

A Comparative Study on the Hot Deformation Behavior of Powder Ti-22Al-24Nb-0.5Mo Alloy (Postprint)

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Abstract

Powder Ti₂AlNb alloy with a nominal composition of Ti-22Al-24Nb-0.5Mo (at.%) was fabricated via pre-alloyed powder hot isostatic pressing (HIP). Compression tests were conducted on the as-HIPed powder alloy, heat-treated powder alloy, and cast Ti₂AlNb alloy of the same composition. The results indicate that the powder Ti₂AlNb alloy exhibits deformation capability comparable to that of cast wrought alloy, while heat treatment has no significant effect on the deformation capability of the powder Ti₂AlNb alloy. The powder alloy demonstrates lower deformation resistance at low temperatures and high strain rates, and is less susceptible to cracking. Powder Ti₂AlNb hot deformation billets were prepared using typical powder metallurgy forming processes, and upsetting and elongation hot deformation with various deformation amounts were performed in the two-phase region. The results show that the deformed powder Ti₂AlNb billets exhibit no macroscopic cracks and display uniform deformation. Tensile test results reveal that the powder Ti₂AlNb alloy after deformation and heat treatment demonstrates superior tensile properties.

Full Text

Preamble

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Comparative Study on Hot Workability of Powder Metallurgy Ti-22Al-24Nb-0.5Mo Alloy

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Abstract

Powder metallurgy (PM) Ti₂AlNb alloy with a nominal composition of Ti-22Al-24Nb-0.5Mo (atomic percentage) was prepared from pre-alloyed powder using hot isostatic pressing (HIPing). Compression tests were conducted on the as-HIPed alloy, heat-treated PM alloy, and wrought Ti₂AlNb alloy of the same composition. The results demonstrate that the PM Ti₂AlNb alloy exhibits deformability comparable to that of the wrought alloy, with heat treatment showing no significant effect on the deformation capability of the PM alloy. The PM alloy demonstrates lower deformation resistance at low temperatures and high strain rates, and is less prone to cracking. PM Ti₂AlNb billets for hot deformation were prepared using typical powder forming processes and subjected to upsetting and drawing operations with various deformation amounts in the two-phase region. The deformed PM Ti₂AlNb billets showed no macroscopic cracks and exhibited uniform deformation. Tensile test results indicate that the deformed PM Ti₂AlNb alloy after heat treatment demonstrates superior tensile properties.

Keywords

metallic materials, Ti₂AlNb alloy, powder metallurgy, hot isostatic pressing, thermal mechanical processing

Introduction

Ti₂AlNb alloys have attracted increasing attention from materials designers due to their excellent high-temperature strength and low density, making them promising lightweight candidates to replace nickel-based superalloys [1-3]. Ti₂AlNb components are primarily fabricated through ingot forging, and most studies on the hot deformation behavior of these alloys have focused on cast Ti₂AlNb alloys [4-7]. While Gleeble compression tests provide valuable references for forging process selection, Ti₂AlNb alloys are prone to compositional macrosegregation, shrinkage cavities, and porosity during melting, which are difficult to eliminate completely.

Powder metallurgy hot isostatic pressing can avoid these traditional casting defects, producing alloys or component blanks with more uniform microstructures and more stable properties, along with better dimensional control than cast alloys [8-10]. Additionally, alloys or components formed by powder metallurgy hot isostatic pressing contain some porosity [11, 12], which can be healed through thermal mechanical processing—a principle already applied in powder GH4169 alloys [13]. However, no titanium alloy or Ti₂AlNb alloy powder metallurgy components have been implemented in China to date. Developing PM Ti₂AlNb alloys combined with thermal mechanical processing may yield components with superior properties and larger dimensions. This study employs Gleeble-3800 thermal simulation testing to compare the high-temperature flow

behavior and deformation capabilities of PM Ti₂AlNb and wrought Ti₂AlNb alloys. Based on the Gleeble compression results, a hot deformation process tailored to the deformation characteristics of PM Ti₂AlNb was developed to forge PM Ti₂AlNb billets. The morphology of the deformed billets was observed, and their tensile properties were tested. Through comparative analysis of thermal simulation compression and actual forging results, the deformation capability of PM Ti₂AlNb alloy was evaluated to provide a reference for the application of Ti₂AlNb alloys prepared by powder metallurgy plus deformation processing.

