Effects of Au Plating on Small-Scale Resistance Spot Welding of Thin-Sheet Nickel

W. TAN, Y. ZHOU, and H.W. KERR

The effects of Au plating on joint formation and joint strength in small-scale resistance spot welding (SSRSW) of Ni sheets have been investigated using tensile-shear testing, optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX). The results show that the mechanisms of the joint formation during the welding of Au-plated Ni sheets involve solid-state bonding, brazing, and fusion welding. The comparison between SSRSW of Au-plated Ni and bare Ni sheets and large-scale resistance spot welding (LSRSW) of Zn-coated steels is also discussed.

I. INTRODUCTION

THE application of resistance spot welding in the fabrication of electronic devices and components (*e.g.*, batteries, capacitors, and sensors) is generally termed as micro-, fine-, or small-scale resistance spot welding (SSRSW), since the metal sheets to be welded are relatively thin or small in diameter (<0.2 to 0.4 mm).[1,2] There are many differences between SSRSW and large-scale resistance spot welding (LSRSW), which is used to join sheet metals of thickness larger than 0.5 mm, mainly in the automotive and appliance industries.[3–6] These differences are not only due to the difference in the scale of the joints, but also due to the fundamental difference in the electrode forces (pressures) used.[3,4] Simply downsizing from LSRSW to SSRSW may lead to problems such as electrode sticking, metal expulsion, and nonrepeatable welding.[2] Furthermore, metals to be welded in SSRSW are mostly nonferrous, while the workpieces in LSRSW are mainly steels and, to a much smaller extent, aluminum alloys.[2,3,7,8]

The base metals (such as Ni, Kovar, and Cu) of many electronic devices and components are frequently plated with materials (such as Au, Ag, and Ni) to improve corrosion resistance or to obtain a unique combination of mechanical, thermal, and electrical characteristics.[1,9] However, these plating materials may dramatically influence joining parameters used during the subsequent assembly processes and affect joint formation and quality, compared to the joining of the same base metals without plating materials. For example, Biro *et al.*[10] have found that Au/Ni and Ni plating reduced the power density required to form a joint during laser welding of very thin aluminum sheets. A joint formed by a combination of fusion welding and brazing was observed in laser welding of Au/Ni-plated Kovar and Ni; the braze layer caused a shift of the location of tensile-shear failure away from the fusion boundary and into the heat-affected zone or base metals. However, there is little work published on how plating materials affect joint formation and joint quality in SSRSW.

In the automotive industry, Zn-based coatings are often used to improve the corrosion resistance of the sheet steels.[5,11] The use of these coatings has significantly affected the weldability of sheet steels in two ways. First, these low-melting-point coatings require a higher welding current or longer weld time in LSRSW. For example, in a study on LSRSW of sheet Zn-coated steel, Gedeon and Eagar[12] have observed that the Zn coating melts at the sheet/sheet faying interface to form a molten Zn disk at a very early stage of welding. This molten coating is then pushed away from the central area under the electrode pressure to form a molten Zn halo. Therefore, the Zn-based coatings have, first, a reduced contact resistance because of the low melting points and, later, an increased contact area and, hence, reduced current density due to the formation of a molten Zn halo. To compensate, an increase in welding current or weld time is needed to achieve the minimum heat input required for weld nugget formation (the melting of the base steel) at the center. It has been observed that the required increase in welding current is related to the melting point of the coatings; the lower the melting point, the larger the increase.[13] Second, interactions between the coatings and electrodes accelerate the deterioration of the electrodes. Most of the research on LSRSW of coated steels has been devoted to this electrode deterioration problem.[11] In the present work, the effect of Au plating on the joint formation and joint strength during SSRSW of 0.2-mm-thick Ni was investigated using metallurgical examination and mechanical testing.

II. EXPERIMENTAL PROCEDURES

Both bare and Au-plated 0.2-mm-thick Ni sheets (Ni 200, annealed) were used in this study. The electrolytic Au plating was about 4-μm thick on both sides. Lap-welded joints were made using either bare or Au-plated coupons approximately 40-mm long and 8-mm wide. The coupons being joined were arranged such that the rolling directions of the two sheets were parallel to each other and to their long axis. The welding system consisted of a Unitek PM7/208 a.c. controller, a Unitek X16/230 a.c. transformer, and a Unitek 80A/115 weld head (air activated). Flat-ended, round RWMA class II (Cu-Cr) electrodes, 3.2 mm in diameter, were used. The firing-electrode force was set to 49 N, and the welding force was 51 N. All joints were made with eight cycles of welding time, with no current ramp-up or ramp-down times. Prior to welding, the unplated sample surfaces

W. TAN, Graduate Student, Y. ZHOU, Assistant Professor, and H.W. KERR, Professor Emeritus, are with the Department of Mechanical Engineering, University of Waterloo, Waterloo, ON, Canada N2L 3G1. Contact e-mail: nzhou@uwaterloo.ca

Manuscript submitted September 6, 2001.

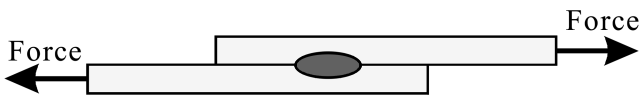
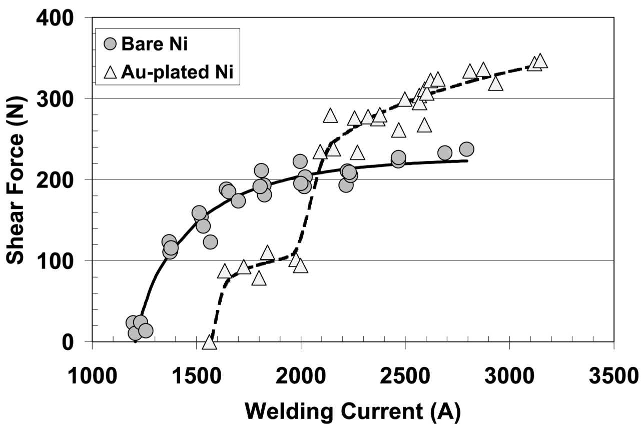
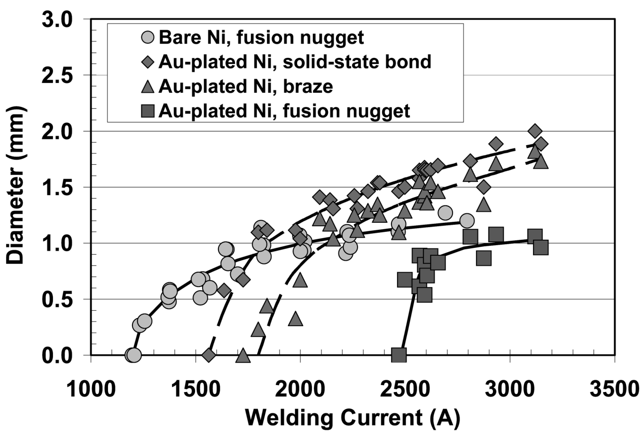


Fig. 1—Schematic of the setup for tensile-shear test.



