The Effects of Specimen Dimensions on the Mechanical Behavior of EBM Produced Ti6Al4V Alloys

R.S. Kircher, A.M. Christensen, K.W. Wurth
Medical Modeling Inc., Golden, CO 80401

Abstract

There are several published studies investigating the microstructures and mechanical properties obtained during additive manufacturing of Ti6Al4V alloys utilizing the Electron Beam Melting (EBM) technique. These studies have concentrated on conventional testing coupon sizes and configurations which allowed for a direct comparison to the properties of conventionally produced Ti6Al4V alloys. One of the many benefits of the EBM process is that it allows the manufacturer to produce components in sizes and configurations unachievable by conventional methods. It becomes important to understand and verify the microstructures and mechanical performance of these smaller components in a manufacturing environment, requiring the use of non-conventional testing configurations. This paper presents case-studies involving the production and testing of non-standard samples and how these samples compare to conventional E8 testing coupons. Differences in mechanical performance were observed and are most likely due to the unique characteristics of EBM produced materials.

Introduction

The rapid prototyping industry is in the midst of transition from an industry that produced models, prototypes, and other non-functional objects to an industry that is not only making functional components, but components that will be expected to meet some of the strictest quality standards encountered in the manufacturing industry. The ability to additively manufacture fully melted metal components out of high-end engineering alloys such as Titanium and other super alloys is a powerful tool, but these high-end alloys are typically only used in extreme environments and for critical applications; namely in the biomedical and aerospace industries. At the very least, a manufacturer must provide its customers with certifications that the additively manufactured components meet a predetermined set of mechanical, chemical and performance properties. In addition to certifications many customers require a thorough quality control system be established, documented and regularly verified to provide a high assurance that the material is consistently meeting the necessary performance criteria.

Certifying a batch of conventionally produced material is a relatively straight-forward and well established practice in the manufacturing industry. For example, if one is going to use wrought Ti6Al4V alloy bar stock to machine a batch of medical implants, they would order a lot of material to a specific standard, such as an ASTM, ISO or AMS standard and the material would be delivered to the manufacturer with the proper paperwork certifying that the proper analyses have been conducted, in the proper manner, and that the results satisfy the necessary values outlined in the standard. Typically these specifications will outline sample frequencies, quantities, configurations, and geometries as well as outline testing conditions and acceptable testing methods. For example, if a lot of wrought ASTM F 1472 Ti6Al4V bar is to be certified, a minimum of one (1) representative chemical analysis must be conducted in addition a tensile test, and a metallographic evaluation [1]. If these evaluations are carried out correctly and the results meet the requirements of the standard, the entire ‘lot’ of material is considered certified for use to that standard. The ASTM F 1472 specification defines a “lot” of material as the total number of mill products produced from one heat under the same conditions at essentially the same time [1], which means that a single material certification may be encompass a large quantity of raw material, perhaps enough material to allow the production of several hundred medical components.

The additive manufacturing industry has yet to adopt a set of terminology, test methods or material specifications to standardize the quality control methods to be used in fabricating and certifying layer-based materials. As a result, the specifics surrounding material certification have typically been negotiated between suppliers and customers on an individual case basis. Standardizing the certification specifics of additive manufacturing technologies will provide a higher comfort level when using additively manufactured materials in addition to eliminating the need to negotiate material certifications on a single contract basis.

The ultimate goal of a material certification is to produce strong evidence that all of the material supplied to a customer meets a specific set of criteria, while minimizing the time and cost of testing necessary to provide that evidence. Additive manufacturing technologies have opened doors by providing a method of producing components with geometries that are unachievable by conventional manufacturing processes. However, this poses an interesting dilemma. Since these are novel part geometries, testing methods to verify the material properties of these components do not exist. In addition to developing and optimizing the manufacturing process necessary to produce a layer-based product, the additive manufacturer must also develop the test methods and acceptance criteria to be used for material certification of that product.

This paper will present case studies investigating the effects of tensile specimen geometries on the measured mechanical properties of one particular metal alloy, Ti6Al4V, produced by the Electron Beam Melting process.

