



Mechanism of reheat cracking in electron beam welded Ti_2AlNb alloys

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Abstract: In order to clarify the characteristics and formation mechanism of the reheat cracking in Ti_2AlNb weldments, a series of heat treatment conditions were performed to the circular joints welded by electron beam, and then the macrostructures and microstructures were investigated using optical microscopy, scanning electron microscopy, X-ray diffractometry, and transmission electron microscopy. The results show that the reheat cracking occurs primarily along the grain boundaries in the weld when the Ti_2AlNb circular welded joints are heated up to about 700 °C. During the heat treatment, an almost complete transformation of $B2 \rightarrow O$ happens while the temperature goes up through the O single-phase region. Then, $O \rightarrow B2+O$ phase transformation occurs primarily along the grain boundaries as the weld metal continues to heat up to the $B2+O$ dual-phase region. Under the high tension stress consisting of welding residual stress and phase transformation stress, reheat cracking occurs at the interface between the $B2+O$ dual-phase layer and the O -phase matrix.

Key words: reheat cracking; electron beam welding; Ti_2AlNb alloy; microstructure evolution

1 Introduction

Over the past decades, Ti_2AlNb -based alloys have attracted wide attention. The alloys contain a large amount of ordered orthorhombic O phase, which was firstly identified by BANERJEE et al in 1988. In addition of the ordered orthorhombic O (Ti_2AlNb) phase, the alloys include α_2 (hexagonal, Ti_3Al), and ordered $B2$ (body-centered cubic) phase as well. Generally, the contents of Al and Nb in the alloys are 22–25 at.% and 20–27 at.%, respectively. Ti–22Al–23Nb (at.%), Ti–22Al–25Nb (at.%), and Ti–22Al–27Nb (at.%) [1,2] are the typical Ti_2AlNb alloys. Due to the high specific strength, attractive creep and corrosion resistance, and superior processability, the Ti_2AlNb alloys show great potential as structural materials in aerospace and elevated temperature fields [3,4].

To fabricate high-quality joined structures, various

welding or joining processes are being developed. The processes to be developed will extend the applications of the Ti_2AlNb alloys. Up to now, several welding methods have been studied to investigate the weldabilities of the Ti_2AlNb alloys, including diffusion bonding [5], linear friction welding [6,7], laser beam welding (LBW) [8–11] and electron beam welding (EBW) [12–14]. ZOU et al [5] have studied the microstructure and strength of the joints during transient liquid phase diffusion bonding of Ti–22Al–25Nb alloy. CHEN et al [6,7] have investigated the microstructure evolution and mechanical properties of linear friction welded Ti_2AlNb alloy under as-welded and post-weld heat treatment conditions. LEI et al [10,11] have investigated the microstructure evolution and tensile properties of laser welded Ti–22Al–27Nb and Ti–22Al–27Nb/TC4 joints, and ZHANG et al [9] have studied the laser weldability of dissimilar Ti–22Al–27Nb/TA15 alloys. The laser welded joints of this type of alloys showed low ductility at ambient and high

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temperatures due to the columnar structure during solidification and the *O* phase precipitated in the *B2* grain boundaries in the welds. EBW is preferable to joining titanium alloy, because it has a clean vacuum chamber and high energy density and relatively low heat input [12–14] that produces a weld with narrow and deep penetration, small heat-affected zone, and low distortion and residual stresses. Therefore, EBW has become a preferred method of the Ti_2AlNb alloys welding. TAN et al [15,16] have conducted dissimilar welding of Ti–22Al–25Nb and TC11 alloys using EBW. In their studies, hot work, such as isothermal deformation accompanied with heat treatment, has been employed to improve the microstructures and the mechanical properties of the welded joints.

