Mechanism of Resistance Micro-welding of Stainless Steel Fine Wires for Medical Applications

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Abstract. Resistance micro-welding (RMW) is an important joining process used in the fabrication of miniature instruments, such as medical devices. The excellent corrosion resistance of 316 low-carbon vacuum melted (LVM) stainless steel (SS) wire makes it ideal for biomedical applications. In this study, optimization of the bonding conditions for RMW of 316 LVM was carried out by examining key welding parameters including force, time and current. Mechanical performance of RMW was tested using micro-tensile testing and fracture surfaces were examined using SEM. Finally, a bonding mechanism is proposed by metallurgical observations of weld cross-sections.

Introduction

316LVM SS wire has been used for medical instruments for several decades because of its excellent corrosion resistance [1, 2]. Medical devices are minuscule and integrated, which results in a reduction of welding joint size from millimeter (mm) to micrometers (µm) [3]. Studies of RMW of Ni sheet, Ni wire, and Au coated Ni wire have been previously investigated [4-6]. Fukumoto and Zhou developed the bonding mechanism for pure Ni wire by incrementally increasing the weld current [5]. However, the bonding mechanism of RMW of SS is not fully understood. The objective of this study is to detail the bonding mechanism of 316LVM SS determined by experimental procedures.

Experimental Method

The chemical composition for the 0.015 in. (0.38 mm) diameter 316 LVM SS wire used in this study is shown in Table 1. The wires were bonded at right angles (90°). A MacGregor DC400P direct-current (DC) controller and Unitek 80A/115 weld head are used for RMW. Flat-ended, round RWMA class 2 (Cu-Cr) electrodes with a 3.2 mm diameter were used. The bonding force was maintained at 1.5 kg and the current hold time was 50 ms (with an up-slope of 10 ms and a down-slope time of 3 ms). Welding current was varied from 90 A to 350 A. The joint breaking force (JBF) was determined using an Instron micro-tensile tester. The cross-section and fracture surface of joints were observed using optical microscopy and SEM, respectively. Samples were etched using 5 ml HNO₃, 25 ml HCl, and 30 ml H₂O at an elevated temperature (80°C).

Table 1. The composition of the 316 LVM (Low-carbon Vacuum Melted) stainless steel wire

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt%</td>
<td>0.03</td>
<td>2.00</td>
<td>0.75</td>
<td>0.025</td>
<td>0.01</td>
<td>17-19</td>
<td>13-15.0</td>
<td>2.25-3</td>
<td>0.5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Results and Discussion

Microstructure and Bonding Mechanism

Observation of the joint microstructure reveals the stages in development of the bond between the wires. Application of the electrode force (1.5 kg) results in an initial set down as the point contact spreads to a deformed contact area. This initial stage was termed ‘Stage 1’ by Fukumoto and Zhou [5], who observed ‘cold collapse’ in RMW of Ni wires. Below the minimum current of 90 A, there
is insufficient heating at the faying surface to initiate bonding. The surface oxide layer and presence of contaminants prevents solid-state bonding.

Beyond the 90 A current threshold, localized heating at the wire interface due to the high contact resistance results in melting of a thin surface film (‘stage 2’ [5]). The molten layer is immediately squeezed out, taking some of the contaminants and oxides to the periphery, leaving behind a clean metallic surface (‘stage 3’ [5]). The squeezed-out flash near the edge of the interface in Fig. 1(a) shows fine liquated grains. Liquated grains have been found in the heat-affected-zone of fusion welded austenitic steels due to low melting point constituents segregated at the grain boundaries [7]. This suggests that the squeezed-out liquid layer in RMW of SS wire is only partially molten.

![Fig. 1. Metallurgical cross-sections of the RMW joints in SS.](image)

Increasing the current to 100 A results in an enlarged temperature field around the interface, triggering dynamic recrystallization of the very fine base metal microstructure, as shown in Fig. 1(b). Continued set-down and recrystallization (‘stage 4’) was also observed by Fukumoto and Zhou [5], who found that solid-state bonding was the mechanism of joint formation in RMW of Ni-
wires. In the case of SS wire, however, grain boundary liquation occurs, likely due to melting of impurity (S, P, and Si) containing compounds segregated at grain boundaries (GB’s). This is exasperated by grain growth, which decreases GB area and increases concentration of impurities at GB’s. For example Kujanpaa et al. found S enrichment at 2000 times the concentration in liquated GB’s of 310 SS [8]. Thus, in the case of SS, initial bonding is facilitated by GB liquation.

At a current of 150 A, the heating is sufficient to initiate melting. This is evident by the dendritic solidification structure shown in Fig. 1(c). The solidification mode is austenite (A) or austenite-ferrite (AF), which is common to austenitic stainless steels [9]. Increasing of the current to 225 A results in full fusion and 100 % set-down as shown in Fig. 1(d). The formation of the fusion zone, or the ‘5th stage’ of bond development, is observed in RMW of SS wires but absent in Ni wires because the electrical resistivity of SS is substantially higher.

Fig. 2. Schematic of the tensile test and joint breaking force of the RMW joint vs welding current

Joint Strength and Fracture Surface Appearance

A schematic of the tensile test is shown in Fig. 2. According to the JBF results in Fig. 2, a minimal current of 90 A was required for bonding. Between 90 A and 200 A there is a gradual increase in JBF. Peaks of JBF were attained when current values surpassed 200 A. However, there is increased scatter in JBF at these currents. Beyond 350 A overwelding occurs, resulting in a significant reduction in cross-sectional area of the wires, and thus the JBF, due to severe melting.

Fracture surfaces for the different welding currents are shown in Fig. 3. The 100 A condition produced interfacial failure (Fig. 3(a)). A small bonded region is evident at the centre of the fracture surface. Dimples in this region are similar to those of diffusion bonding [10]. The periphery is deformed, showing the imprint of the opposite wire. At the 120 A condition shown in Fig. 3 (b), interfacial fracture is once again observed.

However, there is a larger bonded area compared to the 100 A condition which resulted in a higher JBF. As the current is increased to 150 A and the bonding mechanism changes to fusion welding, the JBF increases and the fracture changes to wire failure (Fig. 3(c)). Failure occurs near the fusion zone (FZ) for weld currents up to 200 A. Increasing the weld current to 225 A results in ductile fracture with relatively higher JBF, exceeding 75 N. Failure occurs in the HAZ of the wire, which has been softened by recrystallization (Fig. 3(d)). Therefore, from these results, the optimized bonding mechanism is full fusion.

Conclusions

The RMW of 316 LVM stainless steel wire was investigated by examining mechanical properties, microstructure, and fracture surfaces. At low currents, the bonding mechanism of RMW of SS wires is similar as that of Ni wires - both cases involve cold collapse, surface melting and squeeze-out. In
SS, however, liquation of GB’s occurred with increasing weld current. Furthermore, since SS has a higher electrical resistivity than Ni, fusion welding is possible, resulting in higher JBF. The SS joint at 200 A and 1.5 kg bonding force produces a robust and high strength bond.

1. The proposed bonding process is: 1) cold collapse; 2) surface melting; 3) squeeze-out; 4) recrystallization and liquation; and 5) fusion welding at high current.

2. The joint breaking force increases with increasing weld current. After reaching a maximum of 80 N, values decreased due to HAZ softening at higher currents.

3. Fracture modes in tensile testing change with increasing current from interfacial failure to fusion zone failure and, finally, to HAZ failure.

Fig. 3. Fracture surfaces at various currents after tensile testing

References