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Effect of V/Fe composite interlayer on the microstructure and mechanical properties of electron beam welded joints of Ta-10W and GH3128

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Abstract
Electron beam welding of Ta-10W and GH3128 superalloys without and with the addition of V/Fe composite interlayer was carried out to study the effect of the addition of V/Fe composite interlayer on the microstructure, mechanical properties and fracture characteristics of the welded joints. The results showed that both welded joints were well formed, with the addition of V/Fe composite interlayer having finer grains in each region. The fracture form of both welded joints are brittle fracture, fracture location are in the Ta-10W side. However, some ductile fracture features were present in the fracture of the added V/Fe composite interlayer. In direct electron beam welding, the Ta-10W side of the reaction layer there is a large number of Ta-Ni and other intermetallic compounds, which is the most important reason for its poor mechanical properties of the joint. the addition of V/Fe composite interlayer greatly reduces the tendency of intermetallic compound formation in the weld, changing the microstructure of the reaction layer, the tensile strength of the joint has been significantly increased, the maximum tensile strength of 362 MPa.

1. Introduction
Tantalum is a refractory and rare metal with excellent ductility, weldability and corrosion resistance [1–3]. Pure tantalum is soft, and alloying elements are usually added to pure tantalum to improve its mechanical properties [4]. Due to the similar atomic structures of tantalum and tungsten, they can form an infinite solid solution, and the solid solution strengthened tantalum-tungsten alloy has a series of excellent mechanical properties, such as high melting point, high elastic modulus and low toughness to brittle transition [5–7]. Among them, Ta-10W (Tantalum tungsten alloy containing about 10% tungsten) alloy has been widely used in aerospace, weapons, shipbuilding and other fields for its good high-temperature strength, good weldability, good corrosion resistance and strong impact resistance [8]. GH3128 (A high temperature alloy developed in China, GH is the Chinese pinyin abbreviation for gao wen he jin, and 3128 is its grade) is a super alloy that is currently more widely used in the aerospace field, and it is commonly used in the manufacture of ship turbine blades, aviation and aerospace engine combustion chambers and other components [9, 10]. The high performance connection of Ta-10W and GH3128 is of great significance in super high temperature resistant components, especially in aero engines, which will not only significantly improve the thrust to weight ratio, but also reduce the consumption of Ta, which has good economic benefits [11].

The welding of Ta-10W and GH3128 is a dissimilar metal welding, and because there are great differences in their physical properties including melting point, thermal conductivity and linear expansion coefficient, and tantalum is very sensitive to nitrogen, hydrogen and oxygen at high temperatures, even small amounts of nitrogen, hydrogen and oxygen can reduce the comprehensive performance of tantalum to a great extent [12], so the common welding methods including MAG welding, TIG welding, brazing, and diffusion welding are difficult to complete its effective welding. Vacuum electron beam welding has the characteristics of concentrated
energy, controlled heat input, almost no pollution and small heat affected zone [13–15], which is more suitable for welding of dissimilar metals.

There are few studies on the electron beam welding of tantalum and tantalum alloys with nickel-based (GH3128) or iron-based (Inconel 718) superalloys. In the available studies, it has been found that the mechanical properties of the welded joints are poor when welding is performed directly. It has been found that direct alignment welding results in the formation of a brittle and hard reaction layer near the tantalum side fusion line. In doing mechanical tests, not only tensile fracture occurred in the reaction layer, but also in doing microhardness tests, the maximum hardness also occurred in the reaction layer [9, 12, 15]. This is mainly due to the tendency to form intermetallic compounds such as Ta-Ni and Ta-Cr on the near-tantalum side during welding [16], which cannot be eliminated by solid solution treatment and changing the welding parameters. In dissimilar metal welding, when two materials cannot form an effective connection due to excessive differences in physicochemical properties, the connection is often achieved by adding an interlayer [17–21]. C H Ng et al performed laser welding of NiTi and AISL316L stainless steel with the addition of a 50 um Ta interlayer and made brittle intermetallic compounds by increasing the amount of Ta in the weld (TiFe4, TiCr2, TiFe, etc) content was reduced, and finally welded joints with greatly improved tensile properties were obtained [22]. Xiaolong Cai et al laser welded titanium and nickel-based superalloys with the addition of a V/Cu composite layer, which significantly reduced the formation of brittle phases, eliminated subsequent cracking, and ultimately improved the mechanical properties of the welds [23]. Y. Zhang et al used double pass welds separated

Figure 1. Schematic diagram of composite interlayer design (a) and the metallurgical compatibility of Ta, Ni and other elements (b).

