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Indentation Testing of 3D Metal-Printed Alloys used in Aerospace Applications

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Session
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Indentation Testing of 3D Metal-Printed Titanium Alloy used in Aerospace Applications.

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Abstract

This research is on indentation testing (following ASME standards) of 3D printed Ti- 6Al-4V built by powder-based direct energy deposition technology. Ti-6Al-4V is attractive material for the aerospace and aviation industry. The purpose of this research is conduct indentation or hardness testing using both Rockwell and Vickers testers to examine the mechanical characteristic of the as-3D printed alloy. The hardness data were also compared with wrought Ti-6Al-4V alloy. The comparison of 3D printed and wrought indicates that the mechanical characteristics in terms of hardness does not have significant difference between the two manufacturing processes.

I. Introduction

Titanium alloys are used in the aerospace industry due to their unique mechanical properties. The strength of Titanium alloys is comparable with steel, but because of some additional properties such as such as lightweight, resistance to corrosion and heat, it is a prime metal for aerospace applications [1]. In many cases, high costs involved in machining can outweigh the benefits of Ti-6Al-4V to use. Using additive manufacturing for Ti-6Al-4V components, significantly reduced the machining cost while reducing the material waste as compared to the wrought manufacturing. The most typical alloy mix is 90% Titanium, 6% Aluminum, and 4% Vanadium, commonly known as Ti-6AL-4V (Ti64) [1]. Titanium is one of the most common alloys used in the aerospace industry that has been manufactured with a wide variety of 3D printing techniques, including LENS (Laser Engineered Net Shaping) technology ([2], [3], [4]).

The purpose of this work is to test the mechanical properties of as-built additively manufactured Ti-6Al-4V compare it with the wrought Ti-6Al-4V. The desired outcome of this experiment is for the additive manufactured material to be as close as possible to the wrought material. The mechanical property being tested in this paper is Hardness [5]. It is common practice in literature to compare mechanical properties of 3D printed metals to wrought metals of the same composition [6], [7]. The company OPTOMEC agreed to provide the required sample and to deliver the best quality sample. OPTOMEC is very well known for its LENS technology and it is at the forefront of additive manufacturing technology.