The fusion zone of the EBW welded joint is basically composed of unstable *B2* phase due to fast cooling rate and high content of niobium [17]. On the other hand, Ti_2AlNb alloy is expected to be used at elevated temperature such as 650 °C. Therefore, post-weld heat treatment is necessary to optimize the microstructure and enhance the mechanical properties for the welded joints. However, in our preliminary study, serious cracks were observed in the fusion zone as the EBW joints underwent post-weld heat treatment. This cracking can be classified into reheat cracking. The reheat cracking in Ti_2AlNb weldments has not been investigated except for a very few preliminary results. CAI et al [18] found cracks in the nugget of Ti_2AlNb alloy resistance spot weldments after post-weld heat treatment, and their results indicated that the precipitation of hardening phase (*O* phase) together with the residual stress led to the cracking during post-weld heat treatment. Nevertheless, the characteristics and formation mechanism of the reheat cracking in Ti_2AlNb weldments are not clear up to now.

In this study, a series of post-weld heat treatments were performed to EBW joint of Ti_2AlNb alloy in order to figure out the temperature range where reheat cracking happens. The mechanism of the reheat cracking in Ti_2AlNb EBW joint was investigated by analyzing the characteristics of the crack and the microstructure evolution during the heat treatment.

2 Experimental

2.1 Material and welding process

The base metal used in this study was hot-rolled Ti–22Al–25Nb sheet with the thickness of 5 mm. The nominal composition of the material is 22 at.% Al, 25 at.% Nb and balanced Ti. It was provided by Central Iron and Steel Research Institute, China. The specimens were cut from the sheet into 50 mm × 50 mm coupons. Before EBW, the oxide layer was removed from the

surfaces with specific acid solution (3 mL HF, 30 mL HNO_3 and 67 mL H_2O). And then, the specimens were cleaned with acetone and then dried. The bead-on-plate circular seam welds were made using GENOVA 98 model EBW machine. A schematic diagram of welding process can be seen in Fig. 1. The welding condition is given in Table 1.

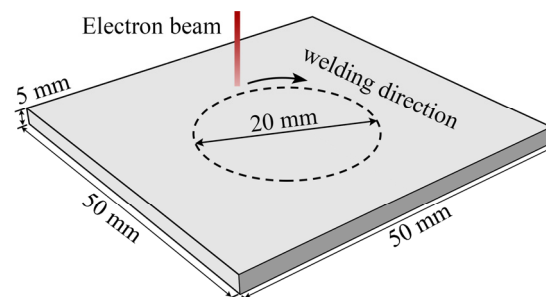


Fig. 1 Schematic diagram of welding process

Table 1 Welding condition

Accelerating voltage, U/kV	Electron current, I_b/mA	Focus current, I_f/mA	Welding speed, $v/(\text{mm} \cdot \text{min}^{-1})$	Work distance, D/mm
60	16	2190	500	200

2.2 Post-weld heat treatment

Previous investigations [6,17] showed that heat treatment in the temperature range of 750–900 °C was often performed to Ti_2AlNb welded joints in order to improve the tensile properties, and the holding time was usually 1–2 h. To investigate the reheat cracking of the Ti_2AlNb EBW joint, various heat treatments were conducted in this study, as given in Table 2. Holding time of 0 min means that the specimen was heated up to the selected temperature and then cooled down immediately. The heat treatments with holding time of 0 min at 400, 500, 600, 700 °C were carried out in a resistor furnace with a heating rate of 10 °C/min, while the others were treated in a vacuum furnace with a heating rate of 20 °C/min. After that, the specimens were examined to check whether there were cracks or not.

Table 2 Heat treatment parameters

Holding time/min	Temperature/°C	Cooling method
0	400, 500, 600, 700, 800	Furnace cooling
60	700, 800, 900	Furnace cooling

2.3 Microstructure characterization

After the welded joints were heat-treated, metallographic specimens were cut from the joints at the representative positions: the steady welding region and ending region, as shown in Fig. 2. And then, conventional titanium metallographic procedures were

used to prepare the metallographic specimens. After mounting, grinding and polishing, the specimens were etched using a special reagent (10 mL HF, 30 mL HNO₃ and 50 mL H₂O₂). The reheat cracks of welded joints were observed using an OLYMPUS BX 51M optical microscope. The microstructures of the joints were observed with a ZEISS Supra 55 scanning electron microscopy (SEM). X-ray diffraction (XRD) was used to identify the phase composition of the weld metal. A slice sample was cut out of the weld zone, mechanically polished and ion-thinned for transmission electron microscopy analysis (TEM, Tecnai G2 F20 S-TWIN).

