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# Effects of extrusion deformation on microstructure, mechanical properties and hot workability of β containing TiAl alloy

W.C. Xu [a,*], D.B. Shan [a], H. Zhang [b], X.A. Li [a], Y.Z. Zhang [c], S. Nutt [c]

[a] School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China
[b] Aerospace Research Institute of Materials & Processing Technology, Beijing 100076, PR China
[c] Department of Chemical Engineering and Materials Science, University of Southern California, Los Angeles, CA 90089-0241, USA

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ABSTRACT

Hot extrusion was performed on a Ti–42Al–9V–0.3Y alloy at 1200–1325 °C to explore effects on mechanical properties and hot workability. The microstructure after hot extrusion was analyzed, tensile tests were conducted, and hot workability was assessed. Three types of microstructures resulted from extrusion at increasing temperature, including a dual-phase microstructure (DPM), a bi-lamellar microstructure with retained gamma phase (BLMG), and a bi-lamellar microstructure (BLM). Hot extrusion of the TiAl alloy in the range of 1275–1325 °C produced the BLM microstructure, yielding superior comprehensive properties. The predominant fracture mode was transgranular cleavage fracture in the DPM, translamellar cleavage and delamination in BLM, and mixed fracture in BLMG. Aggregation of the $YAl_2$ phase accelerated the fracture of the as-extruded alloy. As-extruded Ti–42Al–9V–0.3Y alloy exhibited excellent high-temperature mechanical properties and hot workability, demonstrating the feasibility of precision forming TiAl alloy components by conventional hot forging with nickel-based alloy dies.

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## 1. Introduction

Alloys based on γ-TiAl are promising materials for high-temperature structural applications in aerospace and automobile engine components, including blades, vanes or discs, and turbochargers because of exceptional high-temperature strength, low density, and good oxidation resistance [1–4]. However, low ductility, poor fracture toughness and limited hot workability arise from the intrinsic brittleness of γ and $\alpha_2$ ordered phases and limit the use of such alloys [5]. In addition, coarse-grained microstructures, casting texture, and chemical inhomogeneity typically characterize γ-TiAl cast ingots [6–8]. For high-risk applications, these microstructural deficiencies are a serious concern. Recent reports indicate that hot working can reduce casting inhomogeneity, refine as-cast coarse grains, and greatly improve the mechanical properties of the products [9–15]. Unfortunately, γ-TiAl alloys have limited hot workability, thus limiting the utility of hot deformation in practical production.

An effective way to improve the hot deformability of TiAl alloys is through introduction of β phase [16–20]. Tetsui et al. developed new TiAl alloys (Ti–42Al–5Mn [21] and Ti–42Al–10 V (at%) [22]) containing β phase inclusions, and showed that these could be hot formed above 1250 °C by free forging or closed-die forging. Similarly, Li et al. introduced Y to refine the microstructure of Ti–43Al–9V, resulting in improved ductility in the as-cast β-containing γ-TiAl alloys, albeit with reduced strength [23].

Hot extrusion is often used to breakdown coarse microstructures of as-cast ingots of TiAl alloys and for fabrication of high-performance rods and preforms [24,25]. However, there have been no systematic studies describing how to improve the mechanical properties and hot workability of β-containing TiAl alloys by hot extrusion. In the present study, the effects of hot extrusion on microstructural evolution and mechanical properties of a Ti–42Al–9V–0.3Y β-containing alloy are investigated. Hot extrusion was conducted at 1200–1325 °C. Microstructural analysis and tensile tests were carried out before and after hot extrusion, and hot workability was analyzed using hot processing window maps validated through isothermal forging experiments.