The Electron Beam Melting Process

Like many rapid manufacturing techniques, the EBM process creates a physical component from digital CAD models by building the component in a series of layers. The EBM process starts by distributing a 100 µm layer of fine metal powder on a steel platform. An electron beam is produced by passing current through a Tungsten filament. The electron beam scans areas of the metal powder layer, in an x-y coordinate system, as defined by the computer model fully melting the powder in the areas scanned. Once the beam has scanned the appropriate areas the steel platform is lowered by 100 µm, and a new layer of powder is distributed on top of the previously melted layer. This process continues, layer by layer, until a complete part is produced. During processing the entire build chamber maintains a temperature of approximately 500oC. Once the part has been completed, the build chamber is flooded with He gas to expedite cooling.

The use of an electron beam to supply the energy necessary to melt the metal powder mandates that the process be done in a vacuum chamber, which minimizes chemical reactions between the melting metal powder and the surrounding atmosphere. This feature is extremely beneficial in producing objects out of Ti6Al4V-ELI material, because the low levels of interstitial elements such as O, N and H can be controlled during production. Currently the EBM process is capable of producing parts up to 200x200x200 mm, with a dimensional accuracy of 0.4 mm.

Hot isostatic pressing (HIP) has become an industry standard for investment cast Ti6Al4V alloy components used in the orthopaedic industry. Since EBM produced components will most likely be used in similar applications, unless otherwise noted, the data shown for test specimens in this study was acquired following standard HIP treatment. A standard HIP treatment cycle for titanium alloy consisting of two (2) hours at 900^{o}C and 103.4 MPa was utilized [2].

Case Study 1: Standard E-8 Testing specimens

To date, the vast majority of tensile data available for additively manufactured metals has been generated using the well established ASTM E-8 standard: Test Methods of Tension Testing of Metallic Materials [3]. **Figure 1** is a schematic of a build configuration developed to produce a series of standard E-8 round samples. The vertical cylinders were designed to accommodate tensile testing in the axis parallel to the beam direction (Z-orientation). The large slabs of material were sliced into coupons and machined to accommodate tensile testing in the axis perpendicular to the beam direction (XY-orientation). The sample size chosen for the analyses were 1” (25.4mm) gauge length round specimens with the dimensions listed under specimen 3 as shown in **figure 2** [3].

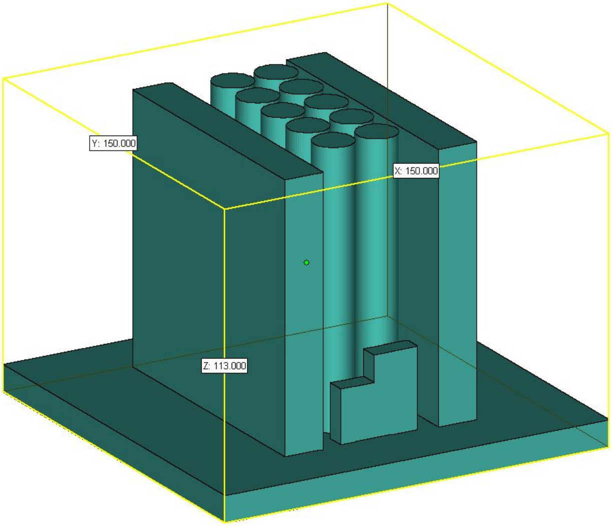
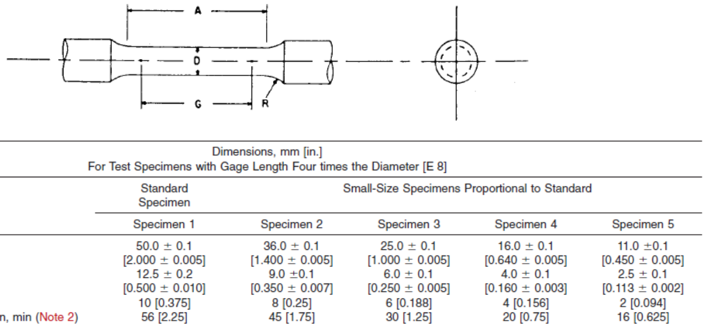


Figure 1: Schematic illustrating the build configuration used to produce standard ASTM E-8 specimens.