1 Experimental Methods

Pre-alloyed powder with a nominal composition of Ti-22Al-24Nb-0.5Mo (atomic percentage) was prepared by electrode induction melting gas atomization (EIGA). PM Ti₂AlNb alloy was fabricated using a typical canned hot isostatic pressing process [14]. Chemical composition analysis of both the powder and the compact was performed. Gas element content was measured using a LECO analyzer, while metallic chemical composition was determined using a PE ICP-OES 7300DV analyzer. The results are presented in . The analysis shows that gas element contents remain at low levels and the alloy composition is uniform, indicating high purity of the pre-alloyed powder and alloy, as well as good process stability.

lists the preparation methods and corresponding designations for the three types of Ti₂AlNb alloys used in this study. The PM Ti₂AlNb alloy was heat-treated using a regime of 980°C/2 h/AC + 900°C/24 h/AC to produce the heat-treated PM alloy. A cast Ti₂AlNb alloy was prepared by vacuum arc remelting and subsequently forged in the two-phase region to produce the wrought alloy.

The initial microstructures of the three Ti₂AlNb alloys were observed using a JSM-6301F scanning electron microscope, as shown in [Figure 1: see original paper]. The Ti₂AlNb alloy prepared by hot isostatic pressing exhibits a typical duplex microstructure, consisting primarily of uniformly distributed black β phase and gray α phase. After heat treatment, B2 phase precipitated in the PM Ti₂AlNb alloy, with gray α phase and white B2 phase alternating in a needle-like distribution within grains, and black β phase at grain boundaries. The grain size ranges from 20–30 μm . The wrought alloy consists mainly of large B2 phase grains, exhibiting a typical Widmanstätten structure similar to the heat-treated condition, with grain sizes of 100–200 μm .

Gleeble thermal compression testing is a common method for investigating material deformation mechanisms [15, 16]. Based on the forging temperatures for wrought Ti₂AlNb alloy, the deformation temperatures for Gleeble tests were designed to range from 930°C to 1050°C, covering both the three-phase and two-phase regions of the Ti₂AlNb alloy. High-temperature compression tests were conducted on the three types of samples using a Gleeble-3800 thermal simulator. Cylindrical samples measuring 8 mm in diameter and 10 mm in length were deformed at strain rates of 0.001, 0.01, 0.1, 1, and 10 s^{-1} , and tempera-

tures of 930, 980, 1005, 1030, and 1050°C. The heating rate was 5°C/s, with a 3-minute hold at temperature before deformation. No canning was used; the sample ends were coated with graphite and covered with tantalum foil. The final engineering strain was approximately 50%.

In actual forging, alloy components are large and exposed to atmosphere, making temperature drop inevitable. Based on the Gleeble compression results, a forging process suitable for PM Ti₂AlNb deformation billets was developed. PM Ti₂AlNb deformation billets measuring 50 mm in diameter and 85 mm in length were prepared using the same HIPing process. Canned forging was used to forge the billets to various deformation amounts. The deformed samples were sectioned along the central axis, and macroscopic morphology was observed using a Canon-Scan D1230U scanner.

Tensile properties at room temperature and elevated temperature were tested for PM Ti₂AlNb alloys in three conditions: undeformed and heat-treated, deformed, and deformed plus heat-treated. Tensile specimens measured M6×f3 mm with a gauge length of 15 mm. Room-temperature tensile tests were performed on a Zwick/Roell-Z050 testing machine, while 650°C tensile tests were conducted on an MTS E45.105 testing machine.

2 Results and Discussion

2.1.1 Deformation Behavior and Stress Level Analysis

To compare the deformation behavior of the three Ti₂AlNb alloys, stress-strain curves at different temperatures were plotted for a strain rate of 0.1 s⁻¹. As shown in [Figure 2: see original paper], the high-temperature flow behavior of the three alloys is similar. Stress reaches a peak at very low strain levels and then exhibits discontinuous yielding, particularly pronounced at lower deformation temperatures. When true strain exceeds 0.2, the stress level stabilizes. Additionally, all three alloys show a “rebound” in stress levels near the phase transformation temperature. For most materials, dislocation motion becomes easier with increasing temperature, requiring less deformation energy, so deformation resistance decreases with temperature. However, [Figure 2: see original paper] reveals that at 980°C, near the phase transformation point of Ti₂AlNb alloy, the peak stress is lower than at 1005°C, and the flow stress at 1030°C is overall lower than at 1050°C. This occurs because phase transformation is a structural response to heat, and during Gleeble compression under adiabatic conditions, stress can induce local heating and phase transformation [17].

