fracture at interface between wires and in HAZ of Ni wire, respectively).

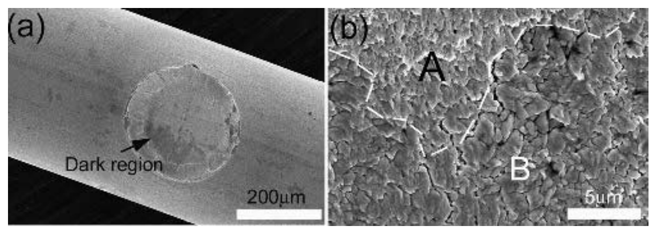

Fig. 8—SEM fractographs obtained from the joint welded at 300 A for 1 ms after tensile-shear test, showing (*a*) interfacial fracture between the wires and (*b*) occasional local bonding (area A) between Au plating corresponding to the dark region in (a); area B represents a micrograph of the original Au-plating surface.

to the braze layer at the interface (Figure 5 and Table I), it is deduced that the liquefaction of Au plating occurred first followed by subsequent liquefaction of the Ni substrate adjacent to the interface. When the fusion nugget was formed resulting from the liquefaction of mass Ni substrate under the welding condition of 80 ms at 800 A, no Au could be detected by EDX in either the solid-state bonded region or fusion nugget region, probably due to its low content below the detection limit of the EDX detector (1500 to 2000 ppm). In addition, for those joints shown in Figure 4, EDX analysis also showed increased Ni content in the braze layer with longer hold time.

B. *Joint Breaking Force*

Figure 6 shows the effect of welding current on the breaking force of Au-plated Ni wire joints made with 1 and 80 ms hold time. The joint breaking force first increased with increasing welding current and subsequently decreased a little after reaching a peak value. For the hold time of 1 ms, no weld could be obtained when the welding current was lower than 300 A and the maximum joint breaking force was reached at a welding current of about 600 A. Prolonging the hold time to 80 ms decreased the current threshold to form a weld. For example, the joint welded at 250 A exhibited a breaking force above 3 kg, compared to the current of 400 A required to achieve the same breaking force when the hold time was 1 ms.

Figure 7 summarizes the variations of the breaking force of Au-plated Ni wire joints as a function of the hold time at welding currents of 350 and 800 A. It was seen that the joint breaking force remarkably increased with hold time in the initial stage of welding at 350 A. While a very short hold time, *e.g.*, 1 ms, was sufficient to form a strong joint at 800 A, no marked effect of the hold time could be seen at the higher current level.

After measurement of the joint breaking force, the fracture surfaces of the specimens were examined using SEM and EDX in order to clarify the fracture mechanisms. Figure 8 shows the SEM fractographs of a joint welded at 300 A for 1 ms. Although no joint breaking force could be registered under this condition, incipient local bonding between Au plating was observed (A in Figure 8(b)). The joint welded at 350 A for 1 ms showed interfacial fracture (breaking force of 1.1 kg), as indicated in Figure 9. Based on the results of EDX analysis on the fractured surface (Table II) and Figure 5, regions B1 and B2 in Figure 9 were identified to be fractured within the braze layer, while regions A1 and A2 fractured along the interface between the braze layer and the Ni substrate, where many voids were present on the fractured surface of the braze layer side (pointed by arrows in Figure 9(c)). The presence of these voids, probably due to the surface roughness and poor wettability of the Ni wire by the Ni-Au brazing alloy because of low temperature (welded at low welding current for a short hold time), should substantially reduce the interfacial strength, leading to an interfacial failure. When both the braze layer and the interface were sufficiently strong, such as in the joint welded at 600 A for 1 ms, fracture in the HAZ from the edge of the fillet was observed, as shown in Figure 10.

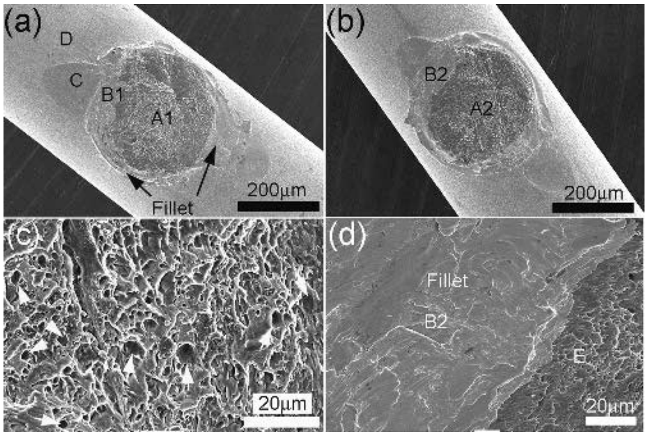

Fig. 9—SEM fractographs obtained from the joint welded at 350 A for 1 ms after the tensile-shear test: (*a*) low magnification of a wire, (*b*) opposite wire, (*c*) details of region A in (a), and (*d*) details of region B2 in (b). (The compositions of different regions are listed in Table II).