Table A summarizes the tensile properties obtained from the analysis of a set of test specimens built in the configuration shown in **figure 1**. Previous studies have shown that chemical composition, especially oxygen and iron content have a significant effect on tensile properties of EBM produced Ti6Al4V material [4]. It should be noted that the results in **table A** were obtained from a powder containing 0.13 wt.% Oxygen and 0.07 wt.% Fe; all other elements were within the required chemical composition requirements of medical grade Ti6Al4V alloy.



Dimensions, mm [in.]
For Test Specimens with Gage Length Four times the Diameter [E 8]

	Standard Specimen	Small-Size Specimens Proportional to Standard			
	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
G—Gage length	50.0 ± 0.1 [2.000 ± 0.005]	36.0 ± 0.1 [1.400 ± 0.005]	25.0 ± 0.1 [1.000 ± 0.005]	16.0 ± 0.1 [0.640 ± 0.005]	11.0 ±0.1 [0.450 ± 0.005]
D—Diameter (Note 1)	12.5 ± 0.2 [0.500 ± 0.010]	9.0 ±0.1 [0.350 ± 0.007]	6.0 ± 0.1 [0.250 ± 0.005]	4.0 ± 0.1 [0.160 ± 0.003]	2.5 ± 0.1 [0.113 ± 0.002]
R—Radius of fillet, min	10 [0.375]	8 [0.25]	6 [0.188]	4 [0.156]	2 [0.094]
A—Length of reduced section, min (Note 2)	56 [2.25]	45 [1.75]	30 [1.25]	20 [0.75]	16 [0.625]

Figure 2: ASTM Standard E-8 round specimen dimensions. Specimen 3 samples were evaluated in this study.

Figure 3 compares the results obtained from these standard E-8 specimens to the standard mechanical property requirements of conventionally manufactured cast and wrought Ti6Al4V products. These results, as well as results from other studies, suggest that EBM produced Ti6Al4V material exhibits mechanical properties that are in line with those required by the established standards [5].

Table A: Summary of the mechanical property data obtained by testing standard E-8 round specimens.

ID	*Orientation (XY or Z)*	*Avg. YS (ksi)*	*Avg. UTS (ksi)*	*Elongation (%)*	*RA (%)*
1	XY	116	130	17.0	55.2
2	Z	116	130	17.7	47.0

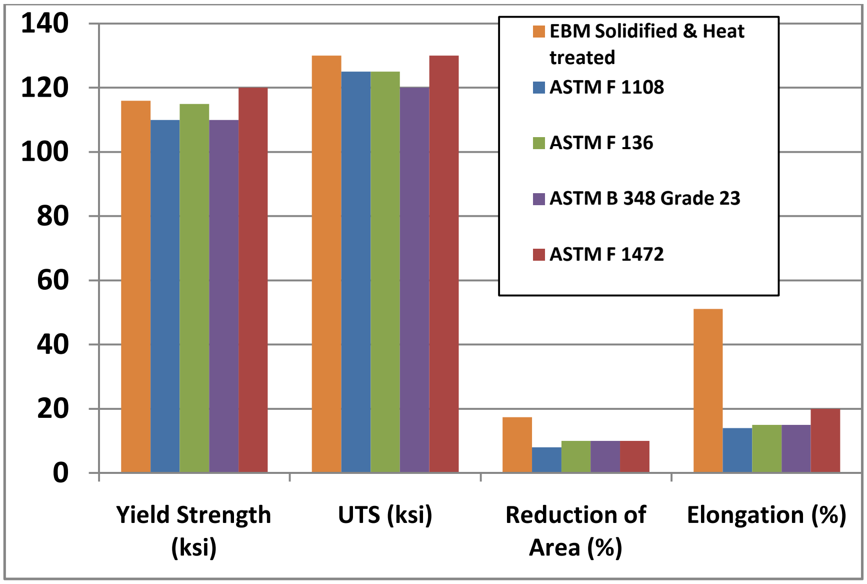


Figure 3: Comparison of EBM produced Ti6Al4V material and conventional Ti6Al4V Standard properties.

