A comparative study on electron beam welding and rigid restraint thermal self-compressing bonding for Ti_6Al_4V alloy

This study focuses on the influence of joining method difference on the joint microstructure and properties. Unlike vacuum electron beam welding (EBW) utilizing electron beam as fusion heat source, rigid restraint thermal self-compressing bonding (TSCB), a new solid-state bonding method proposed by authors, employs vacuum electron beam as the non-melt heat source to bond materials in this work. Meanwhile, a comparative study on the microstructure and mechanical properties of EBWjoint and rigid restraint TSCB joint was conducted to investigate the effect of this difference on joint microstructure and properties. Results show that compared with EBW joints, the rigid restraint TSCB joints as solid-state joints are homogeneous in terms of microstructure and microhardness profile. Strength of both joints are comparable with that of base metal, but the elongation of the rigid restraint TSCB joint is more close to that of base metal. Rigid restraint TSCB joint has better combination of strength and ductility.

2.1. Preparation of the joints

Rigid restraint TSCB is a new solid-state bonding method proposed by the authors [19]. Fig. 1 presents the fundamental principle of rigid restraint TSCB of Ti6Al4V alloy using electron beam as heat source in this study. As shown in Fig. 1, local non-melted heating by electron beam is employed to heat the butt interface of the plates to be bonded. Under the action of localized heating, materials close to the butt interface is expand. Due to the existence of surrounding cool metals and rigid restraints, the expansion of high temperature materials is restrained; and thus a compressive pressure F is developed which compresses the high temperature metals near the bond interface and facilitates the atom diffusion between buttweld specimens to produce permanent solid-state joints [19]. Commercial Ti6Al4V plates with a thickness of 5 mm were employed in this study. The sizes and sampling orientation of buttweld specimens used for EBWand rigid restrain TSCB are illustrated in Fig. 2. Before joining, the Ti6Al4V plates were finely ground by a grinding machine, and subsequently cleaned with acid solution and ethanol.

The EBW and rigid restrain TSCB were carried out in a high voltage vacuum electron beam welding machine ZD150-15MH CV3M. Parameters of EBW are listed in Table 1. During rigid restrain TSCB, focus current was selected as 2759 mA to generate enough thermal compressing effect to promote the atomic diffusion between butt-weld specimens, and multi-beam scanning heating method regulated by electron beam deflection system was utilized to heat the butt-weld specimens. The scanning length is equal to the width of the specimens. Parameters of rigid restraint TSCB are also listed in Table 1.

2.2. Analysis of the joints

Specimens used for metallographic examination were cut from both joints and the cross-sections of the specimens were prepared for inspection by mounting, mechanical polishing and etching. The polished cross-sections of both joints after etching were analyzed by a Leica DM6000M optical microscope (OM) and a QUANTA 250FEG scanning electron microscope (SEM). Electron backscattering diffraction (EBSD) was used to analyze the microstructure of rigid restraint TSCB joint and the step size of 0.3 mm was employed.

Microhardness measurements of both joints were conducted on a hardness tester (HXD1000) at room temperature by holding a test load of 2.97 N for 10 s. Microhardness values were directly attained from the tester. Three tensile specimens perpendicular to the bond interface for every joint and base metal were machined. The tensile specimen dimensions were chosen on the basis of GB/T 228-2002 specification as shown in Fig. 2(b). The sampling orientation and the dimensions of the tensile specimens for the base metal are same to that of welded joints. Tensile tests were carried out at room temperature using an MTS system. The testing result was the average value of three specimens. Fracture morphology of the tensile test specimen for the joint was observed by the QUANTA 250FEG scanning electron microscope.

3. Experimental results and discussions

3.1. Microstructure

The optical photograph of the cross-section of EBWwelded joint is illustrated in Fig. 3. It can be seen that the weld is composed of the base metal (BM), the heat affected zone (HAZ), and the fusion zone (FZ). Due to the directional solidification during the fast cooling process, the columnar grain structure is formed in the FZ.