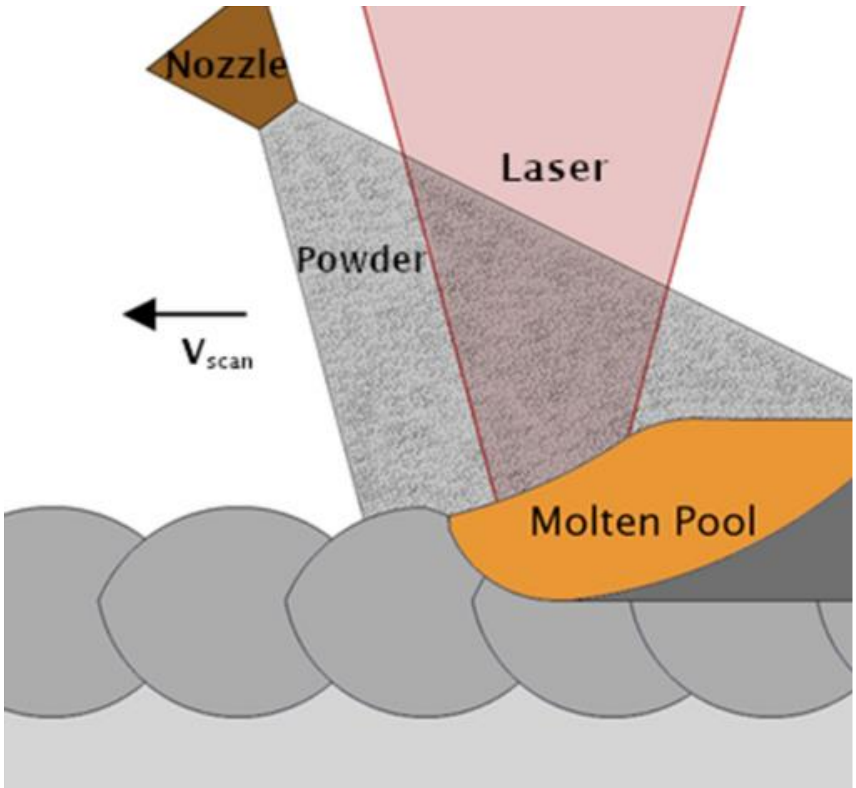

Figure 1: Diagram showing how the Direct Energy Deposition (DED) process works. Material is deposited layer by layer and the movement is CNC controlled. The laser and the powder from the nozzle meet at the molten pool.

II. Methodology

The printing technique used to additively manufacture Ti-6Al-4V in this experiment is powder-based direct energy deposition (DED). The dimensions of the printed specimen were 2 in by 2 in by 0.5 in (0.5 inches in height with a square top). The as-deposited material can be observed in Fig. 2. The material was fabricated with alternating 90-degree hatching directions, with a ratio of layer height to hatch spacing of 1:2.