(*a*)



(*b*)

Fig. 2—(*a*) Tensile-shear force (as a measurement of joint strength) and (*b*) diameter of fusion nugget (or bond area) *vs* welding current for bare and Au-plated Ni joints.

were cleaned by swabbing with alcohol, while no cleaning was performed on the Au-plated samples.

Joint quality was evaluated by tensile-shear testing (Figure 1), using a Quad Romulus IV universal mechanical strength tester at a crosshead speed of 90 μm/s. Diameters of the solid-state bond area, braze area, and fusion nugget were determined from the fractured faying surfaces, the diameter of pullout buttons in tensile-shear testing, and/or the joint cross sections. Tested samples also were examined using optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDX). Metallographic samples were prepared by etching for 3 minutes with a solution containing 13 g $CuSO_4$, 60 mL HCl, 3 mL HF, 3 mL HNO_3, and 150 mL water.

III. RESULTS

Figure 2 shows the maximum tensile-shear force (used as a measurement of joint strength) or the diameter of the fusion nugget/bond area *vs* welding current for both bare Ni and Au-plated Ni lap joints. While both groups of joints showed that the joint strength increased above a certain welding-current threshold, the Au-plated Ni joints showed two distinct stages in the strength curve (Figure 2(a)). This characteristic nature of the joint strength–current curve is the result of different joining mechanisms for Au-plated Ni joints. It can be seen by comparing Figure 2(a) with Figures 3, and 4 that Au-plated Ni joints were formed by brazing and/or solid-state bonding at low welding currents and by a combination of solid-state bonding, brazing, and fusion welding at higher welding currents, while the bare Ni sheets were joined by fusion welding. Further details of the joint formation in SSRSW of both bare Ni and Au-plated Ni sheets are presented as follows.

For bare Ni sheets, when the welding current was lower than 1200 A, no joint was made; only partial surface melting occurred at the faying surfaces (Figure 5). The rolling directions on the coupons in Figure 5 were arranged perpendicular to each other, to have clearer contrast between local melting and the original surface. When the welding currents ranged between 1200 and 1300 A, joints formed, but failed through the nugget (Figure 6(a)). When the welding current was higher than 1300 A, joints failed through the base metal (corresponding to the maximum breaking load) and a pullout button was produced during subsequent tearing (Figure 6(b)). Weld-metal expulsion (Figure 6(b)) and severe electrode sticking were observed when the welding current was above about 2000 A.

For Au-plated Ni sheets, when the welding currents ranged from 1600 to 1800 A, bonding started to occur between the Au plating layers, and the joint failed mainly through the faying surfaces in the tensile-shear test, with a small central region torn out of one of the plated surfaces (Figure 7). The EDX analysis of the fractured faying surfaces indicated that this bonded region was still pure Au. Detailed SEM analysis of the fractured surfaces showed that the bonding was incomplete, with patches of original plating-surface morphology indicating that these regions were not in contact during welding because of the surface roughness (Figure 7(b)). High-magnification examination of the faying surface a little farther from the torn central region revealed small regions of ductile-shear failure surrounded by the original rough porous Au-plated surface (Figure 7(c)). Comparing this bond with a braze formed later as the welding current increased, this joint is considered to be formed by a solid-state bonding process (probably forge welding), since localized high-temperature deformation and bonding should precede melting.

When the welding current was above 1800 A for Au-plated Ni joints, melting started to occur in the center of the bond area (Figure 8), and this melting formed a braze layer between the two Ni sheets. However, the braze layer contributed little to the overall joint strength when the welding current was below 2000 A (Figure 2(a)), which was probably due to the existence of small but numerous voids as a result of gases trapped between the sheets (Figure 8(b)). The joints failed through the solid-state-bonded and brazed layers. The EDX analysis of the fractured faying surfaces indicated that the brazed region (region C in Figure 8(b)) was actually a Au-Ni alloy rather than pure Au, as in the solid-state-bonded region (region B in Figure 8(b)). When the welding current

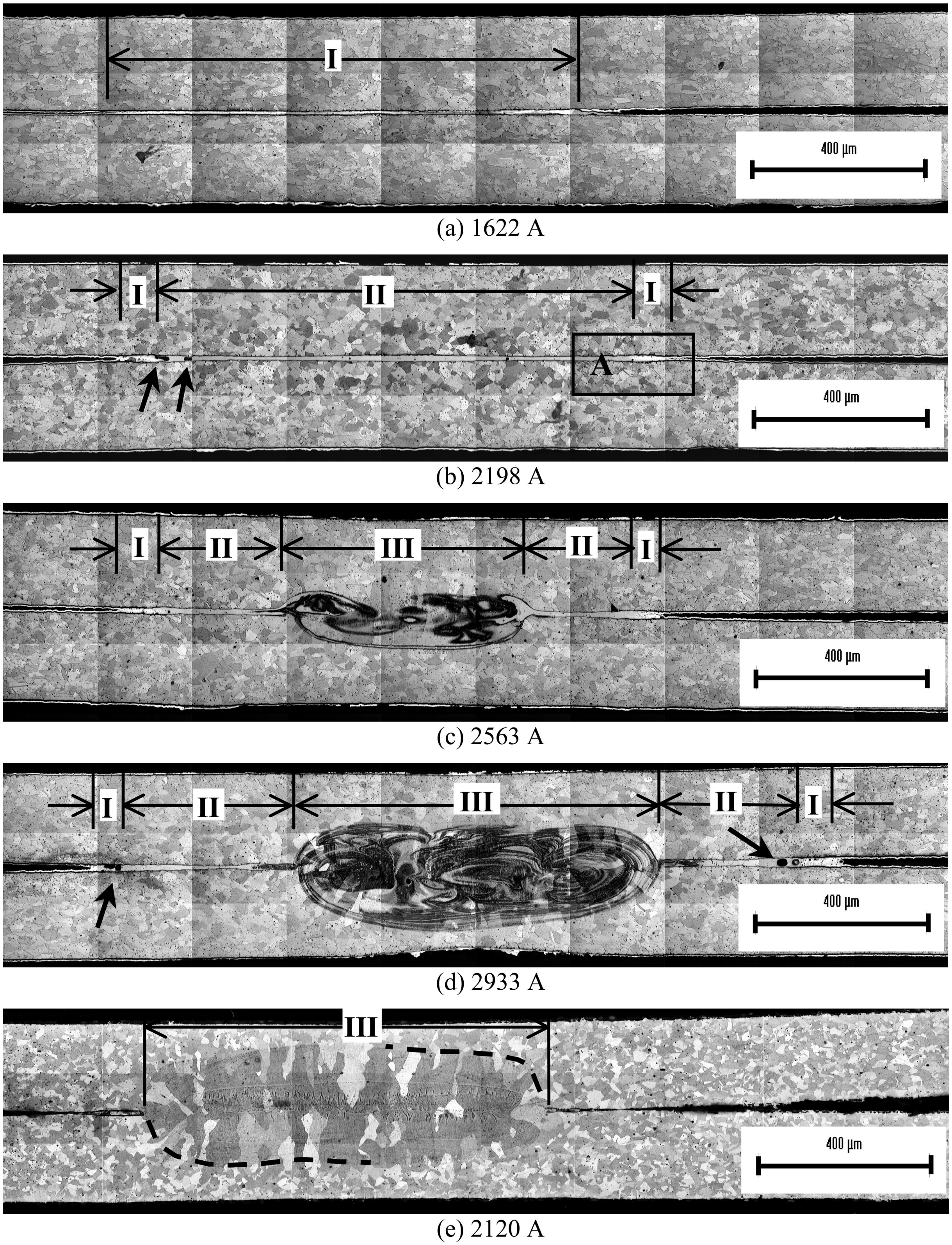


Fig. 3—Cross sections of (*a*) through (*d*) Au-plated Ni and (*e*) bare Ni joints (the welding currents are given below the photos) showing different types of bonds. I: solid-state bond, II: braze, and III: fusion nugget. Large voids are indicated by arrows and part of the fusion boundaries are indicated by dash lines. Details of region A in (b) are shown in Fig. 4.

