

Material data sheet

EOS Aluminium AlSi10Mg

EOS Aluminium AlSi10Mg is an aluminium alloy in fine powder form which has been specially optimised for processing on EOSINT M systems

This document provides information and data for parts built using EOS Aluminium AlSi10Mg powder (EOS art.-no. 9011-0024) on the following system specifications:

- EOSINT M 280
 - with PSW 3.6 and Original EOS Parameterset AlSi10Mg_Speed 1.0
- EOS M 290 400Watt
 - with EOSPRINT 1.0 and Original EOS Parameterset AlSi10Mg_Speed 1.0

Description

AlSi10Mg is a typical casting alloy with good casting properties and is typically used for cast parts with thin walls and complex geometry. It offers good strength, hardness and dynamic properties and is therefore also used for parts subject to high loads. Parts in EOS Aluminium AlSi10Mg are ideal for applications which require a combination of good thermal properties and low weight. They can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required.

Conventionally cast components in this type of aluminium alloy are often heat treated to improve the mechanical properties, for example using the T6 cycle of solution annealing, quenching and age hardening. The laser-sintering process is characterized by extremely rapid melting and re-solidification. This produces a metallurgy and corresponding mechanical properties in the as-built condition which is similar to T6 heat-treated cast parts. Therefore such hardening heat treatments are not recommended for laser-sintered parts, but rather a stress relieving cycle of 2 hours at 300 °C (572 °F). Due to the layerwise building method, the parts have a certain anisotropy, which can be reduced or removed by appropriate heat treatment - see Technical Data for examples.

Material data sheet

Technical data

General process and geometrical data

Typical achievable part accuracy [1] [2]	100 µm
Smallest wall thickness [1] [3]	approx. 0.3 – 0.4 mm approx. 0.012 – 0.016 inch
Surface roughness, as built, cleaned [1] [4]	R _a 6 - 10 µm, R _z 30 - 40 µm R _a 0.24 - 0.39 x 10 ³ inch R _z 1.18 - 1.57 x 10 ³ inch
- after micro shot-peening	R _a 7 - 10 µm, R _z 50 - 60 µm R _a 0.28 - 0.39 x 10 ³ inch R _z 1.97 - 2.36 x 10 ³ inch
Volume rate [5]	7.4 mm ³ /s (26.6 cm ³ /h) 1.6 in ³ /h

- [1] These properties were determined on an EOSINT M 270.
- [2] Based on users' experience of dimensional accuracy for typical geometries. Part accuracy is subject to appropriate data preparation and post-processing, in accordance with EOS training.
- [3] Mechanical stability dependent on the geometry (wall height etc.) and application
- [4] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [5] The volume rate is a measure of the building speed during laser exposure. The overall building speed is dependent on the average volume rate, the time required for coating (depends on the number of layers) and other factors, e.g. DMLS settings.

Material data sheet

Physical and chemical properties of the parts

Material composition	Al (balance) Si (9.0 - 11.0 wt-%) Fe (0.55 wt-%) Cu (0.05 wt-%) Mn (0.45 wt-%) Mg (0.2 - 0.45 wt-%) Ni (0.05 wt-%) Zn (0.10 wt-%) Pb (0.05 wt-%) Sn (0.05 wt-%) Ti (0.15 wt-%)
Relative density	approx. 99.85 %
Density	2.67 g/cm ³ 0.096 lb/in ³

Material data sheet

Mechanical properties of the parts

	As built	Heat treated [9]
Tensile strength [6]		
- in horizontal direction (XY)	460± 20 MPa 66.7 ± 2.9 ksi	345± 10 MPa 50.0± 1.5 ksi
- in vertical direction (Z)	460± 20 MPa 66.7± 2.9 ksi	350± 10 MPa 50.8± 1.5 ksi
Yield strength (Rp 0.2 %) [6]		
- in horizontal direction (XY)	270± 10 MPa 39.2± 1.5 ksi	230± 15 MPa 33.4± 2.2 ksi
- in vertical direction (Z)	240± 10 MPa 34.8± 1.5 ksi	230± 15 MPa 33.4± 2.2 ksi
Modulus of elasticity		
- in horizontal direction (XY)	75± 10 GPa 10.9± 0.7 Msi	70± 10 GPa 10.2± 0.7 Msi
- in vertical direction (Z)	70± 10 GPa 10.2± 0.7 Msi	60± 10 GPa 8.7± 0.7 Msi
Elongation at break [6]		
- in horizontal direction (XY)	(9 ± 2) %	12 ± 2%
- in vertical direction (Z)	(6 ± 2) %	11 ± 2%
Hardness [7]	approx. 119± 5 HBW	
Fatigue strength [1] [8]		
- in vertical direction (Z)	approx. 97± 7 MPa approx. 14.1± 1.0 ksi	