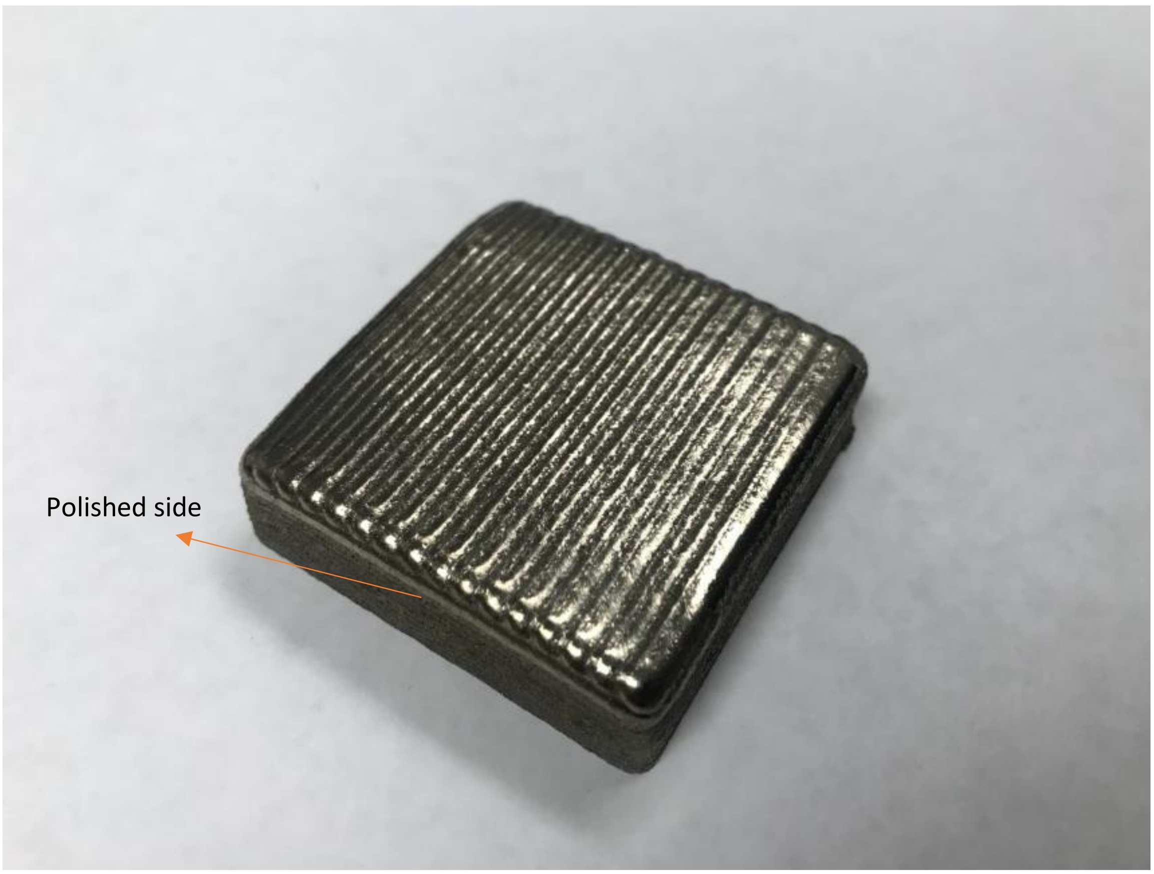

Figure 2: Titanium 6Al-4V sample (as-built)

One side of the block was machined and polished to a surface roughness, Ra, of 5 micro inches [4]. The methods used to study the hardness of the sample were Vickers (Micro indentation) and Rockwell tests. Vickers hardness measurements were made using a standard Vickers diamond pyramid hardness tester with a load of 1000 g. The dwell time was 10 seconds, and an average of 25 values were taken per transverse line. Rockwell Hardness measurements were made suing Rockwell C scale with load of 150 kg with load time of 5 seconds and an average of 13 indents were taken per transverse line. Tests were performed on both the longitudinal direction and transverse directions to investigate any changes. Some builds show different microstructure along different directions, and therefore different mechanical properties ([8], [9], [10]).

Figure 3: As-built Ti 64 sample showing the polished side and the Rockwell indents.

Fig. 3 shows Rockwell indentations performed on the sample. The Rockwell indentations were done after the Vickers indentations. The Vickers test was also performed in a similar fashion to the Rockwell test but not visible due to their very small size.

For the Vickers test, the distance between the indentations and the edge of the sample is a minimum of three indentation diameters/diagonals [11], and for conservative reasons here the assumed diameter is a maximum diameter of 0.2 mm. If indents are closer than this distance to each other, the hardness values could be off. Therefore, three diameters is equal to 0.6 mm. The distance between the indentations along a line is estimated conservatively to be six diameters and six diameters is equal to 1.2 mm. As mentioned in ref. [1], The Vickers hardness is calculated using the following equation:

$$\mathrm{HV} = \frac{(1.8544)P}{d^2} \tag{1}$$

where HV is Vickers Hardness, P is load in kg and d is diagonal length in mm.

