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ORIGINAL RESEARCH ARTICLE

Effects of High-Temperature Deformation and Welding on Microstructure and Thermomechanical Properties of Ti-6Al-4V

J. Nagarjun, M. Senthil Vel, G. Swaminathan, N. Saravanakumar, J. John Rozario Jegaraj, G. Yoganand, and P. Mastanaiah

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The present work investigates the thermal and mechanical behavior of Ti-6Al-4 V alloy across a temperature range from room temperature to 1000 °C, focusing on its application in welding and hot-processing simulations. The study examines temperature-dependent properties, such as phase transformation, thermal expansion, density, and specific heat capacity, with a specific emphasis on the α (hexagonal close-packed, HCP) to β (body-centered cubic, BCC) phase transformation around 800 °C. Various testing methods, including tensile testing, dilatometry, and differential scanning calorimetry (DSC), were used to generate data for these properties. The results show a marked decrease in density and mechanical strength at elevated temperatures, with notable shifts in thermal expansion and heat absorption trends during the α to β phase transition. Microstructural analyses of welded samples reveal distinct regions: the base metal, heat-affected zone, and fusion zone, each showing unique thermal responses and mechanical characteristics. In particular, the HAZ exhibits grain coarsening and reduced mechanical properties, while the FZ displays a dendritic β-phase structure with increased hardness but reduced ductility. These findings provide a detailed database for the thermomechanical modeling of Ti-6Al-4 V alloy, supporting more accurate simulations of welding and hot deformation processes, essential for optimizing performance in high-temperature applications.

Keywords hot tensile deformation, phase transition, thermal expansion, Ti-6Al-4 V alloy

1. Introduction

The Ti6Al4V, a dual-phase α + β titanium-based alloy, has become a material of significant interest due to its excellent mechanical properties, such as high specific strength, corrosion resistance and fatigue strength (Ref 1). As Ti6Al4V exhibits a favorable balance between the properties of mechanical and thermal stability, it is extensively used in the aerospace application (Ref 2). It is also used in marine industries in making of submarine hulls and offshore drilling equipment due to its superior durability in saltwater and harsh environments (Ref 3). The alloy is also frequently used in biomedical applications, such as medical implants and bone fixation plates, due to its excellent biocompatibility (Ref 4). The versatility of applications is mainly due to the material's compatibility of working in extreme operational conditions.

The adaptability of Ti6Al4V with both modern processes like additive manufacturing (AM) and more conventional ones like welding is another factor contributing to the alloy's broad variety of applications. Titanium alloys are welded using arc welding, tungsten inert gas (TIG) welding, electron beam welding, and laser beam welding (Ref 5) and also joined using other techniques, such as diffusion bonding and brazing (Ref 6, 7). During the manufacturing processes, such as welding, the alloy is subjected to complex mechanical and thermal load conditions which can influence its performance. With the advancement of technology in computers and simulation software, the numerical simulation has become more cost-effective in predicting the welding behavior such as temperature gradients, transient stresses, phase transformation, magnitude and distribution of residual stresses (Ref 8). However, the precision of simulation results depends on the accuracy of thermomechanical property database available for the welding material of interest.

The materials during weld are exposed to very high temperatures frequently reaching or exceeding the melting point in the localized regions of the weld, while the adjacent areas relatively remain at lower temperatures. It creates steep temperature gradients which creates different material properties in the weld zone, heat-affected zone and the base metal (Ref 9). At the weld zone, the material melts to form the weld pool and its behavior can be determined by the material properties at elevated temperatures. The amount of heat required to reach the welding temperature is determined by the specific heat capacity of the material. The data are instrumental in providing the information on the thermal field and its effect over the formation of weld pool and the cooling rates (Ref 10).

J. Nagarjun, M. Senthil Vel, G. Swaminathan, and **N. Saravanakumar**, Department of Mechanical Engineering, PSG Institute of Technology and Applied Research, Coimbatore 641062, India; **J. John Rozario Jegaraj, G. Yoganand,** and **P. Mastanaiah**, Defence Research and Development Laboratory, Kanchanbagh, Hyderabad 500058, India. Contact e-mail: msv@psgitech.ac.in.

