Improved quality of resistance spot welded joints for molybdenum sheets in lap configuration by adding titanium interlayer

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Abstract

Resistance spot welding (RSW) exhibits low heat input and high efficiency. However, because Mo exhibits low resistivity and high hot strength, it is difficult to effectively combine the resistance spot welded joints of Mo. The lap joint of 1-mm-thick Mo sheets was welded using RSW. Moreover, the welding parameters (current, welding duration, and electrode force) were optimised. Using Ti foil as the interlayer, the influence of the alloying element on the resistance spot welded joint of the Mo sheets was explored. The results indicate that the success rate of welding can be improved by utilising a high current and short welding duration, and increasing the electrode force causes reduced contact resistance and further failure of the welding. In addition, an excessively high electrode force may result in electrode adhesion. Here, a current of 20 kA, welding duration of 0.4 s, and electrode force of 3726 N were used as the optimised parameters. The joint obtained under the parameters can withstand the highest shear load (about 2.20 kN); the shear load of the joint obtained after adding the Ti interlayer (thickness: 0.03 mm) increases by approximately 54%. After adding the Ti foil, the heat input on the interface increased and Ti melted to form metallurgical bonding with Mo. Under these conditions, the interfacial strength increased significantly. During the tensile–shear test, the heat-affected zone of Mo is fractured, in which the shear fracture is subjected to brittle failure.

1. Introduction

Mo and its alloys have the following advantages: high melting point, high strength, favourable creep resistance, low thermal expansion coefficient, high thermal and electrical conductivity, high high-temperature fatigue strength, and favourable high-temperature seismic behaviours. Therefore, they play an important role in electronics, aerospace, nuclear power, and military fields [1, 2]. Mo also exhibits the advantage of a low neutron absorption cross-section; therefore, it is recognised as one of the three major candidate materials for preparing accident-tolerant fuel cladding in the global nuclear industry [3, 4]. Research on the welding technologies of Mo alloys is important for expanding the application range of Mo alloys. Wang et al and Yang et al reviewed the research status of welding technologies for Mo and Mo alloys [5, 6]. The welding methods for Mo alloys mainly involve tungsten inert gas (TIG) welding, electron beam welding (EBW), laser welding (LW), friction stir welding, and resistance spot welding (RSW) [7–18]. The ductile–brittle transition temperature of Mo is low (140 °C–150 °C), and the joint is substantially embrittled when the temperature is reduced to room temperature during welding [7, 8]. Mo alloys are highly sensitive to oxygen and nitrogen; after welding, impurity atoms such as O and N are likely to be enriched at the grain boundary, thus causing strength reduction of the grain boundary [9, 10]. The melting point of Mo is 2620 °C; thus, Mo materials are usually prepared through powder metallurgy. The generation mechanism of porous defects in joints is relatively complex owing to the high air content in the base metal (BM) [8–10]. Thus, when Mo and Mo alloys are prepared using fusion welding methods (including TIG welding, EBW, and LW), high porosity generally develops, thus causing poor joint performance [11–16]. In friction welding, the following disadvantages are observed: severe wearing of tools, poor corrosion resistance of
weld seams, and high requirements for the shape of the workpiece [17]. Additionally, the initial recrystallisation temperature of Mo does not exceed 1000 °C, whereas the recrystallisation temperature around the welding spot is far higher than 1000 °C during fusion welding. Under these conditions, the Mo grains grow through recrystallisation. Moreover, thermal stress is likely to be generated in the welding spot owing to the high-temperature effect during welding, thus causing cracking of the welding spot [18]. Compared with other welding methods, nuggets are always surrounded by a plastic ring during their formation when using RSW, and the melted metals are isolated from air, which can effectively prevent the weakening effect of impurity atoms (such as O and N) on the grain boundary. Because the heating time is short and the heat is concentrated, the heat-affected zone (HAZ) is small; therefore, there is insignificant deformation and low stress. Hence, RSW can be considered as a preferential method for welding Mo and Mo alloys. Xu et al explored the influence of the welding parameters on the strength of the resistance spot welded joint of a 50 Mo–50 Re (wt%) sheet with a thickness of 0.127 mm. They observed that the joint strength could reach 21.69 MPa under the optimised welding parameters, and they proposed that porous defects still exist and the joint strength can be further improved [19]. Mo exhibits low resistance (resistivity: 53.4 nΩ·m) and low interfacial activity. Thus, it is difficult to achieve effective welding owing to the low resistance heat when the RSW is directly performed.

