Hot-pack Accumulative Roll-bonding (HP-ARB) Process of Ti-44Al-5Nb-1Mo-(V, B) Alloys

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Abstract. Ti-44Al-5Nb-1Mo-(V, B) alloy preforms were processed under hot-pack accumulative roll-bonding (HP-ARB) process directly from HIPed ingot. A thin crack-free HP-ARB sheet was obtained. The corresponding microstructure evolution, alloy element distribution, and tensile properties were systematically studied. The alloy matrix were measured as ~703-844 μm, while the defect-free bonding interfaces were measured as ~96 and 221 μm. Near-lamellae and fine near-duplex microstructure were characterized in the bonding interface and the sheet matrix, respectively. The differences of stress state between the alloy matrix and the plate edge, and large deformation strain during HP-ARB are considered to be the main factors to form the microstructure characteristics. After HP-ARB, the sheet exhibited high performance at room-temperature (RT) as well as high-temperature. Ultimate tensile stress (UTS) of 863 Mpa and ductility of 1.71% were exhibited at RT. The 800 oC and 850 oC UTS/ductility were 754 Mpa/7.24% and 599 Mpa/67.5%, respectively. The pure bonding interface and fine homogeneous microstructure contributed positively to the RT and high-temperature tensile properties.

1. Introduction

TiAl alloys are being considered to be the potential new structural materials due to their attractive properties, such as low density, excellent high-temperature strength, good oxidation and creep resistance [1-3]. However, their industrial applications are limited because of their low-temperature brittleness, poor workability and narrow processing window. Significant effort has been made, including alloying, hot working process, heat treatment, etc., to improve their inherent ductility. Therefore, β-solidifying γ-TiAl alloys which primarily consist of α2, γ and B2 phases were developed to obtain superior hot workability. Some grain refiners such as B, C, Y, etc. are also added which could efficiently increase the applicability of β-solidified γ-TiAl alloys.

TiAl cast ingot generally has inhomogeneous deformation induced by the multiphase structure and complex microstructure during thermal-mechanical processing. The deformation incompatibility could aggravate flow localization and easily induce crack initiation and propagation. Considerable effort has been devoted to microstructure control and grain refinement for TiAl alloys by hot working, such as forging, extruding and rolling [4]. Direct hot pack rolling process by as-cast or as HIPed TiAl alloys, which is considered as an effective low-cost method, has been recently proposed. Furthermore, accumulative roll-bonding (ARB) is widely considered to be an intense straining process for bulk
materials using rolling deformation, which has been applied in various materials, such as aluminum, titanium alloy and steels [5-7]. To date, the strength and ductility at room or elevated temperatures of these alloy sheets are significant improved [8, 9]. However, the ARB process, corresponding microstructure evolution, and mechanical properties remain elusive for TiAl alloys.

In the present study, ARB process was introduced in Ti-44Al-5Nb-1Mo-(V, B) alloys via direct hot-pack rolling. Next, attention was focused on microstructure characteristics and element distributions of the sheet matrix and bonding interface. Finally, the room- and high-temperature tensile properties of the as-rolled alloy were investigated.

2. Materials and experimental procedure
The alloy ingot (about Φ110 mm×420 mm) with nominal composition of Ti-44Al-5Nb-1Mo-2V-0.2B (at. %) was prepared using induction skull melting (ISM) under argon atmosphere. Subsequently, hot isostatic pressing (HIP) was carried out at 1260 °C in Ar atmosphere with a pressure of 175 MPa for 4 h followed by furnace cooling. The preforms for hot-pack accumulative roll-bonding (HP-ARB) were cut by electric-discharge machining from the center zone of the HIPed ingot and cleaned by grinding and acetone. Stainless steel cans were used to encapsulate the several pieces of preforms. Oxidation resistant coating as well as insulation materials between cans and TiAl alloys were necessary to avoid Fe-Ti reaction and oxidation at rolling temperature. The preform preparation and rolling process were manifested by a diagrammatic drawing as shown in Fig. 1a. Fig. 1b shows the crack-free HP-ARB sheet.

![Figure 1](image)

**Figure 1.** (a) Schematics showing the HP-ARB process; (b) macro appearance of the accumulative-rolled Ti-44Al-5Nb-1Mo-(V, B) alloy sheet.

Microstructure, fracture surface, and element distribution analysis were carried out using a Zeiss Ultra 55 scanning electron microscopy (SEM) and a JEOL 8530F Electron Probe Micro-analyzer (EPMA). Both SEM and EPMA specimens were prepared by electro-polishing procedure. The room-temperature (RT) and high-temperature (800 and 850 °C) tensile tests for rolling sheets (along the rolling direction, RD) were conducted using AG-X100kN material testing machine at a speed of 0.5 mm/min.

3. Results and discussions
After hot-pack accumulative roll-bonding (HP-ARB) process, the macro morphology of the sheet on normal direction-rolling direction (ND-RD) plane was characterized in Fig. 2a. The alloy matrix are measured as ~703-844 μm, while the bonding interfaces can be clearly observed with size of ~96 μm and 221 μm which are indicated by red dotted lines. Ti-44Al-5Nb-1Mo-(V, B) alloy preforms are combined together without any impurity or defect.