Table 1. Chemical compositions of Ta-10W (in wt%).

| Chemical element | Ta | W | Ti | Ni | Mo | C | N | O | Si | H |
|------------------|----|---|----|----|----|---|---|---|----|----|
| Wt%              | Balance | 11.0 | 0.1 | 0.1 | 0.02 | 0.01 | 0.01 | 0.015 | 0.005 | 0.0015 |

Table 2. Chemical compositions of GH3128 (in wt%).

| Chemical element | Ni | Cr | Mo | W | Al | Ti | Fe |
|------------------|----|----|----|---|----|----|----|
| Wt%              | Balance | 19.0–22.0 | 7.5–9.0 | 7.5–9.0 | 0.40–0.80 | 0.40–0.80 | ≤0.2 |
| Si               | ≤0.80 | ≤0.50 | ≤0.005 | ≤0.06 | ≤0.05 | ≤0.05 | ≤0.013 | ≤0.013 |
of Ta-10W are 50 mm used as the interlayer. and their chemical compositions are listed in tables 3 and 4, respectively. The dimensions of unmelted V had a tensile strength of 627 MPa intermetallic to improve the microstructure and properties of the titanium alloy-ss joint. The fracture at the interlayer are 50 mm

In this experiment, 2 mm thick Ta-10W and GH3128 plates are used as the base material, and their chemical compositions are listed in tables 1 and 2, respectively. 0.3 mm V foil with 99.9% purity and 0.2 mm Fe foil were used as the interlayer. A composite interlayer Ta/Fe was used to prevent the formation of titanium-iron intermetallic to improve the microstructure and properties of the titanium alloy-ss joint. The fracture at the unmelted V had a tensile strength of 627 MPa. No studies have been reported on the addition of an interlayer for electron beam welding of Ta/GH3128 joints, so this study is of great significance for the performance enhancement and application of Ta/GH3128 joints. After a systematic and scientific screening, the V/Fe composite interlayer was finally chosen as an intermediate layer. Because, in the binary phase diagram, V and Ta have a large solid solution interval, V and Fe are solid soluble, and Fe and Ni are solid soluble. Their physical and chemical properties are more favorable than those of other materials in reducing the formation of intermetallic compounds in welded joints. In this paper, V/Fe composite layer was used to weld Ta-10W and GH3128 by electron beam, and the microstructure and mechanical properties of the welded joints were investigated. With the aim of improving the mechanical properties of Ta-10W and GH3128 welded joints and providing theoretical support and experimental verification for their industrial applications.

2. Materials and methods

2.1. Experimental materials

In this experiment, 2 mm thick Ta-10W and GH3128 plates are used as the base material, and their chemical compositions are listed in tables 1 and 2, respectively. 0.3 mm V foil with 99.9% purity and 0.2 mm Fe foil were used as the interlayer, and their chemical compositions are listed in tables 3 and 4, respectively. The dimensions of Ta-10W are 50 mm (L) × 5 mm (W), GH3128 is 50 mm (L) × 50 mm (W), and the dimensions of V and Fe interlayer are 50 mm (L) × 2 mm (W). Before welding, metallographic sandpaper was used to remove the oxide layer from the surface of the base material and brazing material, followed by ultrasonic cleaning in acetone, and then placed in an oven at 100 °C for drying.

