Resistance Microwelding of SUS304 Stainless Steel Fine Wire

Shinji Fukumoto¹, Taijú Matsuo¹,*; Harushige Tsubakino² and Atsushi Yamamoto¹

¹Graduate School of Engineering, University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2201, Japan
²Hyogo Science and Technology Association, Japan

Resistance microwelding of fine crossed stainless steel wires is of increasing industrial importance for medical devices. Therefore, a study has been performed to clarify the basic joining mechanisms. The effect of main process parameters such as welding current, force and weld time were investigated by detailed mechanical testing and metallurgical examinations. Especially, joint strength and microstructures were sensitive for welding current and force. It should be noted that no fusion nugget was formed at the weld interface. Since the joint breaking force was determined by bond area and interfacial strength in the case of interfacial fracture, both of them are needed to be optimized to obtain sound joint. Moreover, heat affected zone should be minimized. A bonding mechanism with several main process stages, wire collapse, surface melting, liquid phase squeeze out and solid-state bonding, was proposed. [doi:10.2320/matertrans.48.813]

(Received June 26, 2006; Accepted January 24, 2007; Published March 25, 2007)

Keywords: resistance microwelding, crossed wire welding, stainless steel, microstructure

1. Introduction

Resistance microwelding (RMW) is a microjoining process to weld thin metal sheets or wires (< ≦ 0.2−0.5 mm in thickness or diameter), mostly nonferrous metals by resistance heating, and it has importance in fabrication of electric device and components (such as batteries, capacitors and microsensors).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 (> ≦ 0.5−0.7 mm), and, to a much smaller extent, to join sheet aluminum alloys.⁵−⁸ Resistance microwelding of fine metal wires is often used in electronics and instrumentation fabrication, mainly for electrical interconnections.¹⁹−¹² Nowadays, demand of RMW is increasing for medical devices such as cardiac pacemaker, catheter, stent and so on. Although some new alloys were developed for medical implants, stainless steels are still key material. Especially austenitic stainless steel which is nonmagnetic is suitable for medical implant since the magnetic materials would affect a medical treatment with a magnetic resonance imaging (MRI) scanning. Delta ferrite will form in weld metal when austenitic stainless steel is welded by fusion welding processes. On the other hand, in the case of resistance microwelding of crosssed wire, no fusion nugget forms. Previous work on RMW of crossed fine Ni wires using an alternating-current supply showed that the welding mechanism based on solid-state bonding with transient liquid phase.¹³ These mechanisms of joint formation are significantly different from those in RMW of the Ni sheets where a fusion nugget is formed,¹⁴ probably due to different geometric shape of the specimens resulting in different interfacial phenomena during welding.

The purposes of this work are to study the welding process and the joint strength in RMW of cruciform austenitic stainless steel fine wires.

Table 1 Chemical composition of SUS304 stainless steel wire (mass%).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07</td>
<td>0.38</td>
<td>1.22</td>
<td>0.026</td>
<td>8.43</td>
<td>18.13</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

2. Experimental Procedures

Cold-drawn SUS304 stainless steel fine wire whose diameter is 400μm was used in this study. The chemical composition of the wire is shown in Table 1. The wires were bonded by resistance microwelding in the form of a cruciform joint, as shown in Fig. 1. Before welding, the wires were ultrasonically cleaned in acetone. The resistance microwelding system consisted of a Miyachi Technos MDB-2000 direct-current (DC) controller and a Miyachi Technos MH-D20A weld head. Flat-ended, round Cu-Cr electrodes, 3.0 mm in diameter, were used. All weld tests employed the same type of welding current program, in which current was increased from zero with no ramp-up until the current setpoint value (200−400 A) was reached. Then current was maintained constant for a “hold time” (0.1−8.0 ms) before being terminated. When the electrode force reaches at the set-up value, welding current is turned on. After RMW, the joint breaking force, an indication of joint quality and strength, was measured by tensile-shear testing at a crosshead speed of 0.02 mm/s (Fig. 1(a)). At least three joints were tested for each run to average the joint breaking force. Wire deformation in welding was evaluated by the parameter of set down, which was calculated by the thickness of joint assembly before and after welding:

\[
Set\ down = \frac{A - B}{A} \times 100
\]

where A and B are defined in Fig. 1(b). In this study, A is 400μm.