Ti exhibits a resistivity of 420 nΩ·m, which is approximately eight times that of Mo. Therefore, the resistance is expected to increase by adding Ti foils between two Mo sheets during the RSW of Mo, thus further enhancing the heat input. The Mo–Ti binary alloy phase diagram shows that Mo and Ti are infinitely soluble, and thus do not produce the brittle phase. In addition, the Mo–Ti solid solution exhibits a high melting point and favourable high-temperature mechanical performance. The addition of a small amount of Ti alloying element (≤1 wt%) is expected to improve the strength and toughness of the BM of Mo alloys [20, 21]. On this basis, the influences of the RSW parameters (current, welding duration, and electrode force) on the microstructures and mechanical performance of the lap joint of the Mo sheets (thickness: 1 mm) were explored. Based on this, the optimised welding parameters were obtained. Subsequently, the effect of the addition of the Ti interlayer on the strength of the RSW lap joint of Mo was investigated. The research results have practical significance for guiding the RSW technology of Mo and Mo alloys and contribute to enriching the welding theoretical system of refractory materials.

2. Materials and methods

Pure Mo sheets were used in the test, and their chemical compositions are listed in table 1. The pure Ti foils were added as the interlayer, with thicknesses of 0.01, 0.03, 0.05 and 0.10 mm.

The NA-200-4 RSW machine, with a primary voltage of 380 V, secondary voltage of 4.42–8.85 V, rated capacity of 200 kVA, welding time of 0.035–6.75 s, frequency of 65 solder spots per minute, and maximum
pressure of 1400 kgf (about 13730 N) between electrodes, was used to perform the overlap welding of Mo sheets based on the RSW. The electrode diameter and the schematic diagram of the experiment are shown in figure 1.

The upper and lower electrodes were copper electrodes, and the electrode force was produced by an air pressure machine. Welding was performed in the overlapped central zone, as shown in figure 1, by overlapping two Mo sheets with dimensions of 50 mm × 10 mm × 1 mm, with an overlapped length of 15 mm. Resistance spot welding test was conducted according to the standard of Welding Procedure Specification for Resistant Welding (GB/T 19867.5-2008/ISO 15609-5:2004) standard. Before welding, the surfaces of the samples were ground using abrasive paper to remove the surface oxides, immersed in alcohol, and ultrasonically cleaned for 10 min.

First, the influence law of RSW parameters (current, welding duration, and electrode force) on the microstructures and mechanical performance of the lap joint of Mo alloys without the addition of Ti foils was explored. The parameters used are listed in table 2. Thereafter, under the RSW parameters of \(I = 20 \text{kA}, T = 0.4 \text{s}\), and \(F = 5884 \text{N}\), the influence of the addition of the Ti interlayer on the lap joint was surveyed by taking the thickness of Ti foils as a variable. Finally, based on the optimisation of process parameters and the experiment of adding Ti foil with different thicknesses, three groups of single-factor and five-level experiments were designed with \(I = 20 \text{kA}\) and \(T = 0.4 \text{s}\) as the default parameters, and electrode pressure and Ti foil thickness as variables to explore the effects of RSW parameters on the mechanical properties of Mo alloy lap joints with Ti foil interlayers of different thicknesses. Triplicate samples under each condition were subjected to tensile–shear tests. The average value of the tensile–shear load under the same parameter was used to obtain the relationship between the tensile and shear load of the joints and the electrode force. In addition, the relationship between the standard deviation of the tensile–shear load and the electrode force was obtained by taking the standard deviation of the tensile–shear load as a variable.

