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Optimization of resistance spot welding on the assembly of refractory alloy 50Mo–50Re thin sheet

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Abstract

Resistance spot welding (RSW) was employed to pre-join refractory alloy 50Mo–50Re (wt%) sheet with a 0.127 mm gage. Five important welding parameters (hold time, electrode, ramp time, weld current and electrode force) were adjusted in an attempt to optimize the welding quality. It was found that increasing the hold time from 50 ms to 999 ms improved the weld strength. Use of rod-shaped electrodes produced symmetric nugget and enhanced the weld strength. Use of a ramp time of 8 ms minimized electrode sticking and molten metal expulsion. The weld strength continuously increased with increasing the weld current up to 1100 A, but the probabilities of occurrence of electrode sticking and molten metal expulsion were also increased. Electrode force was increased from 4.44 N to 17.8 N, in order to reduce the inconsistency of the welding quality. Welding defects including porosities, columnar grains and composition segregation were also studied.

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1. Introduction

Molybdenum alloyed with rhenium is used in many applications such as heating elements, thermocouple sheathings, vacuum furnace components, electron tube components, and other important industrial and aerospace applications [1]. The strength, creep resistance, and low temperature ductility of W, Mo, Cr metals are all improved with increasing the rhenium content up to its solubility limit. This ‘rhenium effect’ was first reported in 1956 [2]. The yield strength and ultimate tensile strength of commercially available molybdenum are 300 MPa and 350 MPa, respectively at ambient temperature, as compared to 845 MPa and 1053 MPa, respectively for the molybdenum alloy with a rhenium content of 47.5 wt% (so-called 50Mo–50Re) in the fully annealed condition [3]. The elongation of pure Mo is 4.1% [4], while that of this alloy can reach 19% [2] at room temperature.

In this study, a 50Mo–50Re alloy was used as a structure of the heating element in traveling tubes in the microwave telecommunication industry.

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Resistance spot welding (RSW) was employed to pre-join the 50Mo–50Re sheet before brazing. To our knowledge, however, no work was reported in the literature on RSW assembly of Mo–Re alloys. Only limited work was conducted on the other welding methods of assembling Mo–Re alloys. For example [5], by alloying the welded metal with rhenium as a filler metal by automatic arc welding, a Mo had been welded and the plasticity of welded joints in Mo was increased. Besides the lack of knowledge on welding of refractory alloys, there was another difficulty in this study. The thickness of 50Mo–50Re sheet in this study was relatively small, say 0.127 mm. Such a small scale resistance spot welding was only mentioned by Steinmeier [6] and reported by the work of Zhou [7,8]. Significant differences between large scale and small scale resistance spot welding were briefly addressed in these studies. The limited information about small scale resistance spot welding was another challenge in the research field of metal joining.

In resistance spot welding, variables such as weld current, weld time, electrode type and shape, surface roughness and cleaning, and contact resistance between faying surfaces, etc., could all affect the welding quality. The energy produced during the welding is given by the following equation [9]:

$$E = I^2Rt, \tag{1}$$

where I is the weld current through the workpieces, R the electrical contact resistance of the workpieces, t the weld time. Therefore, any variables which influence I, R or t will have effects on the welding quality. As a non-programmable variable, contact resistance R can be affected by some other factors, such as electrode shape, surface roughness of workpieces, and electrode force, etc.

This work was conducted in an attempt to optimize resistance spot welding on the assembly of 50Mo–50Re thin sheet with 0.127 mm in thickness. The effects of several important welding parameters (hold time, electrode shape, ramp time, weld current and electrode force) on the welding quality were determined. The welding parameters were identified to optimize welding quality of the 50Mo–50Re sheet.

2. Experiment

50Mo–50Re alloys in the stress-relieved condition were synthesized by *H-Cross Inc.* They were processed by a powder metallurgy (PM) method. Powders of the alloy with purity over 99.98% were blended homogeneously, pressed and sintered at high temperature. Then, the cold-rolling and annealing steps were repeated until a thickness of 0.127 mm was reached, and annealing at 1050 °C was performed as the last step. The sintering, rolling and annealing mentioned above were all carried out in a hydrogen atmosphere. Fig. 1 shows the typical microstructure of the as-received alloy, illustrating the elongated grain structures along the rolling direction (RD).

