Original Article

Three-pass laser welding of Ti alloy-stainless steel using Nb and Ni interlayers

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ABSTRACT

Nb-YAG laser welding of TC4 titanium (Ti) alloy and 301L stainless steel (SS) were carried out through interlayers Nb and Ni. The laser beam was concentrated at the Ti alloy-Nb interface, Nb-Ni interface and Ni-SS interface, respectively, to ensure that whole Nb and Ni interlayer was not melted. Three-pass welding was employed, which involves the creation of a joint with three welding zones separated by the remaining unmelted Nb and Ni. Interlayer Nb and Ni were employed to prevent the formation of Ti-Fe intermetallics and improve the microstructure and the properties of the Ti alloy-SS joint. The joint fractured at the welding zone of the Nb-Ni interface with the tensile strength of 269 MPa.

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1. Introduction

The joint between Ti alloy and stainless steel (abbreviated as SS) has broad applications in the nuclear industries and the oil-rig of refineries [1–3]. The formation of brittle Ti-Fe intermetallics is considered as the primary metallurgical problem of Ti alloy and SS in the welding, which makes the traditional welding method unable to connect directly [4–6]. The most commonly applied method now is the addition of an interlayer between Ti alloy and SS to improve the microstructures and mechanical properties of the joint. The melting amount of Ti alloy and SS in weld decreased, and the content of Ti-Fe intermetallics in the weld decreased due to the addition of the interlayer. The interlayers such as Cu, Ag, Ni, Al and Mg have been employed to restrict the formation of Ti-Fe intermetallics in the welding [7–12]. As the interlayers form intermetallic phases with Ti and Fe, the strength of such welds is dependent on the brittleness of the Ti x M y and the Fe x M y (M-element of interlayer) in comparison with the Ti x Fe y on the spatial distribution of intermetallics in the joints [13]. However, the Ti and Fe elements will come into reaction in the weld pool as long as the interlayer is wholly melted, which will form the Ti-Fe intermetallics in the welding. In addition, the strength of the joints was also reduced by the Ti x M y and Fe x M y intermetallics generated from Ti or Fe and interlayer elements. The continuous laser welding of AISI 316 L SS to Ti-6Al-4 V alloy via pure V interlayer was studied by Tomashchuk et al. [14]. Because the unmelted V interlayer can avoid the formation of Ti-Fe intermetallics in the joint, two pass welding was employed, which involve the creation of two welding zones separated by the residual unmelted V interlayer. Yet the brittle σ-phase (FeV)
between the SS and the V interlayer reduced the mechanical properties of the joint. Yan Zhang et al. [15] found that the laser can be offset into the Ti alloy by using Nb as an interlayer for joining Ti alloy and SS, while the eutectic bonding occurred on the Nb-SS interface of the joint in the article published recently. This was because the unmelted Nb interlayer could avoid the formation of Ti-Fe intermetallics in the joint. Yet the brittle Nb-Fe intermetallics of the Nb-SS interface reduced the mechanical properties of the joint. Ti, Fe and other elements of binary phase diagram are referenced, and Ti can form an infinite solid solution elements V, Nb, Mo, Ta, W. Besides, Fe do not form the intermetallics with the elements of Ni, Co, Mn, Cu and Ag [16,17]. Accordingly, no element formed a solid solution that did not form the intermetallics with Ti and Fe [18,19]. As the noted analysis suggests, the addition of a single interlayer can prevent the formation of Ti-Fe intermetallics by controlling the welding technology, yet it is not possible to avoid the intermetallics formed between the Ti or Fe elements and the interlayer elements.

Given the foregoing analysis, three-pass laser welding of Ti alloy to SS through composite interlayer Nb/Ni was proposed in this paper. The major aim is to avoid the brittle Ti-Fe, Ti3M3 and Fe3M3 (M-element of interlayer) intermetallics in the joint. By achieving this aim, the microstructure of the joint can be improved. Because Nb does not form intermetallics with Ti and other elements of Ti alloy, there will be no intermetallics in the weld of Nb and Ti alloy. Likewise, Ni does not form the intermetallics with Fe and other elements of SS. In such a way, a joint with three welding zones separated by the unmelted Nb and Ni was acquired, and Ti-Fe intermetallics can be completely avoided in the joint. Thus far, this type of joint has been rarely reported.