Case Study 2: Un-machined Thin Round Specimens

Comparing results from standard ASTM E-8 to the properties of other conventionally produced materials is useful as a benchmarking exercise, and standard E-8 specimens may be sufficient to certify the mechanical properties of certain EBM produced Ti6Al4V products. However, the use of standard samples poses a few problems for the additive manufacturer. Generally, the quantity of material produced by an additive manufacturer is magnitudes less than the amount of material produced by a major casting house or rolling mill. The cost of acquiring machining and tensile testing capabilities to accommodate the ASTM E-8 test methodology is significant to small-scale production. One of the major advantages of additive manufacturing is that one can design a component and literally have a fully functional part in their hands in the span of a few days. If the testing necessary to certify the properties of that component is not conducted at the manufacturing facility, but rather by an independent testing lab, the time involved with obtaining the necessary data adds a significant, undesirable delay in the manufacturing lead-time.

More importantly, standard ASTM E-8 specimens may not be representative of the mechanical properties of EBM produced components with complex geometries, especially components that are smaller than a standard specimen. One of the most promising applications of additive metal manufacturing is the production of truss-like, lattice structures, such as the component shown in **figure 4.** These structures allow an engineer to manipulate properties such as the weight, density, and elastic modulus of designed component by changing the configuration of the lattice. The thickness of structural members, or struts, is generally much less than the thickness of a standard testing coupon. The ideal tensile testing coupon for material certification of EBM produced materials would be a coupon that requires little or no machining, and would mimic the size and production environment of actual components.

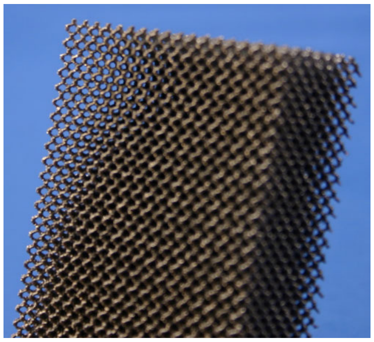


Figure 4: An example of a truss-like structure produced by electron beam melting.

The goal of this case study was to investigate the possibility of producing thin, round tensile samples that would be representative of struts in a designed lattice structure. A secondary goal of the study was to investigate the feasibility of using as-produced Ti6Al4V testing coupons, without any machining prior to tensile testing. To accomplish these goals a series of thin round test specimens, illustrated in **figure 5**, with varying gauge thicknesses were designed and produced in Ti6Al4V alloy using the EBM process. Test coupons were built in three orientations; Z-orientation, XY orientation, and diagonally (45^{o} angle from beam direction).

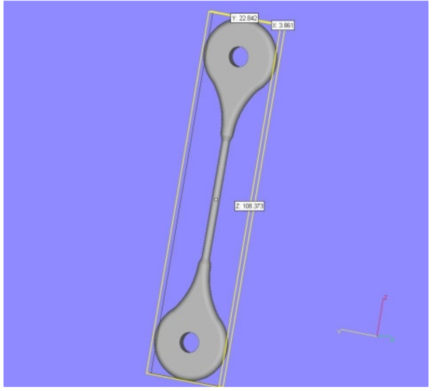


Figure 5: Schematic showing the design of thin round tensile specimens used in case study 2.

The designed sample thickness, EBM produced thickness, and mechanical properties for the three sample sets are presented in **Table B**. The mechanical properties listed in the table were calculated based on the average measured gauge thickness of the un-machined sample. Comparing the measured sample thickness to the designed sample thickness indicates that the EBM process produced samples thicker than the designed geometries. Previous studies have shown that EBM produced components have a inherent surface roughness, and are typically oversized by as much as 0.5 mm on any given surface, especially in the XY plane[4]. What is not well understood is how this additional material influences the mechanical properties of EBM produced components. The effect of this additional thickness and surface roughness on the measured mechanical properties of these specimens is best understood by examining the vertically orientated sample set. **Figure 6** plots the measured yield strength and UTS values for the vertically orientated test specimens as a function of designed sample thickness. In addition to the measured strengths, a theoretical strength is plotted. The theoretical strength was determined by using the designed sample thickness in lieu of the measured sample thickness when calculating the cross-sectional area of the gauge section.