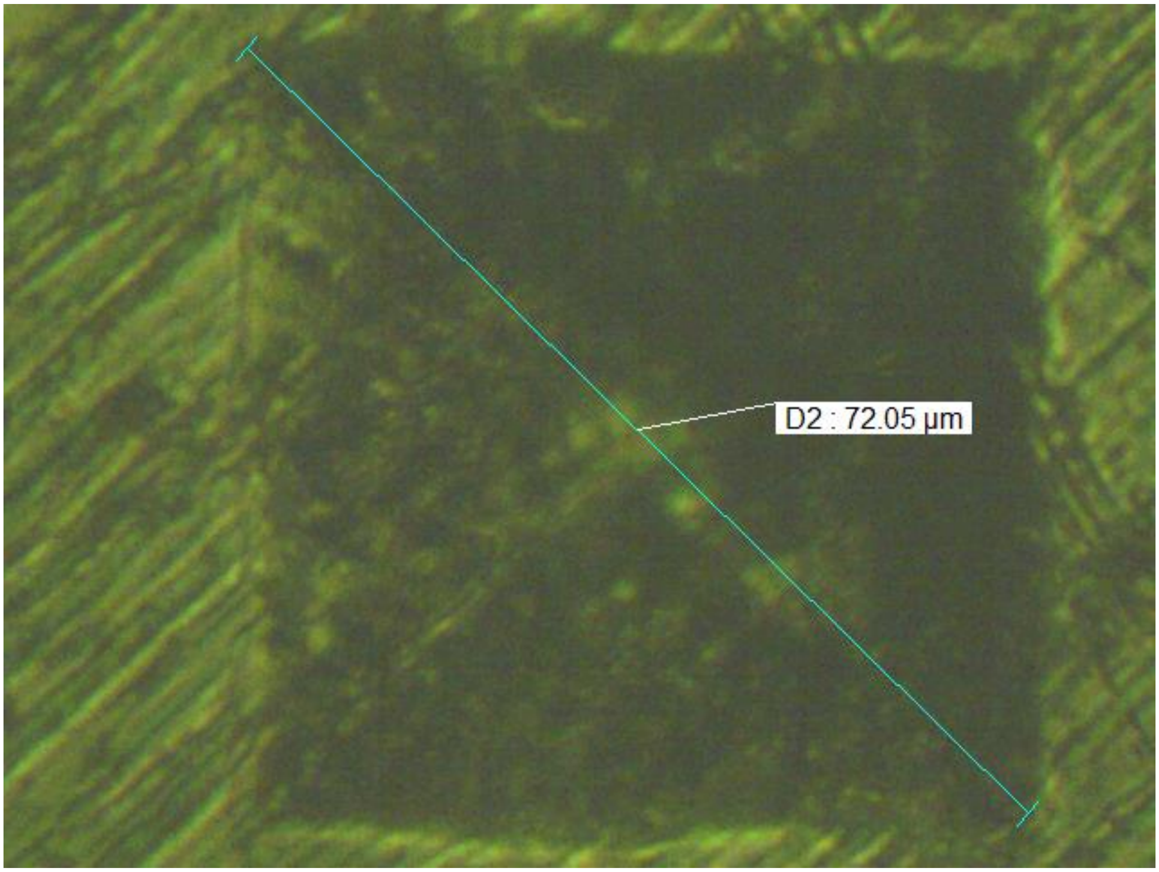

Figure 4: As-built Ti64 Vickers indentation 0.6 mm from Top edge

The wrought bar sample was polished using SiC papers of grit size 120 grit up to 1500 grit before the hardness tests. The indentations were only performed on one line of indentations in the as-received status of this sample. Here, no spatial variation of properties was assumed for the wrought material.

Due to the small height of the printed material with respect to its width and length, it was expected that there would not be a significant change in the heat conditions of the deposited material. Thus, no large variations in hardness were expected in any direction.