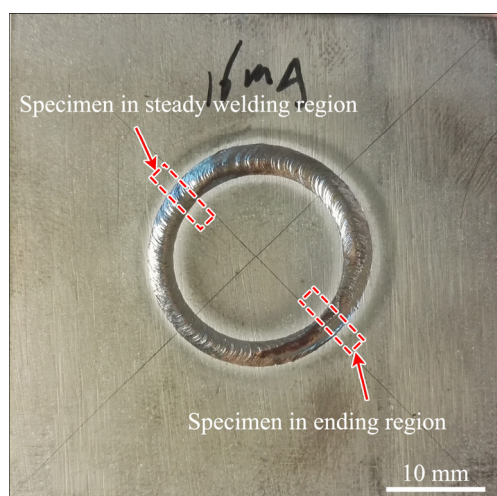


Fig. 2 Schematic diagram of sampling locations

3 Results and discussion

3.1 Effects of heat treatment condition on occurrence of reheat cracking

The cross-sectional macrostructures of the as-welded sample and the heat-treated samples with common heat treatment parameters (700–900 °C, 60 min) were examined at first. As shown in Fig. 3(a), no crack was observed within the fusion zone of the as-welded sample. However, after the samples were heat-treated at 700–900 °C for 60 min, cracking obviously occurred in the samples, as illustrated in Figs. 3(b–d). The cracks were observed both in the steady welding region and ending region. And the cracks were mainly located in the fusion zone. The results indicate that reheat cracking easily occurs in the fusion zone when the common post-weld heat treatments are performed to the Ti₂AlNb EBW joint.

The above results show that obvious cracking occurred in the Ti₂AlNb EBW joints after they were heat treated at high temperature for 60 min. To make clear the stage where the crack happened, the joint was heated up to 800 °C and cooled down immediately, and then, the joint was examined to check whether there were cracks or not. As shown in Fig. 4(a), obvious reheat cracks were

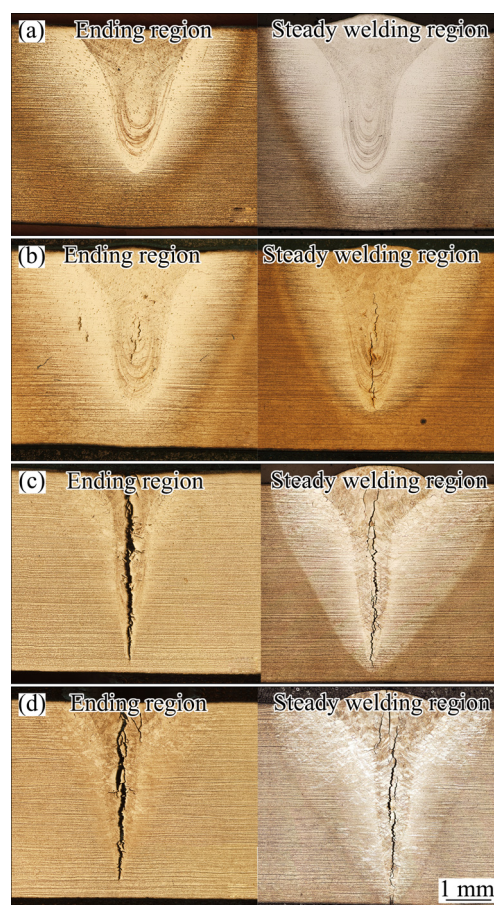


Fig. 3 Macrostructures in fusion zone of Ti₂AlNb EBW joints heat-treated for 60 min: (a) As-welded; (b) 700 °C; (c) 800 °C; (d) 900 °C

still observed in the fusion zone even though the joint was cooled down immediately from 800 °C. This means that the reheat cracking happened in the heating-up period. To further clarify the temperature range where the crack happened, the Ti₂AlNb EBW joints were heated up to 400, 500, 600, 700 °C, respectively, and cooled down immediately. And then, the corresponding cross-sectional macrostructures of the joints were inspected. As shown in Figs. 4(b–e), no cracking occurred in the joints heat-treated below 600 °C, while obvious cracking occurred in the fusion zone of the joints heat-treated above 700 °C. Thus, we can conclude that it is in the heating-up process that the reheat-cracking happens as Ti₂AlNb EBW joints are heated to around 700 °C.