The microstructure of the typical regions at high magnification is given in Fig. 4. The microstructure of BM is made up of original a phase and original b phase. The microstructure in HAZ and FZ changes significantly after vacuum electron beamwelding. The HAZ near the BM is complicated, which consists of original a, original b, the block secondary a, and the acicular martensite a’. The microstructure of HAZ near the FZ is made up of block secondary a and the acicular martensite a0 , which is different from that of the HAZ near the BM, and thus the HAZ can be divided into two parts according to the microstructure difference. The results are similar to the observations of Ti6Al4V EBW joint reported by Liu J et al. [16]. Moreover, Fig. 4(d) shows that the FZ mainly consists of acicular martensite a0 structure. To sum up, it can be seen that the microstructure of the EBW joint is inhomogeneous.

The optical photographs of the base metal and the cross-section of rigid restraint TSCB joint are illustrated in Fig. 5. It can be seen that the base metal is made up of a phase and transformed b microstructure with lamellar a and b phases. Consisting of primary a phases and transformed b structures as shown in Fig. 5(b), the microstructure in the bonded area of rigid restraint TSCB joint is similar to that of base metal, and there is no as-cast microstructure appeared in the rigid restraint TSCB joint.

To further study the characteristics of microstructure evolution of Ti6Al4V alloy during rigid restraint TSCB, EBSD is employed to analyze the microstructure of base metal and bonded area of the joint.

The orientation maps of HCP a phase of the base metal and bonded area are given in Fig. 6, where the color code triangle of HCP a phase is displayed in the bottom right corner and the black zone in the orientation maps represents the BCC b phase. It can be seen that both of the grains in bonded area and base metal have similar equiaxed shape. Meanwhile, after comparing the grain size distributions and misorientation distributions of base metal and bonded area shown in Figs. 7 and 8 respectively, it can be also suggested that there is no notable change of the microstructure after rigid restraint TSCB.

Therefore, it can be seen that with the comparison of EBWjoint, the microstructure of rigid restraint TSCB joint is homogeneous. As is known, the microstructure transformation of welded joints is mostly depended on the thermal cycle during the welding process [20,21]. As a high power density beam welding method, the vacuum electron beam welding has the characteristics of high peak temperature, extremely fast heating and cooling rates [22]. During vacuum electron beam welding of the present Ti6Al4V alloy, the FZ metal is completely melted and the primary a phase completely transfer to b phase because the peak temperature during EBW is higher than the melting point and b transus temperature of Ti6Al4V alloy. Then, due to the very fast cooling rate, the transformation from b phase to steady a phase by atom diffusion have no enough time to occur, and acicular martensite is formed in the FZ by the shear phase transformation of b phase. As for rigid restraint TSCB, the electron beam power is low in this experiment and the peak temperature is lower than the b transus temperature (995 ± 15 _C) of Ti6Al4V alloy, therefore the similar microstructure to base metal is attained in bonded area of rigid restraint TSCB joint at room temperature.

3.2. Mechanical properties

3.2.1. Microhardness

Microhardness distributions on the cross-sections of EBW and rigid restraint TSCB joints are presented in Fig. 9. As shown in Fig. 9(a), the microhardness of EBW joint fluctuates with the increase of the distance from weld center. The average hardness of BM is approximately 336.1HV, while the average hardness in the FZ of EBW welded joint is 360.5HV. The peak of the microhardness distribution is located at the HAZ and the maximum of the microhardness of HAZ is 387.2 HV which increases by 15.2% comparing to the base metal. As for rigid restraint TSCB joint, the average value of the microhardness is 325.3HV, and the majority of the microhardness values are in the interval of 325.3 ± 18.0 HV. It can be suggested that the microhardness profile on the crosssection of the rigid restraint TSCB joint is homogeneous when compared with that of EBW joint.

The difference between the microhardness distributions on the cross-section of the EBW and rigid restraint TSCB joints can be interrupted by the microstructure. The microstructure of FZ of EBW joint reveals as-solidified coarse b columnar grain structure, as shown in Fig. 3. Inside the b columnar grain, the microstructure is composed of the a0 martensite. The microstructure of HAZ near FZ consists of transformed a phase from the prior b phase and the acicular a0 martensite phase, while that near the BM contains the original a phase, the original b phase, transformed a phase from the prior b phase and the acicular a0 martensite phase. In general, the microhardness of the a0 martensite is larger than that of a phase in present Ti6Al4V alloy [21]. Thus, the microhardness of FZ and HAZ are higher than that of base metal, and the peak values for the HAZ near the weld metal is attributed to the dense martensite in this zone [21]. However, the microstructure of rigid restraint TSCB joint is homogeneous as shown in Fig. 4. Therefore, uniform hardness profile is attained accordingly. Results of microhardness measurements and microstructure are consistent with each other.

