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EFFECT OF STRAIN RATE AND TEMPERATURE ON STRAIN HARDENING BEHAVIOR OF A DISSIMILAR JOINT BETWEEN TI–6AL–4V AND TI17 ALLOYS

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The strain hardening behavior of a dissimilar joint between Ti-6Al-4V and Ti17 alloys can be significantly influenced by strain rate and temperature. Here's how these factors typically affect the material behavior:

Strain Rate:

1. **High Strain Rates**: At high strain rates (such as during impact or dynamic loading conditions), the strain hardening response tends to be less pronounced. This is because higher strain rates can limit the dislocation movement and hinder the formation of dislocation structures that contribute to strain hardening. As a result, the material may exhibit lower strain hardening capacity compared to lower strain rates.
2. **Low Strain Rates**: Conversely, at lower strain rates (such as in quasi-static or slower loading conditions), the material has more time to accommodate dislocation movement and form dislocation structures. This allows for more effective strain hardening, leading to a higher increase in strength and hardness of the material.

Temperature:

1. **High Temperatures**: At elevated temperatures, the ability of the material to harden through strain hardening diminishes. This is because higher temperatures promote more rapid diffusion and movement of dislocations, reducing the effectiveness of dislocation interactions that contribute to strain hardening. The material may exhibit lower strain hardening rates and reach a lower peak strength compared to lower temperatures.
2. **Low Temperatures**: At lower temperatures, the mobility of dislocations is restricted, promoting the formation of dislocation structures that enhance strain hardening. Therefore, the material tends to show higher strain hardening capacity and can achieve higher levels of strength and hardness during plastic deformation.

Combined Effect:

The combined effect of strain rate and temperature on the strain hardening behavior of the dissimilar joint between Ti-6Al-4V and Ti17 alloys can vary depending on the specific conditions of loading and deformation. In general:

- **Dynamic or Impact Loading**: High strain rates can reduce the strain hardening capacity, regardless of temperature, due to limited dislocation mobility.
- **Quasi-static Loading**: Lower strain rates promote better strain hardening, especially at lower temperatures where dislocation movement is more restricted.

Understanding these effects is crucial for predicting the mechanical response and designing joints between dissimilar titanium alloys under different operational conditions. Experimental studies and modeling can provide more detailed insights into how strain rate and temperature affect the strain hardening behavior and overall mechanical properties of the joint.

Abstract

The aim of this study was to evaluate the influence of strain rate and temperature on the tensile properties, strain hardening behavior, strain rate sensitivity, and fracture characteristics of electron beam welded (EBWed) dissimilar joints between Ti–6Al–4V and Ti17 (Ti–5Al–4Mo–4Cr–2Sn–2Zr) titanium alloys. The welding led to significant microstructural changes across the joint, with hexagonal close-packed martensite (α') and orthorhombic martensite (α'') in the fusion zone (FZ), α' in the heat-affected zone (HAZ) on the Ti–6Al–4V side, and coarse β in the HAZ on the Ti17 side. A distinctive asymmetrical hardness profile across the dissimilar joint was observed with the highest hardness in the FZ and a lower hardness on the Ti–6Al–4V side than on the Ti17 side, where a soft zone was present. Despite a slight reduction in ductility, the yield strength (YS) and ultimate tensile strength (UTS) of the joints lay in-between the two base metals (BMs) of Ti–6Al–4V and Ti17, with the Ti17 alloy having a higher strength. While the YS, UTS, and Voce stress of the joints increased, both hardening capacity and strain hardening exponent decreased with increasing strain rate or decreasing temperature. Stage III hardening occurred in the joints after yielding. The hardening rate was strongly dependent on the strain rate and temperature. As the strain rate increased or temperature decreased, the strain hardening rate increased at a given true stress. The strain rate sensitivity evaluated via both common approach and Lindholm approach was observed to decrease with increasing true strain. The welded joints basically failed in the Ti–6Al–4V BM near the HAZ, and the fracture surfaces exhibited dimple fracture characteristics at different temperatures.