Table II. EDX Analysis Results of Points A through E Indicated in Figure 9 (Atomic Percent)

Position	Au	Ni	Fracture Location
A1	3.9	96.1	fractured at interface between
A2	0	~100	the braze layer and Ni substrate
B1	37.2	62.8	fractures within the braze layer
B2	67.8	33.2	
C	93.4	6.6	fillet
D	96.8	3.2	original Au-plating surface

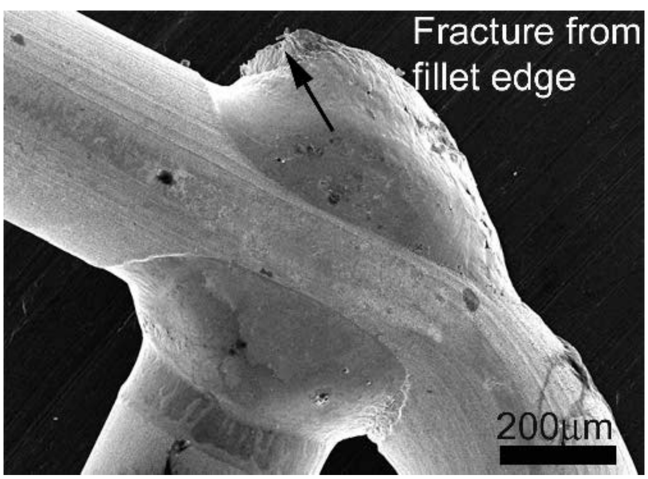

Fig. 10—SEM image showing fracture occurring in the HAZ from the edge of the fillet in the Au-plated Ni wires joint welded at 600 A for 1 ms.

The aforementioned results demonstrated that welding current had significant effects on joint failure mechanism and joint breaking force. At low welding current, the joints fractured through the weak bond interface. Keeping the OM, SEM, and EDX results in mind, it was found that increasing welding current increased Ni content alloyed into the braze layer and the bonded area, resulting in higher strength of the braze layer and higher strength of the interface between the braze layer and the Ni substrate. Consequently, the breaking force that the interface could withstand was increased (Figure 6). On the other hand, too high a welding current could result in increased softening of HAZ because of recrystallization of the originally cold-drawn microstructure. As a result, transition in fracture mechanism from interfacial failure to fracture in HAZ of the Ni wire was observed. Among all the joints examined in the present work, the joints bonded by (brazing + solid-state bonding) presented the highest breaking force, higher than those bonded only by either brazing or solid-state bonding.

IV. DISCUSSION

A. *Mechanism of Joint Formation*

The RMW of Au-plated Ni sheets reported by Tan *et al.* revealed that solid-state bonding occurred first between the Au plating faying surface, followed by brazing and fusion welding in the central region as the welding current was increased.[12] On the other hand, the present work showed that brazing, solid-state bonding, and then fusion welding occurred during RMW of Au-plated Ni wires as the welding current was increased.