Metallographic samples were prepared by electrolytically etching in a water solution containing 10% oxalic acid at 4 V. The microstructure of the fractured surface and cross section of joints were examined using optical microscope (OM) and scanning electron microscope (SEM).
3. Results

3.1 Effect of current

Typical cross sections of the joints made with various welding current are shown in Fig. 2. The wires were squashed and penetrated into each other to varying degrees. Before etching the bond line was not observed even with lower current. The bond interface could be identified after etching, and the bond line eventually disappeared, with new grains growing across the bond interface as the recrystallization progressed (Fig. 2(d)). The recrystallized region that shows equiaxed microstructure is regarded as heat affected zone (HAZ). No fusion nugget was formed at the weld interface as well as RMW of Ni fine wires as long as welding current was not too high. Heat affect zone (HAZ) shows not ditch but step structures, which means M$_{23}$C$_6$ precipitates were not formed at grain boundary during the welding. So the microstructure consisted of austenite single phase. Extent of the HAZ with recrystallized microstructure grew with increasing welding current. When the welding current is too high, melting of bulk material occurred, as indicated by the solidified columnar grains (Fig. 2(c)), and severe electrode-sheet sticking to the wire and weld metal expulsion was observed. A tiny bit of δ-ferrite was observed in the joint made with too high current. Volume fraction of δ-ferrite was smaller than that is estimated by Schaeffler diagram since the
formation of δ-ferrite was suppressed due to rapid cooling rate\textsuperscript{15} in comparison with the other fusion welding processes such as GTAW.

Figure 3 shows the effects of welding current on the joint breaking force (as an indication of joint strength) and set down. The set down increased monotonically as the current increased but the breaking force first increased with increasing welding current and subsequently decreased after reaching peak value. The fracture mode also changed from interfacial shear fracture to tensile fracture in the HAZ. This characteristic behavior of breaking force is believed to result from competition between the improvement of interfacial bonding (determined by both bonded area and interfacial strength) and the local softening of the wire (resulting from recrystallization in the HAZ). When the interfacial bonding was weak, the joint failed through bond interface. The increase in bonded area (as indicated by the increased set down) and/or interfacial strength (as indicated by the disappearing interface in Fig. 2) increased the load required to fracture the bond. However, with increasing welding current, the HAZ near the bond interface became the weaker region of the joint because of recrystallization of the originally cold-drawn microstructure, and the fracture mode switched to HAZ failure. Joint breaking force reached its maximum around this point. Further increase of welding current resulted in a reduction in joint breaking force as the recrystallization continued to progress. Vickers hardness of fully recrystallized HAZ and as received wire were approximately HV260 and HV600, respectively, which means that additional strength of the wire itself introduced by cold drawing during wire manufacture was lost due to the recrystallization. It should be pointed out that even when the joint breaking force continued to decrease, the interfacial strength would continue to increase as the bond interface was disappearing.

The observation that joint breaking force increased before reaching its maximum with an increase of set down is consistent with previous work\textsuperscript{9,10,12} But the optimum set down in this work, at approximately 90%, was much higher than that reported in the literature.\textsuperscript{12} This may be due to many differences in experimental conditions (such as wire compositions, properties and welding power supply).

### 3.2 Effect of weld time

The effect of weld time on microstructure and joint breaking force are shown in Fig. 4 and Fig. 5, respectively. Both set down and extent of the HAZ increased with increasing weld time. All the joints made at the current of 200 A were fractured at weld interface and the strength increased as weld time increased. At least 2.0 ms of weld time, the critical weld time, is necessary to make a joint at 200 A. Higher joint breaking force was obtained with higher welding current at the given welding time. So the critical weld time would decrease as welding current increases. All joints made with 500 A were fractured in HAZ. When the joint is fractured in HAZ, the joint strength depends on extent
and strength of the HAZ as described 3.1. Decrease of joint strength after reaching the peak value is due to the extent and/or softening of HAZ.