3.2 Intergranular feature of reheat cracking

The reheat cracking occurred intergranularly, as shown in Fig. 5. In order to further observe the intergranular cracking, high magnification morphologies for grain boundary (GB) of the fusion zone in as-welded samples and the heat-treated samples were obtained by means of SEM. Figure 6(a) shows SEM image of



Fig. 4 Macrostructures in fusion zone of Ti_2AlNb EBW joints heated to different temperatures with holding time of 0 min: (a) 800 °C; (b) 700 °C; (c) 600 °C; (d) 500 °C; (e) 400 °C

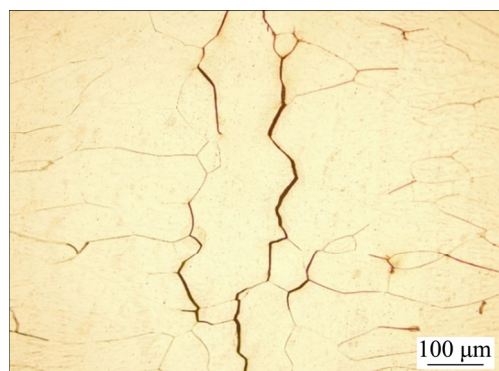


Fig. 5 intergranular characteristic of reheat cracking of sample (700 °C, 60 min)

as-welded samples, indicating that no intergranular precipitation generated along GB in the fusion zone. As shown in Figs. 6(b–d), when the temperature was sufficiently low, such as below 600 °C, the GBs in the fusion zone of the heat-treated samples were almost the same as those of as-welded samples, and no intergranular precipitation was found. On the other hand, when the temperature was increased to 700 °C, a thin precipitation layer distinct from the adjacent matrix formed at the original GB. And the thickness of the precipitation layer increased as the temperature was increased to 800 °C. Figure 7 shows the micro-crack at original grain boundary of the sample heat-treated at 800 °C, indicating that the reheat cracking actually initiated and propagated along the interface between the precipitation layer and the matrix.

3.3 Metallurgical factor affecting reheat cracking

Microstructure evolutions were investigated to clarify the metallurgical factor responsible for the reheat cracking. The XRD pattern in Fig. 8(a) shows that the weld metal of the Ti_2AlNb EBW joints mainly consisted of $B2$ phase, and the low relative peak intensity of O phase indicated the quantity of O phase was very small. It has been reported that, the as-welded Ti_2AlNb is almost composed of $B2$ phase due to the high niobium content in Ti_2AlNb alloys and the fast cooling rate of welding process [17]. Figure 8(b) displays the diffraction patterns of the weld metal under different heat treatment conditions. As illustrated, the weld metal of the Ti_2AlNb joints was still predominantly composed of $B2$ phase while the temperature was below 600 °C. Meanwhile, the relative peak intensity of O phase increased slightly with the increase of temperature, which indicated that the phase transformation $B2 \rightarrow O$ had happened. As the temperature was increased above 700 °C, the relative peak intensity of $B2$ phase decreased significantly to a very low level, which means that an almost complete transformation of the $B2$ phase to the O phase had taken place, and the Ti_2AlNb joints was then mainly composed of O phase.