2.2. Design of the composite interlayer

When looking for a suitable intermediate layer element, considering that the connection between Ta-10W and GH3128 is applied in a high temperature environment, low melting point elements such as Ag, Al, Au, Cu, etc, and also radioactive elements such as Th, U, etc, should be excluded. Next, we try to find an element that can not form intermetallic compounds with both Ta and Ni by binary phase diagram, unfortunately, there is none. So the intermediate layer needs at least two layers of elements, as shown in the figure 1, A is the element that does not form intermetallic compounds with Ta, B is the element that does not generate intermetallic compounds with Ni, we need to find the combination of A and B also does not generate intermetallic compounds. Such combinations are W-Cr, Mo-Cr, Y-Cr, V-Cr, V-Fe. How to filter the optimal combination from these combinations, in order to achieve good welding results 1: A and B should be melting point, thermal conductivity, coefficient of thermal expansion and other physical parameters. 2: A and Ta-10W base metal thermal expansion coefficient and thermal conductivity difference as small as possible. B and GH3128 nickel-based superalloys thermal expansion coefficient and thermal conductivity difference as small as possible. Such combinations are V-Cr (45 K), V-Fe (352 K), Y-Cr (361 K), Mo-Cr (760 K), most of these combinations have Cr, the single Cr is very brittle and hard, and the thermal conductivity of Cr is (91.3 W (m.k)^-1), the thermal expansion coefficient is (6.5 × 10–6/K), the thermal conductivity of GH3128 is (11.3 W (m.k)^-1) and the coefficient of thermal expansion is (11.25 × 10–6/K), it can be seen that these two physical parameters of both of them are very different, which is not good for welding.

This finally leaves the V-Fe combination, in which the coefficient of thermal expansion of V (8.3 × 10–6/K) is close to that of Ta (6.5 × 10–6/K (0 to 100 °C)) and the coefficient of thermal expansion of Fe

| Chemical element | V | Fe | Cr | O | C | Al | Mo | H |
|------------------|---|----|----|---|---|----|----|---|
| Wt%              | Balance | <0.002 | <0.0015 | <0.0012 | <0.0015 | <0.0014 | <0.0015 | <0.0013 |

Table 3. Chemical compositions of V (in wt%).

| Chemical element | Fe | C | S | P | Si | Mn | Ni | Cr | Al |
|------------------|----|---|---|---|----|----|----|----|---|
| Wt%              | Balance | 0.003 | 0.008 | 0.011 | 0.01 | 0.03 | 0.03 | 0.02 | 0.035 |

Table 4. Chemical compositions of Fe (in wt%).
(12.2 × 10−6/K) is close to that of GH3128 (11.25 × 10−6/K), which is useful for metallurgical bonding during welding is beneficial.

2.3. Welding experiment
Electron beam welding experiments were conducted with the addition of an intermediate layer and without interlayer, respectively. In both welding experiments, the electron beam center was aligned with the center of the weld. The schematic diagram of the electron beam welding assembly with the addition of the V/Fe interlayer is shown in figure 2 (the welding assembly without the addition of an interlayer is the same as it), Electron beam welding is conducted in a 2.3 × 10−4 Pa vacuum by a K110 electron beam welding machine and the specific welding parameters are shown in table 5.

2.4. Test methods for microstructure and mechanical properties
After electron beam welding, metallographic and tensile samples were cut out along the vertical welding direction using a wire cutting machine. After that the metallographic samples were mechanically ground, polished and etched for microscopic analysis. In order to study the degree of Ta-10W side interface bonding, after several trials, it was decided to perform a secondary etching of the weld. The first etching solution was a
solution of H₂SO₄, HNO₃ and HF in a 5:2:5 mixture. It was mainly used for the corrosion of Ta and its compounds at the Ta-10W side interface. The second corrosion solution was aqua regia, which was mainly used for the corrosion of the weld area and the GH3128 base material area. After the corrosion was completed, the microstructure of the metallographic samples was examined using an OM (VHX-600K) to observe whether the metallographic samples were successfully etched. The microstructure of the successfully etched metallographic samples and the morphological characteristics of the fracture surfaces were observed using a scanning electron microscope (VEGA 3 XMU (LaB6)) and the corresponding microstructure was analyzed compositionally by energy dispersive spectroscopy (EDS). EBSD experiments were performed on the samples using (MIRA3 LHM) high-resolution scanning electron microscopy. XRD (XPert Pro) was used to identify the phases present within the welds, using a microhardness tester (HXD-1000TMSC/LCD) loaded with 200 g and a dwell time of 15s. The tensile strength of the joint was measured using an electronic general purpose material tester ((ZWick/Roell Z100) at a tensile speed of 1 mm min⁻¹, and the schematic diagram of the tensile specimen is shown in figure 3.

3. Results and discussion

3.1. Characteristics of electron beam-welded joint without interlayer
In order to better explain the effect of adding V/Fe composite interlayer on the organization and properties of GH3128 and Ta-10W electron beam welded joints, the case of GH3128 welded with Ta-10W electron beam without interlayer was first investigated.