2. Experimental

The applied materials are 0.8 mm plates of austenitic SS SUS 301L (69 at.% Fe, 18 at.% Cr and 8 at.% Ni), Ti alloy Ti6Al4V (87 at.% Ti, 6.5 at.% Al and 3.7 at.%V). The specimens for direct welding experiments were machined into 50 mm × 40 mm × 0.8 mm plates. Their chemical compositions and physical properties are given in Tables 1, 2 and 3. Before the welding, the specimens were mechanically and chemically cleaned. Nd:YAG pulsed laser was used, with average power of 1.05 kW, wavelength of 1.064 μm, focal length of 150 mm and beam spot diameter of 0.1 mm. 40 mm × 1 mm × 0.8 mm thick pure Nb sheet (99.99 at.%) and 40 mm × 1 mm × 0.8 mm thick pure Ni sheet (99.99 at.%) served as the interlayer and were placed on end face of the base material fixed in fixture (Fig. 1a). Three-pass welding was applied. In the first pass, Ti alloy was welded to Nb sheet with the laser beam concentrated at the Ti alloy-Nb interface. In the second pass (immediately after the first one), Nb sheet was welded to Ni sheet with the laser beam concentrated at the Nb-Ni interface. In the third pass (immediately after the second one), Ni sheet was welded to SS with the laser beam concentrated at the Ni-SS interface (Fig. 1a).

The welding parameters were as follows: the laser power of 143 W, the pulse duration of 8 ms, the defocusing distance of +2 mm, the pulse frequency of 7 Hz and the welding speed of 200 mm/min. The dimensions of tensile specimens: overall length of 55 mm, grip section length of 29 mm, fillet radius of 6 mm, reduced section length of 16 mm, reduced section width of 4 mm.

3. Results and discussion

The cross section of the joint is shown in Fig. 1b, and there is no obvious crack or porosity in the joint. The joint can fall into five parts: the first welding zone (WZ1) formed at the Ti alloy-Nb interface, the unmelted Nb; the second welding zone (WZ2) formed at the Nb-Ni interface, the unmelted Ni; the third welding zone (WZ3). The formation of Ti-Fe intermetallics was avoided in the joint due to the presence of unmelted Nb and Ni. The first welding zone consisted of molten Ti alloy and Nb (Fig. 1c and Fig. 1f) because the Nb interlayer was not wholly melted in the first welding. The second welding zone consisted of molten Nb and Ni (Fig. 1d and Fig. 1g). The Ni interlayer was not wholly melted in the third welding, and the third weld-

| Table 1 – Main chemical compositions of 301L stainless steel (at.%). |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Si   | Mn  | P   | S   | Cr  | Ni  |
| <1.00 | <2.00 | <0.045 | 0.03 | 16.00-18.00 | 6.00-8.00 | <0.20 Bal |

| Table 2 – Main chemical compositions of TC4 Titanium alloy (at.%). |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Al   | V   | Fe  | C   | N   | H   | O   |
| 6.05 | 4.02 | 0.14 | 0.02 | 0.02 | 0.006 | 0.12 |

| Table 3 – Physical properties of TC4 Titanium alloy and 301L stainless steel. |
|-----------------|-----|-----|-----|-----|-----|
| Material        | Melting point/°C | Tensile strength/MPa | Specific heat capacity/(J kg⁻¹ K⁻¹) | Thermal conductivity/(W m⁻¹ K⁻¹) | Linear expansion coefficient/(10⁻⁶ K⁻¹) |
| TC4             | 1650 | 895 | 536 | 6.4 | 8.7 |
| SUS301L         | 1450 | 550 | 500 | 16.3 | 16.9 |
Fig. 1 – (a) schematic diagram of the welding process; (b) cross sections of the joint by three pass welding; (c) the formation of WZ1; (d) the formation of WZ2; (e) the formation of WZ3; (f) the optical image of WZ1; (g) the optical image of WZ2; (h) the optical image of WZ3.

Fig. 2 – (a) OM image of the WZ1 (refer to the weld center in Fig. 1f); (b) SEM image of the WZ1 (refer to the weld center in Fig. 1f); (c) OM image of the WZ2 (lower left of the WZ2 in Fig. 1g); (d) SEM image of the WZ2 (refer to the weld center in Fig. 1g); (e) OM image of the WZ3 (refer to the weld center in Fig. 1h); (f) SEM image of the WZ3 (lower right of the WZ3 in Fig. 1h).

The welding zone consisted of molten Ni and SS (Fig. 1e and Fig. 1h). Besides, a special phenomenon was observed on WZ1.

