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Development of strength-hardness relationships in additively manufactured titanium alloys

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ABSTRACT

A major concern for additively manufactured (AM) Ti-6Al-4V components is how AM processing parameters and post-process heat treatments impact the resulting mechanical behavior. The applicability of using microhardness measurements as a predictive tool for yield and tensile strengths of AM Ti-6Al-4V would provide a rapid and useful screening mechanism for ensuring that properties meet requirements in complex geometries. However, microhardness measurements on Ti-6Al-4V exhibit high levels of data variability due to the orientational impact of the α phase. In order to overcome this variability in hardness measurements, a methodology for aggregating microhardness data in individual builds has been developed and validated. By compiling mean microhardness values from various AM components produced by electron beam based directed energy deposition (DED), laser based DED, and laser based powder bed fusion (PBF) processes in the as-deposited and post-process heat treated conditions, strong linear correlations between strength and hardness can be developed in AM materials having a lamellar α+β microstructure. With the addition of strain hardening and α phase orientation contributions to the mean microhardness measurement, the strength-hardness correlations of AM Ti-6Al-4V followed empirically derived models, opening the possibility of using these models to predict strengths from AM components regardless of the AM process or post-process state.

1. Introduction

There are various techniques currently being used to additively manufacture (AM) Ti-6Al-4V components. Differences in the processing conditions and structures produced at different locations result in a wide variation in mechanical properties [1,2]. For example, tensile strengths in the as-deposited condition of AM Ti-6Al-4V reported in the literature vary from 775 MPa to 1270 MPa [3]. Much of this variation can be attributed to differences within the processing conditions, such as the selection of the energy source (laser, electron beam, and arc), the power input, travel speed, and feedstock form, such as wire or powder. Location and orientation dependent anisotropy in the tensile properties has also been observed in relation to the build direction [3–11], arising from differing thermal histories experienced at each location [12,13]. In most cases, post-process heat treatments and hot isostatic pressing (HIP) operations are used and shown to significantly alter the as-deposited Ti-6Al-4V structure as well as the resulting tensile properties [5,10,14–19].

In order for AM fabricated components to be used for critical applications, a qualification and certification protocol is needed. A major component of this protocol is to understand how processing conditions, part design, build path planning, and post-process heat treating, among others, will impact the resulting mechanical properties [20,21]. It is costly and impracticable during production to extract specimens from different locations and orientations in AM components to investigate how processing and design changes will impact the local mechanical properties. Microstrucure and phase composition have also been used to predict the mechanical properties [22–24] and toughness [25] for Ti-6Al-4V components, but using these methods requires a detailed microstructural and chemistry composition analysis. In contrast, hardness measurements offer a fast and inexpensive method of measuring material properties at specific locations. A good understanding of the relationship between measured hardness values and the mechanical properties would allow for hardness to be used as a predictive tool for mechanical properties and help streamline the qualification and inspection protocols for AM Ti-6Al-4V components.

Although hardness is widely used as a predictor of strength for steels and other common alloy systems [26,27], similar relationships are not as widely available for titanium alloys. Currently, the only available strength to hardness correlation for Ti-6Al-4V is an empirical relationship, developed by Hickey [28], based on a linear least square fit of the Vickers hardness, H_V, and tensile strength, σ_{UTS}, for investment

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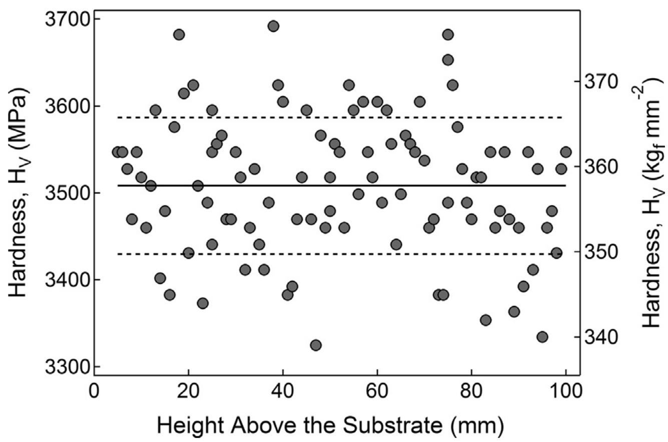

Fig. 1. Vickers microhardness measured as a function of the height above the substrate for an AM Ti-6Al-4V wall structure. The mean is represented by the solid line, and the standard deviation range is represented by dashed lines.

cast Ti-6Al-4V components where:

$$\sigma_{UTS}(\text{MPa}) = \frac{H_V(\text{MPa})}{6.33} + 503 \quad (1)$$

A cursory correlation between hardness and build strength was also attempted for AM Ti-6Al-4V wall structures produced by a laser based directed energy deposition (DED) process [3]. The tensile strengths were found to decrease with increasing height above the build substrate. Hardness measurements made across the height of a wall structure produced using the same processing conditions are shown in Fig. 1. These hardness measurements, though, did not show a significant correlation with the build height, but, rather, exhibited a large spread with no observable trend.