The microstructure of the welded joint is shown in figure 4. The weld melt pool as a whole shows a semi-funnel shape with a wide top and a narrow bottom, where the base material of GH3128 melts much more than that of Ta-10W, which is due to the excessive difference in the melting points of GH3128 and Ta-10W, and the weld tissue is mainly composed of columnar crystals. There are some fine columnar crystals on the fusion line on one side of GH3128 and a reaction layer on the fusion line on the Ta-10W side. There are thick dendritic crystals
Figure 5. Ta-side reaction layer (a), fracture surface (b) and XRD pattern of the fractured surface (c) of the joint without interlayer.

Figure 6. Microstructures of the welded joint with V/Fe composite interlayer (a) GH3128 side; (b) middle part of the weld; (c) Bottom of weld (d) Ta-10W side.
along the fusion line on both sides of the weld perpendicular to the fusion line pointing to the center of the weld, with some equiaxed crystals in the center of the weld. Because the solidification process of the weld pool for GH3128 and Ta-10W electron beam welding has been described \[25\], the focus of this paper is on the reaction layer, which, according to previous studies, is present in the Ni-Ta system with five compounds Ni$_8$Ta, Ni$_3$Ta, Ni$_2$Ta, NiTa, and NiTa$_2$ \[26–28\], and Yi Zhou et al. have some of these Ni-Ta compounds properties were investigated in depth and found that most of the Ni-Ta compounds are ductile, but Ni-Ta, P21/m-Ni$_3$Ta and h.c.-NiTa$_2$ are brittle \[29\], as shown in figures 5(a)–(c). EDS analysis of the reaction and tensile fracture layers

Figure 7. Overview of the dissimilar joint with V/Fe composite interlayer and the corresponding images for distribution maps of major elements.

Figure 8. SEM images of different regions of electron beam welded joints with the addition of V/Fe composite layers and corresponding EDS positions (a) GH3128 side, (b) middle part of the weld, (c) Ta-10W side, (d) Bottom of weld.
was carried out and verified by XRD test analysis of the tensile fracture surface for Ni₃Ta. The presence of intermetallic compounds such as TaNi₅Si, Ta₃Ni₂Si, Cr₃Ni₂, etc. due to the different distances of the reaction layer from the Ta-10W parent material appeared multilayer intermetallic compound layers with different Ta contents. Even though the Ni-Ta compounds in some of the layers are ductile, but due to the presence of W, Cr and other elements in their tissues, the fracture forms that eventually lead to tensile fracture are brittle fracture, the fracture location is in the reaction layer.

In addition, the location of the reaction layer in the vicinity of the Ta-10W fusion line, due to the difference between the melting point of the two materials. The coefficient of linear expansion leads to stress concentration at the reaction layer, while the rapid cooling rate of electron beam welding characteristics also inhibit the release of residual stresses in the welding to a certain extent. Therefore, in the tensile test, the fracture usually first occurs at the reaction layer.

3.2. Characteristics of electron beam welded joint with Fe/V composite interlayer

Figure 6 shows the electron beam welded joint metallographic photographs of the V/Fe composite interlayer. As shown in figures 6(a), (b), (d), The weld shows a semi-funnel shape with a wide top and narrow bottom, and the weld tissue is mainly composed of columnar crystals. The organization near the weld fusion line is characterized by fine columnar crystals in the middle of the elongated dendritic crystals. In the center of the weld there are a large number of fine equigranular crystals. Compared with the organization within the corresponding regions in figures 4(a)–(c), the addition of the V/Fe composite interlayer results in finer grain size and more uniform organization. Most excitingly, the reactive layer near the fusion line on the Ta-10W side disappears and the dendritic organization in the fusion region replaces the reactive layer. However, in figure 6(c), island-like regions are found in the lower weld tissue.

To better understand the effect of the V/Fe composite layer on the welded joint organization, the distribution of the major elements in the weld was first determined by performing an EDS surface scan of the weld area. As shown in figure 7, the distribution of the major elements in the weld is very uniform, which is very favorable for the organization and properties of the welded joint. In order to further analyze the tissue composition of each region of the weld, EDS analysis was performed on the main characteristic regions of the weld tissue and XRD tests were performed on the weld.