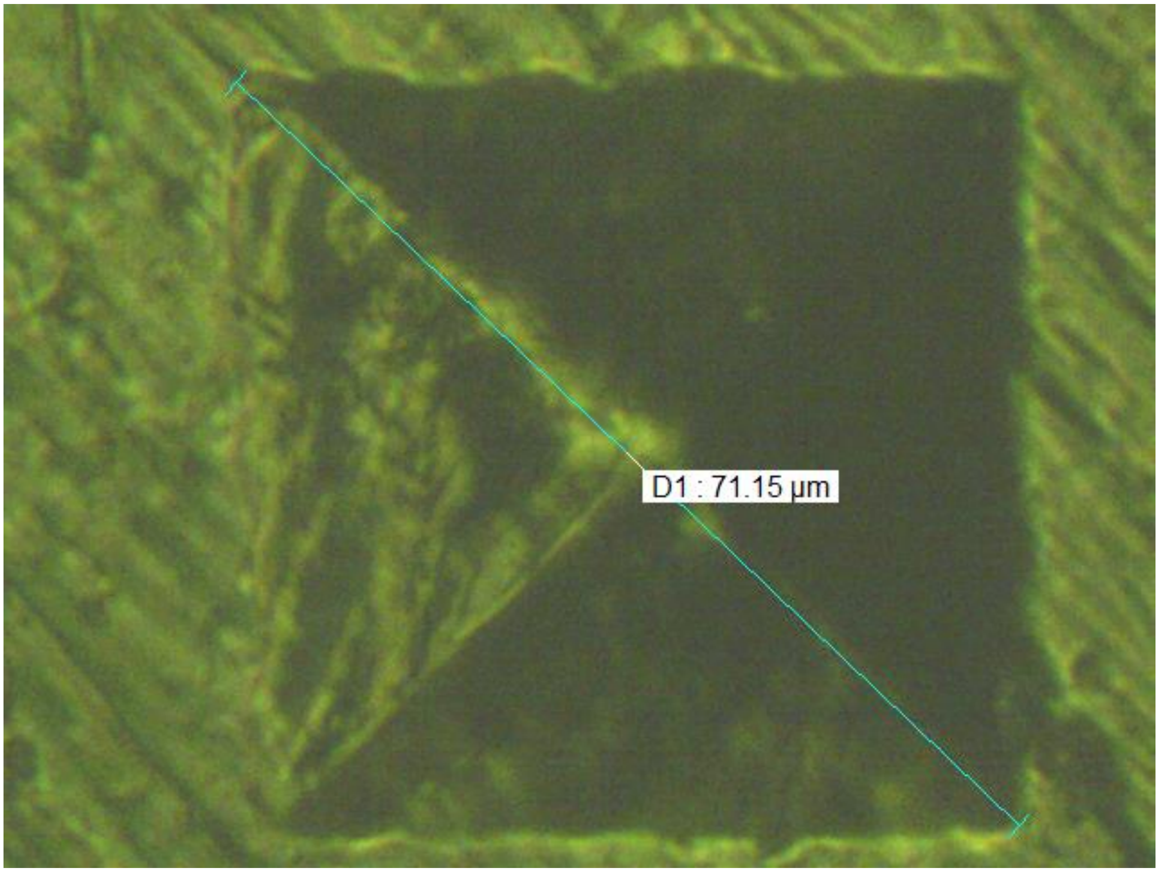

Figure 5: Wrought Ti64 Vickers indentation

Fig. 4 and Fig. 5 show, respectively, pictures taken of the Vickers indentations of the as-built Ti64 sample and the wrought Ti64 sample using a digital camera and metallurgical software. The calibrated software measurement shows the length of the diagonal, which is used in equation [1] to calculate the Vickers hardness. The software was calibrated using a standard specimen supplied by the device manufacturer.

For the Rockwell test, the distance between the indentations and the edge of the sample is three indentation diameters [12], and for conservative estimates, the assumed indentation diameter was 1 mm. Therefore, three diameters is equal to 3 mm. The distance between the indentations along a line is three diameters as well.

IV. Results and Discussion

The mean of the 25 Vickers micro indentations at each of the three heights was calculated, along with the standard deviation, and documented as follows:

Table 1: Vickers average/standard deviation results

Material/Location of indent	HV/standard dev.
Titanium 64 (0.6 mm from bottom edge)	369.7/9.17
Titanium 64 (3.3 mm from bottom edge)	383.5/13.6
Titanium 64 (11.5 mm from bottom edge)	373.0/11.2
Wrought Titanium 64	396.3/11.15

The standard deviation was in the 9.17-13.6 range for all 4 indented lines, which is maximum 3.5% of the mean. This indicates close measures and precision of data.

The mean of the 13 Rockwell indentations at each of the three heights was calculated, along with the standard deviation, and documented as follows:

Table 2: Rockwell average/standard deviation results

Material/Location of indent	HRC/standard dev.
Titanium 64/Top line	37.5/0.68
Titanium 64/middle line	37.0/0.60
Titanium 64/bottom line	38.1/0.42
Wrought Titanium 64	37.6/1.17

The standard deviation was in the 0.42-1.17 range for all the 4 indented lines, which is maximum 3.1% of the mean. This indicates close measures and precision of data.