| Serial number | Actual current \(I(\text{kA})\) | Welding duration \(T(\text{s})\) | Electrode force \(F(\text{N})\) | Thickness of Ti foil, \(D(\text{mm})\) |
|---------------|-----------------|-----------------|-----------------|-----------------|
| Parameters optimisation test without Ti addition | | | | |
| 1–1 | 17 | 0.4 | 5884 | 0 |
| 1–2 | 18 | 0.4 | 5884 | 0 |
| 1–3 | 19 | 0.4 | 5884 | 0 |
| 1–4 | 20 | 0.4 | 5884 | 0 |
| 1–5 | 20 | 0.4 | 3726 | 0 |
| 1–6 | 20 | 0.4 | 4805 | 0 |
| 1–7 | 20 | 0.4 | 5884 | 0 |
| 1–8 | 20 | 0.4 | 6962 | 0 |
| 1–9 | 20 | 0.2 | 5884 | 0 |
| 1–10 | 20 | 0.3 | 5884 | 0 |
| 1–11 | 20 | 0.5 | 5884 | 0 |
| 1–12 | 20 | 0.6 | 5884 | 0 |
| Parameters optimisation test with Ti addition | | | | |
| 2–1 | 20 | 0.4 | 5884 | 0 |
| 2–2 | 20 | 0.4 | 5884 | 0.01 |
| 2–3 | 20 | 0.4 | 5884 | 0.03 |
| 2–4 | 20 | 0.4 | 5884 | 0.05 |
| 2–5 | 20 | 0.4 | 5884 | 0.10 |
| 3–1 | 20 | 0.4 | 3726 | 0 |
| 3–2 | 20 | 0.4 | 4805 | 0 |
| 3–3 | 20 | 0.4 | 5884 | 0 |
| 3–4 | 20 | 0.4 | 6962 | 0 |
| 3–5 | 20 | 0.4 | 8041 | 0 |
| 3–6 | 20 | 0.4 | 3726 | 0.01 |
| 3–7 | 20 | 0.4 | 4805 | 0.01 |
| 3–8 | 20 | 0.4 | 5884 | 0.01 |
| 3–9 | 20 | 0.4 | 6962 | 0.01 |
| 3–10 | 20 | 0.4 | 8041 | 0.01 |
| 3–11 | 20 | 0.4 | 3726 | 0.03 |
| 3–12 | 20 | 0.4 | 4805 | 0.03 |
| 3–13 | 20 | 0.4 | 5884 | 0.03 |
| 3–14 | 20 | 0.4 | 6962 | 0.03 |
| 3–15 | 20 | 0.4 | 8041 | 0.03 |
deviation of the three load values obtained from the shear test under the same parameter, to investigate the influence of electrode force on the quality repeatability of the joint.

The cross-sections of the lap joint were ground, polished, and etched. The etchant contained 1 ml potassium ferricyanide, 1 ml NaOH solution, and 8 ml H2O. The microstructures of the cross-sections of the welded joints were observed using a Nikon inverted metallographic microscope, and the shear performance of the welded joint was tested using an Instron universal electronic tensile testing machine at a shear velocity of 0.5 mm min⁻¹. The joint strength was related to the load and nugget diameter (diameter of the fracture), whereas the strength index of the welded joint was only correlated with the load in practical applications. Thus, the load was considered as a strength index during the test. The specimen size of shear test for the overlap welding of the Mo alloy sheets is shown in figure 2. Cushion blocks (thickness: 1 mm) were added at the clamped positions at the two ends to prevent eccentric tension. The fracture morphologies were observed by applying an SU3500 tungsten filament scanning electron microscope equipped with an Oxford energy dispersive spectrometer (EDS) for elemental analysis.

3. Results and discussion

3.1. Influence of the RSW parameters on joints without Ti addition

3.1.1. Influence of current

The shear loads and macroscopic morphologies of the fracture during the shear test of the resistance spot welded joint of Mo sheets under different currents are shown in figure 3. As shown in figure 3, the splitting region is not observed at the fracture (i.e. the lapped interface of Mo sheets) at currents of 17 and 18 kA. This indicates that the heat input during welding is insufficient because of the excessively low currents; hence, the interfaces could not be melted and bonded. The samples were not welded successfully. Therefore, the strength was recorded as zero.
An obvious splitting region appeared at the fracture when the current reached 19 kA, implying that the Mo sheets were successfully bonded. Finally, a significant splitting region was observed at the fracture when the current reached 20 kA. This indicates that the Joule heat generated by the current was sufficient for the interfaces of the Mo sheets to be melted and bonded, exhibiting the highest shear strength of 1632.7 N.