As shown in figure 8, the weld is mainly composed of grey and white areas within the weld. In order to observe whether there are differences in the composition of the grey and white areas in different regions, EDS analysis was performed separately. From the data in table 8, it can be obtained that the gray composition of the GH3128 side and the center of the weld as well as the bottom area of the weld is basically the same. From the GH3128 side to the center of the weld and then to the Ta side, the content of V and Fe elements showed a trend of first increasing and then decreasing. While the content of Ta element increases significantly near the Ta-10W side region and the content of Ni element decreases gradually. Also, according to the XRD analysis in figure 9, there are (Fe, V), (Ta, V) and (Fe, Ni) solid solutions in the weld. The decrease in the elemental Ni content on the Ta-10W side is due to the combination of some Ni elements with the added V and Fe elements, which reduces the formation of Ta-Ni brittle intermetallic compounds. Compared to the electron beam welding without
intercalation, some island-like areas appear in the lower part of the weld, and this welding feature may be due to the different liquid phase line temperatures of the filler metal and the base material [30]. It can be determined that too low heat input leads to the appearance of islanded regions in the weld [31]. After EDS analysis of the islanded region, it can be found that the chemical composition is similar to the organization near the fusion line of GH3128. It was also found that the grains within the islanded region were very small, which was caused by the rapid melting and rapid cooling of the metal during the welding process. For this experiment, it was speculated that the islanded region was formed when the V/Fe composite layer was added for electron beam welding, and due to the small gap between the V/Fe layers, the electron beam crossed the substrate between the more easily melted V/Fe layers, causing increased melting in the lower part of the substrate. The electron beam stirring effect in the lower part is weaker relative to the electron beam stirring effect without the addition of the intermediate layer at the same welding parameters, causing part of the substrate to melt and then solidify rapidly to form an island area. This is also consistent with the electron beam welding with the addition of a V/Fe composite interlayer having a larger bottom melting depth relative to electron beam welding without the interlayer.

3.3. Mechanical properties of the welded joint
Microhardness tests and metal tensile tests are commonly used to analyze the mechanical properties of welded joints. In this paper, the mechanical properties of electron beam welded joints without interlayer and with the addition of V/Fe composite interlayer are also investigated by these two methods.

![Figure 10. Hardness distribution along the cross section of the weld (a) without interlayer (b) with V/Fe composite interlayer added.](image)
Figure 11. (a) Stress-strain curves of electron beam welded joints between GH3128, Ta-10W, and added V/Fe composite layers. (b) Stress-strain curves of electron beam welded joints without interlayer and with V/Fe composite interlayer added.

Table 6. The EDS results for reactive layers without interlayer electron beam welding (in wt%).

| Chemical element | W  | Ta  | Mo  | Cr  | Ni  |
|------------------|----|-----|-----|-----|-----|
| 1                | 6.93 | 23.58 | 9.98 | 15.77 | 37.23 |
| 2                | 7.45 | 18.07 | 5.49 | 13.97 | 49.01 |
| 3                | 20.89 | 24.08 | 8.43 | 9.33  | 20.42 |
| 4                | 10.34 | 45.18 | 2.7  | 4.51  | 20.05 |
| 5                | 13.93 | 62.08 | 2.18 | 2.4   | 12.2  |
| 6                | 11.74 | 68.22 | 2.62 | 2.4   | 6.13  |
3.3.1. Hardness distribution of the electron beam welded joint

Figure 10 is the microhardness diagram of the electron beam welded joint tissue as shown in figure 10(a). The microhardness of the electron beam welded joint tissue without additive layer shows a pattern of higher hardness in the weld zone than in the base material zone on both sides and a surge of hardness in the weld zone on the Ta-10W side of the reaction layer. The microhardness of the weld zone is higher than that of the base material zone because the weld zone tissue is finer grained compared to the base material zone, and grain refinement results in enhanced microhardness [32, 33]. Based on the EDS compositions in tables 6 and 7 and the XRD analysis in figure 5. We can obtain the presence of a large number of intermetallic compounds, such as Ni-Ta, in the reaction layer, and these intermetallic compounds increase the microhardness of the reaction layer dramatically. As shown in figure 10(b), the microhardness of the weld zone of the electron beam joint tissue with the addition of the V/Fe composite layer is higher than that of the base material zone on both sides, and the microhardness of the weld zone is relatively uniformly distributed. Compared with figure 10(a), the microhardness of the weld zone with the addition of the V/Fe composite layer is significantly higher than that of the weld zone without this layer, and the reason for this phenomenon is mainly due to grain refinement [34]. From figures 4 and 5, it can be found that the grain size of the electron beam welded joint tissue with the addition of V/Fe composite layer in the corresponding weld area is much finer. More importantly, there is no surge in microhardness in the weld area on the Ta-10W side, which also confirms the change in the reaction layer after