The length and width of all the samples were 76.2 mm and 2.54 mm, respectively. The length direction was along the transverse direction (TD) of the sheet. Before resistance spot welding, the surfaces of the samples were thoroughly cleaned by deoxidization using the decomposed hydrogen from ammonia gas at 1200 °C for 10 min. Pairs of samples with a lap-shear geometry with a 3.81 mm

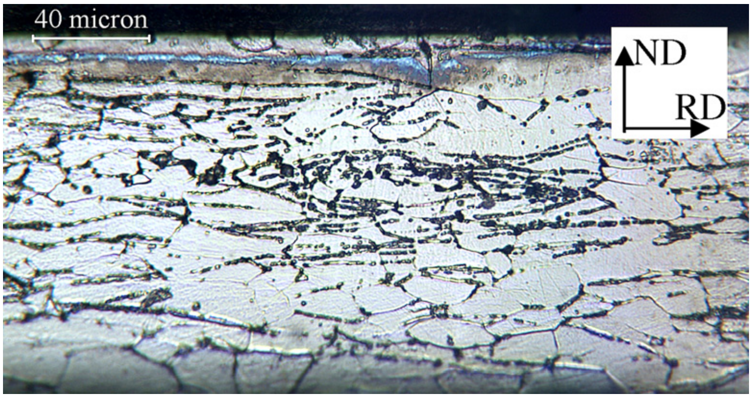

Fig. 1. Microstructure of a 50Mo–50Re alloy RD – rolling direction and ND – short transverse direction.

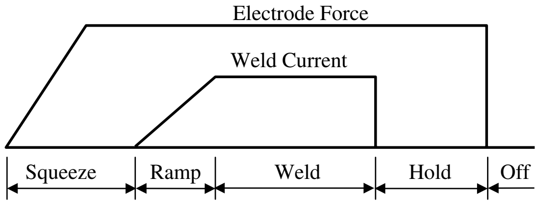

Fig. 2. A diagram of weld current and electrode force profiles in resistance spot welding.

overlap length were welded using a Unitek Peco Model DC25 linear DC resistance welding equipment, which was driven by air, preventing over loading and assuring the reproducibility of the applied load. Fig. 2 schematically shows electrode force and weld current profiles during resistance spot welding. Different types (such as Mo, W, 25 wt% Cu–75 wt% W) and shapes (such as a flat mandrel and rod, rod and rod) of electrodes were used in welding. The rod-shaped electrodes had a diameter of 1.524 mm. Surface roughness was also varied by grinding using different grits (240, 400 and 600) of SiC grinding paper after surface cleaning in preliminary experiment. However, no change was found in strength of the welded samples. This was possibly because the sample surface had been so well cleaned that the effect of surface roughness became insignificant on the welding quality. As a result, the samples used in this study were not roughened after surface cleaning. Characterized by a ZYGO's NewView 5000 3D surface profiler, the roughness of the samples before RSW is 0.14 μm. Although the weld time is also an important factor controlling the welding quality, it was fixed at 2 ms in this work. However, its effect is being studied in this group, and the corresponding results will be published in the future. Different welding parameters were adjusted in turn in the welding, in order to evaluate their effects on the welding quality. If not specified, the other welding parameters were from the default ones which are listed in Table 1. The real-time measurements of actual current, resistance, voltage and power input, were conducted on a computer.

Table 1
Default welding parameters

Squeeze time: 150 ms	Weld time: 2 ms
Hold time: 999 ms	Current: 900 A
Bottom electrode: Mo(+)	Top electrode: W (−)
Electrode force: 8.90 N	Electrode diameter: 1.524 mm

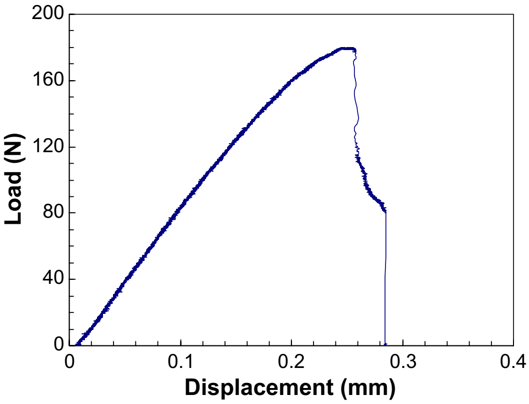

Fig. 3. A typical load–displacement curve of a tensile-shear test on a welded 50Mo–50Re sample.