The differences in the welding processes can be ascribed to the following aspects. In theory, solid-state bonding should be relatively easily achieved between Au plating layers if the welding current is too low to melt the Au plating. No evidence of the formation of such stable solid-state bonded joints between Au-plating faying surfaces was found in wire-to-wire welding, which is quite different from what was found in welding of sheets.[12] This difference in behavior appears to be related to the much smaller and variable contact area during wire welding. The initial contact area in the case of wires was estimated to be approximately 0.03 mm^2, which is much smaller than that between the Ni sheets (approximately 3.2 mm^2).[12] Accordingly, a current density more than 8000 A/mm^2 is generated in a joint between Au-plated Ni wires, which is ~30 times greater than that in RMW of Au-plated Ni sheets. On the other hand, according to the Au-Ni phase diagram,[17] complete solubility between the Ni and the Au occurs in both liquid and solid phases at high temperature. In addition, there exists a composition at 42.5 at. pct Ni with the minimum melting point of 955 °C, which is lower than the melting point of Au at 1064 °C. As soon as the welding current is applied, the temperature at the Au-Ni interface can be rapidly increased to a temperature that is higher than 955 °C but less than the melting point of Ni. As a result, instead of the formation of a solid-state bonded joint in Au-plated Ni sheets,[12] Au plating melts, probably due to interdiffusion between the Au and the Ni atoms, to form a low-melting-point liquid layer initially at 42.5 at. pct Ni, and then the liquid layer widens to consume a residual solid Au-plating layer to form an Au-Ni braze layer between the Ni wires (a brazed bond). In addition, the braze liquid at the interface is much more easily squeezed out of the interface in the case of wires compared with the Au-plated Ni sheet joint in which the solid-state bonded region adjacent to the braze periphery prevents the braze from squeezing out of the interface,[12] resulting in the formation of solid-state bonding between the wires after brazing.

A schematic diagram of the joint formation is shown in Figure 11 to assist the following discussion. During welding, as mentioned previously, melting starts at the Au-Ni interface and forms an Au-Ni braze layer between the Ni wires, resulting in a bond. Such localized bonding of Au plating has been observed in the present work (Figure 8). As the welding current increases, deformation of the wires also increases to bring more wire surface into intimate contact, leading to the formation of an Au-Ni braze on almost all the interfacial area between the Ni substrates. Simultaneously, more Ni atoms are dissolved and mixed into the molten braze, resulting in a large increase in the Ni content of the liquid. This was confirmed by EDX analysis; for instance, the brazed layer and fillet formed in the joint made at 250 A for 80 ms contained much higher Ni (Figure 5 and Table I), compared with the low-melting-point Au-Ni alloy (42.5 at pct Ni). During the process, a part of the liquid braze alloy is squeezed out of the interface to form an incomplete fillet at the edge of the joint due to the limited amount of molten braze (Figures 2(a), 3(a1), and 11(a)). At relatively higher welding current or time, more braze alloy is formed due to the dissolution of the Ni substrate, and then the braze liquid is squeezed out of the interface to form a smooth fillet as well as a thinner and denser brazed layer with increased Ni content (Figures 3(c1), (c2), and 11(b) and Table II).

A solid-state bonded interface can form at the region where the braze alloy has been completely squeezed out of the interface, forming a brazed and solid-state bonded joint (Figures 3(d2) and 11(c)). Further increase of welding current will squeeze all the braze alloy out of the interface. In such a case, the wires are bonded only by the solid-state bonding process (Figures 3(e1), (e2), and 11(d)). Eventually, the temperature at the joint center will rise above the melting point of Ni at 1455 °C as the welding current increases, leading to the formation of a fusion nugget around which solid-state bonding is maintained with the disappearance of the interface between the wires (Figures 3(f1), (f2), and (e)).

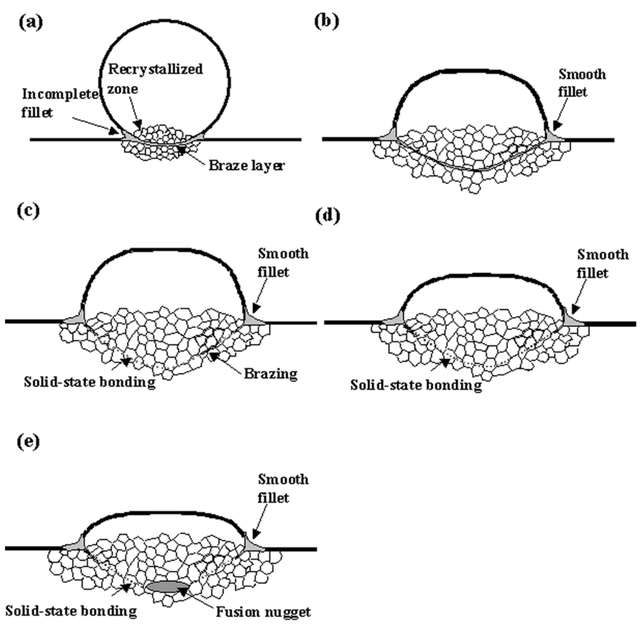

Fig. 11—Schematic illustration of joint formation during RMW of Au-plated Ni wires: (*a*) brazing at low welding current with the formation of incomplete fillet, (*b*) brazing at high welding current with the formation of smooth fillet and increased Ni content within braze layer, (*c*) combinations of brazing and solid-state bonding at the interface, (*d*) solid-state bonding, and (*e*) combinations of solid-state bonding and fusion welding.