| Chemical element | Ta  | Ni  | W   | Cr  | C   |
|------------------|-----|-----|-----|-----|-----|
| 1                | 32.09 | 13.25 | 4.04 | 1.41 | 47.88 |
| 2                | 49.12 | 18.02 | 10.73 | 2.17 | 19.24 |
| 3                | 53.21 | 9.53  | 5.74  | 1.13 | 29.14 |
| 4                | 67.12 | 11.66 | 9.15  | 1.4  | 9.46  |

| Chemical element | Ta  | Ni  | W   | Cr  | V   | Fe  |
|------------------|-----|-----|-----|-----|-----|-----|
| 1                | 5.0  | 44.4 | 6.1  | 14.9 | 7.7 | 7.9 |
| 2                | 6.3  | 31.5 | 10.2 | 15.3 | 6.9 | 6.2 |
| 3                | 5.4  | 41.4 | 5.5  | 13.7 | 9.2 | 10.1|
| 4                | 9.2  | 28.4 | 8.5  | 13.9 | 9.2 | 7.8 |
| 5                | 9.3  | 33.6 | 6.2  | 11.9 | 7.5 | 7.5 |
| 6                | 16.1 | 38.2 | 6.8  | 11.3 | 7.2 | 7.1 |
| 7                | 53.3 | 15.4 | 10.8 | 6.0  | 3.5 | 2.3 |
| 8                | 6.4  | 43.2 | 7.1  | 15.6 | 7.2 | 7.1 |

Table 7. The EDS results of tensile fracture surfaces without interlayer electron beam welding (in wt%).

Table 8. The EDS results of different regions of electron beam welded joints with the addition of V/Fe composite layer (in wt%).
the addition of the V/Fe composite interlayer, which is very beneficial to improve the performance of the welded joint.

3.3.2. Tensile strength of electron beam welded joints
Tensile experiments were performed at room temperature on electron beam welded joints of GH3128, Ta-10W, without the addition of an interlayer and with the addition of a V/Fe composite layer. As shown in figures 11(a), (b): the tensile properties of GH3128 and Ta-10W are very good, the tensile properties of the electron beam welded joints without intermediate layer are weak, and the tensile properties of the electron beam welded joints with the addition of V/Fe composite layer are greatly improved. Figure 12 shows the maximum tensile strength of different welded joints. The maximum tensile strength of GH3128 is 889 MPa. the maximum tensile strength of Ta-10W is 535 MPa. While the maximum tensile strength of the electron beam welded joint without interlayer is 211 MPa, which is only about 24% of the maximum tensile strength of GH3128 and about 39% of the maximum tensile strength of Ta-10W. The maximum tensile strength of the electron beam welded joint with the addition of the V/Fe composite interlayer was 362 MPa, which reached approximately 41% of the maximum tensile strength of GH3128 and approximately 68% of the maximum tensile strength of Ta-10W. The maximum tensile strength is increased by about 72% compared to the electron beam welded joint without interlayer. From the grain morphology in different regions of figure 4 and figure 6, the addition of V/Fe composite interlayer resulted in more grain refinement in all parts, and the grain refinement led to the improvement in mechanical properties [35]. But more important is the change in the reaction layer on the Ta-10W side after the addition of the V/Fe composite interlayer. Since tensile fractures all occur on the Ta-10W side, the change in the reaction layer is the most important reason for the improved tensile properties of the electron beam welded joints with the addition of the V/Fe composite interlayer.
Figure 13 shows the SEM image of the fracture pattern of the welded joint without interlayer. From figure 13 we can see that the fracture surface there is a deconstruction step and many lamellar areas, for the typical brittle fracture characteristics. For its lamellar areas of EDS results as shown in table 7, the composition and the EDS results of some areas of the reaction layer in table 6 is very close. Also in figure 10(a) the microhardness surge occurs in the Ta-10W side of the reaction layer, these are Proof of fracture occurred at the brittle hard reaction layer.