To further characterize the phase composition in the weld metal, especially in the vicinity of GB, TEM examination was performed on this region under as-welded condition and (800 °C, 0 min) heat treatment condition. A bright-field image of the weld metal under as-welded condition is shown in Fig. 9(a). The selected area electron diffraction (SAED) from area in the red ring was accordance with the patterns corresponding to $B2$ (Fig. 9(b)), and no other diffraction patterns corresponding to α_2 or O were found. However, a quite different phase composition was found in the weld metal under (800 °C, 0 min) heat treatment condition, as shown in Fig. 10. The SAED patterns in Figs. 10(b) and (d)

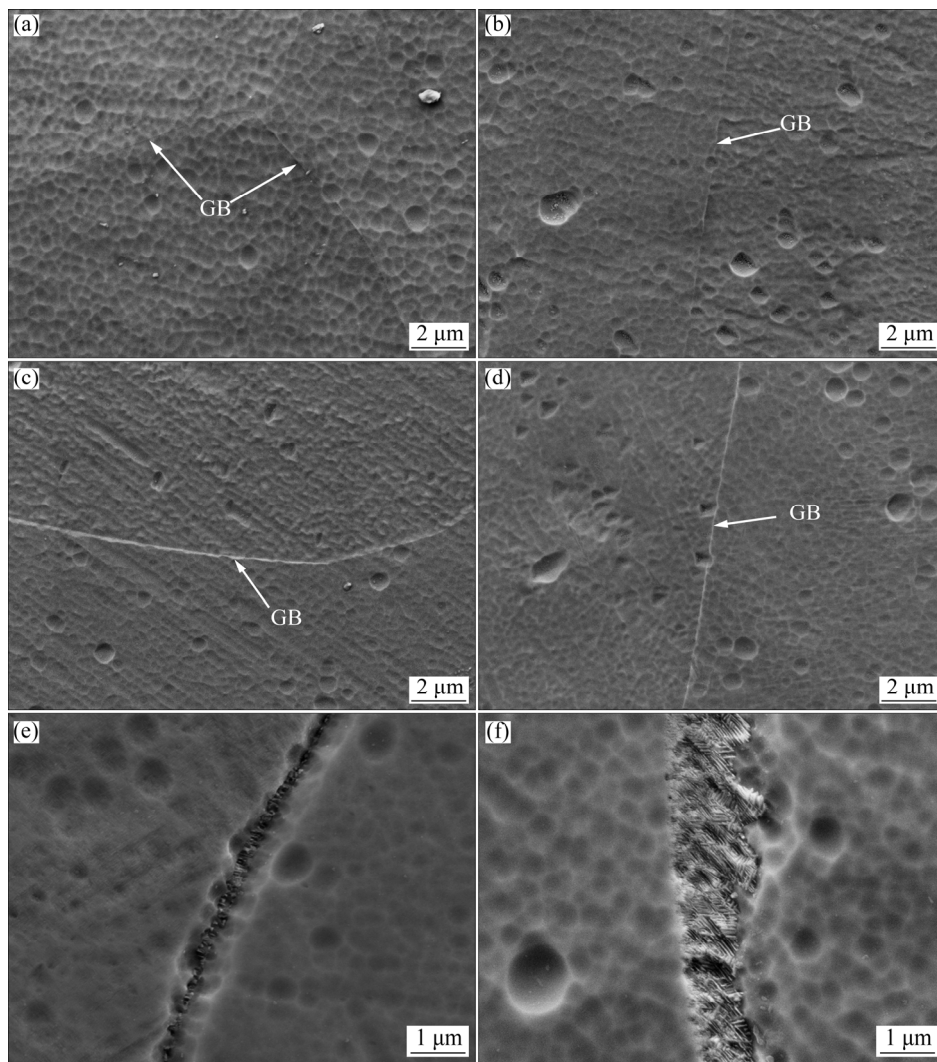


Fig. 6 SEM images of grain boundary: (a) As-welded; (b) 400 °C, 0 min; (c) 500 °C, 0 min; (d) 600 °C, 0 min; (e) 700 °C, 0 min; (f) 800 °C, 0 min

