Additive manufacturing processes effect on Ti-6Al-4V durability

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Abstract.

This empirical study compares the mechanical performance of titanium machined from mill stock material vs. additive manufactured titanium. The study also shows mechanical characteristics of machined titanium compared to direct laser sintering (DMLS) titanium that has undergone a shot peening process.

The scope is limited to evaluating Ø6mm round Ti6Al4V rods (per ASTM F136) in static and dynamic four-point bending per ASTM F2193. In addition, a static tensile testing (per ASTM E8) was performed to evaluate machined Ti6Al4V vs additive manufactured Ti6Al4V.

In the first comparison (machined vs additive manufacturing) there was no substantial performance difference in static testing, with a bending stiffness of 867.18 +/-28.53 (N/mm) for all specimens. For dynamic testing, the machined rods reached 2,000,000 cycles without evidence of failure at a stress of 167ksi. Applied stress was reduced to 69ksi for the DMLS rods to reach 2,000,000 cycles. Fracture occurred at 41ksi on the EB rods.

Testing to compare machined titanium vs shoot peened DMLS titanium is currently underway. The null hypothesis is that there is no difference between the mechanical performance and material characteristics between the different manufacturing and post-manufacturing processes.

1.Theoretical considerations

1.1 Tensile properties basics

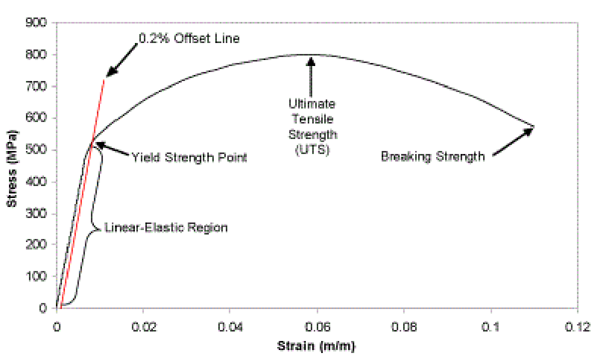

Figure 1. Stress/Strain curve

Stress

It is the ratio between the force applied and the cross-sectional area of the specimen.

Strain

It is used to relate the elongation with the initial length.

Poisson's ratio

The negative of the ratio of the lateral (transversal) strain to the axial strain for a uniaxial stress state.

Uniform Elastic Deformation

The region up to the Yield Strength Point. Material has the tendency to recover after deformation when stress is removed

Yield Strength

Stress required to produce a very small amount of plastic deformation. The offset yield strength is the stress corresponding to the intersection of the stress-strain curve and a line parallel to the elastic part of the curve offset by a specified strain (in the US the offset is typically 0.2% for metals and 2% for plastics).

Tensile Strength

Force applied to break the fibers of the cross-sectional area is known as tensile strength.

Ultimate Tensile Strength

The ultimate tensile strength (UTS) or, more simply, the tensile strength, is the maximum engineering stress level reached in a tension test. The strength of a material is its ability to withstand external forces without breaking.

Uniform Plastic Deformation

The region between Yield Strength Point and Ultimate Tensile Strength Point.

Breaking strength point

The place where the fracture occurs.

1.2 Fatigue

Fatigue fracture is one of the primary damage mechanisms of structural components. This fracture results from cyclic stresses that are below the ultimate tensile stress, or even below the yield stress of the material.