[Figure 3: see original paper] compares the stress-strain curves of the three Ti₂AlNb alloys at a strain rate of 0.1 s⁻¹ and temperatures of 1005°C and 1030°C, parameters close to actual Ti₂AlNb forging processes. The figure shows no significant differences among the three alloys. At 1005°C, the peak stresses are similar, with the wrought alloy showing the highest stress level, slightly higher than the as-HIPed condition and about 50 MPa higher than the heat-treated condition at true strains greater than 0.3. At 1030°C, the heat-treated

samples exhibit the highest stress level, while the wrought alloy curve falls between the two PM alloy curves.

presents statistics of peak stresses for the three alloys under various deformation conditions, confirming their similar deformation behavior. The results indicate no obvious difference in peak stress among the three alloys. Particularly at high temperatures and low strain rates (e.g., 1050°C, 0.001 s⁻¹), the stress levels are very close. At low temperatures and high strain rates (e.g., 930°C, 10 s⁻¹), the PM alloys (HIPed, HIPed+HT) exhibit lower stress levels than the wrought alloy.

Observation of sample morphology after compression at 930°C and strain rates above 0.1 s⁻¹ revealed that PM Ti2AlNb alloys maintained intact, smooth surfaces, while the wrought Ti2AlNb alloy samples developed wrinkles on their sides. An additional Gleeble compression test was conducted at 830°C with a strain rate of 0.1 s⁻¹, and the macroscopic morphology after deformation is shown in [Figure 4: see original paper]. Without canning, the PM Ti2AlNb alloy surface remained intact after deformation, whereas the wrought Ti2AlNb alloy exhibited obvious cracking. This is attributed to the fine grains, uniform composition, and isotropic nature of the HIPed Ti2AlNb alloy, which provide stronger coordinated deformation capability during straining.

2.1.2 Comparison of Thermal Activation Energy

Hot deformation of materials is a process where strain hardening and dynamic softening gradually reach equilibrium. In addition to strain rate and temperature, thermal activation energy (Q) is a primary parameter for analyzing and evaluating the hot deformation performance of metallic materials, as it more accurately reflects plastic deformation capability [18]. Approximating the Arrhenius equation, the relationship between steady-state flow stress (σ) and strain rate is given by:

$$\sigma = \exp\left[- \right]$$

Taking logarithms of both sides of equation (1) and assuming Q is temperature-independent yields:

$$\ln \sigma = \ln$$

Taking partial derivatives at constant temperature with respect to strain rate and at constant strain rate with respect to 1/T provides an approximate calculation for Q:

$$Q = \frac{R \left[\frac{\partial \ln \sigma}{\partial \ln \dot{\epsilon}} \right] T \left[\frac{\partial \ln \sigma}{\partial (1/T)} \right]}{1}$$

where σ represents peak stress, R is the ideal gas constant (8.314 J · mol⁻¹ · K⁻¹), and fitting was performed using Gleeble experimental data. [Figure 5: see original paper] shows the fitting results of peak stress versus temperature for HIPed and wrought Ti2AlNb alloys, while [Figure 6: see original paper]

presents the fitting results of strain rate versus peak stress. Similar results can be obtained for the HIPed+HT condition.