B. *Effect of Au Plating*

The present study showed that the behaviors of Au plating on Ni wire during RMW are quite different from those of Au plating on Ni sheets, as discussed previously. Therefore, RMW of bare Ni wires was also carried out in order to investigate the role of Au plating in RMW of Ni wires. Figure 12 shows the effect of welding current on the breaking force of bare Ni wire joints made for hold times of 1 and 80 ms. Comparing Figure 12 with Figure 6, it was found that the welding current required to form a joint was similar in both cases. However, it is worth noting that the joint breaking force of bare Ni wires was lower than that of Au-plated Ni wire, especially for the hold time of 1 ms. For example, the Au-plated Ni wires joint fractured through the recrystallization zone with breaking forces of above 6 kg, instead of an interfacial fracture (between faying surfaces) with breaking forces of about 3 kg that occurred in the bare Ni wires joint made at the same welding condition (400 A for 80 ms). In addition, a decrease in joint breaking force at higher welding current, *e.g.*, 800 A, either for 80 or 1 ms hold time, was more significant in the case of bare Ni wires. Figure 13, showing a typical OM micrograph obtained from a joint welded at 400 A for 80 ms, indicated a solid-state bonded joint with sharp notches at the edge (as indicated by arrows), compared to the fillet formation in Figures 2 and 3 for joints between Au-plated Ni wires. In addition, Figure 13 shows more plastic deformation of bare Ni wires than that of Au-plated Ni wires (compared with Figure 3(d1)). Particularly, the sharp notch should increase stress concentration during a tensile-shear test, making cracks easy to extend along the

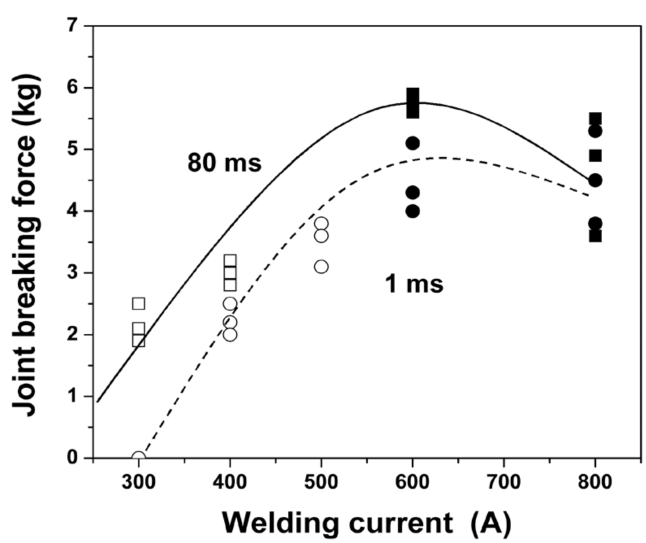

Fig. 12—Effect of welding current on breaking force of joints between bare Ni wires welded with 1 and 80 ms hold time (open and closed symbols indicate fracture at interface between wires and in the HAZ of Ni wire, respectively).

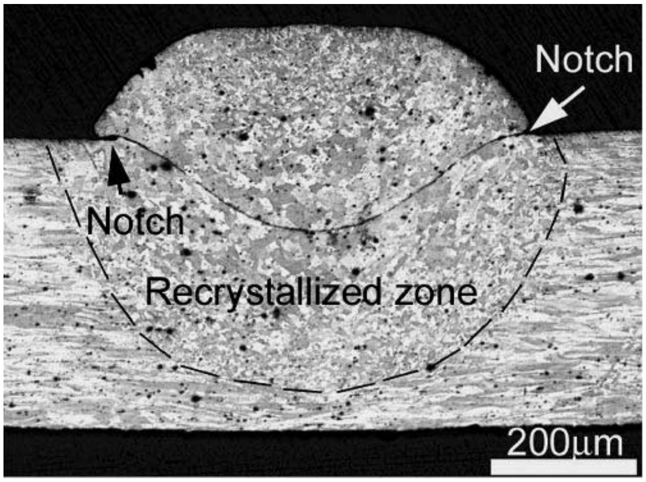

Fig. 13—OM cross-sectional micrograph of the joint between bare Ni wires welded at 400 A for 80 ms, showing solid-state bonding at the interface as well as the presence of a sharp notch at the edge of the joint and more deformation of Ni wires compared with the Au-plated Ni wires joint (Fig. 3(d1)).