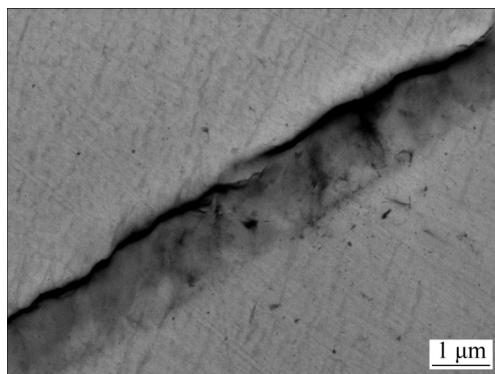


Fig. 7 Micro-crack at original grain boundary of sample (800 °C, 0 min)

show that the $B2$ phase in the weld matrix transformed to O phase. According to the above results, a thin precipitation layer formed along the original GB in the weld metal when the temperature was increased above 700 °C. The precipitation layer was also observed by

TEM, as shown in Fig. 10(a). The SAED pattern in Fig. 10(c) shows that the precipitation layer was composed of $O+B2$ dual phases, and the orientation relationship between the O phase and $B2$ phase was $(001)_O // (110)_{B2}$ and $[1\bar{1}0]_O // [1\bar{1}1]_{B2}$.

Figure 11 shows phase diagram of Ti–22Al– x Nb (at.%) [19]. Combining the phase diagram and the above microstructure examination results, the microstructure evolution of the weld metal during the heating-up process can be better analyzed. As shown in Fig. 11, the O single-phase region of Ti–22Al–25Nb (at.%) is below around 640 °C, and the $B2+O$ dual-phase region of this alloy is about 640–900 °C. As the Ti_2AlNb welded joint is heated up through the O single-phase region, the $B2$ phase in the weld metal transforms to O phase entirely. This transformation has been observed by MURALEEDHARAN et al [20,21] in the Ti–24Al–15Nb (at.%) alloy, and demonstrated to be a massive transformation by a shearing mechanism, without change