Tensile-shear tests of the welded samples were conducted on an Instron Series IX Testing System with a 0.2 mm/min tension rate at room temperature. Fig. 3 shows a typical load–displacement curve of a welded sample. It shows that in the tensile-shear test the load–displacement curve exhibits a nonlinear region before reaching the peak load. The load started to drop as the crack initiates [10]. The peak load in the load–displacement curve was used to evaluate the welding quality in this work. Peak load measured was regarded as strength of weldment. The strength of the tensile-shear test for each combination of parameters was obtained from the average value of five samples.

Metallographic observations of the fracture surfaces and cross-sections of the welded samples were made by optical microscopy and SEM (Hitachi 3200 N).

3. Results and discussion

3.1. The effect of hold time

Hold time, which was the additional time for the weld head to continue applying force after the weld current was turned off, significantly affected the welding quality. The strength of the weldment was enhanced from 100.0 N to 113.0 N when the hold time was increased from 50 ms to 999 ms, without varying the other default welding parameters. Fig. 4 shows the fractography of the welded samples with different hold times. It is shown that the hold time of 999 ms (Fig. 4(b)), which was the maximum hold time that could be applied in the welder, yielded ductile weldments, compared with the brittle

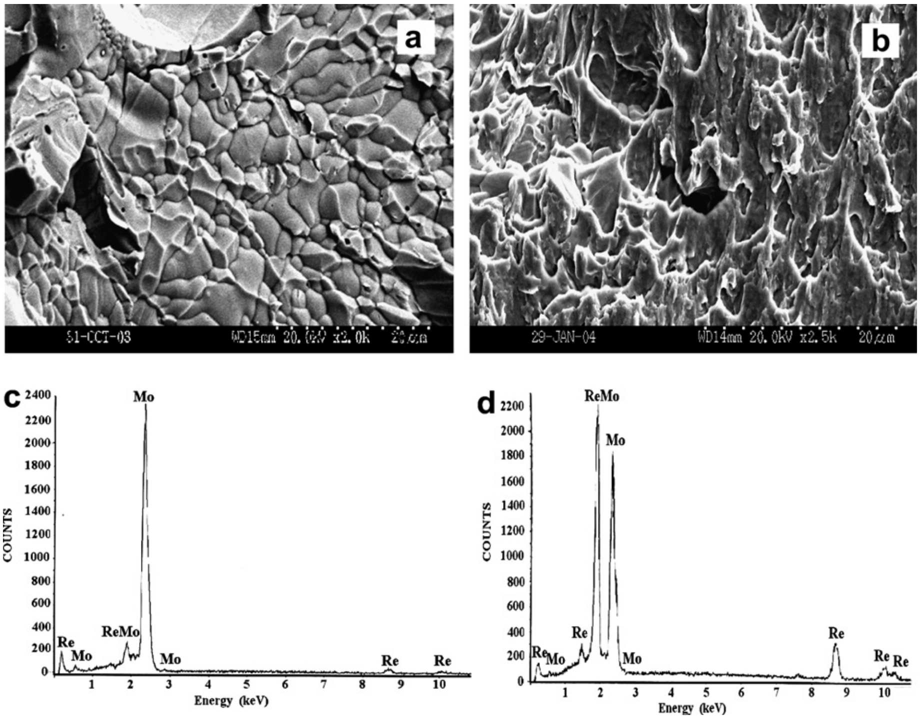

Fig. 4. Fracture surfaces of welded Mo–Re sheet: (a) hold time of 50 ms, and (b) hold time of 999 ms. Chemical compositions of welded Mo–Re sheet analysed by EDS: (c) hold time of 50 ms, and (d) hold time of 999 ms.

weldments obtained when using only 50-ms hold time (Fig. 4(a)). EDS (Fig. 4(c)) obtained in the weldment processed by using 50-ms hold time showed Mo-rich grain boundaries in the nugget, while in the case of 999-ms hold time, the chemical composition of the nugget (Fig. 4(d)) was the same as that of the base material (47 wt% Re). The increase in hold time benefited the welding quality due to the higher cooling rate after welding [11]. Fusion welding was often viewed as 'casting a small amount of molten metal into a metal mold' [12]. Therefore, higher cooling rate after welding prevented Mo segregation at grain boundaries. Mo is brittle in nature, whereas the Mo–Re solid solution is ductile. As a result, the nugget produced with a hold time of 999 ms exhibited ductile fracture. Higher cooling rate could also engender a smaller heat affected zone (HAZ), which is normally the weakest region in weldments, and accordingly benefit the quality of welding [13]. Based on the result, the hold time of 999 ms was set in the next experiments.

