Effect of laser beam offset on dissimilar laser welding of tantalum to 304 stainless steel

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Abstract
Cylinders made of tantalum (Ta) and tubes made of 304 stainless steel (304SS) were successfully joined by laser welding under different offsets. The experimental results indicated that satisfactory weld formations were obtained. The fusion zone (FZ) was found to consist of the Fe–Cr solution and the Fe2Ta phase. In addition, the intermetallic compounds (IMCs) layer was generated at Ta/FZ interface. When the laser beam offset was −0.2 mm (0.2 mm laser beam offset on the 304 stainless steel side), the interfacial IMC consisted of Fe2Ta. Thicker IMC with the compositions of Fe2Ta + FeTa was generated at offsets of 0 mm (center) and +0.2 mm (0.2 mm laser beam offset on the Ta side). Numerical simulation results showed that the interfacial peak temperature would be increased when the laser beam offset from 304 stainless steel side to Ta side, which led to the thicker IMC and new generation of FeTa. The microhardness in the FZ also fluctuated since the FZ was composed of hard Fe2Ta and soft Fe–Cr solution. Tensile test results indicated that the highest value of 308.3 MPa was obtained under the laser beam offset of −0.2 mm.

Keywords Laser welding · Tantalum · 304 Stainless steel · Interfacial microstructure · Mechanical properties

1 Introduction
Refractory metal tantalum (Ta) has excellent wear resistance and stable mechanical properties at high temperature [1, 2], and it is usually adopted as heaters of cathode assembly in aerospace electric propulsion systems. 304 Stainless steel (304SS) exhibits high strength and strong corrosion resistance, and it is usually employed as supporting tubes for the heater cylinder. Therefore, obtaining a satisfactory connection between tantalum cylinder and 304 stainless steel tube is essential, and welding can provide a solution. Obtaining a refractory metal/steel dissimilar joint with high strength faces great challenges due to the huge differences in thermal physical properties and metallurgical performance between base metals [3–5]. Laser welding technology can provide a solution since it has the advantages of small heating area, large welding speed, fast heating and cooling rate, and high automation [6–10]. Therefore, obtaining a satisfactory laser welded Ta/304SS joint is significant for aerospace.

For the refractory metal/steel joint, weld formation and microstructure determined the joint strength as the dominant factors. For instance, Zhang et al. [11] found that the coarse surface of Mo/stainless steel joint would cause the generation of cracks which would finally reduce the joint strength. Hajitabar [12] discovered that pits and extrusion in the Nb/steel joint would evolve as the origination of cracks, leading to the reduction of joint strength (the joint with and without pits and extrusion exhibited the tensile strength of 82 and 170 MPa, respectively). Yu et al. [13] noticed that a thinner intermetallic compounds (IMCs) layer was more beneficial for the improvement of TZM/stainless steel dissimilar joints. The joint strength increased from 165 to 313 MPa when interfacial IMC thickness was reduced from 10 to 0 μm.

From the above research, it could be found that a satisfactory weld formation and an interfacial IMC with
thinner thickness were beneficial for the joint strength, which had a great association with welding heat input. For instance, Gao et al. [14] found that excessive heat input would cause the severe fluctuation of molten pool and finally lead to the formation of coarse weld appearance. Sang et al. [15] indicated that excessive heat input in the Ta/GH3218 joints would cause the generation of porosities (due to the excessive melting of base metals under excessive high temperature) and cracks (due to the huge asynchrony of melting and cooling under excessive peak temperature). Chen and Yuan [16] reported that thick IMC was generated in the Ta/304SS joint due to the severe diffusion of atoms resulting from melted base metals at excessive heat input. In the above research, the coarse weld appearance, porosities, and thick IMC which resulted from unreasonable heat input had a negative effect on the joint strength. During laser welding, the heat input could be flexibly adjusted by the variations of laser beam offset [14]. By adopting laser beam offset, the heat input could be distributed in a more reasonable method and inhibit the aforementioned defects [11]. Laser offset refers to the distance between the focus of the laser beam and the interface between two base metals. Nevertheless, research about the laser welding of Ta cylinder to 304 stainless steel tube (to form heterogeneous structure) under various laser beam offsets were rarely reported.