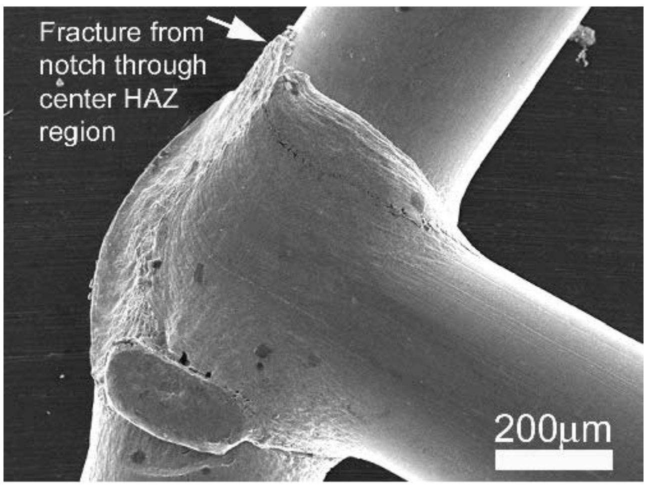

Fig. 14—SEM images showing HAZ fracture occurring from the root of the joint between the bare Ni wires through the center region of the HAZ (welded at 600 A for 1 ms).

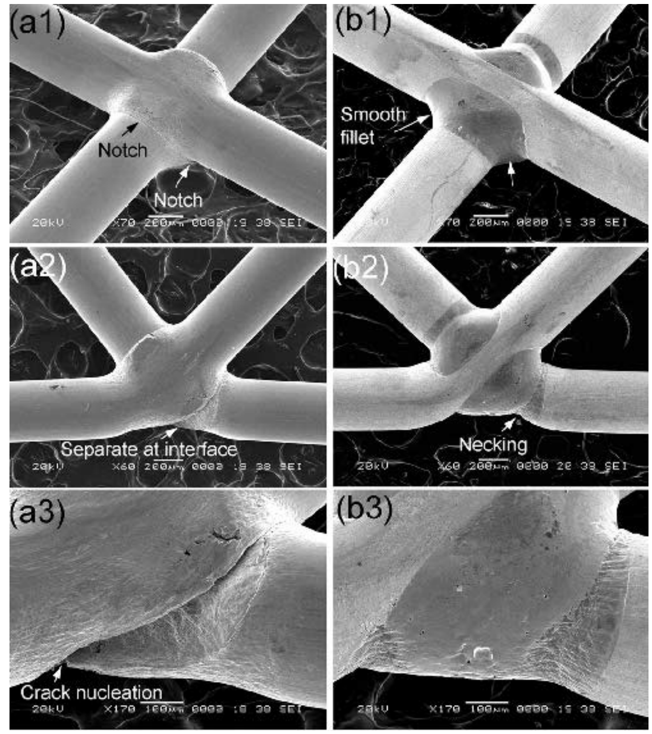

Fig. 15—SEM images of (*a*) joints between Au-plated Ni wires and (*b*) joints between bare Ni wires welded at 600 A for 1 ms (1: as-welded joints, 2: after loading, and 3: details of the necking region or the interface region).

weak joint interface. This was confirmed by the results of breaking tests, where fracture occurred very near the root of the joint, that is, the crack passed through the central region of the HAZ (Figure 14), rather than through the peripheral region of HAZ in the case of Au-plated Ni joints due to the presence of a fillet (Figure 10). Accordingly, a lower breaking force of bare Ni wire joints resulted because the softening of the HAZ center region was more significant than the HAZ edge region.

To further investigate the reason the failure location was so different between the two kinds of joints, additional tensile-shear tests were carried out on both joints of bare Ni wires and Au-plated Ni wires. However, in this case, the joints were unloaded when the load reached 90 pct of their average joint breaking forces. Figure 15 shows SEM images of those samples before and after loading. Although the bare Ni wires joint showed initial necking on the base wire, the bonded interface had already separated upon loading due to the presence of a notch (Figures 15(a2) and (a3)), allowing the crack to penetrate into the central region of the HAZ from the separated interface. In contrast, the fillet formed in Au-plated Ni wires joint provided a thicker section and a smooth transition from one wire to the other (Figure 15 (b1)). No separation at the bonded interface occurred, and the necking was clearly observed at the edge of the fillet (Figures 15(b2) and (b3)). Clearly, the stress concentration was significantly reduced due to the presence of the fillet in the joint between Au-plated Ni wires, so fracture occurred from the edge of the fillet through the peripheral region of the HAZ. As a result, bare Ni wire joints fractured through the central HAZ region corresponding to a lower joint breaking force.