3.2. The effect of electrodes

Different types of electrodes (Mo and W, 25 wt% Cu–75 wt% W and 25 wt% Cu–75 wt% W) were tested in resistance spot welding of the Mo–Re alloy. In the study, when using 25 wt% Cu–75 wt% W rods with diameters of 1.524 mm as top and bottom electrodes, significant sticking occurred. The significant sticking should be due to the relatively low melting point of Cu, as compared with that of Mo–Re alloy. Therefore, refractory metals are preferred to be used as electrodes in RSW of Mo–Re alloy. To study the effect of electrode shape on the welding quality, a Mo flat mandrel and a Mo rod of 1.524 mm in diameter were separately used as the positive bottom electrode in RSW in this study. The combination of the positive electrode being Mo and the negative electrode being W was found to give rise to better welding quality. Because W had higher resistivity ($5.60 \times 10^{-8}\ \Omega$ m) than Mo ($5.20 \times 10^{-8}\ \Omega$ m), W and Mo were selected as negative and positive electrodes to compensate the effect of polarity that higher heat would be generated on the interface between the workpiece and positive electrode if using the same electrodes to weld the same workpieces. Using the default welding parameters shown in Table 1, the microstructures of nuggets for the mandrel and the rod electrodes are shown in Fig. 5(a) and (b), respectively. For the flat mandrel electrode, the nugget

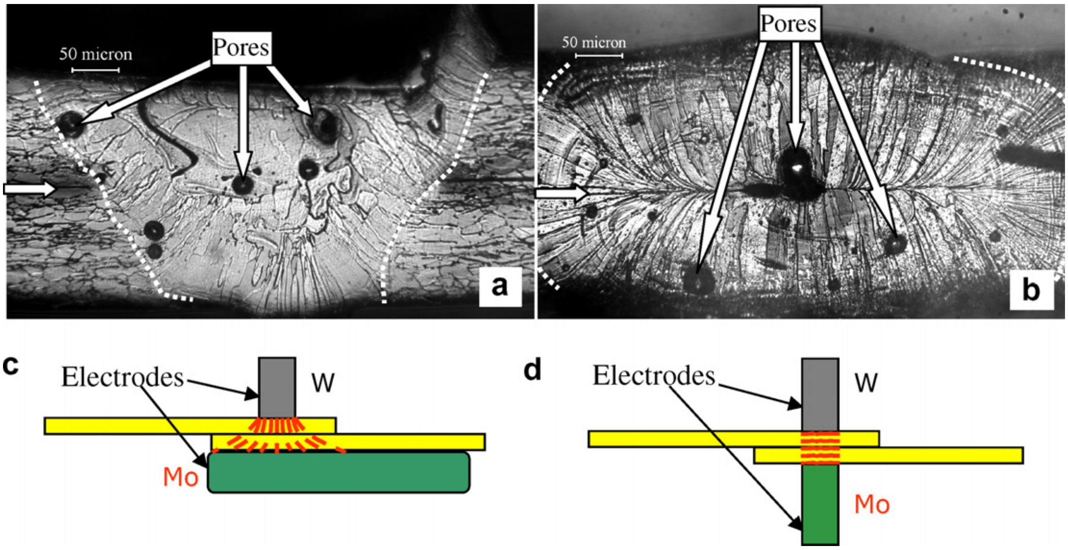

Fig. 5. (a) and (b) The shape and microstructure of the nuggets welded using the electrodes shown in (c) and (d), respectively. The horizontal arrows show the interfaces between two workpieces in (a) and (b).

was highly asymmetric (Fig. 5(a)), while it was nicely symmetric and located approximately at the center of the two workpieces for the rod-shaped electrode (Fig. 5(b)).

The corresponding current density distributions with different shapes of bottom electrodes are schematically shown in Fig. 5(c) and (d). When the bottom electrode was flat, the electric current flowing through the sample adjacent to the bottom electrode was spread over a large area, hence reducing the current density in the bottom workpiece, since there was more contact area between this electrode and the bottom workpiece. The current distribution, i.e., the heat distribution, was asymmetric, as a result. Using the Mo rod bottom electrode, the current density in both the upper and lower workpieces was much more symmetric. The strength of the welded samples with a symmetric nugget was 125.8 N, compared with 113.0 N strength in the asymmetric nugget case. Note that the nugget size was also increased from ~375 μm to ~565 μm, since the heat generated between the workpieces became much higher when the Mo rod was used as the bottom electrode. The nugget sizes are 24.6% and 37.1% of the diameter of the top electrode, when the Mo mandrel electrode and the Mo rod electrode were used, respectively. It had been recognized before that, in small scale resistance spot welding, the maximum diameter of a nugget was limited to only about 30–40% of electrode tip diameter, whereas in large scale resistance spot welding the nugget and electrode tip diameters were comparable [7]. In this study, the nugget size was 37.1% of electrode tip diameter in the symmetric case, which was right within the range of 30–40%.