The problem with using hardness as a predictive tool for Ti-6Al-4V structures is that the measurement is impacted by the orientation of the underlying hexagonal closed packed (HCP) α phase. With the limited slip systems available in the HCP system, the energy required for slip varies with the crystallographic orientation in relation to the force direction [29]. Slip preferentially occurs on the closest packed planes, and, for HCP systems, the planes exhibiting the highest packing density are governed by the c/a lattice parameter ratio. For titanium alloys, the c/a ratio of the α phase is less than the ideal packing ratio (1.633), and the prism planes ($\{10\bar{1}0\}$ and $\{11\bar{2}0\}$ planes) will exhibit a higher packing density than the basal plane $\{0001\}$ [30]. Thus, slip is expected to preferentially occur on the prism planes, and this has been observed experimentally for α and α+β titanium alloys [29,31]. Impurity atoms such as oxygen and nitrogen also influence the slip mode and can make the pyramidal planes the preferred slip system [32,33]. Regardless of whether slip preferentially occurs on the pyramidal or prism planes, the basal planes are the least preferential slip planes. Hardness measurements obtained from α grains oriented with the basal plane normal to the measurement direction for α and α+β titanium alloys are significantly higher than those obtained for other crystallographic orientations [29,34–37]. Viswanathan et al. experimentally found that the hardness obtained by nanoindentation on α grains presenting the basal plane exhibited 50% higher hardness than α grains presenting the prism planes [34].

The variability introduced by the underlying α grain orientation on the hardness measurement is a major contributor to the wide measurement spread observed in AM Ti-6Al-4V components. In Ti-6Al-4V, the structure consists primarily of α phase (> 85% for wrought [38,39] and > 90% for AM Ti-6Al-4V [18,40,41]), and this phase would be expected to dominate the hardness measurements. Fig. 2(a) shows a Vickers microhardness indent made with a 1 kg_f load within an AM Ti-6Al-4V microstructure that was fabricated using an electron beam based DED process. Even though this single hardness indent encompasses a number of α lathes, the crystallographic orientation of the underlying α phase could vary significantly from one hardness measurement location to another resulting in significantly different hardness measurements within the same area. For example, in Fig. 2(b), the hardness varied from 2.85 to 3.41 GPa within a 1.5 mm^2 area for an AM electron beam based DED Ti-6Al-4V microstructure where the orientational differences of the α phase are highlighted using polarized light.

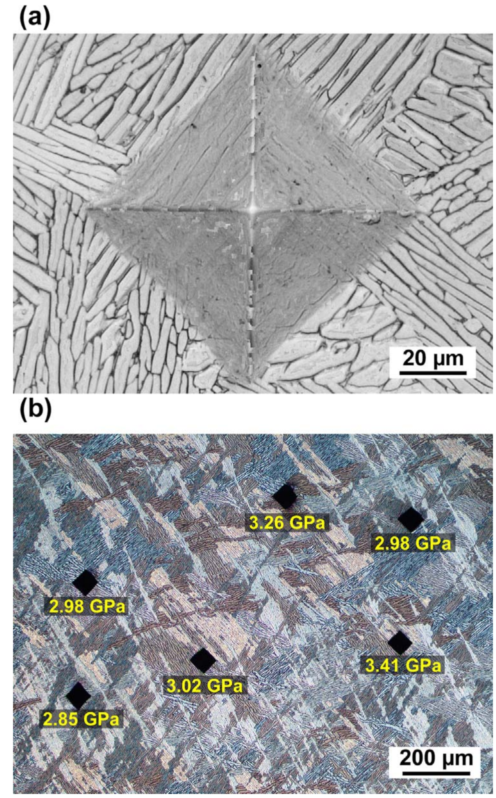

Fig. 2. A representative Vickers microhardness indent (a) made with a 1 kg_f load on an etched AM Ti-6Al-4V microstructure produced by an electron beam based DED process; and (b) a microstructural area listing the measured hardness values obtained from microhardness measurements where polarized light highlighted orientational differences of the α phase.

The unknown impact of the underlying microstructure on the resulting hardness makes correlating the measured hardness and strength problematic. In order to obtain a hardness to strength relationship over a wide range of processing and post-processing conditions, this investigation compiled room temperature microhardness and strength measurements from AM Ti-6Al-4V components fabricated by laser based DED with a powder feedstock, electron beam based DED with a wire feedstock, and laser based powder bed fusion (PBF) AM processes in the as-deposited and post-process heat treated conditions. A methodology for aggregating hardness data obtained for each processing condition was developed. The mean microhardness was then correlated to the strengths for analyzing the strength to hardness relationships. As part of the methodology for aggregating the hardness data, a specific number of Vickers microhardness measurements were made at locations corresponding to those where static mechanical testing specimens were extracted. It is shown that when these statistical variations are taken into account, hardness measurements can be used to predict strength in AM Ti-6Al-4V regardless of the fabrication technology or post-processing conditions.