## 2. Experimental

An ingot with the nominal composition Ti–42Al–9V–0.3Y (at%) was prepared by induction skull melting (ISM) and casting into a steel mold to produce a sample Φ120 × 200 mm. Before hot extrusion, the ingot was hot isostatic pressed (HIP) at 1250 °C/175 MPa for 4 h to eliminate casting porosity. The composition, determined by X-ray fluorescence spectroscopy, was 41.49% Al,

* Corresponding author. Tel.: +86 451 86416221; fax: +86 451 86418640.
E-mail address: xuwc_76@hit.edu.cn (W.C. Xu).

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9.4% V, 0.26% Y and the balance Ti. The phase transformation temperatures were measured by differential scanning calorimetry (DSC) following the proposed ternary phase diagram for Ti–Al–V [26], revealing that $T_{\beta+\gamma+\alpha_2\rightarrow\beta+\gamma+\alpha}$ was ~1209 °C, $T_{\beta+\gamma+\alpha\rightarrow\beta+\alpha}$ was ~1267 °C, and $T_{\beta+\alpha\rightarrow\beta}$ was ~1333 °C.

Cylindrical billets 42 mm in diameter × 35 mm in length were cut from the ingot by electrical discharge machining (EDM), and the billets were insulated by ceramic fiber blankets and capsulated in 5 mm thick stainless steel cans. After heating to the selected extrusion temperatures and holding for 60 min, the samples were extruded in a single pass using a hydraulic press of 3150 kN and the reduction in area was 1/9. Six extrusion temperatures were selected in the range of 1200–1325 °C in different phase regimes to study microstructure evolution and mechanical properties of the TiAl alloy.

The mechanical properties were measured by tensile experiments using a load frame (Instron-5500R), and hot workability was evaluated by compression experiments on a simulator (Gleeble-1500). Tensile specimens with gauge section Φ3 × 21 mm and cylindrical compressed specimens of Φ8 × 12 mm were cut from the extruded billet with the loading direction parallel to the extrusion direction. Tensile tests were conducted at room temperature (RT) and 700 °C at a strain rate of $3.75\times10^{-4}\,s^{-1}$, and compression experiments were performed at strain rates from $10^{-3}$ to $1\,s^{-1}$ at 950–1150 °C.

Microstructures were observed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Samples for SEM observation were etched in a Kroll's reagent of 5% $HNO_3$, 3% HF and 92% $H_2O$ (vol%). Samples for TEM observation were prepared by twin-jet polishing using a solution of 60% methanol, 35% butyl alcohol and 5% perchloric acid at −3 °C and 35 V. Fracture surfaces of tensile specimens were observed by SEM.

## 3. Results and discussion

### 3.1. Microstructure evolution during hot extrusion

Fig. 1 presents the XRD pattern of the as-cast Ti–42Al–9V–0.3Y alloy, and the pattern indicated that the TiAl alloy was composed primarily of γ and β phase. Fig. 2 shows the cast microstructure, which exhibited γ phase (dark contrast) distributed evenly in the β matrix (graywhite contrast). Energy dispersive X-ray spectroscopy (EDS) indicated that the β phase contained a high V content (22.31 at%) while the γ phase was rich in Al. There was much more β phase relative to other TiAl alloys due to the introduction of β-stabilizing V element. In addition, particles were distributed in a discontinuous network along as-cast grain boundaries (bright contrast), identified as $YAl_2$, which was below the detectability limit of the XRD analysis.