Columnar grains are produced along the direction of electrodes (as shown in Fig. 5(a) and (b)), no matter which electrodes are used. In fusion welding, when the molten metal solidifies, the grain structure reflects the cooling condition; in other words, the direction of the columnar grains is always along the direction of heat flow during cooling. Since the cooling rate is the highest in the direction of electrode, it is common that the directions of columnar grains growing in these samples are roughly perpendicular to the welded sheet metal when the molten nugget is within the two workpieces. The shape and the grain structure of the nugget in Fig. 5(a) indicates that excessive melting took place at the interface between the top electrode and the workpiece, i.e., the molten nugget was centered at this interface, as the columnar grains were all along the radial lines converging at the interface. In contrast, the columnar grains in Fig. 5(b) are slightly converging at the interface between the two workpieces.

As shown in Fig. 5, there are also pores formed in the nugget in both welding conditions. Some pores were on the edges of weld nugget, and others were in the center of weld zone. Using the flat Mo mandrel electrode, the center of weld zone moved to the upper workpiece where some large pores were formed (as shown in Fig. 5(a)). Applying the Mo rod as the bottom electrode, large pores were often observed in the center of two faying surfaces (as shown in Fig. 5(b)). The weld joints in alloys produced by powder metallurgy often contain voids which are produced by residual volatile materials [13]. In this project, 50Mo–50Re sheets were synthesized by a powder metallurgy method, thus it might not be surprising to observe pores frequently in the weld zone of this alloy. The large pores observed in the center of nugget might be also produced by metal expulsion upon welding. Further work needs to be done to understand the mechanism for the formation of these large pores in the nugget.

3.3. The effect of ramp time

The duration for the weld current to reach its required value is called 'ramp time' in this study (also called 'upslope period' elsewhere [6]), as shown in Fig. 2. The ramp time was varied to study its effect on the welding quality in this study. As shown in Fig. 6, when the ramp time was varied from 0 ms to 16 ms, the strength of the welded samples increased from 125.8 N to 171.9 N. It can be seen in Fig. 6 that 8 ms ramp time gave rise to the highest strength at 184.7 N, 58.9 N higher than that of the weldment with the ramp time being zero. It was previously reported that the basic weld current profile with zero ramp time worked well when welding thermally conductive materials such as copper and brass [6]. However, such a weld current profile could cause metal expulsion and/or electrode sticking to the workpiece when welding thermally resistive materials, such as the 50Mo–50Re alloy whose thermal conductivity is as low as 36.8 W/m K at 10 °C. Therefore, it was preferable to use a weld current profile with a ramp time of several milliseconds to improve the welding property in this study.

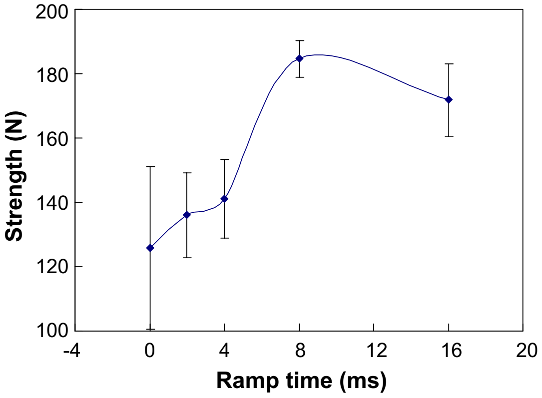

Fig. 6. The effect of ramp time on the strength of the welded 50Mo–50Re samples.