Some interesting conclusions can be made by comparing these two strength values. Consider the case where the additional gauge thickness measured in these samples consisted of a uniform layer of fully dense, smooth material with the same properties as the rest of the material. If this were the case, the measured strength values would not be influenced by the thickness of the designed gauge section. Since the measured strength drops considerably as the designed sample thickness is decreased, it can be concluded that this additional surface material does not possess the same load-bearing capabilities as the base material. Now consider the case where the additional gauge material offers no load-bearing capacity. If this were the case, the theoretical strength values would not be affected by the designed gauge thickness. This is obviously not the case, as **figure 6** indicates that the thin gauge specimens are capable of bearing much more load than expected. The implication of these results is that if an engineer were to design an EBM produced lattice structure consisting of 1mm struts, the structure would actually support more load than the design would indicate. This is because the struts in the as-produced component would be larger than 1mm when produced by the EBM system. However, if a material testing lab was presented with the same EBM produced lattice component, and followed conventional methods for determining strength values they would conclude that the material properties of the component were below the expected values for Ti6Al4V alloys. To accurately determine the mechanical behavior of thin sectioned EBM components the excess surface layer must be removed.

Table B: Summary of tensile properties of un-machined thin round testing specimens.

	XY Orientation			*Diagonal Orientation*			*Vertical Orientation*		
Designed Thickness (mm)	***Measured Thickness (mm)***	***Yield Strength (ksi)***	***UTS (ksi)***	***Measured Thickness (mm)***	***Yield Strength (ksi)***	***UTS (ksi)***	***Measured Thickness (mm)***	***Yield Strength ksi***	***UTS (ksi)***
1.00	N/A	N/A	N/A	1.83	71	80	1.78	80	90
1.50	1.78	105	118	2.16	92	102	2.26	90	100
2.0	2.16	125	140	2.54	97	109	2.70	94	104
2.5	2.67	120	122	2.92	105	116	3.05	107	118
3	2.18	130	142	3.40	107	117	3.56	107	118
3.5	3.68	128	136	3.94	105	116	4.06	109	120
3.8	3.94	131	144	4.17	110	121	4.32	110	121

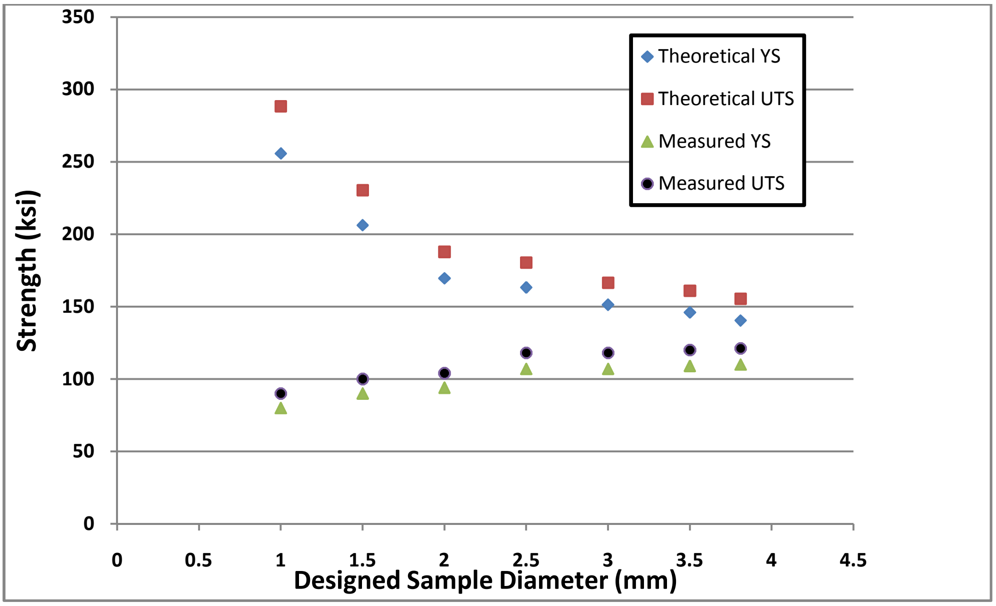


Figure 6: Comparison of measured and theoretical strength values for vertically produced un-machined thin tensile samples.