1.2.1 Fatigue Load Application

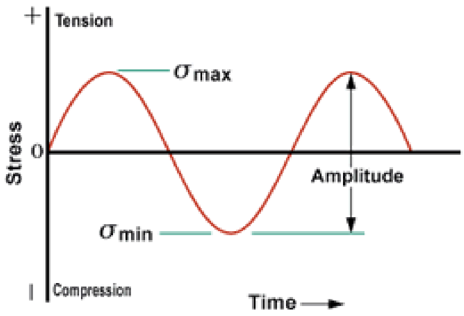

Figure 2. Tension/ Compression Sinusoidal Loading

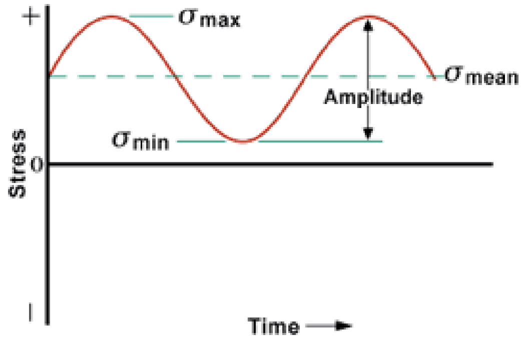

Figure 3. Tension/ Tension Sinusoidal Loading

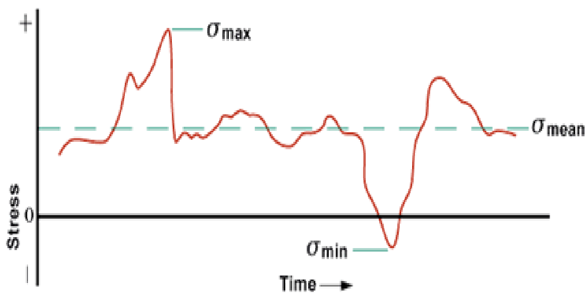

Figure 4. Variable Amplitude Loading

1.2.2 Fatigue testing procedures

There are two general types of fatigue tests.

One test focuses on the nominal stress required to cause a fatigue failure in a number of cycles. This type of test is known as cyclic stress-controlled fatigue test. The data is presented as a plot of stress (S) against the number of cycles to failure (N), which is known as an S-N curve. A log scale is almost always used for N.

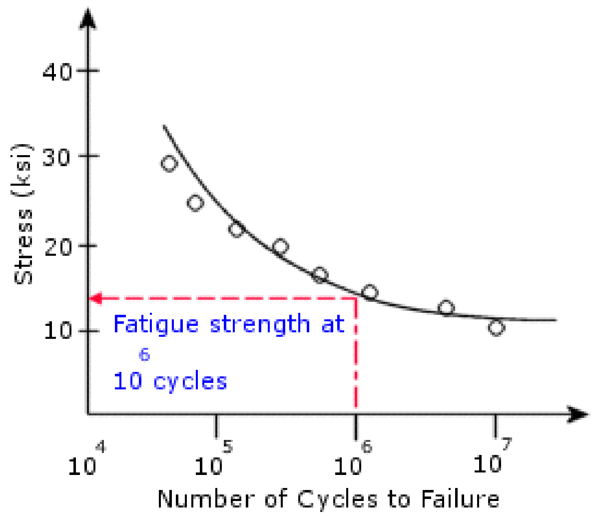

Figure 5. S-N Diagram

The data is obtained by cycling specimens until failure. The usual procedure is to test the first specimen at a high peak stress where failure is expected in a fairly short number of cycles. Then the test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles. For metals this number is usually at least 10^7 cycles. There are applications, like medical devices, where the number of cycles to failure is smaller ($2x10^6$ or $3x10^6$). The highest stress at which a runout (non-failure) occurs is taken as the fatigue threshold.

Another test widely performed especially in thermal cycling is the strain-controlled cycling loading. In this test, the strain amplitude is held constant during cycling. Cracks might appear as a result of thermal expansions and contractions. In this case an ε-N diagram is created.

1.3 Shot peening

Shot peening is a cold work process used to modify mechanical properties of metals. Shot peening is used to strengthen and relieve stress in mechanical components. The process involves blasting the surface of the material with small spherical shots (metal, glass or ceramic). The shot acts like a peen hammer, dimpling the surface and causing compression stresses under the dimple. As the media continues to strike the part, it forms multiple overlapping dimples throughout the metal surface being treated. The surface compression stress strengthens the metal, ensuring that the finished part will resist fatigue failures.

2. Empirical Testing

2.1. Material composition

To perform the testing, certified Ti6Al4V round rods were acquired, with a chemical composition defined by the ASTM F136-13 [1].

Element	Composition, % (mass/mass)
Nitrogen, max	0.05
Carbon, max	0.08
Hydrogen, max	0.012
Iron, max	0.25
Oxygen, max	0.13
Aluminum	5.5-6.5
Vanadium	3.5-4.5
Titanium	Reminder

Table 1. Ti6Al4V chemical composition by ASTM F136

Additive manufactured Ti-6Al-4V coupons were certified to have a chemical composition shown in the table below, compatible with ASTM F3001-14 [2].