Therefore, the aim of the present study was to investigate the influence of laser beam offsets on the welding formation and microstructure of the laser welded Ta cylinder/304SS tube joints. Then the interfacial thermal cycles were calculated to reveal the interfacial heat distribution under various laser beam offsets and further provide analysis for the welding formation and interfacial microstructure evolutions. Finally, tensile tests were conducted to clarify the joint strength variations under different laser beam offsets.

**2 Experimental procedures**

**2.1 Base metals**

Rolling-stated tantalum and austenite 304 stainless steel were employed as base metals in this work as seen in Fig. 1. Chemical compositions of Ta and 304 stainless steel are presented in Table 1. The detailed longitudinal sections of cylindrical 304SS and tubular Ta and their sectional views are exhibited in Fig. 2. The A face (as marked in Fig. 2) of the 304SS workpiece was fitted to the B face (as marked in Fig. 1) of Ta workpiece during the assembly process. Both of the A and B face had an outer diameter of 8 mm and an inner diameter of 6 mm. Therefore, 304SS cylinder and Ta tube were assembled together as a lock butt joint.

**2.2 Laser welding process**

Figure 3 shows the schematic diagram of laser welding Ta to 304SS. The shield cover and rotary fixture were put on a pad. The welding process was carried out by an IPG YLS-6000 fiber laser system with 6-kW maximum output power, 1070-nm laser beam wavelength, 8-mm mrad beam parameter product, and 0.6-mm-diameter focused beam. The energy distribution for the focused laser beam was Gaussian volume. Ta and 304SS were assembled by

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**Table 1 Chemical composition of the base metals (wt.%)**

| Element | Ta      | C   | Cr | Ni  | Ti  | Fe |
|---------|---------|-----|----|-----|-----|----|
| Ta      | ≥99.99  | 0   | 0  | 0   | 0   | 0  |
| 304 SS  | 0       | ≤0.12 | 17–19 | 8–11 | 0.5–0.8 | Bal |

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a special rotary fixture. KR16-2 KUKA robot with six axes was employed in the process. Argon gas was used as shielding gas to prevent oxidation of molten metals. Before final welding, optimization of welding parameters was carried out and the optimized welding parameters were selected based on the satisfactory weld appearance. Table 2 lists the final adopted laser welding parameters in the present study. Laser beam offset indicated the distance between laser spot center and the Ta/304SS interface. When the center of the laser spot was irradiated on the 304SS, the offset was recorded as a negative value, while on the Ta, the offset was recorded as a positive number. The laser beam offset ranged from −0.6 mm (0.6 mm laser beam offset on 304SS side) to +0.2 mm (0.2 mm laser beam offset on Ta side). We defined the joints obtained under the laser beam offsets of −0.2 mm, 0 mm, and +0.2 mm as joint 1, joint 2, and joint 3, respectively. Before the welding process, standard chemical cleaning and mechanical polishing were adopted to remove the oxidation films and contaminations of base metals.

### 2.3 Numerical simulation

The commercial finite element method (FEM) software ABAQUS was adopted to calculate the thermal cycles during laser welding. The schematic diagram of the numerical models and divided meshes are demonstrated in Fig. 4. The model of 304SS was simplified to a cylinder with a tab by removing the part away from the weld, and the specific dimensions were shown in the label in Fig. 4. Finer meshes (0.1 mm) and coarse meshes (0.5 to 1.0 mm) were respectively generated at the welding zone and outer regions to reduce computational duration based on acceptable accuracy. All the meshes were set as eight nodes and hexahedron elements. The total number of elements for Ta and 304SS were 6852 and 8748, respectively.

Considering the deep penetration characteristics of laser welding in the present study, combined Gauss surface + volume heat source was adopted as seen in Eqs. (1)–(3) [17]:

\[
Q_s(x, y, z) = \frac{3\varphi \eta P}{\pi r_s^2} \exp(-3) (x - x_{laser})^2 + (y - y_{laser})^2 \]

\[
Q_v(x, y, z) = \frac{6(1 - \varphi)\eta P}{\pi r_s H_m + 2r_v} \exp(-3) (x - x_{laser})^2 + (y - y_{laser})^2 \]

\[
Q(x, y, z) = Q_s(x, y, z) + Q_v(x, y, z)
\]