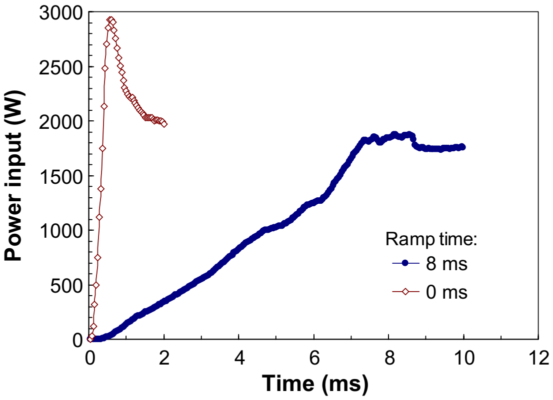

Fig. 7. The profiles of power input versus time during resistance spot welding of Mo–Re alloy sheet at ramp times of 8 ms and 0 ms.

Fig. 7 shows the real-time measurement of the power input in the resistance welding at ramp time of 8 ms and 0 ms, respectively. It could be seen that the power input was increased relatively gradually at 8 ms ramp time, compared with a spike in the power input curve at 0 ms ramp time. During welding, it was also observed that molten metal expulsion occurred significantly at 0 ms ramp time, whereas there was almost no expulsion taking place at a weld current of 500 A and a ramp time of 8 ms. The upslope, relatively slowly introducing current to the workpieces to be joined, not only minimized the metal expulsion but also reduced the variation in contact resistance between the electrodes and workpieces [13]. Hence, it resulted in a more uniform melting between the faying workpieces and improved the quality of welding of Mo–Re sheet.

3.4. The effect of weld current and electrode force

Fig. 8 shows the plots of strength versus weld current at different electrode forces, with hold time of 999 ms, and ramp time of 8 ms, using a Mo rod bottom electrode and other default welding parameters. The strength increased with increase in weld current at different electrode forces. Using an electrode force of 17.80 N, the strength was relatively lower than those when using 4.44 N and 8.90 N electrode forces at 500 A weld current. The strength at 17.80 N electrode force, however, surpassed those at 4.44 N and 8.90 N electrode forces when using

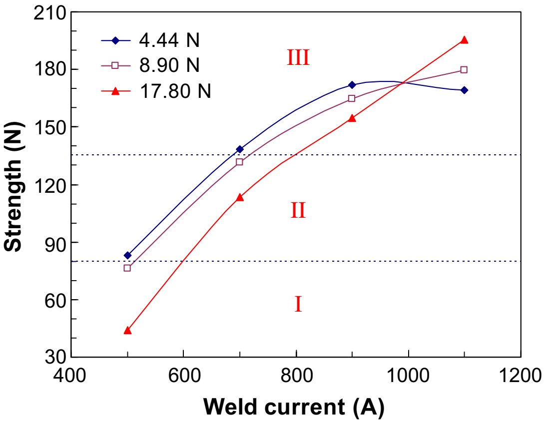

Fig. 8. Strength versus weld current plots measured under different electrode forces: zone I, none electrode stickness and no expulsion; zone II, minor to medium level of electrode stickness and medium level of expulsion; zone III, high level of electrode stickness and severe expulsion.

1100 A weld current. A larger electrode force could reduce the contact resistance at the sheet/sheet (S/S) and sheet/electrode (S/E) interfaces. Thus, less heat was generated at the S/S and S/E interfaces. The nugget was therefore smaller when using a larger electrode force, especially at a smaller weld current, i.e., 500 A.

As shown in Fig. 8, the strength versus weld current curves at different electrode forces can be divided into three zones: zone I, none stickness between the electrode and workpiece, and no molten nugget expulsion (as an S/S interface after shear–tensile test shown in Fig. 9(a)); zone II, minor to medium level of electrode stickness and medium level of expulsion; and zone III, high level of electrode stickness and severe expulsion (as an S/S interface after shear–tensile test shown in Fig. 9(b)). Although the increase in weld current enhanced the strength, electrode sticking and molten metal expulsion could still become problematic in welding, and had to be minimized. In RSW at small electrode forces, such as 4.44 N, these problems frequently occurred in this study. Since the electrode sticking reduces the life of the electrode and molten metal expulsion leads to the formation of pores, a compromise between higher strength and avoidance of electrode sticking and molten metal expulsion may have to be made in the resistance spot welding of Mo–Re thin sheet. The reason for the existence of the three zones in the strength–weld current curves at different electrode forces was likely to be related to the heat generation at S/S and S/E interfaces. It had been reported that the S/E resistance was generally greater than S/S resistance [14]. Based on Eq. (1), the heat generated at the S/E interface was normally higher than that at the S/S interface. During the formation of nugget, some part of the heat at S/E interface was conducted to the S/S interface. Therefore, in order to obtain an appropriate weld nugget at the center of two workpieces of the 50Mo–50Re alloy, a desirable electrical current should be transmitted through. Such an electrical current, also, produces relatively high energy at S/E interface in a short time. This may be the reason why higher strength of weldment is obtained with stronger electrode sticking and molten metal expulsion.