Element	Composition, % (mass/mass)
Nitrogen, max	0.05
Carbon, max	0.08
Hydrogen, max	0.012
Iron, max	0.25
Oxygen, max	0.13
Aluminum	5.5-6.5
Vanadium	3.5-4.5
Yttrium, max	0.005
Other elements, each, max	0.1
Other elements, total, max	0.4
Titanium	Remainder

Table 2. Ti6Al4V chemical composition by ASTM F3001

2.2 Testing environment.

All testing was performed in laboratory ambient air at room temperature.

2.3 Four Point Bending Test Methods - ASTM F2193

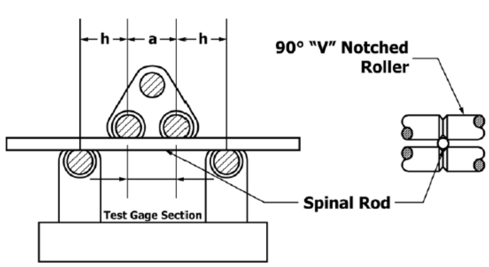

Figure 6. Four Point Bending Test Rig

2.3.1. Four point bending for static and dynamic testing was setup per ASTM F2193. The "a" and "h" values for all testing was 25mm.

2.3.2 Static Four Point Bending

2.3.2.1. Rods from each control group were tested in static compression four point bending, setup per ASTM F2193.

2.3.2.2 A displacement control mode at a rate of 0.1 mm/sec was used.

2.3.2.3. Displacement and force data were recorded at a rate of approximately 60Hz.

2.3.2.4. Testing was performed until the load dropped by 20% of UTS or until set-up geometric limit were reached.

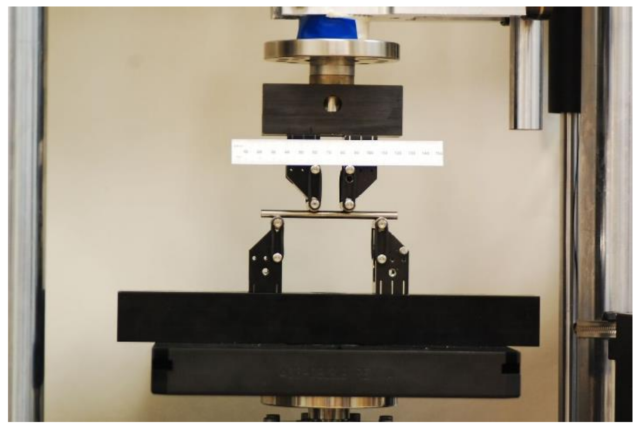

Figure 7. Four Point Bending Setup Picture

2.3.3. Dynamic Four Point Bending

2.3.3.1. Six (6) rods from each control group were tested in dynamic compression four point bending, setup per ASTM F2193.

2.3.3.2. Dynamic testing was performed at frequency of 10 Hz.

2.3.3.3. Loading was applied with a sinusoidal waveform with an R-Ratio of 10.

2.3.3.4. The initial loading conditions for dynamic four point bending were determined based upon the information from the static testing of the CNC machined titanium rods. The loading was approximately 90% of the Yield.

2.3.3.5. Peaks and valleys were captured at every 1000 cycles and saved.

2.3.3.6. Testing was performed until device failure (visible fractures and/or fractures observed at 10x magnification) or achieving run-out of 2 000 000 cycles.

2.5 Test Coupon Information

2.5.1 Ø6 mm x 100 mm Ti-6Al-4V rods were used for all testing

2.5.2 Additive manufactured Ti-6Al-4V, EBM process rods and DMLS process rods, had the layering cross-section transverse to the rod axis.