Figure 14 shows the SEM image of the fracture morphology of the welded joint with the addition of V/Fe composite layer. From figure 14, we can see that the fracture surface there is a deconstruction step and river-like pattern, for the typical brittle fracture characteristics, but some of its regions also exist tough nest, which is characteristic of ductile fracture, according to the stress-strain curve in figures 11 and 14, The tensile fracture mode of the electron beam welded joint with the addition of V/Fe composite interlayer is brittle fracture, but it is characterized by ductile fracture in some of its regions.

3.4. EBSD analysis of electron beam welded joints with the addition of V/Fe composite layer

In order to better study the tensile fracture behavior of the electron beam welded joints between the added V/Fe composite layers, EBSD analysis was carried out on the welded joints.

Figure 15(a) shows that the columnar crystals in the weld pool grow from the fusion line on both sides of the weld to the center of the weld. The grain growth direction is the opposite of the cooling direction. The grains on the GH3128 side are more slender than the Ta-10W side. Figure 15(b) shows the orientation difference of adjacent grains with a length of 50um through the Ta-10W side fusion line is measured at an interval of 5um. From figure 15(b), the orientation difference of adjacent grains of the Ta-10W fusion line at this position can be obtained. Figure 15(c) shows the large-angle and small-angle grain boundaries of the electron beam welded joint. The red line on the side marked with Ni-superalloy represents the large-angle grain boundary, and the green line represents the small-angle grain boundary. The purple line on the Ta mark side represents the large-angle grain boundary, and the yellow line represents the small-angle grain boundary. From figure 15(c), it can be seen that the grain boundaries in the base metal area on both sides of the weld are mainly high-angle grain
boundaries, and the grain boundaries in the weld are mainly large-angle grain boundaries. Grain boundaries, there are also a small number of small-angle grain boundaries. In order to more clearly show the types of grain boundaries near the Ta-10W side fusion line, a clearer EBSD grain boundary analysis was performed on the Ta-10W side fusion zone in figure 15(c). As shown in figure 15(c), it can be seen that the small-angle grain boundaries are concentrated near the Ta-10W side fusion line, and the small-angle grain boundaries have the characteristics of small orientation difference between adjacent grains, which is also in line with the phenomenon shown in figure 15(b). The small-angle grain boundary easily passes through the adjacent grains when the dislocations move, causing local slippage, resulting in an increase in the local dislocation density, leading to stress concentration. In metal tensile experiments, fractures generally occur in the stress concentration [36, 37].

In this study, the V/Fe composite interlayer was used to successfully connect Ta-10W and GH3128 nickel-based superalloy using electron beam welding technology. The connection strength was significantly improved, but the tensile fracture mode of the welded joint was still brittle fracture, which is its industrial application. It is unfavorable. In the follow-up, we can study the influence of the thickness and ratio of the V layer and Fe layer on the microstructure and mechanical properties of different joints [38, 39]. At the same time, we can also study the effect of welding position and welding sequence on the microstructure and mechanical properties of different welded joints [40]. These studies are of great importance for their industrial applications.

4. Conclusions

Different welding of Ta-10W and GH3128 between no intermediate layer and added V/Fe composite layer was carried out with electron beam. The microstructure and mechanical properties of the joint were studied, and the following main conclusions were obtained.

1. When directly electron beam welding Ta-10W and GH3128, there are brittle intermetallic compounds such as Ni3Ta, TaNiSi, Ta3Ni2Si, Cr3Ni2 in the reaction layer on the Ta-10W side, which is the main reason for its poor mechanical properties.

2. When V/Fe composite layers are added, the elements in the weld are evenly distributed, the microstructure of the reaction layer transforms into columnar crystals, and the formation of brittle and hard intermetallic compounds in the weld is greatly reduced.

3. Adding V/Fe composite layers can greatly increase the joint strength. The maximum tensile strength at room temperature is 362MPa, which is about 68% of the Ta-10W base material. Compared with the maximum tensile strength of the electron beam welding joint without interlayer, the tensile strength is increased by about 72%.

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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