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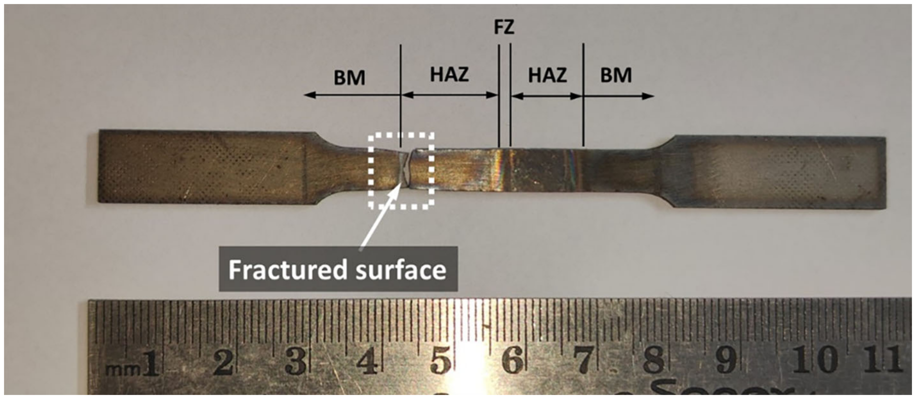

Fig. 12 Tensile tested sample of welded Ti-6Al-4 V alloy. BM, HZA, and FZ mentioned in this figure represent base metal, heat-affected zone, and fusion zone, respectively

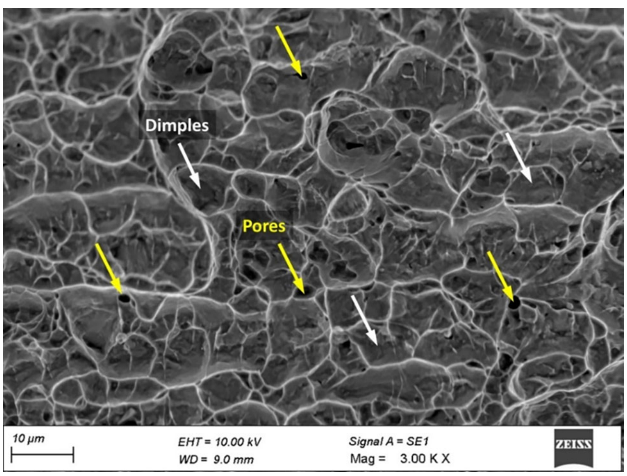

Fig. 13 SEM image of the post-welded fractured surface after tensile deformation at room temperature

The study also details the variations in thermal expansion and density across the temperature spectrum, with notable shifts around the α to β phase transformation. Such data enable simulations to model the alloy's expansion and contraction more accurately under thermal loads, which is essential for predicting residual stresses and thermal strain in welded and hot-processed parts. These insights into thermal behavior are critical for high-stress applications, where residual stress management is crucial to maintain part integrity. However, while the database developed is comprehensive, further validation through long-term service simulations and real-world applications would strengthen the applicability of the results.

4. Conclusions

The thermal and mechanical behavior of Ti-6Al-4 V alloy was investigated under high-temperature conditions relevant to welding and hot-processing applications. The following conclusions are made based on the experimental work:

1. The α to β phase transformation in Ti-6Al-4 V alloy occurs around 800 °C, which significantly affects its density, thermal expansion, and strength. The density decreases at a faster rate in the β-phase region, with the rate increasing from approximately 0.16×10^{-3} g/cm^3/°C in the α-phase to 1.2×10^{-3} g/cm^3/ °C in the β-phase.
2. The yield strength and ultimate tensile strength of Ti-6Al-4 V decrease gradually as temperature increases, dropping by nearly 50% from room temperature up to 800 °C. This trend is accompanied by changes in the alloy's stress–strain response, which shifts from strain hardening at lower temperatures to softening at higher temperatures due to thermal activation and dynamic recovery processes. Also, it is found that the nil-strength temperature of the alloy is 982 °C.
3. During welding, distinct microstructural zones form: the heat-affected zone (HAZ) shows grain coarsening, leading to reduced mechanical stability, while the fusion zone (FZ) exhibits a dendritic β-phase structure due to rapid cooling, resulting in higher hardness but lower ductility.
4. Fractographic analysis reveals a shift in fracture behavior with temperature. At room and intermediate temperatures, the alloy shows a ductile fracture mode with dimple formation, indicating plastic deformation. At higher temperatures (around 1000 °C), fracture becomes a mix of ductile and brittle characteristics, with cleavage facets appearing alongside dimples.
5. This study provides a comprehensive database on Ti-6Al-4 V alloy properties across a wide temperature range, supporting accurate simulation models for welding and hot-processing applications. These data allow for improved prediction of thermal gradients, stress distributions, and structural stability in high-temperature environments.

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Data Availability

The raw data that support the findings of this study are available in one of the authors research gate profile (controlled access repository). Link to access the raw and processed data related to this work: https://www.researchgate.net/publication/385706728_Raw_Data_-_Effects_of_High_Temperature_Deformation_and_Welding_on_Microstructure_and_Thermo-Mechanical_Properties_of_Ti-6Al-4V

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