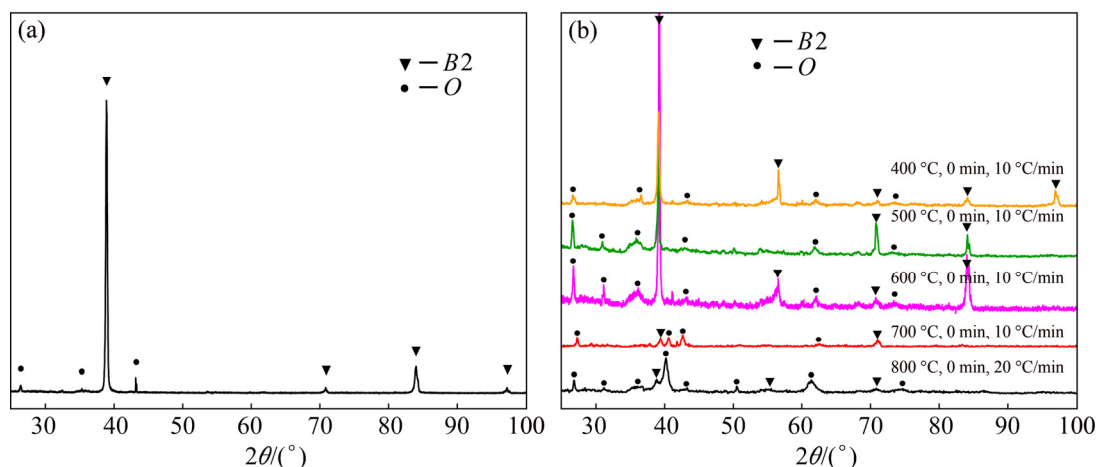


Fig. 8 XRD patterns of weld metal: (a) As-welded; (b) Heat-treated

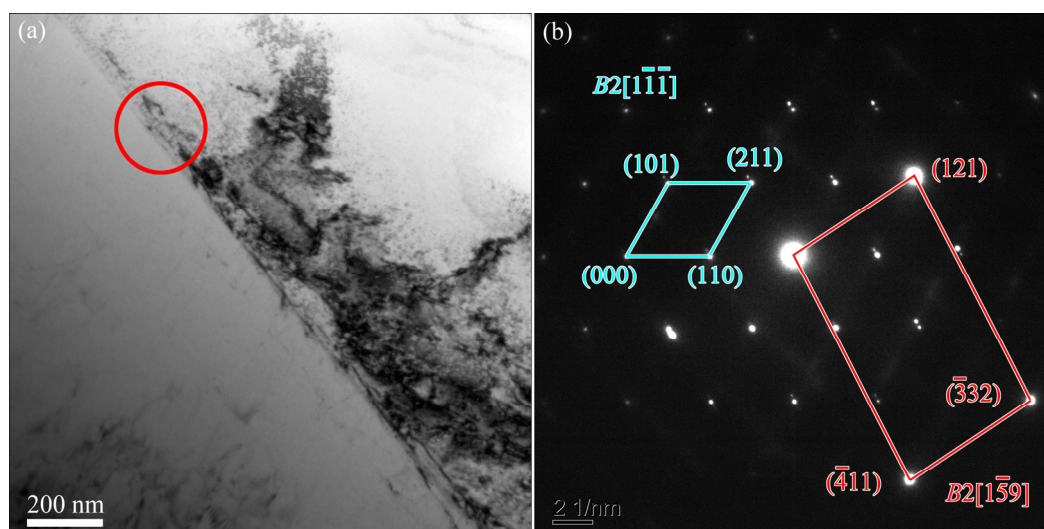


Fig. 9 TEM images of weld metal under as-welded condition: (a) Bright-field image; (b) SAED pattern

in composition. As the temperature continues to increase in the $B2+O$ dual-phase region, the O product can decompose to $B2+O$ dual-phase microstructure, and the orientation relationship is $(001)_O // (110)_{B2}$ and $[1\bar{1}0]_O // [1\bar{1}1]_{B2}$. The $O \rightarrow B2+O$ phase transformation is prone to occur at grain boundary, resulting in a thin precipitation layer composed of $B2+O$ dual-phase at the original GB. Compared with the interiors of crystals, grain boundaries exhibit higher energy due to many crystal defects such as vacancies and dislocations. Moreover, grain boundaries provide high diffusivity (“short-circuit”) paths leading to faster diffusion of the solute atoms along the grain boundaries. Therefore, grain boundaries meet the thermodynamic and kinetic criteria for the nucleation and growth of new phase, resulting in the phase transformation occurring primarily along the grain boundaries. There are significant differences between the fully- O microstructure and the $O+B2$ dual-phase microstructure on structure and mechanical

properties [22]. As a consequence, stress-concentration probably happens at the interface between the O -phase matrix and the $B2+O$ dual-phase layer, resulting in the interfacial stress exceeding the interfacial strength, and thus cracking happens. This has been demonstrated by the fact that reheat cracking occurred along the interface between the precipitation layer and the matrix, as shown in Fig. 7. To summarize, the $B2+O$ dual-phase layer, inducing stress-concentration, is a key factor responsible for the reheat cracking.

3.4 Stress factor affecting reheat cracking

The $B2+O$ dual-phase layer has been demonstrated to be a key factor for the reheat cracking. However, the reheat cracking was observed in the above circular weldment but not in straight weldment with the same post-weld heat treatment, as shown Fig. 12. The microstructures of the circular and straight weldments were mainly composed of $B2$ phase, but the stress levels

stress level in the circular weldment. Therefore, we consider that the residual stress produced during welding is another necessary factor for the reheat cracking. In addition, the phase transformations may also produce some stress. Under the high tension stress consisting of welding residual stress and phase transformation stress, the interfacial stress exceeds the interfacial strength, and reheat cracking occurs at the interface between the $B2+O$ dual-phase layer and the O -phase matrix.