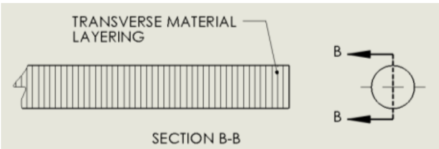

Figure 8. DMLS and EBM Ti-6Al-4V layering

2.5.3 Surface finish
CNC machined rods: 16.9µin
EBM rods: 1290.1 µin
DMLS rods: 497.1µin

2.6. Static Tensile Machined Ti6Al4V vs DMLS and EBM Ti6Al4V Test Results

Specimen	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation	Young's Modulus (Msi)	Poisson's Ratio
CNC	161.5	140.5	18.5%	15.5	0.322
DMLS	158.0	146.0	18.0%	17.9	0.334
EB	146.0	133.5	18.0%	17.5	0.331

Table 3. Machined Ti6Al4V vs DMLS and EB Ti6Al4V material properties

2.6. Static four point bending Machined Ti6Al4V additive manufacturing Ti6Al4V test results

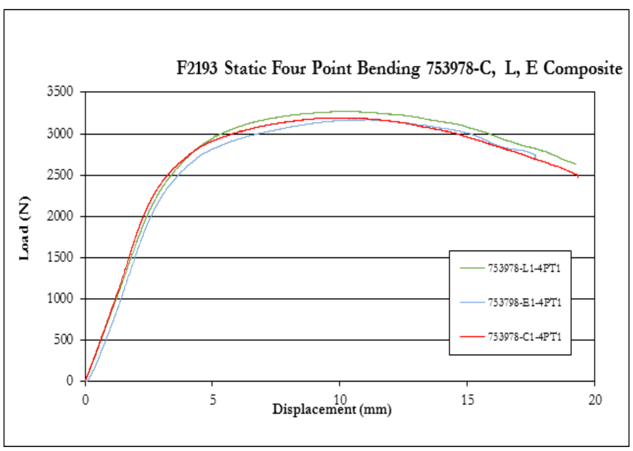

Figure 9. Stress/Strain curve for Machined Ti6Al4V vs DMLS and EB Ti6Al4V

Figure 10. Machined Ti6Al4V vs DMLS and EB Ti6Al4V after four point bending static test

Specimen #	753978-C1-4PT1	753978-L1-4PT1	753798-E1-4PT1
Manufacturing process	CNC	Laser Sintering	E-beam
0.2% Yield Displacement (mm)	2.42	2.5	2.45
0.2% Yield Load (N)	2 132.47	2 074.77	2 049.56
Bending Stiffness (N/mm)	899.91	847.58	854.05
Bending Structural Stiffness (N-m²)	5.86	5.52	5.56
Bending Strength (N-m)	26.66	25.93	25.62
Ultimate Strength (N)	3 191.78	3 270.88	3 169.04
Displacement @ Ultimate Strength (mm)	10.21	10.34	11.03
Ultimate Bending Moment (N-m)	39.9	40.89	39.61
Linear Fit Offset (mm)	0.06	0.05	0.22

0.2% offset: 0.05 mm; a=h=25 mm
Failure Mode: Permanent deformation of the rod.