was above 2000 A, the strength of the brazed joint increased considerably (Figure 2). At these higher welding currents, most of the voids seemed to be pushed away from the central area and accumulated near the periphery of the braze layers (Figure 9(c) and the arrows in Figure 3). The joints failed through the solid-state-bonded layer and the weak braze (the

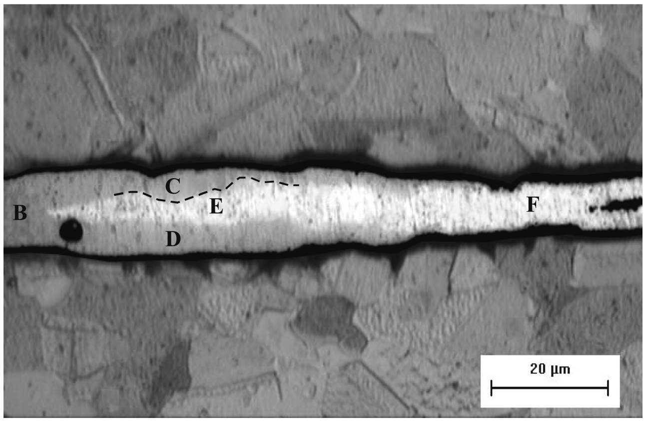
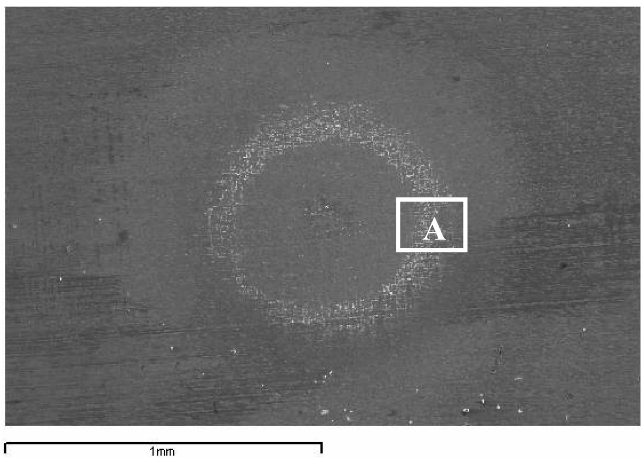
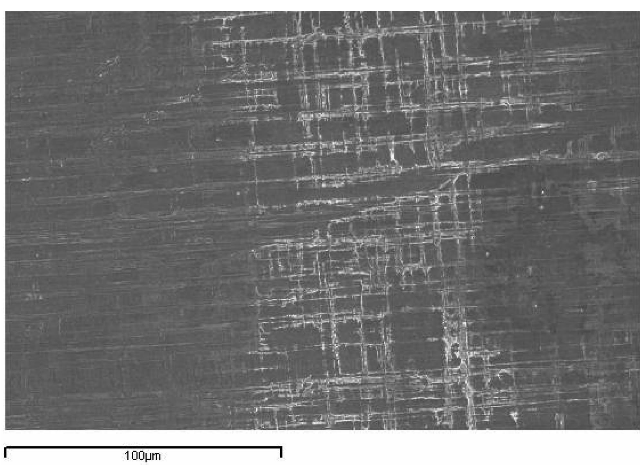


Fig. 4—Details of region A in Fig. 3(b) showing that Au and Ni mixed to form an Au-Ni alloy at the interface between the Au plating and Ni substrate. The dashed line indicates part of the upper boundary between the braze and the solid-state bonded Au layer. The composition of different regions is listed in Table I.



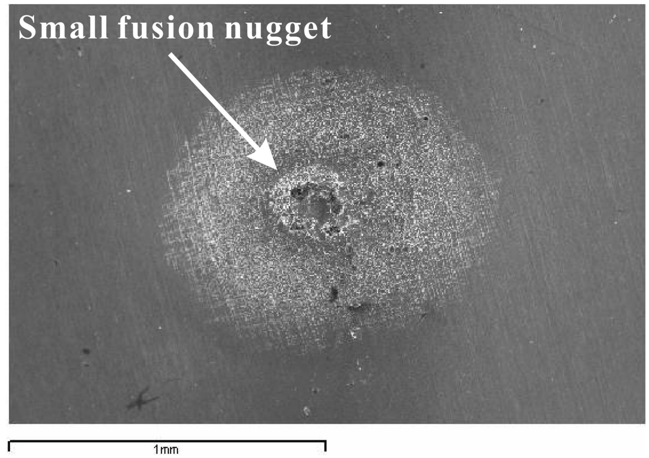
(*a*)



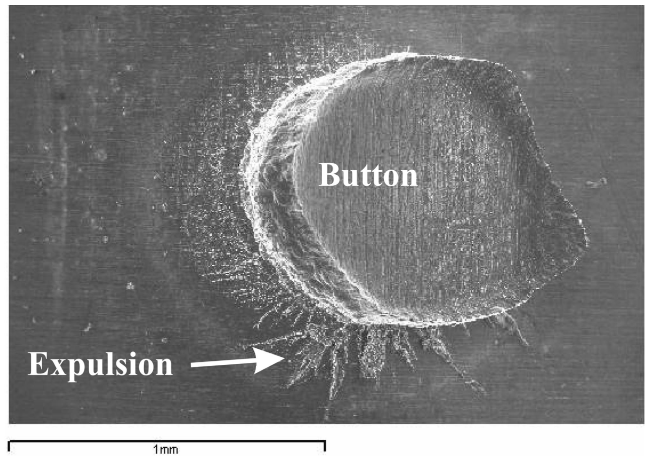
(*b*)

Fig. 5—A faying surface from a bare Ni joint made at 1197 A and failed along interface during testing showing (*a*) a ring of partial surface melting and (*b*) details of area A in (a).

area with numerous voids and next to the solid-state area, Figure 9(c)) and then through base metal (Figure 9(a)), reaching the maximum breaking load. The fracture of the central



(*a*)



(*b*)

Fig. 6—(*a*) A bare-Ni joint made at 1233 A and failed through nugget and (*b*) a bare-Ni joint made at 2217 A and failed through base metal. A pullout button was produced during subsequent tearing after the base metal failure occurred.

strong braze (the area with one or a few voids, Figure 9(b)) occurred during subsequent tearing during the tensile-shear testing. Cross sections near the braze periphery also showed that the braze layers penetrated into the interface between the Au plating and Ni substrate (Figure 4). This penetration is a result of the mixing of Au and Ni at the interface, producing an alloy with a lower melting point than both Au and Ni. The EDX analysis indicated that the braze layers were Au-Ni alloys with about 15 to 21 wt pct Ni (Table I). Figure 4 also shows the solid-state-bonded pure Au layer (regions E through F) between two thin alloyed braze layers near the original Ni interfaces. Therefore, for these conditions, the joint is really formed by a combination of solid-state bonding and brazing, often with a partial or complete ring of accumulated void near the interface between the weak and strong braze areas (Figure 9(c)).