Substituting the linear fitting results into equation (3) yields the deformation activation energy Q values for the three alloys. lists the thermal activation energy results for the Ti2AlNb two-phase region from this study, compared with results from other researchers. Reference [4] calculated a two-phase region activation energy of $436.2 \text{ kJ} \cdot \text{mol}^{-1}$ for cast Ti-22Al-25Nb alloy after initial forging in the single-phase region. Reference [19] reported a two-phase region activation energy of $734.8 \text{ kJ} \cdot \text{mol}^{-1}$ for hot-pressed Ti-22Al-25Nb alloy. Comparison shows that the activation energy of PM Ti-22Al-24Nb-0.5Mo alloy prepared by HIPing in this study is similar to that of the wrought alloy and close to cast Ti-22Al-25Nb alloy overall, but lower than hot-pressed Ti-22Al-25Nb alloy. Hot pressing is also a powder metallurgy method, but the different fabrication processes result in significantly different microstructures between hot-pressed and HIPed Ti2AlNb alloys, which may account for this difference.

Analysis of stress-strain curves and thermal activation energy indicates that PM Ti2AlNb alloy possesses deformation capability comparable to wrought Ti2AlNb alloy, with no significant effect of pre-deformation heat treatment on deformation behavior. Numerous studies have investigated forging parameters for cast Ti2AlNb after initial breakdown, leading to preliminary applications of high-performance bars and sheets [20-22]. This study compares Gleeble compression results to theoretically enhance understanding of the feasibility of PM Ti2AlNb alloy deformation.

2.2.1 Morphology Observation After Deformation

[Figure 7: see original paper] shows the macroscopic morphology of an upset billet with 50% deformation (FIG. 7a) and a billet subjected to upsetting and drawing with approximately 75% total cumulative deformation (FIG. 7b). The PM Ti2AlNb alloy forged directly to 50% deformation shows tight bonding with the can and intact morphology without any cracks. The billet subjected to upsetting and drawing (with over 75% cumulative deformation) exhibits complete, smooth internal morphology without cracking. These observations indicate that the PM Ti2AlNb alloy billets prepared in this study are of stable and reliable quality, the Gleeble compression results are relevant, and the PM Ti2AlNb alloy demonstrates good coordinated deformation capability and deformation potential under the specified conditions.

2.2.2 Mechanical Properties After Deformation

The room-temperature and 650°C mechanical properties of PM Ti2AlNb alloys in the deformed and deformed+heat-treated conditions were compared with those of the undeformed heat-treated alloy, as shown in [Figure 8: see original paper]. Comparison between the deformed and deformed+heat-treated conditions reveals that the deformed PM Ti2AlNb alloy exhibits very high tensile

strength but poor ductility at both room and elevated temperatures. After heat treatment, the room- and high-temperature tensile ductility of the deformed PM Ti₂AlNb alloy significantly improves. Heat treatment can enhance the tensile properties of both PM Ti₂AlNb and cast wrought alloys [14, 23]. Because the properties of PM Ti₂AlNb alloy are more sensitive to phase composition and the unstable chemical potential accumulated during powder production is difficult to eliminate during HIPing, heat treatment is essential for obtaining high-performance PM Ti₂AlNb alloy components.

[Figure 8: see original paper] also presents tensile results for deformed+heat-treated and undeformed heat-treated conditions. The results show similar yield and tensile strengths for both PM Ti₂AlNb alloy conditions. The deformed+heat-treated alloy exhibits reduced room-temperature ductility but improved elevated-temperature ductility, with both room- and high-temperature elongation exceeding 10% and providing substantial ductility reserves. This indicates that deformation can improve the tensile properties of PM Ti₂AlNb alloy, likely because the thermal mechanical process can heal defects, resulting in more stable performance of the deformed alloy.

Conclusions

1. PM Ti-22Al-24Nb-0.5Mo alloy prepared by pre-alloyed powder hot isostatic pressing exhibits similar deformation behavior, comparable deformation resistance, and similar thermal activation energy to wrought Ti₂AlNb alloy produced by typical processes. Under Gleeble thermal simulation conditions, PM Ti₂AlNb alloy possesses a broader processing window, capable of withstanding lower processing temperatures and higher strain rates without cracking.
2. According to the thermal mechanical processing parameters developed in this study for PM Ti-22Al-24Nb-0.5Mo alloy, billets subjected to upsetting (~50% deformation) or upsetting plus drawing (~75% deformation) showed no surface or internal cracking after deformation. The high-temperature tensile ductility significantly improved after deformation, with more stable properties, demonstrating that PM Ti-22Al-24Nb-0.5Mo alloy possesses excellent hot workability.

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