The Mo RSW test in this study revealed that, given the limitation that the maximum current of the equipment is only 20 kA, the strength of the Mo RSW joint decreased with the increase in current. Xu et al obtained similar results for the 50 Mo–50 La resistance welding [19]. However, it should be highlighted that, theoretically, the joint strength first increases, then decreases as current increases. This phenomenon has also been observed in numerous studies on steel resistance welding [22, 23]. In other words, there is a critical current value, $I_C$, where the opposite trend in the relationship between current and joint strength was observed. The value of $I_C$ is closely related to the material resistance, melting point, and thermal conductivity. Table 3 compares the resistivity, melting point, and thermal conductivity of Mo and Fe. Table 3 shows that Mo has a lower resistivity, higher melting point, and higher thermal conductivity than Fe. Therefore, the value of $I_C$ in the Mo RSW was larger than that in Fe. Therefore, the results of this study are due to the limitations of the equipment conditions and the properties of Mo with high melting point, high thermal conductivity, and low resistivity.

### 3.1.2. Influence of the welding durations

The shear loads and macroscopic morphologies of the fracture during the shear test for the resistance spot welded joint of Mo sheets under different welding durations are shown in figure 4. The figure shows that the shear load of the joint increases as the welding duration prolongs from 0.2 s to 0.4 s. When the welding duration reached 0.4 s, the shear load of the joint was the highest; in this case, the Mo sheets were slightly oxidised. As the welding duration continued to increase, the shear load of the joint declined, and the joint adhered to the copper electrodes, as shown in figure 5. The reason is that copper is taken as the electrode material during the test, and its melting point (1083.4 °C) is considerably lower than that (2620 °C) of Mo. Owing to the presence of contact resistance, considerable heat may be generated at the interfaces between the copper electrode and Mo sheets during welding. As a result, the copper electrodes adhered to the Mo sheets when the welding lasted for a prolonged period. Therefore, surface oxidation, blackening, and electrode adhesion should be prevent by increasing the shielding gas in subsequent studies.

![Figure 4.](image)

**Figure 4.** Shear loads and the macroscopic morphologies of the fracture during the shear test of the lap joint of Mo sheets under different welding durations.

| Materials                  | Mo     | Fe     |
|----------------------------|--------|--------|
| Resistivity ($\mu\Omega\cdot$cm) | 5.00   | 9.71   |
| Melting point (K)          | 2919   | 1835   |
| Thermal conductivity (W m$^{-1}$$\cdot$K$^{-1}$) | 135    | 80     |

![Table 3.](image)

**Table 3.** Comparison of the materials properties of Fe and Mo.
From figure 4, the splitting region appeared on the macro morphology of all the shear fractures. The splitting region was most significant at a welding duration of 0.4 s, indicating that the bonding strength of the joint was the highest. The heat input during the RSW can be calculated using equation (1) [24].

\[ E = I^2RT \]

where \( I \), \( R \), and \( T \) refer to the current flowing through the workpiece, resistance, and welding duration, respectively. From equation (1), it can be shown that the heat input during welding gradually increases when the welding duration increases from 0.2 s to 0.4 s. The melted metals on the surface of the Mo sheets gradually increased; therefore, the bonding of the samples improved. When the welding duration increases from 0.2 s to 0.4 s, although the heat input increases, the Joule heat generated by the contact resistance between the Mo sheets and copper electrodes also gradually grows, which consumes some heat, and the HAZ of the BM expands, thus influencing the shear load of the welded joint.