Table 4. Four point bending static test results

2.7. Dynamic four point bending Machined Ti6Al4V vs DMLS and EBM Ti6Al4V Test Results

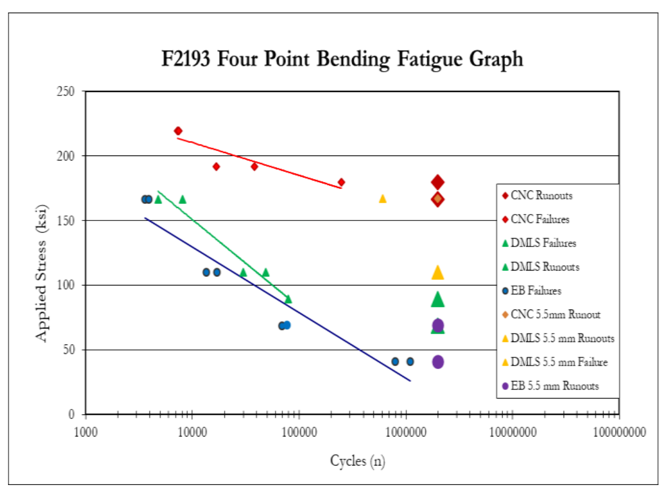

Figure 11. S-N composite diagram Machined Ti6Al4V vs DMLS and EBM Ti6Al4V

Specimen	Applied Load (N)	Applied Stess (ksi)	Cycles Tested (n)	Status	Comments
753978-C2-F1	1950	167	2,000,000	Runout	
753978-C3-F2	2568	220	7,408	Failure	
753978-C4-F3	2247	192	16,806	Failure	
753978-C5-F4	1950	167	2,000,000	Runout	
753978-C6-F5	2247	192	38,391	Failure	
753978-C7-F6	2568	220	7,226	Failure	
753978-C8-F7	2100	180	248,212	Failure	
753978-C9-F8	2100	180	2,000,000	Runout	
753978-C10-F9	1505		77,855	Failure	Turned down to 5.5mm; removing out of testing. Load cell problems.
753978-C11-F10	1505	167	2,000,000	Runout	Turned down to 5.5mm

Table 5. Dynamic four point bending test results for CNC machined rods

Specimen	Applied Load (N)	Applied Stess (ksi)	Cycles Tested (n)	Status	Comments
753978-L2-F1	1950	167	4,752	Failure	
753978-L3-F2	1285	110	30,117	Failure	
753978-L4-F3	803	69	2,000,000	Runout	
753978-L5-F4	1043	89	2,000,000	Runout	
753978-L6-F5	1950	167	8,133	Failure	
753978-L7-F6	1285	110	48,876	Failure	
753978-L8-F7	803	69	2,000,000	Runout	
753978-L9-F8	1043	89	79,277	Failure	
753978-L10-F9	1505	167	603,510	Failure	Turned down to 5.5mm
753978-L11-F10	990	110	2,000,000	Runout	Turned down to 5.5mm

Table 6. Dynamic four point bending test results for DMLS machined rods

Specimen	Applied Load (N)	Applied Stess (ksi)	Cycles Tested (n)	Status	Comments
753978-E2-F1	1950	167	3,882	Failure	
753978-E3-F2	1285	110	16,933	Failure	
753978-E4-F3	803	69	77,939	Failure	
753978-E5-F4	482	41.2	797,732	Failure	
753978-E6-F5	1950	167	3,583	Failure	
753978-E7-F6	1285	110	13,569	Failure	
753978-E8-F7	803	69	68,715	Failure	
753978-E9-F8	482	41.2	1,092,846	Failure	
753978-E10-F9	1505	167	15,936	Failure	Turned down to 5.5mm
753978-E11-F10	371.2	41.2	2,000,000	Runout	Turned down to 5.5mm
753978-E12-F11	619	69	2,000,000	Runout	Turned down to 5.5mm

Table 7. Dynamic four point bending test results for EBM machined rods

2.8 Machined Ti6Al4V vs post manufacturing processed DMLS Ti6Al4V

2.8.1 Hot Isostatic Pressed (HIP) Process

All specimens from the As-built DMLS combined with HIP group, single pass shot peened group and double pass shot peened group were thermally treated by a hot isostatic compression process under inert atmosphere at 100 MPa and 920 ± 10 °C soaking at a constant temperature of 2 hours ± 30 minutes, and cooled under inert atmosphere to below 150 ºC.

2.8.2 Shot Peening Process Specifics

All specimens in the single pass shot peened group and double pass shot peened group were shot peened per AMS-2430U, *Shot Peening* [3]. The single pass shot peened specimens were shot peened with MI-230-H^A peen media (Cast steel; hardness 55-62 HRC, 0.023 inch diameter) at an intensity of 0.012-0.015A with 100% coverage. The double pass shot peened specimens were processed initially with the single pass shot peened specimens per the same parameters. After the initial pass, the double pass shot peened specimens underwent a second pass with MI-230-H^B peen media (Cast steel; hardness 55-62 HRC, 0.01 inch diameter) at an intensity of 0.005-0.008A with 100% coverage. The intensity was measured via 0.051 inch Almen strip deflection.