When the welding current reached 2500 A for the Au-plated Ni joints, a fusion nugget (as a result of the melting of the Ni substrates) started to form (Figure 3(c)), with only gradual increases in joint strength being observed (Figure 2(a)). The mixing of the two liquid phases (the molten Au-Ni braze and melted Ni substrates) was incomplete (Figure 3(c)), and this poor mixing was still obvious even as the

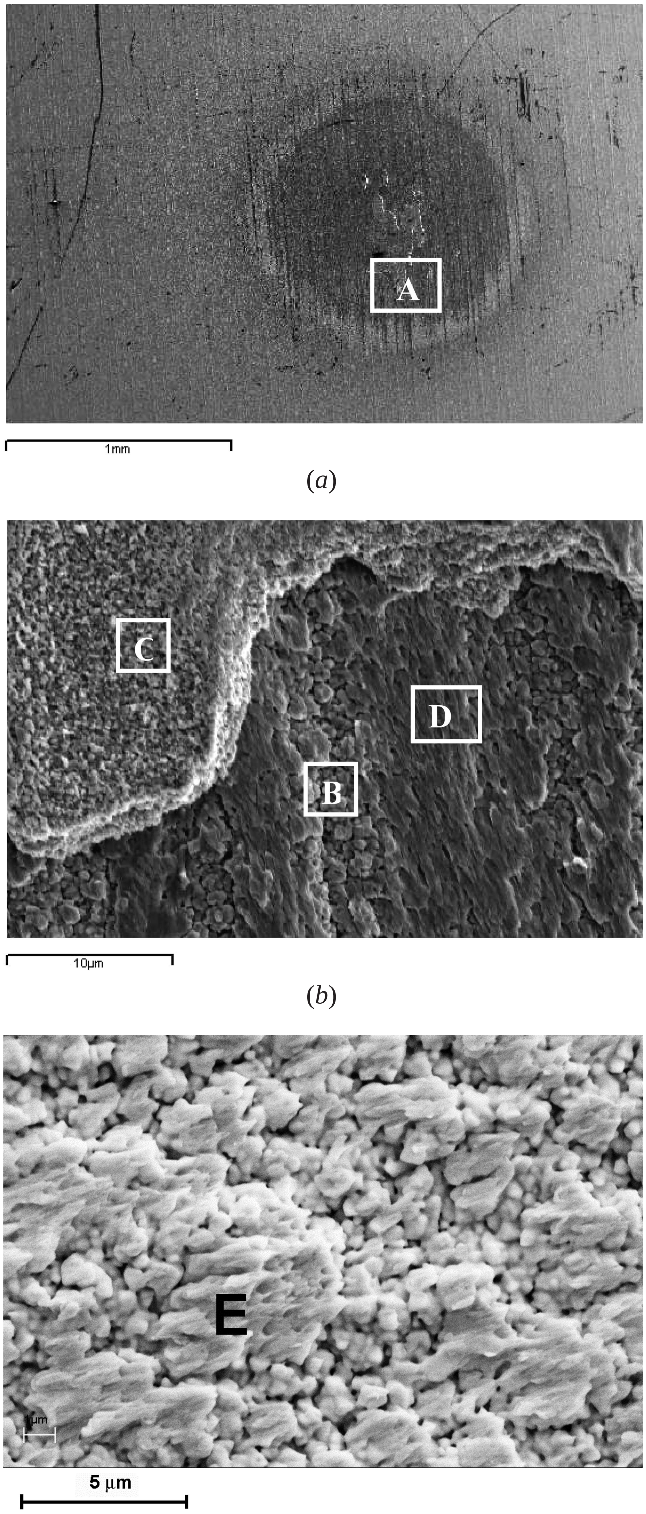


Fig. 7—(*a*) A fractured faying surface of Au-plated joint made at 1726 A: (*b*) details of the area A in (a) showing an incomplete bond area (indicated by the original plating surface morphology at B, with region C showing fractured Au plating and region D showing fractured faying surface); and (*c*) high-magnification photo of fractured faying surface further from the center, showing small regions (*e.g.*, E) of ductile fracture and the original Au-plating surface surrounding them.

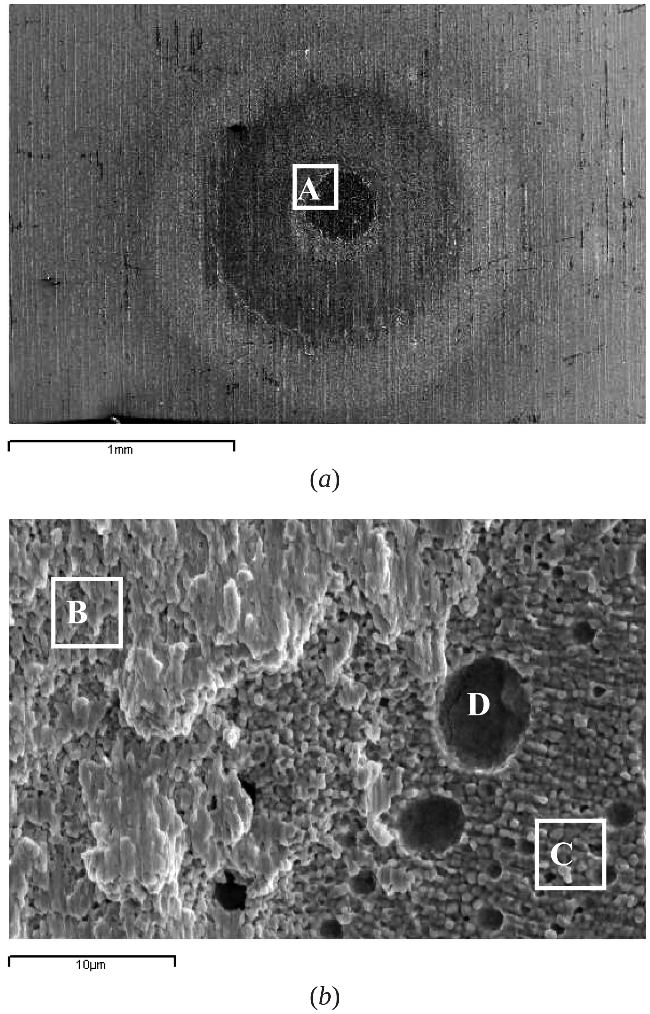
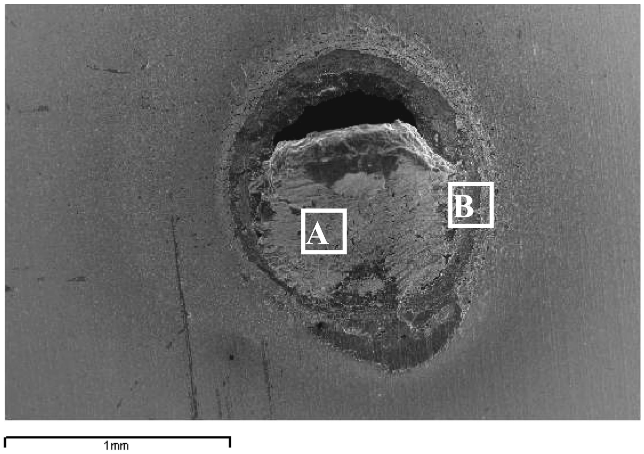