3.1.3. Influence of the electrode force

The influences of different electrode forces on the shear load and macroscopic morphologies of the fracture during the shear test for the resistance spot welded joint of Mo sheets are shown in figure 6. The figure shows that the shear load of the joint decreases with increasing electrode force. When the electrode force exceeds 6962 N, the shear load of the joint is equal to zero, meaning that it fails to form an effective connection. Based on the fracture morphologies, it can also be observed that the splitting region is hardly observed when the electrode force is larger than 6962 N. This implies that the Mo sheets were not melted and bonded. When the electrode force was lower than 5884 N, an obvious splitting region was observed, and the joint was effectively bonded. Under an electrode force of 4805 N, although the shear load of the joint was higher than that under 5884 N, the
joint also significantly adhered to the copper electrodes. Under an electrode force of 3726 N, the shear strength reached a maximum of 2.21 kN, and the fracture did not appear as splitting at the interface but tearing of the BM of the Mo sheet at one side. When the electrode force is too low, point contact is formed between the samples owing to the uneven surface of the samples, which results in a high contact resistance. Equation (1) indicates that the higher the contact resistance, the greater the heat input. In addition, owing to the point contact between the electrodes and samples, the contact area of both is small; therefore, there is poor heat dissipation. As a result, the cumulative heat in the weld zone is high, and Mo sheets can be melted and bonded to form an effective connection. As the electrode force increases, the point contact between the electrodes and Mo sheets and between the Mo sheets gradually evolves into the surface contact under the effect of the electrode force. Furthermore, the total resistance and current density are lowered; thus, the heat production declines while the heat dissipation increases. In this case, the tensile–shear strength of the welded joint is reduced. This is consistent with the law found by Fan et al when they explored the RSW of Ti/Al dissimilar materials [25].

3.2. Influence of adding Ti foils

3.2.1. Cross-section morphologies

With the addition of the Ti interlayer different thicknesses, the cross-sections of the resistance spot welded joint of Mo sheets and their energy dispersive spectroscopy (EDS) plane scan results are shown in figure 7. As shown in figure 7(a), without the addition of Ti foils, the interface between the two Mo substrates almost disappeared completely, exhibiting a favourable bonding effect. However, no significant nugget was found, and the grains in the HAZ were considerably coarse. In the Mo sheets with the addition of Ti foils, the thickness of the Ti foil at the weld seam increased from the centre to the edge of the welding spot. This is particularly true for the joint added with the Ti foil (thickness: 0.01 mm), in which the Ti foil at the centre of the welding spot disappeared completely, as shown in figure 7(b). The Ti foil is tightly bonded to the surface of the BM of the Mo sheets, without the generation of various defects such as cracks and pores, and the interface between the Ti foil and Mo sheets is uneven, as shown in figure 7(c). Figure 8 shows that no significant HAZ is observed from the cross-section of the welded joint with the addition of Ti foils. The thermal conductivity of Mo is 135 W/m·K, which is approximately nine times that of Ti (15.24 W/m·K). For the joint without the addition of Ti foils, the energy is rapidly transferred to the BM of Mo sheets during welding because of the high thermal conductivity of Mo and fails to concentrate on the interface. As a result, the grains in the BM recrystallised to form a HAZ. After adding Ti foils, the interfacial resistance of the lap joint greatly increased owing to the low thermal conductivity of Ti. Furthermore, the heat input at the interface increased. Moreover, Ti exhibits a low melting point (1668 °C); therefore, the Ti foil was melted with the surrounding BM of Mo sheets to form a molten pool. Line scan analysis was conducted on the Ti–Mo interface of the joint with the addition of thick Ti foil (thickness: 0.03 mm); the results are shown in figure 8. The figure shows that the centre of the Ti–Mo transition zone shifts to the Ti foil zone, which implies that some of the Ti foils have been melted and subjected to metallurgical bonding with Mo during the welding.