where \(Q_s\) is heat flux of Gauss surface heat source; \(Q_v\) is heat flux of Gauss volume heat source; \(Q\) is the total heat flux; \(\varphi\) is the ratio of surface heat source; \(\eta\) is the absorption coefficient of the laser beam; \(P\) is the total laser power; \(r_s, r_v\) are the radii of surface and volume heat source, respectively; \(H_m\) is the effective depth of volume heat source; \(m\) is energy distribution coefficient of volume heat source in the depth direction; \(x_{laser}, y_{laser}\) are the coordinates of laser heating center; and \(x, y,\) and \(z\) are the coordinates of laser heating center along \(x, y,\) and \(z\) directions, respectively. The material properties in the models were quoted from data provided in the literature [18, 19] and presented in Fig. 5. The densities of Ta and 304SS were set as constant values of 6160 and 7930 kg/m³, respectively.

Natural boundary condition on the workpiece was expressed as follows:

\[
k \frac{\partial T}{\partial x} - Q_x + h(T - T_0) + \sigma \varepsilon (T^4 - T_0^4) = 0
\]

where \(k\) is the thermal conductivity, \(Q_x\) is the heat flux, \(h\) is the convection heat transfer coefficient, \(\sigma\) is Stefan–Boltzmann constant (5.67 W/(cm²·K⁴)), \(\varepsilon\) is the emissivity of the metal surface, and \(T_0\) is the environment temperature (20 °C).
In order to simplify the boundary conditions, a total heat transfer coefficient was introduced to sum convection and radiation coefficients in the model [20] as presented in Eq. (5):

$$h_{eff} = 2.4 \times 10^{-3} \times \varepsilon \times T^{1.61}$$  \hspace{1cm} (5)

### 2.4 Analysis methods

Optical microscopy (OM) and field emission scanning electron microscopy (SEM) were employed to observe the cross-sectional and typical fracture surface morphology. The elements distribution near the interface were analyzed by energy dispersive spectrometer (EDS), and the interfacial phase compositions at the fractured surface were confirmed by X-ray diffraction (XRD). The joint strengths obtained under various laser beam offsets were evaluated by lap shear tests with a universal testing machine of 1 mm/min at room temperature. Then the joint strength of the workpiece was calculated as follows:

$$\sigma = \frac{F}{\pi(R^2 - r^2)}$$  \hspace{1cm} (6)

where $\sigma$ (MPa) is the joint strength, $F$ (N) is the fractured force, $R$ (mm) is the outer diameter of the tantalum cylinder, and $r$ (mm) is the inner diameter of it. The average tensile strength of three specimens was calculated to improve the accuracy.

**Fig. 4** Developed numerical models in this work: a developed geometric model for 304SS and Ta; b geometric dimensions for 304SS and Ta (unit: mm); c generated meshes for the model; d generated meshes at the cross-section for the model

**Fig. 5** Temperature-dependent thermo-physical properties for base metals: a Ta [18]; b 304SS [19]
3 Results and discussion

3.1 Welding formation

Figure 6a–c shows the weld appearances of the tantalum/304 stainless steel joints with different laser beam offsets while Fig. 6d–f presents corresponding cross-sections of the joints. Two typical welding and brazing interfaces were produced in these joints. Satisfactory weld formations without cracks or undercut were obtained under these welding conditions, which indicated that the welding parameters used in this work were reasonable.

The cross-sectional morphology of joint 1 is shown in Fig. 6d. A typical welding-brazing joint appeared mainly between fusion zone (FZ) and Ta base metal. The flat interface between Ta base metal and FZ indicated that the Ta base metal did not melt, which was a typical feature of welding-brazing. The cross-sectional morphology of joint 2 is shown in Fig. 6e. Ta base metal was slightly melted at the top surface due to the smaller distance between the laser heating center and the top surface of Ta base metal. Welding-brazing interface was found in regions A and B. In addition, the fusion depth was also decreased and an obvious reaction layer could be observed at region C. The cross-sectional morphology of joint 3 is shown in Fig. 6f. Welding-brazing interface was also observed in this joint and the weld width of Ta base metal at the top surface became larger. This was caused by the laser beam offset on Ta base metal. Furthermore, the joint had the shallowest fusion depth compared with the previous two joints.