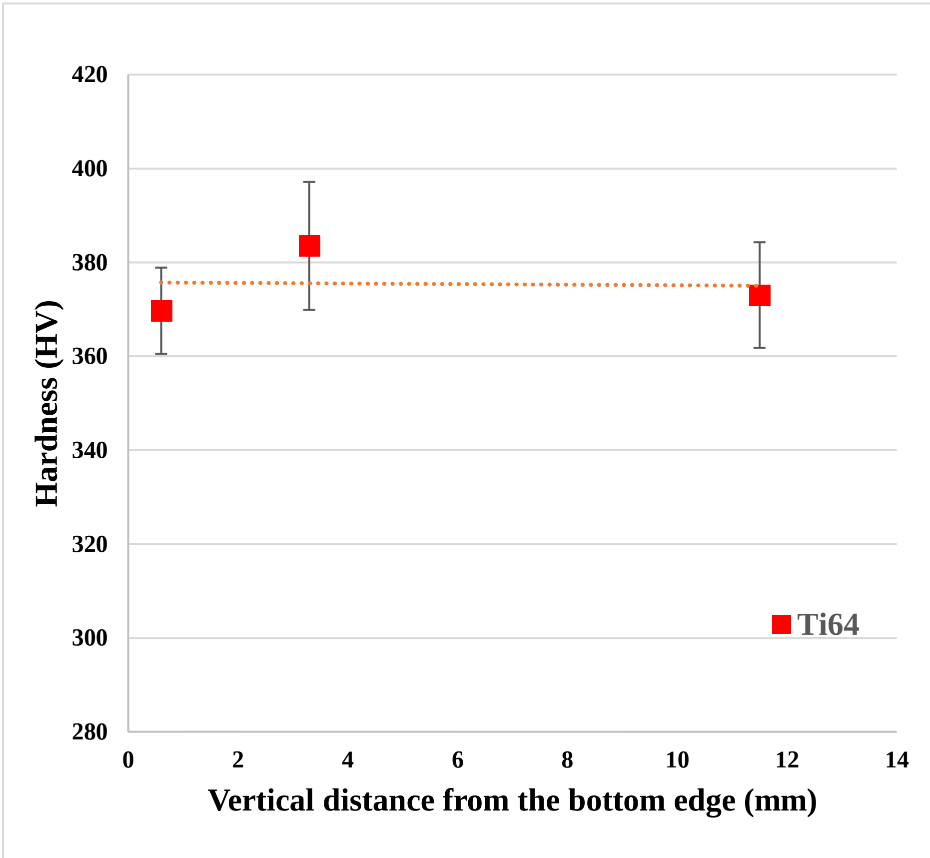

Figure 6: Ti64 Vickers hardness vs vertical distance

There are conversion charts, see [13] for example, between different hardness measurements. For example, the last reference shows that 37.5 HRC is equivalent to 367.5 HV. Comparing the data in Tables 1 and 2, it is seen that average HRC values of about 37.5 in Table 2 are equivalent to about 370 HV (i.e. the data in Table 1). This comparison provides another verification for the results in this work.

The as-built Ti-6AL-4V hardness results show that it is almost identical to the wrought Ti-6AL-4V sample. Table 1 and Table 2 show that the as-built Ti64 and the wrought Ti64 materials are similar to each other in their average values (within the standard deviation range).

Fig. 6 shows that there is no significant change of hardness along the vertical direction. Fig. 7 as well shows that there is no change along the transverse, i.e. horizontal, direction. The results are consistent which suggest similar microstructure in longitudinal and transverse directions.