3.2.2. Mechanical performance

Figure 9 shows the shear loads and macroscopic morphologies of the shear fracture of the welded joint with the addition of Ti foils of different thicknesses. As shown in the figure, the shear load of the joint first increases, then decreases as the thickness of the Ti foils increases. The joint delivers the maximum shear load (2891.8 N) when the thickness of the Ti foil is 0.03 mm, which increases by approximately 43% compared with that of the samples without the addition of Ti foils (2021.4 N). This indicates that the addition of Ti foil can significantly improve the joint strength. However, the shear load of the joint decreased when the Ti foil was too thick. The joint added with the Ti foil (thickness: 0.03 mm) was fractured in the HAZ at the Mo side during the tensile–shear test while the other joints are fractured in the weld seam zone between two Mo sheets. According to the cross-sectional morphologies of the welded joints, it is inferred that after adding the Ti foil, the interfacial resistance increases and the heat input at the interface increases. Furthermore, the Ti foil is melted to form metallurgical bonding with Mo; therefore, the bonding strength of the interface is high. Based on the cross-section morphologies, an uneven, thin reaction layer is formed on the Mo–Ti interface, which contributes to improving the tensile–shear strength of the resistance spot welded joint [26]. Liu et al showed that there is an optimal addition amount of Ti foils, under which the Mo–Ti alloy exhibits the highest strength. Part of the Ti foil is subjected to a solid solution in the Mo matrix, thus enhancing the tensile strength of the materials; the remaining Ti foils were combined with O in the Mo and Mo alloys to form second-phase particles of the composite oxide MoxTiOz, which can refine grains and purify the grain boundary [20].

Figure 10 compares the morphologies of the shear fractures of the welded joints with and without the addition of the 0.03 mm-thick Ti interlayer. As shown in the figure, the fracture of the Mo sheet without the addition of Ti foils is relatively even, on which only a small splitting region is found, which implies that the
interface of the welded joint without adding the Ti foil is poorly fused. In contrast, there is a large region in the fracture of the joint with the addition of the 0.03 Ti foil, showing an intergranular fracture, which is a significant brittle fracture. By conducting the EDS point scan on the fracture of the welded joint with the addition of the 0.03 Ti foil, it was observed that the compositions at the fracture were 100 wt% Mo. Figure 7 shows that the
Figure 8. EDS line scan analysis of the cross-section of the welded joint (with the actual current of $I = 20$ kA, welding time of $t = 0.6$ s, the electrode force $f = 5884$ N and the thickness of Ti foils of $D = 0.03$ mm).

Figure 9. Shear loads and macroscopic morphologies of the shear fracture of the welded joint with the addition of Ti foil with different thicknesses.

Figure 10. Morphologies of the shear fractures of the welded joint without and with the addition of 0.03 mm-thick Ti interlayer.
welded joint with the addition of the Ti foil is subjected to strong metallurgical bonding and samples are fractured in the HAZ at the Mo side during the shear test.

3.3. Influences of RSW parameters on the joint with Ti addition

3.3.1. Influence of electrode force on the mechanical properties of welded joints

The relationship between the joint tensile–shear load and the electrode force is shown in figure 5. As shown in figure 11, the variation trend of the tensile–shear load of the joint with the electrode force after adding Ti foil is the same as that without adding Ti foil. That is, the tensile–shear load of the joint decreases as the electrode pressure increases. When the electrode pressure increases to 6962 N and 8441 N, the weldability is extremely poor.

In the resistance spot welding process, the welding parts are in contact with the electrode force, and the electrode force affects the welding process by affecting the contact area, heat dissipation effect, and contact resistance. The contact area is related to the electrode diameter. The heat dissipation effect is related to material properties. The contact resistance $R_c$ is related to the material properties, surface state, and temperature, and can be expressed by the following relationship:

$$R_c = \tau F^{-m}$$  \hspace{1cm} (2)

where $R_c$ is a constant related to the contact materials and contact surface conditions, which is usually obtained by testing. $F$ is the electrode force or the force of the contact surface (N). The $M$ index is related to the material properties and surface states, which generally varies between 0.5 and 1. Therefore, in this test, with an increase in the electrode force, the contact resistance between the Mo substrate and between the Mo and Ti foil decreases, resulting in a decrease in the thermal input at the interface, which is not conducive to melting and metallurgical bonding near the interface. Therefore, the tensile–shear load of the joint gradually decreased, as shown in figure 11. In this test, when the electrode force is 3726 N, the current is 20 kA, the welding time is 0.4 s, and 0.03 mm-thick Ti foil is added, the tensile–shear load of the joint is the highest, which is $\sim 3388$ N.