3.2 Microstructure

Figure 7 presents the microstructure and element distribution for joint 1 and Table 3 presents the measured chemical compositions in the selected regions. The joint was mainly connected by the brazing interface as shown in Fig. 7a. Figure 7b demonstrates the microstructure of the fusion zone. It consisted of gray matrixes and scattered phases. The gray matrixes and scattered phases were determined as Fe–Cr solutions since they mainly contained 75.95 at.% Fe and 22.13 at.% Cr, which was also observed in previous studies [16]. The content of Ta was as low as 1.93 at.%, and this implied that only limited Ta element was diffused to the fusion zone due to its solid state during the welding process. Figure 7c shows the brazing interface at the upper region of Ta base metal, which was remarked as region c in Fig. 7a. An obvious Fe–Ta–Cr elemental transition layer was produced at this region, and this indicated that an interfacial IMC formed. The formation of interfacial IMC could be also proved by the stable Fe–Ta elemental diffusion zone as seen in Fig. 7d. According to the EDS results, this IMC layer was also Fe2Ta since it had the
compositions of 81.12 at.% (Fe + Cr) and 18.88 at.% Ta [16]. The interfacial IMC thickness became smaller from the top to the bottom at this region. This was caused by the reduction of peak temperature along the thickness direction, which resulted from the larger distance to the laser heating area. Figure 7e depicts the microstructure of region e in Fig. 7a. A transition layer was also produced between Ta and the FZ. According to the EDS tested results in Table 3, it contained 84.95 at.% (Fe + Cr) and 14.05 at.% Ta, which was proved to be Fe2Ta. Figure 7f presents the edge of the Ta/FZ interface at the bottom area as marked region f in Fig. 7a. An unbounded interface was observed to produce at this region due to the insufficient heat input, which was disadvantageous for the joint strength.

Figure 8 presents the microstructure and element distribution for joint 2 and Table 4 lists the measured chemical compositions in the selected regions. The top edge of Ta base metal was not square, and this indicated that the Ta was partially melted. The observed results in the fusion zone, as marked in region b, were seen in Fig. 8b. In this region, the FZ consisted of gray matrixes and columnar crystals. The gray matrixes were determined as Fe–Cr solutions while the columnar crystals were determined as Fe2Ta, which was different from joint 1. The generation of Fe2Ta in the fusion zone resulted from the slight melting of Ta base materials as seen in Fig. 8a. The interface between melted Ta and FZ was remarked as region c and its corresponding microstructure is shown in Fig. 8c. Two different transition layers were found in this region: layer 1 nearby the FZ and layer 2 adjacent to the Ta substrate. According to the listed EDS results in Table 5, layer 1 was determined as Fe2Ta (72.42 at.% (Fe + Cr) and 27.58 at.% Ta) while layer 2 was determined as FeTa (53.81 at.% (Fe + Cr) and 46.19 at.% Ta). Figure 8d shows the Ta/FZ interface at the lower part of Ta base material. This interface was composed of extrusion in the vicinity of FZ as remarked by layer 3 and continuous diffusion zone as remarked by layer 4. Layer 3 was Fe2Ta (72.42 at.% (Fe + Cr) and 27.58 at.% Ta) while the inner layer 4 was FeTa (48.68 at.% (Fe + Cr) and 51.32 at.% Ta). The elemental scanning results of this interface as seen in Fig. 8e also showed that a stable atomic transaction zone occurred at this region, which indicated the formation of interfacial IMC. The microstructure at the bottom region of Ta is presented in Fig. 8f. Brazing occurred at the interface and a dendritic structure formed in the fusion zone. The dendritic

![Fig. 7](image-url) Microstructural morphologies and EDS results for joint 1: a cross-section; b FZ; c middle region; d line scanning results; e bottom of Ta; f unreacted region

| Position | Fe    | Ta    | Cr    | Possible phases     |
|----------|-------|-------|-------|--------------------|
| 1        | 75.94 | 1.93  | 22.13 | Fe–Cr solution     |
| 2        | 76.94 | 2.44  | 20.62 | Fe–Cr solution     |
| 3        | 63.81 | 18.88 | 17.31 | Fe2Ta              |
| 4        | 64.29 | 14.05 | 21.66 | Fe2Ta              |
structure was determined as Fe₅Ta, according to the EDS results listed in Table 4.