In resistance welding, heat generation $W$ is determined by the following equation,

$$W = I^2 R t$$  \hspace{1cm} (2)

Where $I$ is welding current, $t$ is the duration of the current (weld time) and $R$ is resistance of workpieces. The resistance includes contact resistance at the electrode/workpiece interfaces and at the faying interface between two workpieces, and bulk resistance of the workpieces and electrodes. These resistance values change during the process. Among them, resistance at faying interface, that is contact resistance, drops drastically at the initial stage of welding process. As a result, heat generation after contact resistance becomes negligible is mainly due to bulk resistance of workpiece. Therefore, too long weld time would not be necessary to obtain sufficient heat generation.

3.3 Effect of welding force

Figure 6 shows typical cross sections of joints made with different welding force. Larger set down was obtained with higher welding force. The microstructures of weld interface and HAZ show different features depending on welding force. Obvious weld line was identified in the joint made at higher welding force. (Fig. 6(d)) On the other hand, in the case of lower welding force, weld line was vague and the HAZ looked obvious instead. (Fig. 6(a)) The HAZ formed with lower welding force consists of two regions such as step and ditch structures. The region of ditch structure where $\text{M}_{23}\text{C}_6$ would be formed at the grain boundary was formed as band like, which is indicated by arrows in Fig. 6(b). So the original faying surfaces would exist between the bands.

![Figure 6](image)
Figure 7 shows a typical indentation on a wire from a cross-wire assembly that was subjected only to welding force but no current, which would be close to the initial contact area. The size and contact condition of this initial contact area, as determined by the welding force, wire hardness and surface condition, would affect the initial contact resistance. A greatly increased contact area during welding would cause a sharp drop in contact resistance, which implies that, with such a special joint geometry in this work, the initial contact resistance would play a major role in determining heat generation (eq. (2)).

Table 2 Diameter of initial contact area.

<table>
<thead>
<tr>
<th>Welding force (N)</th>
<th>Diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.6</td>
<td>90</td>
</tr>
<tr>
<td>39.2</td>
<td>124</td>
</tr>
<tr>
<td>58.8</td>
<td>155</td>
</tr>
</tbody>
</table>

The joint breaking force curve showed a peak value against the welding force when the joints were fractured at the weld interface (Fig. 8). This is because the joint breaking force was determined by both weld area and interfacial bond strength. When the welding force is too small, set down must be too small, resulting in low joint breaking force despite high interfacial strength. When the welding force is large, contact resistance is small, resulting in insufficient heat generation, which leads to low interfacial strength.

4. Discussion

4.1 Welding mechanism

Welding mechanism of resistance crossed wire welding is different from resistance spot welding of sheet metals. No fusion nugget was formed at the weld interface. The difference results from the geometry of joint. Depending on joining process employed (fusion welding, brazing/soldering, and solid state bonding), roughly three approaches are used to eliminate surface contamination (mainly oxide films), which is the greatest single impediment to metallurgical bonding between two metallic surfaces. One is the use of a chemical flux, which removes oxide films from surfaces being jointed (as in brazing and soldering); this is not relevant in this work since no fluxes were used. Another approach is by melting and/or washing away of oxide films, as in fusion welding, when adjacent base metal becomes molten. The last, as in solid-state bonding processes, is by breaking up oxide films by mechanical means (e.g., surface extension due to plastic flow as in pressure welding). The last two (i.e., melting and plastic flow) are possible in this work, since both resistance heating and electrode force (pressure) are available. The present work suggests that resistance microwelding of crossed fine stainless steel wires is a mixture of effects in which the joint is formed mainly by solid-state bonding but with a transient liquid phase formation, similar to some other resistance welding process (such as flash welding, high frequency welding and possibly projection welding) such that thin films of molten metal are formed at faying surfaces and subsequently squeezed out by forging force. In fact, resistance microwelding of crossed fine nickel wires is based on the mechanism, that is, solid state bonding with a transient liquid phase.