2.8.3 Static four point bending Machined Ti6Al4V post manufacturing processed DMLS Ti6Al4V results

One (1) CNC lathe machine rod, one (1) as built DMLS rod, one (1) as-built DMLS combined with HIP rod, one (1) single pass shot peened rod and one (1) double pass shot peened rod were tested in static four-point bending per ASTM F2193. Table 2 contains the results for each tested specimens. A composite graph with all samples is shown in Figure 12.

Testing was stopped when there was a reduction of force greater than 20% of the maximum measured force. The failure mode for all specimens was permanent deformation of the rod with marks on the rod from the loading and support v-notch type rollers.

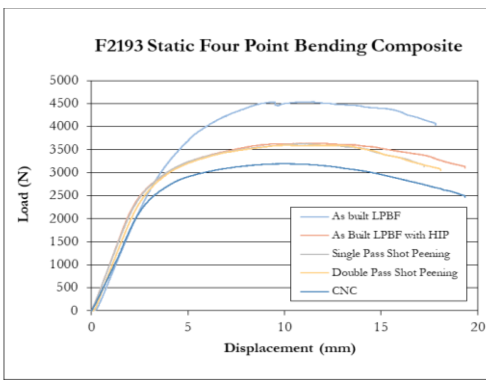

Figure 12. Stress/Strain curve for Static four point bending Machined Ti6Al4V vs post manufacturing processed DMLS Ti6Al4V

Rod Type	CNC	As-built LPBF	As-built LPBF with HIP	Single Pass Shot Peened	Double Pass Shot Peened
0.2% Bending Yield Load (N)	2 132	2 048	2 139	2 079	1 998
Bending Stiffness (N/mm)	900	1 010	1 126	1 099	1 084
Bending Structural Stiffness (N-m^2)	5.9	6.6	7.3	7.2	7.1
Bending Strength (N-m)	26.7	25.6	26.7	26	25
Ultimate Strength (N)	3 192	4 540	3 638	3 626	3 597
Ultimate Bending Moment (N-m)	39.9	56.8	45.5	45.3	45

Table 8. Static four point bending Machined Ti6Al4V vs post manufacturing processed DMLS Ti6Al4V test results

2.8.3 Dynamic four point bending Machined Ti6Al4V vs post manufacturing processed DMLS Ti6Al4V

Eight (8) CNC lathe machine rods, six (6) as built DMLS rods, six (6) as-built DMLS combined with HIP rods, six (6) single pass shot peened rods and six (6) double pass shot peened rods were tested in dynamic four-point bending. Tables 3 -7 contains the fatigue testing results for each tested specimen.

Two (2) CNC lathe machined rods were tested at an applied stress of 167 ksi and achieved the endurance value of 2 000 000 cycles without evidence of failure. Six (6) specimens were tested at three (3) different stress levels higher than 167 ksi which resulted in failure. The failure mode for all failure samples was a partial fracture of the rod within the load span.

Six (6) as built DMLS rods were tested at five (5) different stress levels. The initial specimen was tested at the runout stress of the CNC machined rod of 167 ksi. Upon failure, stress levels were reduced for each consecutive specimen until a stress of 41 ksi was reached. All samples resulted in failure. The failure mode for all failure samples was a complete or partial fracture of the rod within the load span.

Six (6) as built DMLS combined with HIP rods were tested at five (5) different stress levels. The initial specimen was tested at the runout stress level of the CNC machined rod of 167 ksi. Upon failure, stress levels were reduced for each consecutive specimen until a runout value was reached. Two (2) as built DMLS combined with HIP rods were tested at an applied stress of 56 ksi and achieved the endurance value of 2 000 000 cycles without evidence of failure. Samples tested at higher stress levels resulted in failure. The failure mode for all failure samples was a complete or partial fracture of the rod within the load span.

Six (6) single pass shot peened rods were tested at four (4) different stress levels. The initial specimen was tested at the runout stress level of the CNC machined rod of 167 ksi. Upon failure, stress levels were reduced for each consecutive specimen until a runout value was reached. Two (2) single pass shot peened rods were tested at an applied stress of 69 ksi and achieved the endurance value of 2 000 000 cycles without evidence of failure. One sample was tested at a stress of 89 ksi and achieved the endurance value of 2 000 000 cycle but the results of the second sample at 89 ksi is to be determined. Samples tested at higher stress levels resulted in failure. The failure mode for all failure samples was a complete or partial fracture of the rod within the load span.