Fig. 8—(*a*) A fractured faying surface of Au-plated joint made at 1977 A showing melting at the center of the bond area and (*b*) details of area A in (a). Note B is solid-state bonded region, C is brazed region, and D is a void.

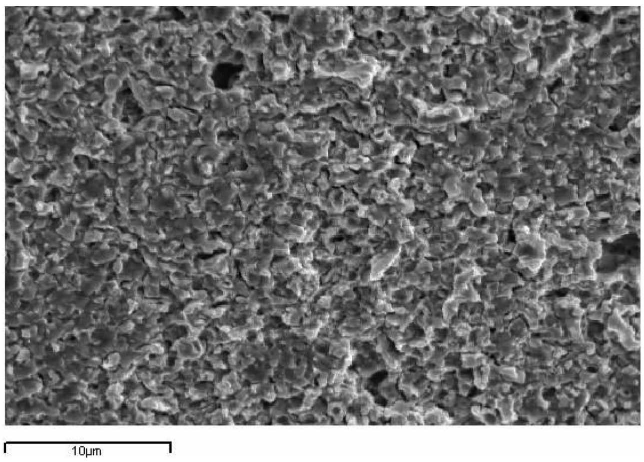
welding current increased (Figure 3(d)). The welded joint of Au-plated Ni sheets now consisted of an outer solid-state-bonded halo, an inner brazed halo, and a fusion nugget in the center. In the current range from 2500 to 3100 A, most joints failed through the solid-state-bonded layer, the weak braze, and then through the base metal. The fracture through the strong braze and nugget region occurred during subsequent tearing after the maximum breaking load during tensile-shear testing. The fractured-nugget region also showed a result of incomplete mixing of Au and Ni (Figure 10(b)). At welding currents above 3100 A (Figure 11), the joints failed again through the solid-state-bonded layer, the weak braze, and then the base metal, but a “pullout button” was produced in the subsequent tearing after the maximum breaking load. Severe electrode sticking was experienced when the welding current exceeded 2800 A. However, weld-metal expulsion was not observed even when the welding current was above 3200 A in Au-plated Ni joints, which may be due to the existence of the solid-state-bonded rim, which contained the molten metal and prevented it from splashing.

IV. DISCUSSION

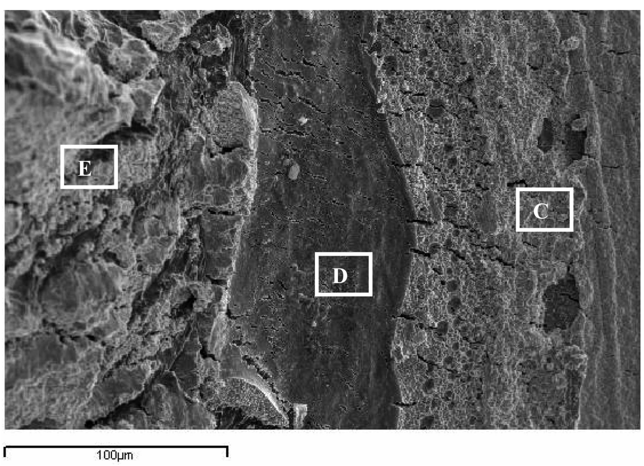
The effects of Au plating during SSRSW of Au-plated Ni sheets are discussed in this section under the following



(*a*)



(*b*)



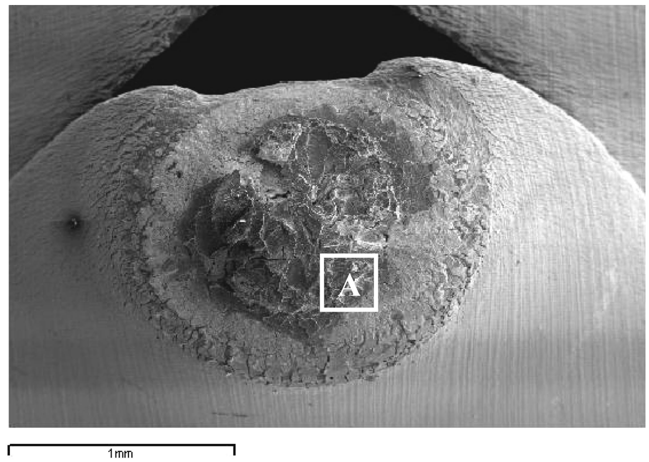
(*c*)

Fig. 9—(*a*) A fractured faying surface of a fully developed brazed joint of Au-plated Ni sheets made at 2271 A (note the base metal failure); (*b*) details of the fractured brazed area A in (a); and (*c*) details of B in (a). Note C is solid-state bonded area, D is a riverlike void resulted from accumulated small voids, and E is brazed area. A small region of weak braze exists between C and D.

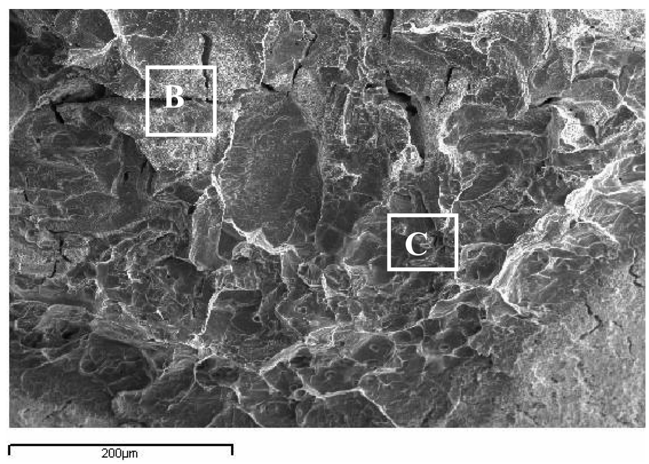
topics: the mechanisms of joint formation, the effect of Au on required welding current, and the increased joint strength in Au-plated Ni joints at high welding currents. Differences

Table I. Composition of the Solid-State Bonded and Brazed Areas

Locations in Figure 4	Au (Wt Pct)	Ni (Wt Pct)
B	79	21
C	85	15
D	81	19
E	100	0
F	100	0



(*a*)



(*b*)

Fig. 10—(*a*) A fractured surface of Au-plated joint made at 2621 A and (*b*) details of region A in (a). Note region B is Au-Ni alloy and region C is mostly pure Ni.

between SSRSW of Au-plated Ni sheets and LSRSW of Zn-coated steels are also discussed.