Figure 9 shows typical crossed stainless steel fine wire joint and details of its flash. Solidification structure was observed on the surface and cross sections of flash. Since any solidification structures were not observed at the weld interface in most joints (Fig. 2(a) and (b), Fig. 4), initial transient liquid phase would be squeezed out by the welding force to form the flash. In some cases, microstructure of flash looks connecting continuously to the microstructure of weld interface where is located between band like HAZ regions as shown in Fig. 6(a) and (c). This type of microstructure tends to be formed when the welding force is low. Low welding force causes large contact resistance, resulting in large heat generation as followed by eq. (2) which produces much more molten metal, and small set down. Thus initial liquid phase is not squeezed out completely because of not only much more...
Because, in general, fusion welded SUS304 stainless steel by conventional fusion welding process such as GTAW shows sufficient strength. But bonded area must be small when welding force is too small, resulting in low joint breaking force.

Therefore, based on the above results and discussion, a process sequence of resistance cross-wire microwelding of fine stainless steel wires is proposed as follows. First, an indentation between crossed wires would occur, Stage I. Since point contact between the wires would deform when subjected to the electrode force. After the current is turned on, surface melting occurs at the contact area because of the high initial contact resistance (and hence heat generation), Stage II. recrystallization would occur near the bond interface as the temperature field builds up and wire deforms around the interface. The liquid phase would be almost immediately squeezed out carrying some of the surface contaminants as the wires rapidly collapsed at the elevated temperature, resulting in relatively clean faying surface for metallurgical bonding, Stage III. The wires would continue to collapse/deform due to the combined effect of elevated temperature and welding force but the heat generation would be greatly reduced since most of the contact resistance at the faying interface would disappear due to expansion and cleaning of the faying surface, and any further heat generation would come mainly from the bulk resistance. The bond interface would ultimately disappear as new grains grow across the interface as a result of recrystallization, Stage IV. Welding force could be considered mainly as a forging force in this stage. Therefore, resistance cross-wire microwelding of fine stainless steel wires is basically a solid state joining process with transient surface melting at the early stage of the process, which is similar to that of crossed fine nickel wire welding. It is believed that sufficient surface melting and subsequent squeezing out of this transient liquid phase is a prerequisite for strong solid-state bonding.

Figure 10 shows a typical fracture surface of sound joint. Fracture surface shows inhomogeneous morphology due to its character of welding mechanism. Fracture surface consists of mainly two regions such as dimple (Fig. 10(c)) and relatively flat (Fig. 10(b)). The former region that must have high interfacial bond strength surrounded the later. Relative interfacial movement is important factor to break oxide films and to obtain closely contact in the case of cold pressure welding. In the present study, as wires collapse, relative interfacial movement is most likely larger in the vicinity than the central region, resulting in higher interfacial bond strength in the vicinity. Again, initial liquid phase is squeezed out to form flash (Fig. 10(e)). These results also correspond to the above proposed welding mechanism.

5. Summary

Resistance microwelding of crossed fine stainless steel wires was investigated by means of detailed mechanical testing and metallurgical examinations. The main conclusions include:

(1) Welding current and force had the greatest effects on joint microstructure evolution and hence joint strength.
Increasing welding current increased joint breaking force but too high a current caused lower breaking force because of recrystallization softening in the HAZ. Optimum welding force was seen, with low welding force resulting in too much heat generation and low bonded area and excessive welding force reducing the breaking force because of low interfacial strength.

(2) It is proposed that resistance microwelding of crossed fine nickel wires includes the following stages: 1. cold wire collapse; 2. surface melting; 3. liquid phase squeeze out; and 4. solid-state bonding. It is believed that sufficient surface melting and subsequent squeezing out of the liquid phase is needed to produce fresh metal surfaces for strong solid-state bonding.

Acknowledgement

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C), 16560638, 2005.

REFERENCES