Six (6) double pass shot peened rods were tested at four (4) different stress levels. The initial specimen was tested at the runout stress level of the CNC machined rod of 167 ksi. Upon failure, stress levels were reduced for each consecutive specimen until a runout value was reached. Two (2) double pass shot peened rods were tested at an applied stress of 110 ksi and achieved the endurance value of 2 000 000 cycles without evidence of failure. Samples tested at higher stress levels resulted in failure. The failure mode for all failure samples was a complete or partial fracture of the rod within the load span.

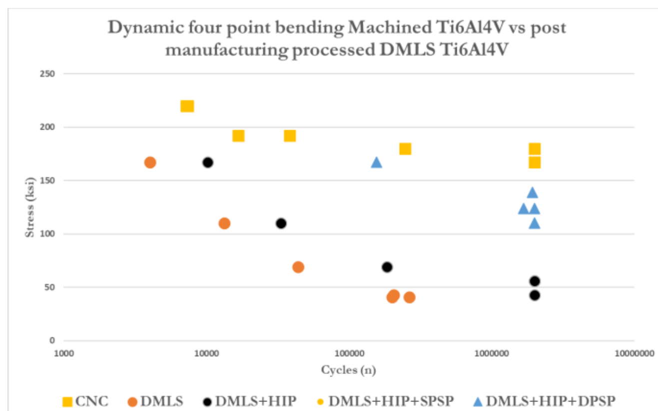

Figure 13. S-N composite diagram for Dynamic four point bending Machined Ti6Al4V vs post manufacturing processed DMLS Ti6Al4V

Specimen	Applied Stress	Cycles Tested	Failure modes and/or Comments
	(ksi)	(n)	
753978-C2-F1	167	2 000 000	Runout. Marks from rollers observed.
753978-C3-F2	220	7 408	Partial fracture of the rod within the load span.
753978-C4-F3	192	16 806	Partial fracture of the rod within the load span.
753978-C5-F4	167	2 000 000	Runout. Marks from rollers observed.
753978-C6-F5	192	38 391	Partial fracture of the rod within the load span.
753978-C7-F6	220	7 226	Partial fracture of the rod within the load span.
753978-C8-F7	180	248 212	Partial fracture of the rod within the load span.
753978-C9-F8	180	2 000 000	Runout. Marks from rollers observed.

Table 9 Dynamic four point bending CNC Machined Ti6Al4V

Specimen	Applie d Stress	Cycles Tested	Failure modes and/or Comments
	ksi	(n)	
755679-Control-F1	167	4 025	Complete fracture of the rod within the load span.
755679-Control-F2	110	13 384	Complete fracture of the rod within the load span.
755679-Control-F3	69	43 960	Complete fracture of the rod within the load span.
755679-Control-F4	43	205 764	Partial fracture of the rod within the load span.
755679-Control-F5	41	264 196	Complete fracture of the rod within the load span.
755679-Control-F6	41	201 303	Complete fracture of the rod within the load span.

Table 10. Dynamic four point bending for "as manufactured" DMLS Ti6Al4V test results

Specimen	Applied Stress	Cycles Tested	Failure modes and/or Comments
	ksi	(n)	
755679-HIP-F1	167	10 242	Complete fracture of the rod within the load span.
755679-HIP-F2	110	33 246	Partial fracture of the rod within the load span.
755679-HIP-F3	69	185 162	Partial fracture of the rod within the load span.
755679-HIP-F4	43	2 000 000	Runout. Marks from rollers observed.
755679-HIP-F5	56	2 000 000	Runout. Marks from rollers observed.
755679-HIP-F6	56	2 000 000	Runout. Marks from rollers observed.

Table 11. Dynamic four point bending for "as manufactured" DMLS plus HIP Ti6Al4V test results

Specimen	Applie d Stress	Cycles Tested	Failure modes and/or Comments
	ksi	(n)	
755679-SP-1-F1	167	40 013	Complete fracture of the rod within the load span.
755679-SP-1-F2	110	1 730 119	Partial fracture of the rod within the load span.
755679-SP-1-F3	69	2 000 000	Runout. Marks from rollers observed.
755679-SP-1-F4	69	2 000 000	Runout. Marks from rollers observed.
755679-SP-1-F5	89	2 000 000	Runout. Marks from rollers observed.
755679-SP-1-F6	89	2 000 000	Runout. Marks from rollers observed.