Fig. 10 shows the plots of the standard deviation of strength versus weld current at different electrode forces. Relatively high standard deviation in strength (35.6 N) was observed at 4.44 N electrode force and 900 A weld current. Using higher

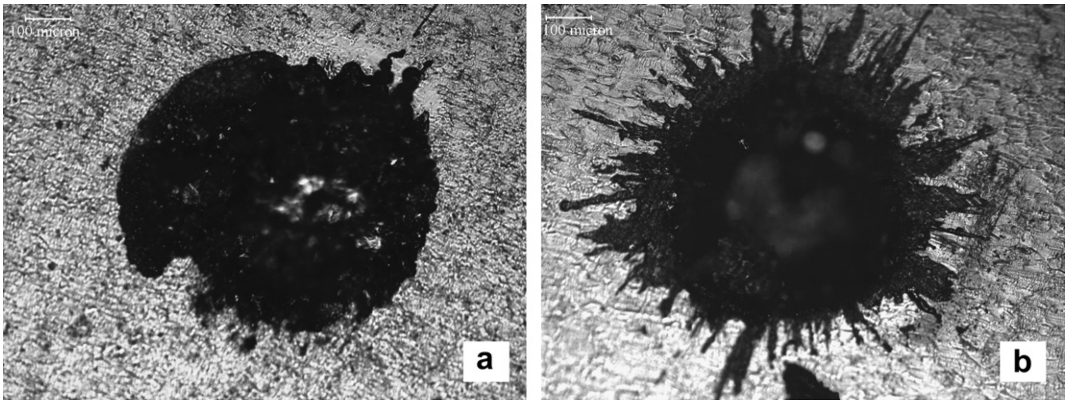

Fig. 9. Typical shapes of the welded area at the interface of the two workpieces welded using the parameters as shown in Fig. 8.: (a) zone I and (b) zone III.

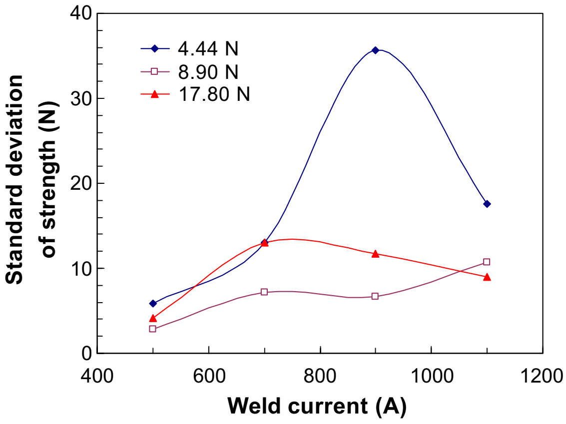

Fig. 10. Standard deviation of strength as a function of weld current using different electrode forces.

electrode forces of 8.90 N and 17.80 N, standard deviations of strength were smaller, varying from 2.8 to 13.1 N. It demonstrated that a low electrode force, such as 4.44 N, yielded a poor consistency of weld strength, and that a higher electrode force gave rise to a better consistency of weld quality. Resistance welding is a thermal–electrical–mechanical process in which heat is generated at the interface of the parts to be joined by passing electric welding current [9]. The generated heat is shown in Eq. (1), where contact resistance R can be varied by the change of electrode force. If the electrode force is too low, the contacts between two workpieces and between electrodes and workpieces may be small and inconsistent. Therefore, higher heat with more inconsistency may be produced at S/S and S/E interfaces. To obtain a weldment with consistent weld quality, a higher electrode force is preferable in the resistance spot welding of the 50Mo–50Re sheet in this study.