A. *Joint Formation*

It appears from the previous section that three joining mechanisms (solid-state bonding, brazing, and fusion welding) occurred in SSRSW of Au-plated Ni sheets, while fusion welding may be the only joining mechanism during SSRSW of bare Ni sheets. In LSRSW of Zn-coated steels,[12] no solid-state bonding was observed; only the melting of Zn and fusion welding of the steel occurred. A schematic diagram of

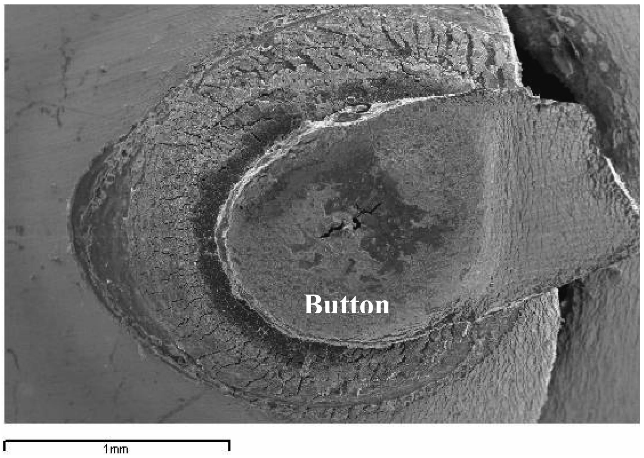


Fig. 11—A tested joint of Au-plated Ni made at 3216 A showing a pullout button was produced during subsequent tearing after the base metal failure occurred.

joint formation during SSRSW of Au-plated Ni is given to assist the following discussion (Figure 12).

In theory, two ideal metallic surfaces (*e.g.*, both perfectly clean and atomically flat) will bond together if brought into intimate contact, because they will be drawn together spontaneously by the interatomic forces until the distance separating them corresponds to the equilibrium interatomic spacing.[14,15] In reality, heat and/or pressure are applied to overcome the impediments of engineering surfaces (*i.e.*, surface roughness and contamination) to make a metallurgical joint; both are available during resistance spot welding in forms of electrode force (pressure) and resistance heating. There are three major types of joining mechanisms: solid-state bonding, brazing/soldering, and fusion welding.[14,15] Solid-state bonding is mainly achieved by deformation where no melting occurs; therefore, by definition, solid-state bonding occurs at temperatures lower than the melting point of the metals to be joined, if the interfaces are brought into contact and the pressure/temperature combination permits localized high-temperature deformation. Fusion welding and brazing/soldering are achieved by melting and epitaxial solidification, but localized melting of base metals occurs in fusion welding, and (in initial stages, at least) only the melting of filler metals occurs in brazing/soldering.

In the present case of Au-plated Ni sheets, Au is not oxidized, so the surface of Au is relatively clean, with only a layer of adsorbed gases and water vapor.[16,17] Most engineering metals, including nickel, have a metallic oxide layer beneath the adsorbed gases and water vapor, because oxide formation is favored thermodynamically.[16,17] Therefore, solid-state bonding is relatively easy to achieve between Au layers, since the applied heat and pressure are only needed to overcome surface roughness and bring the interfaces into intimate contact. In this connection, gold also has a lower melting temperature than nickel, favoring more deformation at a given temperature. These facts may explain why a solid-state bond (probably by forge welding) is observed in Au-plated Ni sheets, while the surface contaminants (mainly nickel oxides) and higher hardness of bare Ni sheets would prevent such a bond from occurring in bare Ni joints. It is believed that in LSRSW of Zn-coated steels, the presence of the oxide also inhibits solid-state bonding, and the low melting temperature of the Zn favors melting.

According to the Au-Ni binary-phase diagram (Figure 13),[18] complete liquid and solid solubility occurs at high temperatures, but there exists a composition at 18 wt pct Ni with a minimum melting point of 955 °C, which is lower than the melting point of Au at 1064 °C. Therefore, when welding Au-plated Ni, melting would start at the Au-Ni interface due to the mixing of Au and Ni to form the low-melting-point alloy at 18 wt pct Ni (Figure 12(b)). It was confirmed by the EDX analysis (Table I) that the brazed layer is very close to the composition of Au-18 wt pct Ni. Preferential melting at the Au/Ni interface is evident from the braze penetration into the interface at the periphery of the braze layer (Figure 4). As the welding current is increased, the molten Au-Ni alloy at the Au/Ni interface will grow to consume the Au plating to form a braze between the Ni substrates (Figures 3(b), 12(c), and 12(d)). But, braze layers formed at low welding currents are filled with small voids as a result of gases trapped between the sheets (Figure 12(c)). Most of the voids are pushed away and accumulated near the periphery of the braze layers at high welding currents, leaving a relatively dense and strong braze at the center (Figure 12(d)).

Eventually, the temperature at the joint center will rise above the melting point of Ni at 1455 °C as the welding current increases: a fusion nugget is formed (Figures 3(c) and (d) and 12(e)), and this nugget grows as the welding current increases. Mixing of the two liquid phases (molten Au-Ni braze and melted Ni substrates) is initially very poor (Figure 3(c)), but increases with increased welding current (Figure 3(d)), presumably as a result of stronger electromagnetic stirring as the current is increased. Figure 12 illustrates the main steps of the joint formation during SSRSW of Au-plated Ni sheets: solid-state bonding, followed by brazing and fusion welding. For bare Ni sheets, fusion welding becomes the only joining mechanism, because no low-melting-point plating is present on the surfaces and the surface oxides prevent solid-state bonding from occurring.

In LSRSW of Zn-coated steels, no solid-state bonding was observed, but melting of the Zn coating was observed;[12] therefore, soldering (since the temperature is less than 450 °C) is possible in welding of Zn-coated steels. However, the joint formed by the Zn soldering offers little practical significance, because Zn is low in strength and the constrained thin Zn layer tends to cleave parallel to the basal plane, making it brittle. The molten Zn is later pushed away from the center during welding; hence, only a very small amount of Zn is trapped at the center area and mixed with Fe to become part of the nugget.[12] Unlike LSRSW of Zn-coated steels, Au plating is always part of the Au-plated Ni joints (as in the solid-state-bonded/brazed layers and fusion nuggets), and brazed Au-plated Ni joints can be even stronger than the bare Ni joints (Figure 2). Resistance brazing, in fact, is used to hermetically seal electronics packages (*e.g.*, Au-plated Kovar devices[1]).

B. *Welding Current and Joint Strength*

Similar to the effect of Zn in LSRSW of Zn-coated steels,[11] Au greatly reduces the contact resistance because of its low resisitivity and low hardness. Our static contact-resistance measurements have indicated that an interface between Au-plated Ni sheets has a contact resistance about 7 pct of that for a Ni/Ni interface at room temperature.