Upon adding 0.01 and 0.03 mm-thick Ti foil, the joint loads of the 0.03 mm-thick Ti foil were higher than those of the welded joints with 0.01 mm-thick Ti foil and without Ti foil when the electrode pressure is between 3726 N and 5884 N. The joint load with the addition of 0.01 Ti foil is higher than that without Ti foil, which is consistent with the experimental results of adding Ti foil with different thicknesses in the last section.

3.3.2. Influence of electrode force on weld quality stability

The relationships between the standard deviation of the tensile–shear load and electrode force with various thicknesses of Ti foil are shown in figure 12. Figure 12 shows that the standard deviation of the tensile–shear load decreases as the electrode force increases, indicating that the greater the electrode force, the better the stability of the joint quality. In production, the stability of quality is crucial; therefore, a trade-off between the stability of quality and the joint tensile–shear load is necessary in order to select the appropriate electrode force parameters.
4. Conclusions and prospects

The RSW parameters of the lap joint of the Mo sheets were optimised. Under the optimised parameters, the joint strength was further increased by adding the Ti interlayer. The following conclusions were drawn.

1. The shear load of the joint increases as the current increases owing to the limitation of equipment conditions and properties of Mo with a high melting point, high thermal conductivity, and low resistivity.

2. As the welding duration increases, the shear load of the joint first grows, then reduces. The joint strength is highest at $t = 0.4$ s; the joint strength declines as the electrode force increases.

3. After adding the Ti foil, the HAZ significantly shrinks, and the Ti foil is melted and subjected to metallurgical bonding with Mo.

4. After adding Ti foil, the shear strength of the joint was significantly improved; in particular, the joint strength reached 2891.8 N after the addition of 0.03 mm-thick Ti foil. However, the joint strength decreased as the thickness of the Ti foil continued to increase.

5. The shear fracture of the lap joint of the Mo sheets appears as a brittle fracture. After adding the Ti foil, the range of the splitting region in the fracture was remarkably expanded, and the Ti–Mo interface was favourably fused.

6. The joint strength can be further improved from 2892 N to 3388 N under a lower electrode force, while the stability of the joint quality decreases.

The feasibility of the RSW of the lap joint of Mo sheets was preliminarily verified. Future research can be conducted on the following aspects:

1. The heat input during welding is only evaluated based on the current, and is not further analysed during the test. Finite element analyses can be used to investigate the influence of the technological parameters on the heat input during the welding and temperature field in the process of RSW. The temperature field distribution of the lap joint of Mo alloy sheets during RSW is expected to be simulated using a finite element software. Based on the test, the influence of the technological parameters on the heat input during welding and the temperature field can be analysed. Furthermore, the influence law of the heat input during welding on the nugget, microstructures of the HAZ, and formation of the lap joint will be surveyed.

2. The shear test revealed that the weak zone of the lap joint of the Mo alloy sheets corresponds to the interface and HAZ of the BM of the Mo sheets. The bonding strength of the interface was successfully enhanced by adding Ti foils; however, the HAZ of the BM of the Mo sheets is still considered as the weak zone of the lap joint. Some scholars have investigated the influence of the addition of Zr foils on laser-welded Mo alloys. They found that Zr rapidly diffuses at the grain boundary of the HAZ of Mo sheets during welding to
generate the effect of second-phase strengthening, thus improving the strength of the HAZ of the welded joint [27]. Therefore, it is necessary to survey the influence of the addition of Zr foils on the lap joint of the Mo alloy to explore whether Zr foils rapidly diffuse in the HAZ during the RSW of the lap joint of the Mo alloy, thus increasing the joint strength.

(3) In the specific application to the sealing of the nuclear fuel cladding, the tube-rod lapping method is used to facilitate the connection. Therefore, it is suggested that the influence of the technological parameters and the addition of an interlayer during the RSW on the microstructures and mechanical performance of the welded joint by applying the tube-rod lapping method.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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