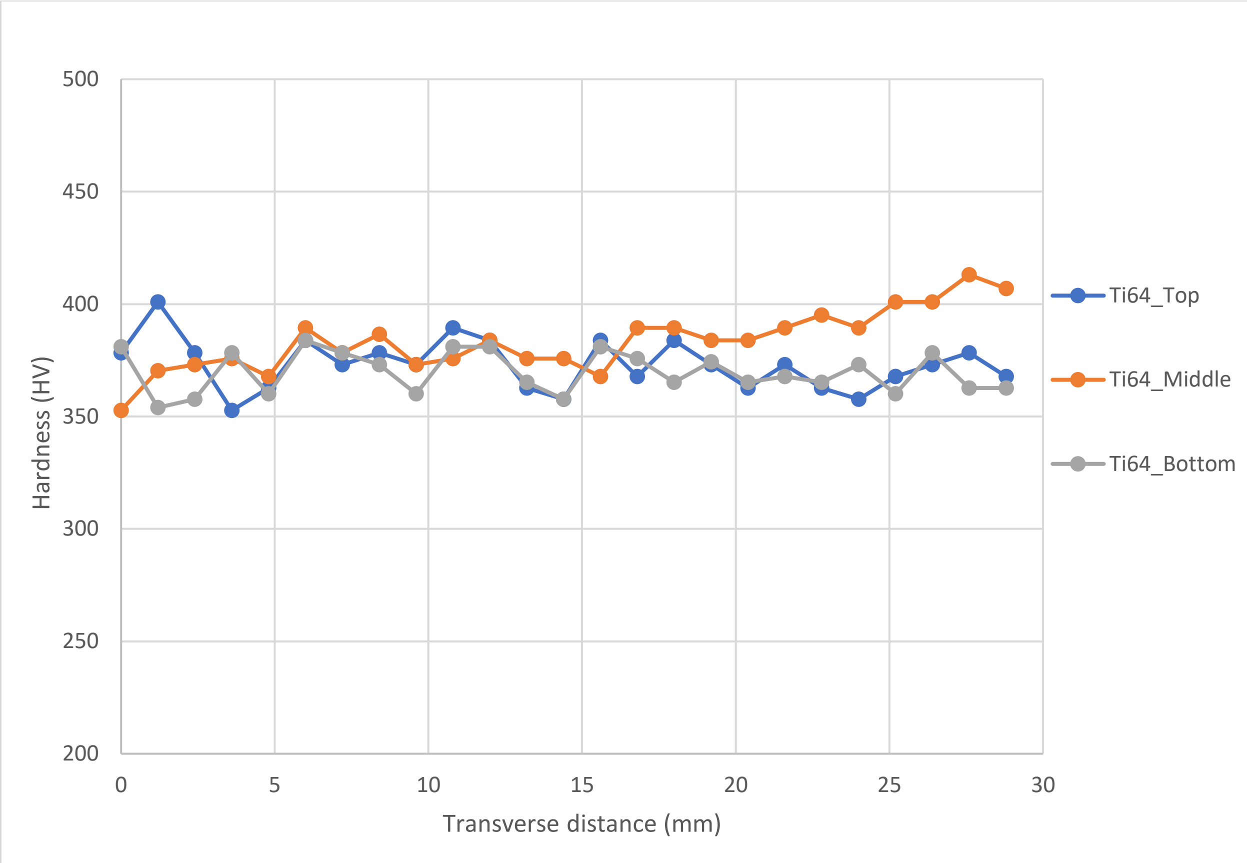

Figure 7: Vickers hardness vs Horizontal distance

V. Conclusion

Studying the hardness of a material is important because it offers a valuable insight into its strength, durability and how the material could be useful. Two of the purposes of additive manufacturing is to save material and build parts and shapes that can't be casted, and once it's proven that it can achieve same mechanical properties, industry can use it in a variety of ways. The indentation (Vickers or Rockwell) results are consistent across the indented specimen's side which suggests similar, or at least not much different, microstructure in the longitudinal and transverse directions. In addition, the results of the wrought and as-built samples are very similar as well which is a feature of a good build and also suggest not much different microstructure between the two. However, more future work is needed to ascertain these microstructural comments. Studying the microstructure is important because it gives the ability to predict the mechanical and chemical properties of the material.

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13. Hardness Conversion Chart - *Provides Values for Brinell, Rockwell A, Rockwell B, Rockwell C, Rockwell D, Rockwell E, Rockwell F, Rockwell Superficial 15-N, Rockwell Superficial 30-N, Rockwell Superficial 45-N, Rockwell Superficial 30-T, Vickers 136, Shore, and Tensile Strength Psi Hardness*, Retrieved February 15, 2021, from http://www.carbidedepot.com/formulas-hardness.htm

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