Figure 9 presents the microstructure and element distribution for joint 3 and Table 6 lists the measured chemical compositions in the selected regions. The observed results in the FZ as marked in region b are seen in Fig. 9b. In this region, the FZ mainly consisted of a large number of dendritic and island-like Fe₅Ta phases which contained 75.48 at.% (Fe + Cr) and 24.52 at.% Ta as listed in Table 5. The generation of large amounts of Fe₅Ta in the FZ was attributed to the massive melting of Ta base materials. Figure 9c shows the edge of the Ta/FZ interface at the top region as region c marked in Fig. 9a. Two different transition layers were also generated in this region, i.e., layer 1 nearby the FZ and layer 2 adjacent to the Ta base materials. According to the listed EDS results in Table 5, layer 1 was determined as Fe₅Ta since it had a composition of 73.65 at.% (Fe + Cr) and 26.35 at.% Ta. Layer 2 was detected as FeTa since it had a composition of 43.95 at.% (Fe + Cr) and 56.05 at.% Ta. The Ta/FZ interface at the lower part of FZ as region d is presented in Fig. 9d. This interface consisted of extrusion near the weld and continuous diffusion zone. These two zones were respectively marked as layer 3 and layer 4 as shown in Fig. 9d. According to the EDS results, layer 3 was identified as Fe₅Ta (71.04 at.% (Fe + Cr) and 28.96 at.% Ta) while the inner layer 4 was determined

| Table 4 Component of different points in Fig. 8 (at.%) |
|------------|------|-----|-----------------|
| Position   | Fe   | Ta  | Cr  | Possible phases |
| 1          | 70.68| 9.56| 19.76| Fe–Cr solution |
| 2          | 58.32| 24.56| 17.12| Fe₅Ta           |
| 3          | 70.78| 9.73| 19.49| Fe–Cr solution |
| 4          | 58.34| 27.58| 14.08| Fe₅Ta           |
| 5          | 41.86| 46.19| 11.95| Fe₂Ta           |
| 6          | 4.27 | 93.16| 2.57 | Ta              |
| 7          | 58.34| 27.58| 14.08| Fe₂Ta           |
| 8          | 40.75| 51.32| 7.93 | FeTa            |
| 9          | 3.80 | 93.43| 2.77 | Ta              |
| 10         | 61.98| 14.68| 23.34| Fe₅Ta           |

| Table 5 Component of different points in Fig. 9 (at.%) |
|------------|------|-----|-----------------|
| Position   | Fe   | Ta  | Cr  | Possible phases |
| 1          | 60.24| 24.52| 15.24| Fe₅Ta           |
| 2          | 59.05| 26.35| 14.60| Fe₅Ta           |
| 3          | 39.97| 56.05| 3.98 | FeTa            |
| 4          | 3.44 | 92.99| 3.57 | Ta              |
| 5          | 55.92| 28.96| 15.12| Fe₅Ta           |
| 6          | 35.64| 60.37| 3.99 | FeTa            |
| 7          | 4.21 | 92.79| 3.00 | Ta              |
as FeTa (39.63 at.% (Fe + Cr) and 60.37 at.% Ta). The thickness of interfacial IMC in joint 3 was thicker than that in joint 1 and joint 2. This was caused by the closer proximity to the area of the laser heating center and the increase of interfacial heat input. Figure 9e shows the elemental scanning results of the interface as marked in Fig. 9d. The observed results indicated that a stable atomic transition zone occurred at this region, which proved the formation of interfacial IMC. The morphology at the bottom region Ta is presented in Fig. 9f. An unfused area was produced in this region due to insufficient heat input.

To better verify the influence of laser beam offset on the microstructure variations, the elemental distribution at three joints was observed and the corresponding results are shown in Fig. 10. The EDS mapping results showed that the elemental distribution of Cr and Fe was identical, which was due to the infinite solution between Cr and Fe elements. Less Fe and Cr but more Ta element was distributed in the FZ, as the laser beam offset on Ta side. Hence, it had a higher content of Fe–Ta IMC as seen in Figs. 7, 8 and 9. In Fig. 10f, a Ta-rich area was produced and this caused the formation of Fe–Ta interfacial IMC as seen in Fig. 8d.