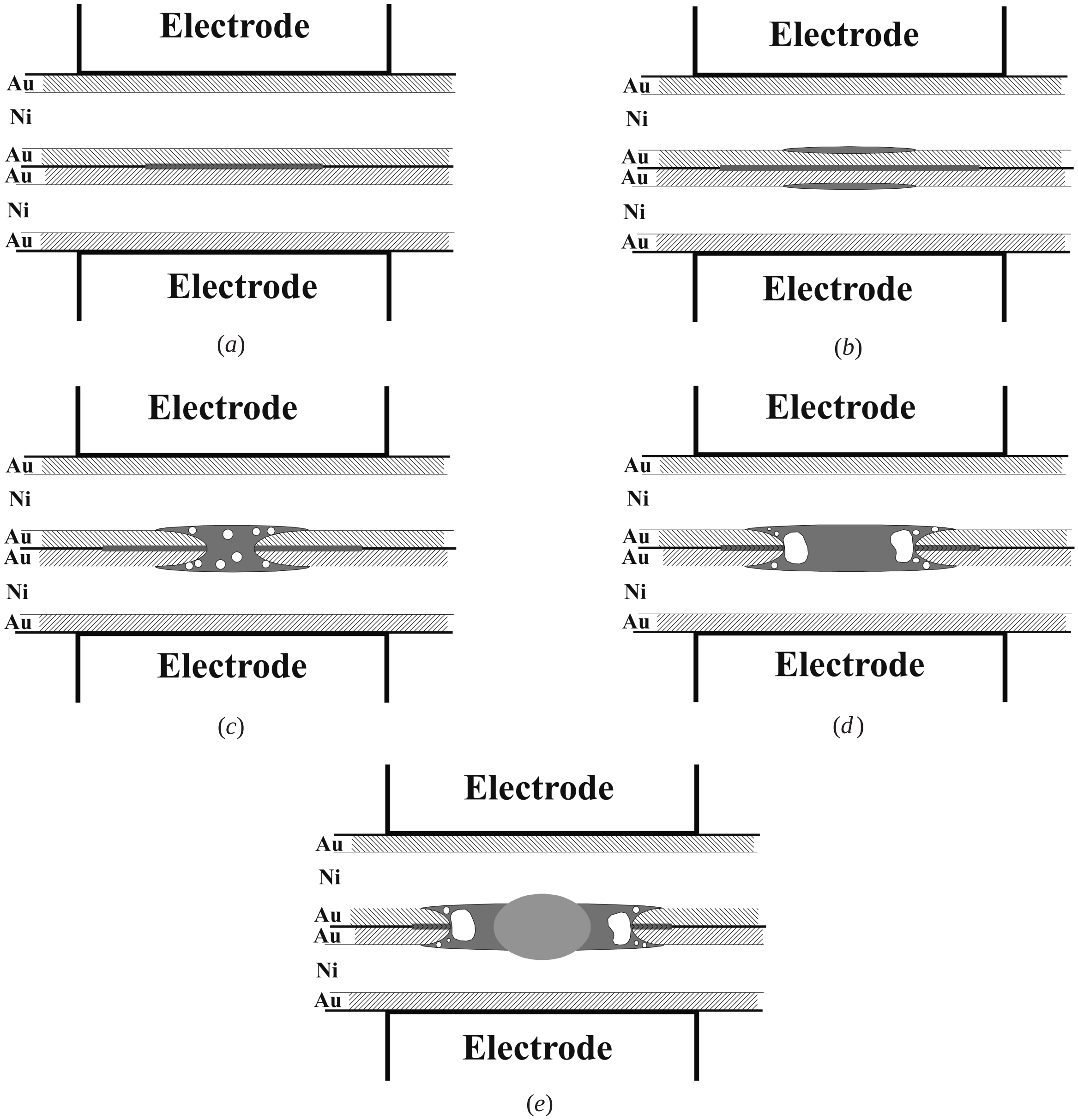


Fig. 12—Schematic diagram of joint formation during welding of Au-plated Ni sheets: (*a*) solid-state bonding, (*b*) melting initiates at the Au/Ni interface, (*c*) brazing at low welding current (with small but numerous voids resulted from trapped gases), (*d*) brazing at high welding current (with accumulated voids at the periphery of the braze), and (*e*) fusion nugget formed. Note the sketches are not in proportion in dimensions, and especially the thickness of the Au plating is exaggerated to permit better visualization of the stages.

In this connection, Holm[19] has reported that the contact resistance of Au/Au interfaces is about 40 times less than that of Ni/Ni interfaces at room temperature. Later, gold increases the contact area by forming a molten Au-Ni braze and, thus, reduces the current density. Both these factors would require an increase in welding current/welding time. The required increase in welding current for Zn-coated steels is generally about 25 to 100 pct compared to uncoated steels.[11] In the present work on Au-plated Ni sheets, the required increase in welding current depends on the types of joints desired or, more importantly, on the joint strength required. For example, a simple comparison of the threshold welding currents indicate 1600, 1800, and 2500 A for solid-state bonding, brazing, and fusion nugget formation, respectively, for the Au-plated Ni joints, which are increases of about 30, 50, and 110 pct compared with the current of 1200 A for the bare Ni sheets (Figure 2(b)). However, the Au-plated Ni joints formed by solid-state bonding are weak (at about 100 N of tensile-shear force), which is probably due to the porous nature of the Au plating and the incomplete bonding. On the other hand, the fusion nuggets in the bare Ni joints at this strength level (100 N) were not fully developed in size (at about 0.5 mm in diameter). The strength of the bare Ni joints was about 200 N when the welding current was about 1900 A, the point when the fusion nuggets were almost fully developed (at about 0.9 to 1.0 mm in diameter). If Au-plated Ni joints are required to match this strength level, well-developed brazed joints would be needed (Figure 2). This requires a welding current above 2100 A, compared with that of 1900 A for bare Ni sheets, which is only about a 10 pct increase. At even higher welding currents, the strength of these brazed joints continued to increase with

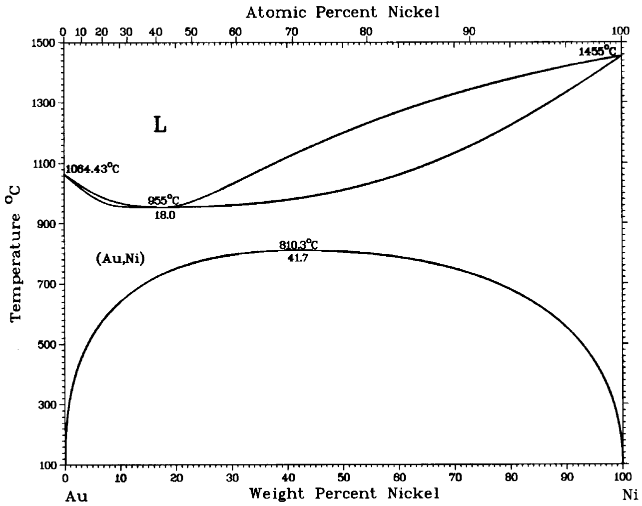


Fig. 13—Au-Ni binary phase diagram.[18]