The present study showed that Au plating has significant effects on joint formation, joint breaking force, and RMW parameters needed to form a reliable joint. During RMW of Au-plated Ni wires, Au plating greatly reduces the contact resistance and temperature because of its low resistivity and low hardness, which was evidenced by the measurements of static contact resistance; *e.g.*, an interface between Au-plated Ni wires had a contact resistance about 7 pct of that a Ni/Ni interface at room temperature. This agrees well with the effect of Au in RMW of Au-plated Ni sheets.[12] However, the low melting point of Au or Au-Ni alloy (~900 °C) favors formation of a brazed joint at low temperature. On the other hand, although the maximum temperature that could be reached in joining of the bare Ni wires is higher than that in the Au-plated Ni wires joint due to higher contact resistance between bare Ni wires, the melting point of Ni is about 400 °C to 500 °C higher than that of Au or Au-Ni alloy, resulting in only solid-state bonding when the welding current is lower than 900 A in RMW of bare Ni wires.[16] As a result, there is no remarkable difference in the welding current required to form a joint between bare Ni wires compared to Au-plated Ni wires.

Among the parameters associated with RMW of Au-plated Ni and bare Ni wires, the welding current is the most significant variable affecting interfacial bonding, affecting the bonded area as well as the softening of HAZ, because the heat generated is proportional to the square of welding current. In contrast to the results of Zn coating on steel sheets[18,19] and Au plating on Ni sheets,[12] which require an increase in the welding current due to a decrease of contact resistance, the present work revealed that Au plating on the surface of Ni wires substantially reduced the welding current to form a joint with comparable breaking force (comparing Figures 6 and 12). As mentioned previously, these differences result from the different mechanism by which the joint is formed. For example, to obtain a joint with 3-kg breaking force, the welding current can be reduced to 250 A (80 ms) for Au-plated Ni wires (brazed joint, Figure 3) from 400 A for bare Ni wires (solid-state bonded joint, Figure 13). Furthermore, when welding was carried out at a current of 400 A for 80 ms, a strong brazed and solid-state bonded joint was achieved between plated wires with limited softening of the HAZ (Figure 3), resulting in the maximum breaking force (HAZ failure, Figure 6). On the contrary, only a weak solid-state bond was formed at these parameters for welding a bare Ni joint, leading to an interfacial fracture under a low breaking force. Although strong solid-state bonded interfaces can be obtained at a higher welding current for bare Ni joints, significant softening of HAZ once again resulted in a relatively low breaking force (Figure 12).

In short, the advantages of Au plating can be summarized as follows. The Au plating favors formation of a brazed joint at low welding current, while it reduces the softening of the HAZ at high welding current, because the heat generation is decreased due to low contact resistance between the Au plating compared with the bare Ni wires joint. Moreover, the formation of a fillet at the edge of a joint due to squeezing out of braze liquid reduces the stress concentration during tensile-shear testing, which is responsible for increasing the joint breaking force.

V. CONCLUSIONS

The interfacial phenomena and the breaking force of RMW of cruciform joints between Au-plated Ni wires, as well as the effect of Au plating on the welding quality, have been investigated. The major conclusions are summarized as follows.

1. The mechanism of joint formation during RMW of Au-plated Ni wires involves brazing at low welding current, a combination of brazing and solid-state bonding at intermediate welding current, and a mixture of solid-state bonding and fusion welding at high welding current.
2. The joint breaking force increases with increasing welding current first, and subsequently decreases slightly after reaching a peak value due to recrystallization softening in the HAZ at high welding currents.
3. The formation of a fillet at the edge of Au-plated Ni joints reduces the stress concentration compared with the presence of a sharp notch in joints of bare Ni wires, and therefore, fracture occurs from the fillet edge through the peripheral region of the HAZ in the Au-plated wires joints instead of through the HAZ center region in bare Ni wires joints, which is responsible for increasing the joint breaking force.

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