Fig. 2a presents the optical image of WZ1. The SEM image of the WZ1 is shown in Fig. 2b. It can be seen that the WZ1 has a columnar structure. The compositions in different positions of joint (denoted by letter A-D in Fig. 2) were analyzed by SEM-EDS. The average chemical composition of WZ1 (see Table 4) was approximately 2.18 at.% Al, 52.40 at.% Ti, 43.36 at.% Nb and 2.06 at.% V. According to the Ti-Nb binary phase diagram, the main elements of Ti and Nb in WZ1 do not show intermetallics. Therefore, the main microstructure of this weld zone was (βTi, Nb) solid solution.

The optical image of WZ2 is presented in Fig. 2c. SEM image of WZ2 is shown in Fig. 2d. WZ2 produced a compound layer on the Nb side as shown in the Fig. 2c. In accordance with the EDS analysis in Table 4, this compound layer is identified as the Ni3Nb layer. The average chemical composition of WZ2 (see Table 4) was nearly 72.47 at.% Ni and 27.53 at.% Nb. This
is because the melting point of Nb was much higher than that of Ni (a difference of 1000 °C), and the melting amount of Ni was much larger than that of Nb in the welding. In line with the Nb-Ni binary phase diagram, (Ni, Nb) solid solution and a small amount of Ni₃Nb phase were the primary microstructure of WZ₂. Because Nb and Ni did not form an infinite solid solution, Nb-Ni intermetallics were formed in the WZ₂. Nb-Ni intermetallics were formed in the WZ₂. Its brittleness is lower than Ti-Fe intermetallics and the addition of Nb and Ni interlayer can help decrease the brittleness of the joint. Besides, Nb and Ni have excellent plasticity. They can coordinate the deformation in the welding, reduce the interface stress and the internal stress in the joint, and compensate for the weakening by the brittle phase, thus improving the performance of the WZ₂.

The optical image of WZ₂ is presented in Fig. 2e. SEM image of WZ₂ is presented in Fig. 2f. The average chemical composition of WZ₂ (see Table 4) was nearly 5.52 at.% Cr, 45.36 at.% Fe, 49.12 at.% Ni. In accordance with the Ni-Fe binary phase diagram, the primary microstructure of WZ₂ was γFe, Ni) solid solution. In the WZ₂, there are columnar grains growing towards the center of the weld at the fusion lines on both sides, and there are small cell crystal zones in the welding center (Fig. 2e). Because the highest temperature gradient was produced along the direction perpendicular to the solid/liquid interface [20]. The grain rapidly grows along this direction, perpendicular to the fusion line to the weld center, which induced formation of the columnar crystal structures, as shown in Fig. 2f.

The tensile strength and the elongation of the joint could reach 269 MPa and 1.5 %, respectively (Fig. 3a). Fracture occurred at Nb side of WZ₂ as shown in Fig. 3b. SEM image of the fracture surface was present in Fig. 3c, which suggests that fracture mode of the joint was brittle fracture. Besides, XRD analyses of fracture surface detected Ni₃Nb phase as shown in Fig. 3d. This confirmed that the fracture occurred in the compound layer of WZ₂. This was primarily because the Ni₃Nb phase was more brittle than (Ni, Nb) solid solution. WZ₂ become the weak zone of the joint, which led to the failure in the tensile test.

4. Conclusions

According to the previous analysis, the Ti-Fe intermetallics and the intermetallics produced by Ti or Fe and other interlayer elements were the most damaging to the Ti alloy-SS

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### Table 4 - EDS analysis of different zones in the joint.

<table>
<thead>
<tr>
<th>Region</th>
<th>Composition (at.%)</th>
<th>Potential phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Nb 43, V 2, Al 3, Ti 52</td>
<td>(βTi, Nb)</td>
</tr>
<tr>
<td>B</td>
<td>Nb 27, V 73, Cr 81</td>
<td>Ni₃Nb</td>
</tr>
<tr>
<td>C</td>
<td>Nb 19, V 45, Al 49, Ti 6</td>
<td>(Ni, Nb)₃+Ni₃Nb</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td>γFe, Ni)</td>
</tr>
</tbody>
</table>

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**Fig. 3 –** (a) tensile test curve; (b) fracture location; (c) SEM image of fracture surface; (d) XRD analysis results of fracture surface.
joints. In this paper, Ti alloy/Nb/Ni/SS joint was discussed and all intermetallics formed by Ti or Fe in the Ti alloy-SS joint were avoided. No intermetallics were formed in the WZ1 and WZ3 except the solid solution. Only Nb-Ni intermetallics were formed in the WZ2, which reduced the mechanical properties of the joints. Yet the brittleness of the joints will be greatly reduced in comparison with the brittleness of the joint including Ti-Fe intermetallics and other intermetallics formed by Ti or Fe.

Conflict of interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

REFERENCES