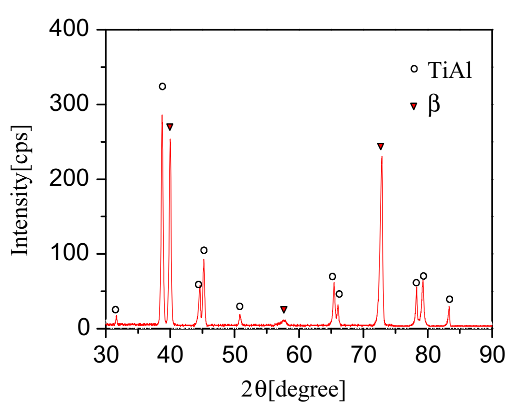


**Fig. 1.** XRD pattern of Ti–42Al–9V–0.3Y.

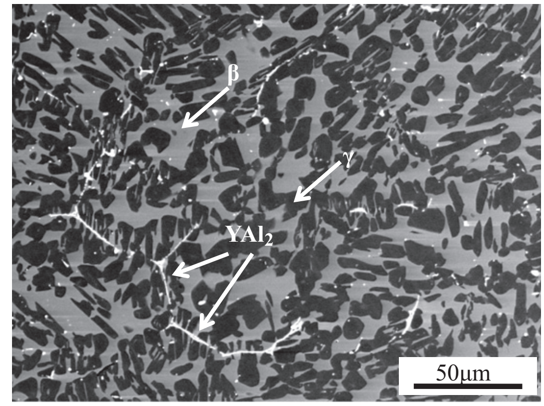


**Fig. 2.** BSE micrograph of the as-cast Ti–42Al–9V–0.3Y alloy.

The microstructures after hot extrusion at 1200–1325 °C are shown in Fig. 3. Extrusion temperatures of 1200 °C–1225 °C and 1275–1325 °C are in the $\beta+\gamma+\alpha_2$, $\alpha+\beta+\gamma$ and $\alpha+\beta$ phase fields, respectively. When specimens were extruded at 1200 °C, massive γ phase appeared as elongated inclusions (Fig. 3b). Also, β phase supersaturated with Al precipitated as strips of γ phase during air cooling. At an extrusion temperature of 1225 °C, the amounts of both retained massive γ and β phases decreased markedly, and lamellar colonies of α/γ and β/γ appeared (Fig. 3c and d). As the extrusion temperature was increased to 1275 °C and beyond, the retained massive γ phase disappeared almost completely (Fig. 3e–h). At these temperatures, the $\alpha_2/\gamma$ lamellae grew gradually and uniformly, comprising increasing volume fractions of the matrix (Fig. 3e–j). Detailed microstructure descriptions are listed in Table 1. The as-extruded microstructures are categorized into dual phase microstructure (DPM), bi-lamellar microstructure with retained gamma phase (BLMG), and bi-lamellar microstructure (BLM), respectively, according to the microstructural evolution at 1200–1325 °C.

TEM images of the microstructures after hot extrusion are presented in Fig. 4. Fig. 4a shows dislocated γ twins, while Fig. 4b and c shows recrystallized grains of retained massive γ and β subgrains, respectively. Fig. 4d and e shows $\alpha_2/\gamma$ and β/γ lamellar structures, determined by diffraction analysis. Fig. 4f shows retained β phase between $\alpha_2/\gamma$ lamellar colonies. Because of the high extrusion speeds and limited slip systems available, twinning occurred during hot extrusion, typically in the retained massive γ grains (Fig. 4a). The large extrusion strains and high temperatures induced localized dynamic recrystallization of the γ grains (Fig. 4b and g). In contrast, the dislocation density was typically much lower in β grains, and many β subgrains appeared due to dynamic recovery (Fig. 4c and h). Streaks in diffraction patterns from the β phase presumably resulted from elastic distortion of the crystal lattice originating from compositional fluctuation in the $\beta\rightarrow B_2$ ordering transformation during air cooling [27]. Typically, β grains were distributed along the boundaries of lamellar $\alpha_2/\gamma$ colonies (Fig. 4f). Because the disordered β phase with bcc lattice provides enough independent slip systems at high temperature, β phases are more easily deformed and dynamically softened [16,28], which could work like a lubricating layer to coordinate plastic deformation of harder $\alpha_2/\gamma$ phases [29], thus contributing to the enhanced hot deformability of the Ti42Al9V0.3Y alloy.

Microstructures extruded at 1275 °C were characterized by lamellar $\alpha_2/\gamma$ and β/γ structures, as shown in Fig. 4 d–e. Because large quantities of V-rich β phase remain in the as-cast microstructure, they were not completely dissolved in the

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