To further determine the interfacial microstructure evolutions under different laser beam offsets, micro-XRD tests were conducted in the region including the FZ and interface. Figure 11a–c shows the test zone for these three joints, respectively, while the corresponding results are presented in Fig. 11d. For joints 2 and 3, diffraction peaks of Fe2Ta were discovered. It provided further evidence for the formation of Fe2Ta in the two

![Fig. 9 Microstructural morphologies and EDS results for joint 3: a cross-section; b FZ; c direct irradiation region; d middle region; e line scanning results; f unreacted region](image)

![Table 6 The comparison of the width between simulated resulted and experimental joints](table)

| Laser beam offset (mm) | W1 (μm) | W2 (μm) | W3 (μm) | Average relative error (%) |
|------------------------|---------|---------|---------|--------------------------|
| −0.2                   | Experimental 1017.6 | 832.0 | 1018.5 | 5.78 |
|                        | Numerical 929.32 | 806.5 | 961.6 |
| 0                      | Experimental 1632.0 | 795.2 | 723.2 | 5.27 |
|                        | Numerical 1552.0 | 756.0 | 680.0 |
| +0.2                   | Experimental 1808.0 | 926.5 | 600.0 | 9.92 |
|                        | Numerical 1556.0 | 892.8 | 560.0 |
joints. The diffraction peak of Fe$_2$Ta was not indexed in joint 1, which had a good coincidence with SEM and EDS results as seen in Fig. 7 and Table 3, respectively. It should be noted that FeTa was not detected since the FeTa was only generated near the interface between the FZ and Ta in a small amount. The solid solubility of Ta in Fe was very small; it was 1.28% at 1215 °C and 0.71% at 965 °C. The inter-content of elements Fe and Ta exceeds the values and therefore IMC would be generated.

### 3.3 Thermal cycles

The interfacial microstructure evolutions were closely associated with thermal cycles. Therefore, interfacial thermal cycles in the present study were calculated. First, the reasonability of developed numerical models was verified by the comparisons between numerical and experimental weld profiles. Corresponding results are presented in Fig. 12 and detailed weld profile dimensions are listed in Table 6. The weld profile had a satisfactory coincidence between numerical and experimental results, which proved that the developed numerical model in this research was reasonable and trustworthy.

Three points were selected from top to bottom along with the interface of these models as marked in Fig. 12d–f. Their temperature histories were extracted and plotted as curves in Fig. 13, and the 3020 °C marked in this figure indicated the melting point of Ta [18]. The 1775 °C marked in Fig. 13 represented the generating temperature of Fe$_2$Ta, while the generating temperature of FeTa was above 1800 °C [18]. The temperature history curves for joint 1 are shown in Fig. 13a. Only the peak temperature of point 1 reached the melting point of Ta (3020 °C). It was consistent with the fact that only a small amount of Ta melted at the top as shown in Fig. 7.

![Fig. 10](image-url) EDS mapping results of Ta/304SS joints with different laser beam offsets: (a–c) – 0.2 mm; (d–f) 0 mm; (g–i) + 0.2 mm
Figure 13b presents the temperature history curves corresponding to joint 2. The peak temperatures at all three points reached the melting point of Ta, indicating that Ta melted at these three locations and produced the IMCs as seen in Fig. 8. Figure 13c shows the temperature history curves corresponding to joint 3. The peak temperatures of the points at the top and middle of the Ta/FZ interface (6823.5 and 3712.3 °C, respectively) both exceeded the melting point of Ta. The melting depth of joint 3 in Fig. 9 was shallow and Ta in the bottom of the Ta/FZ was solid state due to its lower peak temperature (1581 °C < 3020 °C). This agreed quite well with the results of numerical simulation results.

3.4 Mechanical properties

Figure 14 shows the microhardness distribution along selection regions for three joints. The average hardness values of 304SS and Ta base metal were 180 HV and 120 HV, respectively. The hardness in the fusion zone and interface was higher than those of base materials due to the formation of Fe2Ta + Fe–Cr solution. The hardness
of joint 2 and joint 3 was larger than that of joint 1 due to the larger amounts of IMCs generated in FZ as seen in Figs. 7, 8 and 9. Furthermore, the hardness at the Ta/FZ interface was higher than the fusion zone due to the higher volume of the generated IMC transition layer (Fe₂Ta or Fe₂Ta + FeTa). In the FZ, the hardness fluctuated within a certain range since the FZ was composed of a Fe–Cr solution matrix and Fe₂Ta brittle phase. The Fe₂Ta brittle phase had a higher hardness than the Fe–Cr solution, and this finally led to the inhomogeneous hardness distribution.