The microstructure and their higher magnification morphologies of the interface and matrix for HP-ARB sheet are shown in Fig. 2b and c, respectively [10]. There is no clear boundaries between the matrix and the interface, except the different contents of γ phase, B2 phase and lamellar colonies. The microstructure of the bonding interface is near-lamellae, while near-duplex microstructure is obtained in the sheet matrix. Coarse colonies, which are ~10-30 μm in size, with fine γ grains (~5-10 μm) at colony boundaries are indicated in Fig. 2b. Moreover, fewer B2 phase can be seen compared with the sheet matrix. Homogeneous microstructure consisting of fine equiaxed colonies, γ and B2 grains with mean size of ~10 μm is shown in Fig. 2c.
Figure 2. SEM/BSE images of the accumulative-rolled Ti-44Al-5Nb-1Mo-(V, B) alloy sheet observed on ND-RD plane: (a) macro morphology of the sheet, microstructure of (b) the bonding interface, and (c) the alloy matrix; The instes in (b) and (c) are the higher magnification morphologies.

Figure 3. EPMA analysis of the accumulative rolling Ti-44Al-5Nb-1Mo-(V, B) alloy sheet interface: (a) EPMA/BSE and (b) EPMA/SE images for the bonding interface; (c) distribution maps for different elements.
To explain the causes of the interface formation, the accumulative-rolled Ti-44Al-5Nb-1Mo-(V, B) alloy sheet was studied by EPMA [11] as shown in Fig. 3. Here, all the relevant alloy elements as well as O, and N which may have effects on the interface bonding results were scanned and discussed.

Fig. 3a and b show the EPMA scanned BSE and SE images, in which the white dotted box was selected for element analysis. It can be clearly seen in Fig. 3b that a band exist at the image center which is identified as bonding interface under EPMA observation. It is distinctly smoother than the surrounding matrix ascribed to its better corrosion resistance during electro-polishing procedure. Obvious element segregation and distribution differences between interface and matrix can be observed in Fig. 3c, especially for Ti, Al and Mo elements. The Al, Nb, Mo, and V elements tended to migrate into the TiAl matrix during the intense straining process, while Ti migrated to the opposite direction. There is nearly no visible element enrich at the interface comparing with the matrix, that is to say higher homogeneities have been obtained. As strong β-stabilizers, blocky enrichments of Mo and V elements are shown in the sheet matrix indicating the high contents of B2. Furthermore, several borides, enriched by Nb and B, are observed at the upper part and bottom in the vision field. The HP-ARB process would reduce the boride particle quantity within bonding interface.

In order to rule out the effects of O and N elements on the formation of these microstructure characteristics, their distributions were also acquired. Completely homogeneous element distribution mapping were shown in Fig. 3c-O, and N. Therefore, the differences of stress state between the alloy matrix and the plate edge, and large deformation strain during hot-working are deemed to be the main influence factors [12].

The room- and high-temperature tensile properties of the HP-ARB Ti-44Al-5Nb-1Mo-(V, B) sheet were tested using samples with a gauge section of 15 × 5 × 2 mm3. The specimens for high-temperature tensile tests were homogenized for 20 min at the target temperatures (800 or 850 °C) to ensure the temperature homogeneity. The following Table 1 shows the tensile property results.

|          | YS / Mpa | UTS / Mpa | δ / % |
|----------|----------|-----------|-------|
| RT       |          | 862.63    | 1.71  |
| 800 °C   | 422.85   | 745.20    | 7.24  |
| 850 °C   | 368.82   | 599.99    | 67.50 |

NOTE: RT represents room temperature, YS represents yield strength, UTS represents ultimate tensile strength, and δ represents breaking elongation.

The UTS at RT of the as-ARBed sheet was 862.6 MPa with an elongation of 1.71% which performed well. At high temperatures, the sheet still exhibited excellent properties. When the tensile temperature was 800 °C, the YS, UTS and elongation for the ARB sheet were 422.8 MPa, 745.2 MPa and 7.24%, respectively. As the test temperature increased to 850 °C, the YS and UTS decreased to 368.8 MPa and 599 MPa, while superior performance of ductility of 67.5% exhibited which is more excellent than the majority of β-γ TiAl alloys.

4. Conclusion
In this study, hot-pack accumulative roll-bonding (HP-ARB) directly from HIPed Ti-44Al-5Nb-1Mo-(V, B) alloy ingot was progressed. The corresponding microstructure characteristics were discussed. RT, 800 and 850 °C tensile properties were tested. The following are the main conclusions:

Thin crack-free sheet was obtained by HP-ARB process. The alloy matrix were measured as ~703-844 μm, while the defect-free bonding interfaces were measured as ~96 and 221 μm. The preforms were combined well without any impurity or defect.

Near-lamellae and fine near-duplex microstructure were characterized in the bonding interface and the sheet matrix, respectively. Fine and homogeneous microstructure was observed. The differences between the sheet matrix and interface were ascribed to the different stress state between the alloy matrix and the plate edge.
After HP-ARB, the sheet exhibited good performance at room and high temperatures. At RT, the UTS and ductility were 863 Mpa and 1.71%. The 800 and 850 °C UTS/ductility were 754 Mpa/7.24% and 599 Mpa/67.5%, respectively. The pure bonding interface and fine homogeneous microstructure contributed positively to the tensile properties.

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