In RSW of thick sheet, it is true that the nugget covering 80% of thickness of two workpieces is suitable to obtain a sound weldment. If over 80% of thickness of two workpieces is melted during RSW, the heat affected zone, which is generally the weakest region, would cover the whole thickness of workpieces and make the weldment weak. However, as shown in Fig. 11, although the total thickness of two workpieces was melted in RSW when using moderate weld current (i.e. 700 A) with 2-lb electrode force, the strength was still ascending when higher weld current was applied. The reason is that the nugget diameter needs to be increased, in order to improve the strength for each weldment. As shown in Fig. 12, nugget diameter is increased

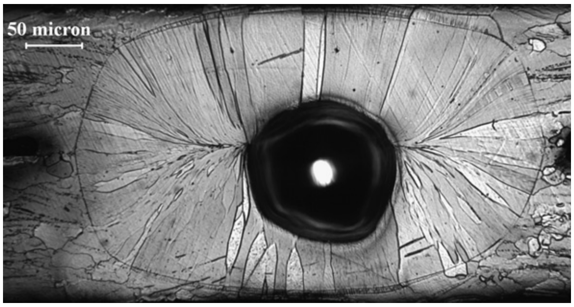

Fig. 11. Microstructure in the nugget cross-sectioned through thickness when using 700 A weld current with 2-lb electrode force.

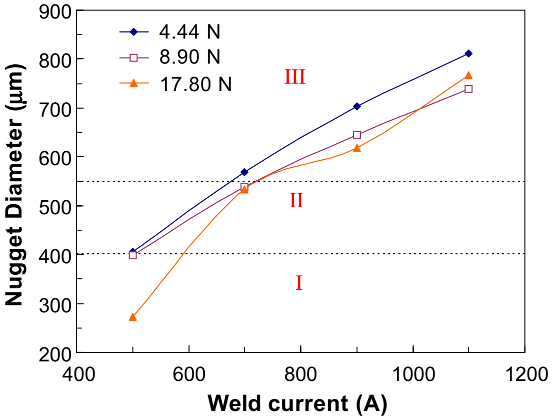

Fig. 12. Plots of nugget diameter versus weld current under different electrode forces. Similar to Fig. 8, three zones can be identified in the curves.

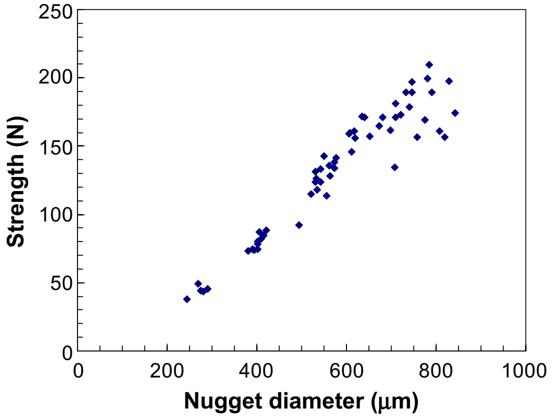

Fig. 13. Strength as a function of nugget diameter of all the nuggets studied in this work.

with increase in weld current at different electrode forces, which showed the same trend as strength versus weld current in Fig. 8. Fig. 13 suggests that larger nugget diameter contributed to higher strength.

Therefore, the criteria for a desirable nugget with 80% of thickness of two workpieces in RSW of thick sheet should not be applicable in RSW of thin sheet.

Although higher weld current produces larger nugget diameter of weldment, higher tendency of electrode sticking and molten metal expulsion restrict its extensive application in RSW. One probable solution is to combine lower weld current with longer weld time, which was not discussed in this study and will be attempted in the future to better understand the principle of RSW of thin sheet.

4. Conclusions

By adjusting five important welding parameters, hold time, electrode shape, ramp time, weld current and electrode force, the quality of resistance spot welding of refractory alloy 50Mo–50Re thin sheet was been improved significantly. Some conclusions are drawn and listed as follows:

(1) Increase in hold time increased the welding quality due to the cooling rate of the weld nugget being increased. Ductile weld was achieved with longer hold time. Higher cooling rate prevented Mo segregation in the weld.
(2) The electrode shape significantly influenced welding quality. Compared with the asymmetric weld obtained by using a flat Mo mandrel electrode, a symmetric nugget was obtained when using a Mo rod electrode. Pores and columnar grains were common in the weld nugget of 50Mo–50Re.
(3) Ramp time minimized stickness between the electrode and workpiece, and molten nugget expulsion, by gradually increasing power input.
(4) Weld current and electrode force played significant roles on the weld quality. Increasing weld current enhanced the weld quality, however, increased the probability of sticking and expulsion. Higher electrode force reduced the inconsistency of weld quality, therefore was preferred during welding operation.

After evaluating the effects of all the studied parameters except the weld time on the welding quality, the optimized parameters were proposed and applied in the pre-joining of refractory alloy 50Mo–50Re thin sheet before brazing. It is, however, still desirable to study the effect of the weld time, in order to further improve the welding quality of the Mo–Re thin sheet.

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