Figure 15 shows the tensile strength of Ta/304SS joints obtained with different laser beam offsets. The tensile strength increased first and then sharply decreased as the laser beam offset further increased. The tensile strength of the joints reached the largest value when laser beam offset was −0.2 mm (308.3 MPa, 59.9% of the value of 304SS and 65.3% of the value of Ta). The maximum strength of the joints had reached the strength level obtained by the electron beam welding [15, 16].

Fracture behaviors of these three joints are presented in Fig. 16. Corresponding EDS analyses at selected regions are presented in Table 7. Figure 16a–c depicts the whole fractured surfaces for three joints, and it could be found that the 304 stainless steel tube was pulled out from the tantalum cylinder. To further investigate the fractured details of these three joints, the fractured interface in the selected regions was observed and the corresponding results are shown in Fig. 16d–l.

Figure 16d–f shows the fracture paths of these joints. Relevant EDS analyses were performed to confirm the phase components, and the results are listed in Table 7. The joint was fractured along with the interface, as the laser beam offset was −0.2 mm and 0 mm. When the laser beam offset became +0.2 mm, the joint was fractured along the FZ + partial FZ. Figure 16g–i shows the fracture interface of these joints. For joint 1, the Fe₂Ta was left at the fractured interface in the FZ side. This indicated
that the interface was fractured along the Fe$_2$Ta layer or Fe$_2$Ta/Ta interface. For joints 2 and 3, the FeTa was left at the fractured interface in the FZ side and this proved that the interface was fractured along the FeTa layer or FeTa/Ta interface.

To better clarify the fracture behaviors for these joints at the Ta side, the morphology of the corresponding fracture surfaces was observed and the SEM images are shown in Fig. 16j–l. Figure 16j shows the fracture surface of joint 1 and the Fe$_2$Ta (EDS results showed that point 4 was composed of 78.88 at.% (Fe + Cr) and 21.12 at.% Ta) was detected at the surface. It indicated that the fracture occurred in the Fe$_2$Ta layer, combined with the Fe$_2$Ta observed at the FZ side of fractured interface as shown in Fig. 16g.

Fig. 16  Fracture behaviors for the joints obtained with different laser beam offsets: (a–c) macrofractured surfaces for three joints; (d–i) fractured paths and locations for three joints; (j–l) fractured surfaces at Ta side for three joints
1. Satisfactory appearances of the joints were obtained. When the laser beam offset from 304SS to Ta, the penetration depth of FZ became shallower and partial melting of Ta base materials occurred when the laser was center and 0.2 mm laser beam offset on Ta side.

2. Fe–Cr solid solution and brittle IMC Fe2Ta formed in the FZ. The content of Fe2Ta in the FZ and interfacial IMC thickness were increased as the laser beam offset on Ta side. IMC of Fe2Ta would be also generated in the Ta/FZ interface in the joints produced under the laser beam offset of −0.2 mm. When the laser beam offsets were 0 and +0.2 mm, FeTa would be newly produced adjacent to Ta base materials.

3. Numerical simulation results showed that the interfacial peak temperatures increased when the laser beam offset from 304SS to Ta. In addition, duration at high temperature was improved. With these two combined reasons, more Ta base material was melted and thicker IMC was generated.

4. Fractured behaviors showed that two different fractured paths appeared, namely, that interface and interface + partial FZ. The highest joint strength of 308.3 MPa was obtained when the laser beam offset was −0.2 mm under the fractured paths of the interface. This indicated that Fe2Ta with smaller thickness has weaker influence on the joint strength.

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Availability of data and material The authors confirm that the data and material supporting the findings of this work are available within the article.

Code Availability Not applicable.

Declarations

Ethics approval Appropriate.

Consent participate All authors approved the manuscript to participate.

Consent for publication All authors approved the manuscript for publication.

Conflict of interest The authors declare no competing interests.

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