Introduction

Titanium and its alloys have been increasingly used as one of key structural materials in the aerospace applications due to their excellent combination of properties such as high strength-to-weight ratio, high fatigue life, toughness, excellent resistance to corrosion [1], [2], [3], [4], [5]. The structural application of titanium alloys unavoidably involves welding and joining [6]. The welding of titanium alloy is fairly challenging, since it becomes very reactive with most atmospheric gases such as oxygen, nitrogen, carbon, and hydrogen at temperatures above 550 °C and particularly in the molten state [7]. While these interstitial elements increase the strength, they reduce ductility and toughness and cause severe embrittlement [7], [8]. Poor preparation and cleaning of the base metal (BM) before welding, poor shielding of the joint or impurities present in the shielding gas during welding can also cause serious contamination [7]. To overcome these problems, electron beam welding (EBW) is considered to be an ideal process to join titanium and its alloys. The high vacuum inside the chamber where the process is carried out protects the hot metal from contamination. Moreover, a narrow and deep joint can be achieved with a high beam power density, when compared to the conventional welding processes [9]. A relatively small heat-affected zone (HAZ) is obtained in this process while producing lower thermal stresses compared to other welding techniques [9], [10]. Therefore, EBW is recognized as a promising process for joining relatively thick, refractory metals and their dissimilar combinations. The previous studies about the electron beam welded (EBWed) titanium alloy joints mainly involved the effects of heat treatment and welding parameters on the microstructure, hardness, tensile properties, and fatigue properties [11], [12], [13], [14], [15], [16], [17], [18]. For example, Thomas et al. [14] studied the effect of pre- and post-weld heat treatment on the mechanical properties of EBWed Ti–6AI–4V joints. Pederson et al. [15] reported the effect of different beam scanning patterns on the microstructure and mechanical properties of EBWed Ti–6Al–4V joints. Fu et al. [16] and Wang et al. [17], [18] further evaluated the strain-controlled low cycle fatigue behavior of EBWed titanium alloy joints. However, it is unclear about the strain hardening behavior of EBWed titanium alloy joints, although a few studies have been reported on the strain hardening behavior of other types of welded joints including laser welded DP980 steel joints [19] and Mg joints [20], [21], and friction stir welded Al joints [22] and Mg joints [23], [24], [25], [26], [27]. Therefore, it is necessary to evaluate the strain hardening behavior of the EBWed titanium alloy joints.

Strain hardening (or work hardening) is one of the most important considerations in the evaluation of plastic deformation of metallic materials [23], [28]. The strength, ductility, toughness and deformability of materials are intimately related to strain hardening characteristics [29]. For this reason, many investigations have been carried out on the strain hardening behavior and physical mechanism of conventional metallic materials [30], [31], [32]. The strain hardening behavior of cubic metals is fairly well understood, and the accumulation of a forest of dislocations is the predominant hardening mechanism [31], [32]. HCP metals present a more complex case due to their low symmetry which restricts the number of slip systems and their strong plastic anisotropy [31], [33], [34]. Hitherto many studies have been reported on the strain hardening behavior of Ti alloys [35], [36], [37], [38]. For example, Honarmandi and Aghaie-Khafri [37], and Rao and Tangri [38] studied the strain hardening behavior of Ti–6Al–4V and $TiAl_x$ alloy, respectively, by means of compression testing at high temperatures and observed different stages of strain hardening, while Bystrzanowski et al. [36] investigated the tensile flow behavior of Ti–46Al–9Nb sheet material and observed only stage III strain hardening at high temperatures. In spite of many studies on the strain hardening behavior of titanium alloys and other alloys, as well as the strain hardening behavior of several welded joints including laser welded DP980 steel joints [19] and Mg joints [20], [21], and friction stir welded Al joints [22] and Mg joints [23], [24], [25], [26], [27], to the authors' knowledge no information on the strain hardening behavior of EBWed dissimilar titanium alloy joints is available in the open literature. It is unknown what strain hardening stages would occur, and how the strain rate and test temperature affect the strain hardening behavior in an EBWed dissimilar joint of titanium alloys. This study was, therefore, aimed at evaluating the tensile properties and identifying the strain hardening behavior in an EBWed dissimilar joint between Ti–6Al–4V and Ti17 alloys at varying strain rates and temperatures.

Section snippets

Material and experimental procedure

The materials used in the present study were forged Ti–6Al–4V and Ti17 titanium alloys of 10 mm in thickness, with their chemical compositions listed in Table 1, Table 2, respectively. Both alloys were machined into the plates with a dimension of 140 mm × 80 mm × 10 mm, and then mechanically and chemically cleaned before welding. EBW was carried out using HDZ-15B EBW machine with an accelerating voltage (V) of 60 kV, a beam current (I_b) of 68 mA, a focus current (I_f) of 2230 mA, and a welding speed (v) of

Microstructure

Fig. 1 shows the microstructures of BMs of Ti–6Al–4V and Ti17, respectively. Ti–6Al–4V alloy was composed of globular α grains and colonies of secondary elongated α grains surrounded by intergranular β phase (Fig. 1(a)), while Ti17 consisted of fine α plates embedded in the β matrix (Fig. 1(b)). Fig. 2 shows a significant microstructural change occurred in the fusion zone (FZ) and HAZ of the joint after EBW. The FZ was narrow (∼2 mm wide) and was mainly composed of acicular and fine martensite α'

Conclusions

Tensile tests were conducted on dissimilar Ti–6Al–4V/Ti17 titanium alloy joints made with EBW, and the effect of strain rate and temperature on the UTS, YS, strain hardening behavior, strain rate sensitivity, and fracture mechanisms of the joints were evaluated. The following conclusions can be drawn from this investigation:

- 1.
  The microstructure across the dissimilar welded joint exhibited a considerable change, mainly consisting of HCP martensite α' and orthorhombic martensite α'' in the FZ, α' in

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