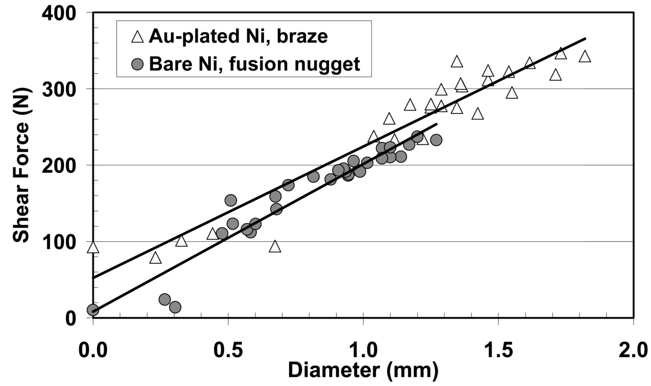


Fig. 14—Shear force *vs* the diameter of braze area or fusion nugget for the Au-plated and bare Ni joints, respectively.

increased welding current, whereas the bare Ni joints leveled off at a lower strength.

Various failure modes were observed during tensile-shear testing of the bare Ni joints: interfacial failure, weld failure, and base-metal failure (button pullout). Interfacial failure results due to weak bonding between the metal sheets (Figure 5). Once a fusion nugget is formed in a bare Ni joint, the joint fails through the nugget when the nugget is small (Figure 6(a)) or through the base metal when the nugget diameter is above a certain size (Figure 6(b)), and a pullout button was produced during the subsequent tearing. This is consistent with the observations made in LSRSW of steels.[5] However, the failure modes for Au-plated Ni joints are more complex because of the combined joining mechanisms. Joints with only a solid-state bond and weak braze failed through bonded areas (Figures 7 and 8). Once a strong braze was formed, base-metal failure occurred, and the fracture through the strong braze and fusion nugget occurred during subsequent tearing when no nugget formed or the nugget diameter was small (Figure 9(a)). When the nugget diameter was large (about 1.0 mm), at a welding current above 3100 A, a pullout button was produced during subsequent tearing after base failure occurred (Figure 11). In comparison, the minimum nugget diameter was about 0.5 mm when a pullout button was observed in bare Ni joints.

In the automotive industry, the diameter of pullout buttons is used as a quality indicator, because the strengths of resistance spot-welded joints are generally correlated to the diameter of the fusion nugget,[5] and the Zn coating contributes little to the joint strength. The strengths of the bare Ni and Au-plated Ni joints are plotted as a function of nugget and braze diameters, respectively, in Figure 14. In both cases, the strength appears to be linearly dependent on the diameter of the fused area. This is similar to the effect of nugget diameter on resistance spot-weld strength in LSRSW.[5,20] However, even without the formation of a fusion nugget, brazed joints of Au-plated Ni sheets can be stronger than the bare Ni joints with a nugget, such as between 2100 and 2500 A in the present experiments (Figure 2). At still higher currents, the braze diameter continues to increase in the Au-plated Ni case, further increasing the strength over the unplated Ni case (Figures 2 and 14).

V. CONCLUSIONS

The effects of Au plating on joint formation and joint strength during SSRSW of thin-sheet nickel were investigated. The major conclusions are summarized as follows.

1. The bonding mechanisms during SSRSW of Au-plated Ni may be solid-state bonding at low welding currents, a combination of solid-state bonding and brazing at intermediate welding currents, and a mixture of solid-state bonding, brazing, and fusion welding at high welding currents.
2. The Au plating increases the threshold welding current required to form a joint during SSRSW of Ni sheets, due to the reduction of contact resistance. The increases in threshold welding currents for the Au-plated Ni sheets compared to the bare Ni sheets are about 30 to 110 pct, depending on the bonding mechanisms involved.
3. At high welding currents (>2100 A), the brazed joints of Au-plated Ni sheets are stronger than the bare Ni joints even without a fusion nugget formed.

REFERENCES

1. *Introduction to Microjoining*, K.I. Johnson, ed., TWI, Abington, United Kingdom, 1985.
2. David Steinmeier: *Weld. J.*, 1998, vol. 77, pp. 39-47.
3. K.J. Ely and Y. Zhou: *Sci. Technol. Weld. Join.*, 2001, vol. 6 (2), pp. 63-72.
4. B.H. Chang, M.V. Li, and Y. Zhou: *Sci. Technol. Weld. Join.*, 2001, vol. 6(5), pp. 273-80.
5. D.W. Dickinson: *Welding in the Automotive Industry*, Reports SG 81-5, American Iron and Steel Institute, Washington, DC, 1981.
6. *Resisance Welding Manual*, 4th ed., Resistance Welder Manufacturers' Association, Philadelphia, PA, 1989.
7. Y. Zhou, P. Gorman, W. Tan, and K.J. Ely: *J. Elec. Mater.*, 2000, vol. 29 (9), pp. 1090-99.
8. Y. Zhou, S.J. Dong, and K.J. Ely: *J. Elec. Mater.*, 2001, vol. 30(8), pp. 1012-20.
9. *Microelectronics Packaging Handbook*, R.R. Tummala and E.J. Rymaszewski, eds., Van Nostrand Reinhold, New York, NY, 1989.
10. E. Biro, Y. Zhou, D.C. Weckman, and K.J. Ely: *J. Laser Appl.*, 2001, vol. 13 (3), pp. 96-104.
11. M.R. Finlay: *Resistance Spot Welding of Metallic Coated Steels and PVD Coated Electrodes*, CRC No. 18, Australian Welding Research, Silverwater, NSW, Australia, Oct. 1996.
12. S.A. Gedeon and T.W. Eagar: *Metall. Trans. B.*, 1986, vol. 17B, pp. 887-901.
13. T. Saito: *Weld. Int.*, 1992, vol. 6 (9), pp. 695-99.
14. W.F. Savage: in *Welding Imperfections*, A.R. Pfluger and R.E. Lewis, eds., Addison-Wesley, London, 1968.

15. R.W. Messler, Jr.: *Principles of Welding: Processes, Physics, Chemistry and Metallurgy*, John Wiley & Sons, New York, NY, 1999.
16. K. Miyoshi: in *Handbook of Micro/Nanotribology*, B. Bhushan, ed., CRC Press, Boca Raton, FL, 1995, pp. 81-107.
17. D.R. Gaskell: *Introduction to Metallurgical Thermodynamics*, 2nd ed., Hemisphere Publishing Corporation, New York, NY, 1981.
18. *Binary Alloy Phase Diagrams*, T.B. Massalski, ed., ASM INTERNATIONAL, Materials Park, OH, 1990.
19. Ragnar Holm: *Electric Contacts Theory and Application*, Springer-Verlag, New York, NY, 1967.
20. P.H. Thornton, A.R. Krause, and R.G. Davies: *Weld J. Res. Suppl.*, 1996, vol. 75 (3), pp. 101-s-108-s.