Table 12. Dynamic four point bending for "as manufactured" DMLS plus HIP plus Single Pass Shot Peening Ti6Al4V test results

Specimen	Applied Stress ksi	Cycles Tested (n)	Failure modes and/or Comments
755679-SP-2-F1	167	156 266	Partial fracture of the rod within the load span.
755679-SP-2-F2	110	2 000 000	Runout. Marks from rollers observed
755679-SP-2-F3	139	1 933 535	Partial fracture of the rod within the load span.
755679-SP-2-F4	124	2 000 000	Runout. Marks from rollers observed.
755679-SP-2-F5	124	1676 672	Complete fracture of the rod within the load span.
755679-SP-2-F6	110	2 000 000	Runout. Marks from rollers observed.

Table 13. Dynamic four point bending for "as manufactured" DMLS plus HIP plus Double Pass Shot Peening Ti6Al4V test results

Conclusions

A. Dynamic four point bending Machined Ti6Al4V vs DMLS and EBM Ti6Al4V

No significant performance differences were noticed in static four point bending between the three control groups. In the dynamic testing case, CNC machined rods reached the runout under higher stress conditions overall. Specimens made of EBM Ti6Al4V performed poorly even under much lower load conditions comparing to the CNC machined specimens. Removing the poor surface finish layer (turning the rods down to 5.5 mm) improved the fatigue performance of both DMLS and EBM rods.

B. Dynamic four point bending Machined Ti6Al4V vs post manufacturing processed DMLS Ti6Al4V

The null hypothesis was that there is no difference between the mechanical performance and material characteristics between the different manufacturing and post manufacturing processes of round rods.

For static testing, the null hypothesis was correct as there is no substantial difference of the stiffness and yields for the different manufacturing processes tested. There is a difference that is noted in the Uniform Plastic Deformation area and also in the UTS values. For dynamic testing, the null hypothesis was incorrect as there was a notable difference in the dynamic mechanical performances among the different manufacturing and post manufacturing processes.

The CNC machined group resulted in a stress level of 167 ksi reaching the endurance limit of 2 000 000 cycles. The CNC machined group resulted in the highest runout stress of all groups tested. The as printed group with no additional post processing resulted in the most extreme difference in fatigue life with no endurance limit achieved at the lowest tested stress of 41 ksi. The post manufacturing processes on the additive manufactured rods resulted in increased fatigue life. The as printed rods that underwent HIP resulted in a runout stress of 56 ksi. The additive manufactured rods that underwent HIP and a single pass of shot peening resulted in a runout stress of 89 ksi. The additive manufactured rods that underwent HIP and a double pass of shot peening resulted in a runout stress of 139 ksi.

Although the additive manufactured rods that underwent different post manufacturing processes improved fatigue life, the fatigue life of additively manufactured rods did not meet the fatigue life of a CNC machined rod.

Future testing

The investigation to compare the additive manufactured metal parts with parts machined from wrought is ongoing. We are planning to perform the following testing in the near future:

1. More tensile testing to check consistency over multiple specimens.
2. Test different geometry specimens
3. Push the run-out from 2 000 000 cycles to a more standard 10 000 000 cycles and test more specimens
4. Turn additive manufactured rods to remove the poor surface finish layer and compare them with the same diameter CNC machined from wrought rods.

References

[1]ASTM F136-13, *Standard Specification for Wrought Titanium-6Aluminum-4Vanadium ELI (Extra Low Interstitial) Alloy for Surgical Implant Applications (UNS R56401)*, ASTM International, West Conshohocken, PA, 2013, www.astm.org

[2] ASTM F3001-14, *Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion,* ASTM International, West Conshohocken, PA, 2013, www.astm.org

[3]AMS-2430U, *Shot Peening,* SAE International, Warrendale, PA, 2018, www.sae.org