Case Study 3: Comparison of Flat and Round Specimen Geometries

The ASTM E-8 standard contains over 20 specimen geometries. The sample geometry used to certify a given product is dependent on how the material is produced, and the final dimensions of product. Thin sheet steels are certified using thin flat 'dog-bone' sample geometries, while large Ti6Al4V bar stock is certified using large round tensile specimens. Additive manufacturing poses an interesting dilemma with respect to the selection of sample geometries. The testing coupons produced for material certification of additively manufactured components are typically produced separately allowing for virtually and test sample configuration. The goal of this case study was to compare the mechanical properties of EBM produced Ti6Al4Vmaterial obtained using standard E-8 flat 'dog-bone' testing specimens (**figure 7**[2]) to results obtained using the standard 1" gauge length round samples. The necessary samples were harvested out of large blocks of EBM produced Ti6Al4V material and were tested along in the XY Orientation. The material tested in this study was not subjected to HIP prior to testing.

Table C summarizes the results obtained from during this study. The sample size in this study was not sufficient to draw any strong conclusions, as the values for both testing specimen geometries are rather close, but the round specimens are slightly stronger. A larger scale study will be necessary to determine if a difference in the results obtained between the sample geometries exists.

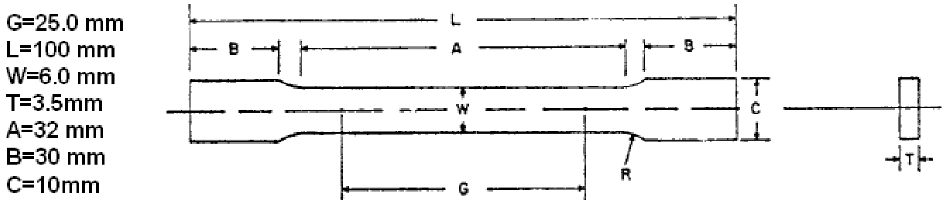


Figure 7: Flat E-8 specimen geometry

Table C: Summary of the mechanical properties obtained from both flat and round standard ASTM E-8 specimens

Sample Configuration	*Number of Samples*	*Avg. YS (ksi)*	*Avg. UTS (ksi)*	*Reduction of Area (%)*	*Avg. Elong. (%)*
Flat	**6**	**120**	**134**	**33**	**15**
Round	**6**	**123**	**135**	**39**	**17**

Conclusions

This paper presents case studies that investigate the effects of sample geometries on the measured mechanical properties of EBM produced Ti6Al4V alloys. Utilizing standard round ASTM E-8 test specimens it was shown that EBM produced materials have properties similar to conventionally produced Ti6Al4V alloys.

Although standard E-8 specimens provide useful information about the overall capabilities of the EBM production process, they provide some logistical challenges for the additive metal manufacturer, and they do not necessarily represent the mechanical behavior one can expect from EBM produced components with complex geometries. Particularly, truss-like structures pose an interesting dilemma as they are much thinner than conventionally produced test specimens, and have an inherent excess surface roughness. This excess surface roughness makes it difficult to predict and test mechanical performance of a lattice structure because it increases the cross-sectional area of the structural members, but the extent of its load-bearing contribution is unknown. The use of flat specimens opposed to round specimens may yield slightly lower yield and UTS; however additional testing will be necessary to show a statistically significant difference.

The ultimate goal of the additive manufacturing industry should be to develop a standard testing methodology tailored to unique challenges and capabilities associated with layer based deposition of material. These case studies provide information that can be used to aid further studies in developing such standards.

References

1. Annual Book of ASTM Standards, Vol. 31.01 Medical and Surgical Materials and Devices, 2006.
2. R. Boyer, G. Welsh and W.W. Collings, Material Properties Handbook: Titanium Alloys, ASM International, Materials Park, OH, 2003.
3. ASTM Standard: E 8-08 Test Methods for Tensile Tension Testing of Metallic Materials, ASTM, 2008.
4. Christensen, A., Lippincott, A., Kircher, R., *Qualification of Electron Beam Melted (EBM) Ti6Al4V-ELI for Orthopaedic Applications*, MPMD, Palm Desert, CA, 2007.
5. Murr, L.E., et al., *Microstructure and mechanical behavior of Ti-6Al-4V produced by rapid-layer manufacturing, for biomedical applications*, Journal of Mechanical Behavior of Biomedical Materials, May, 2008, pp 20-32.