3.2.2. Tensile mechanical properties

The tensile test results of BM, EBWjoint and rigid restraint TSCB joint are shown in Table 2. It can be seen that the joint efficiency values of EBWand rigid restraint TSCB joints are 100.7% and 103.7% respectively which indicates that the strength of both joints are comparable with the strength of Ti6Al4V base metal. However, in term of the elongation, the value of rigid restraint TSCB is more close to that of base metal when compared with EBW joint. Therefore, it can be suggested that the rigid restraint TSCB joint has better combination of strength and ductility. The mechanical properties of materials are closely dependent upon the microstructure. According to the microstructure presented above, a0 martensite is formed in the FZ and HAZ of EBW joint as shown in Fig. 3. Due to the lower ductility of a0 martensite comparing to a phase and b phase, EBW joint exhibits decreased ductility as compared with the base metal. However, the microstructure of rigid restraint TSCB is homogeneous, which is responsible for the elongation of the joint is comparable to that of base metal.

The fracture locations of all the tensile specimens of EBW and rigid restraint TSCB joints are base metal as shown in Fig. 10, which suggests that the strength of both joints are comparable to that of base metal. Fracture morphologies of the tensile specimens for the EBW and rigid restraint TSCB joints are shown in Fig. 11. They all present a typical dimple fracture appearance, from which it can be concluded that the fracture mechanism of the EBW and rigid restraint TSCB joints is ductile failure mode. SEM result of fracture surface is in good agreement with the testing result of tensile mechanical properties.

4. Conclusions

In this work, vacuum electron beam was employed as a nonmelt heat source to perform the rigid restraint thermal selfcompressing bonding of Ti6Al4V alloy. Meanwhile, the microstructure and mechanical properties of the rigid restraint TSCB solidstate joint were compared with that of vacuum electron beam fusion welding. The main conclusions are drawn as follows:

(1) The microstructure of EBW joint is inhomogeneous, with a0 martensite in the FZ and in the HAZ. However, microstructure of rigid restraint TSCB joint is similar to that of base metal, consisting of primary a phases and transformed b structures.

(2) The microhardness of FZ and HAZ in EBW joint are higher than that of base metal owing to the formation of a0 martensite. By contrast, the microhardness profile of the rigid restraint TSCB joint is homogeneous due to the homogeneous microstructure.

(3) Compared with EBW joint, the rigid restraint TSCB joint has better combination of strength and ductility.

Fig. 1. Illustration of rigid restraint TSCB of Ti6Al4V alloy using electron beam

Fig. 2. (a) Dimensions of welding specimens and the location of tensile specimens for EBW, (b) dimensions of welding specimens and the location of tensile specimens for rigid restraint TSCB, (c) geometry of tensile specimen

Fig. 3. The optical photograph of the cross-section profile of EBW welded joint.

Fig. 4. Microstructure of the typical regions of EBW welded joint. (a) Base metal, (b) HAZ near the base metal, (c) HAZ near the FZ and (d) FZ.

Fig. 5. Microstructure of the (a) base metal and (b) rigid restraint TSCB joint

Fig. 6. The orientation maps of HCP a phase in the (a) base metal and (b) bonded area of rigid restraint TSCB joint.

Fig. 7. The grain size distributions of (a) base metal and (b) bonded area of rigid restraint TSCB joint.

Fig. 8. The misorientation distributions of (a) base metal and (b) bonded area of rigid restraint TSCB joint.

Fig. 9. Microhardness distribution on the cross-section of (a) EBW joint and (b) rigid restraint TSCB joint.

Fig. 10. The fracture locations of the tensile specimens of (a) EBW joint and (b) rigid restraint TSCB joint.

Fig. 11. The fracture morphology of the tensile specimens of (a) EBW joint and (b) rigid restraint TSCB joint.

Table 1
Parameters of electron beam welding and rigid restraint thermal self-compressing bonding.
Table 2
Tensile properties of base metal and joints.