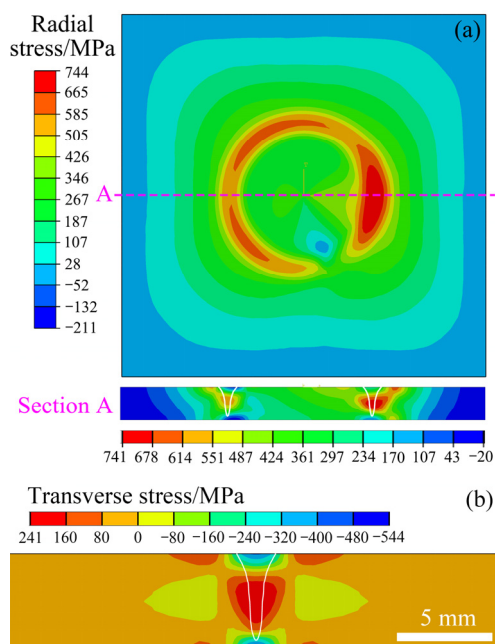


Fig. 13 Residual stress distributions: (a) Radial stress of circular weldment; (b) Transverse stress of straight weldment

3.5 Discussion

The weld metal of the Ti_2AlNb EBW joints mainly consists of $B2$ phase, and endured high welding residual stresses. During the post weld heat treatment, an almost complete transformation of the $B2$ phase to the O phase happens while the temperature goes up through the O single-phase region. The phase transformation of $B2 \rightarrow O$ is a massive transformation by a shearing mechanism, without change in composition. The O product is metastable, and it subsequently decomposes to $B2+O$ as the weld metal continues to heat up to the $B2+O$ dual-phase region, which is about 640–900 °C. Since the grain boundaries meet the thermodynamic and kinetic criteria for the nucleation and growth of new phase, the $O \rightarrow B2+O$ phase transformation occurs primarily along the grain boundaries. A thin precipitation layer composed of $B2+O$ dual-phase forms at the original GB due to the $O \rightarrow B2+O$ phase transformation. The interface between the O -phase matrix and the $B2+O$ dual-phase layer is the weak site because of the significant differences between the fully- O microstructure and the $O+B2$ dual-phase

microstructure on structure and mechanical properties. Under the high tension stress consisting of welding residual stress and phase transformation stress, reheat cracking occurs at the interface between the $B2+O$ dual-phase layer and the O -phase matrix. In a word, the $B2+O$ dual-phase layer forming at the original grain boundary together with the high residual stress leads to the reheat cracking during the post-weld heating process in EBW weldments of Ti_2AlNb alloy.

4 Conclusions

(1) Reheat cracking easily occurs in the fusion zone when the common post-weld heat treatments are performed to the Ti_2AlNb EBW joint. And it is in the heating-up process that the cracks happen as the temperature is increased to around 700 °C.

(2) As the temperature is increased to about 700 °C, the $B2$ phase in fusion zone transforms to O phase entirely and then a $B2+O$ dual-phase layer forms at the original grain boundary. The orientation relationship of the dual-phase structure is $(001)_O // (110)_{B2}$ and $[1\bar{1}0]_O // [1\bar{1}1]_{B2}$.

(3) Stress concentration is probably induced by the significant differences between full O microstructure and $O+B2$ dual-phase microstructure on structure and mechanical properties. Under the high tension stress consisting of welding residual stress and phase transformation stress, the interfacial stress exceeds the interfacial strength, and thus reheat cracking occurs at the interface between the $B2+O$ dual-phase layer and the O -phase matrix.

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Ti₂AlNb 合金电子束焊接头再热裂纹的形成机理

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摘 要: 为了阐明 Ti₂AlNb 合金焊缝中再热裂纹的特点及形成机理, 对 Ti₂AlNb 电子束环焊接头进行一系列的焊后热处理, 并采用 OM、SEM、XRD 和 TEM 对接头的宏观组织和显微组织进行分析。结果表明, 当 Ti₂AlNb 电子束环焊接头加热到 700 °C 左右时, 再热裂纹主要沿焊缝原始晶界产生。热处理过程中, 当温度升高经过 O 相单相区时焊缝组织由焊态的 B2 相几乎完全转变为 O 相; 当温度继续升高进入 B2+O 双相区后, 沿着原始晶界优先发生 O→B2+O 相转变。在焊接残余应力和相变应力综合形成的高拉应力作用下, B2+O 双相和 O 相基体的界面上开始产生再热裂纹。

关键词: 再热裂纹; 电子束焊; Ti₂AlNb 合金; 显微组织演变

(Edited by Bing YANG)