- [6] Mechanical strength tested as per ISO 6892-1:2009 (B) annex D, proportional specimens, specimen diameter 5 mm, original gauge length 25 mm (1 inch).
- [7] Hardness test in accordance with Brinell (HBW 2.5/62.5) as per DIN EN ISO 6506-1. Note that measured hardness can vary significantly depending on how the specimen has been prepared.
- [8] Fatigue test with test frequency of 50 Hz, R = -1, measurement stopped on reaching 5 million cycles without fracture.
- [9] Stress relieve: anneal for 2 h at 300 °C (572 °F).
- [10] These properties were determined on an EOSINT M 280-400W. Test parts from following machine type EOS M 290-400W correspond with these data.

Material data sheet

Thermal properties of parts

	As built [1]	Heat treated [1] [9]
Thermal conductivity (at 20 °C)		
- in horizontal direction (XY)	approx. 103 ± 5 W/m°C	approx. 173 ± 10 W/m°C
- in vertical direction (Z)	approx. 119 ± 5 W/m°C	approx. 173 ± 10 W/m°C
Specific heat capacity		
- in horizontal direction (XY)	approx. 920 ± 50 J/kg°C	approx. 890 ± 50 J/kg°C
- in vertical direction (Z)	approx. 910 ± 50 J/kg°C	approx. 890 ± 50 J/kg°C

Abbreviations

approx. approximately
 wt weight

Notes

The data are valid for the combinations of powder material machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS, EOSINT and DMLS are registered trademarks of EOS GmbH.

2014 EOS GmbH – Electro Optical Systems. All rights reserved.

Material data sheet

EOS CobaltChrome MP1

EOS CobaltChrome MP1 is a cobalt-chrome-molybdenum-based superalloy powder which has been optimized especially for processing on EOSINT M systems.

This document provides information and data for parts built using EOS CobaltChrome MP1 powder (EOS art.-no. 9011-0012) on the following system specifications:

EOSINT M 270 Installation Mode Standard

with PSW 3.3 or 3.4 and default job CC20_MP1_020_default.job or
CC20_MP1_040_default.job

EOSINT M 270 Dual-Mode

with PSW 3.5 and EOS Original Parameter Set MP1_Surface 1.0 or
MP1_Performance 1.0

EOSINT M 280

with PSW 3.5 and EOS Original Parameter Set MP1_Surface 1.0, MP1_Performance 1.0
or MP1_Speed 1.0

Description

Parts built from EOS CobaltChrome MP1 conform to the chemical composition UNS R31538 of high carbon CoCrMo alloy. They are nickel-free (< 0.1 % nickel content) and are characterized by a fine, uniform crystal grain structure. As built EOS CobaltChrome MP1 meets the chemical and mechanical specifications of ISO 5832-4 and ASTM F75 for cast CoCrMo implant alloys, as well as the specifications of ISO 5832-12 and ASTM F1537 for wrought CoCrMo implants alloys except remaining elongation. The remaining elongation can be increased to fulfil even these standards by high temperature stress relieving or hot isostatic pressing (HIP).

Parts made from EOS CobaltChrome MP1 can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required. They are suitable for biomedical applications (note: subject to fulfilment of statutory validation requirements where appropriate), and for parts requiring high mechanical properties in elevated temperatures (500 - 1000 °C) and with good corrosion resistance. Due to the layerwise building method, the parts have a certain anisotropy, which can be reduced or removed by appropriate heat treatment - see Technical Data for examples.

Material data sheet

Technical data

General process data

Typical achievable part accuracy [1]

- small parts	approx. \pm 20 – 50 μm approx. \pm 0.8 – 2 $\times 10^{-3}$ inch
- large parts	approx. \pm 50 – 200 μm approx. \pm 2 – 8 $\times 10^{-3}$ inch

Min. wall thickness [2]

approx. 0.3 mm
approx. 0.012 inch

Surface roughness [3]

- as built

MP1 Surface (20 μm)	R_a 4 – 10 μm ; R_z 20 – 40 μm R_a 0.16 – 0.39 $\times 10^{-3}$ inch, R_z 0.79 – 1.57 $\times 10^{-3}$ inch
---------------------------------	---

MP1 Performance (40 μm)

R_a 7 – 10 μm ; R_z 35 – 50 μm
 R_a 0.28 – 0.39 $\times 10^{-3}$ inch,
 R_z 1.37 – 1.96 $\times 10^{-3}$ inch

MP1 Speed (50 μm)

R_a 8 – 12 μm ; R_z 38 – 50 μm
 R_a 0.31 – 0.47 $\times 10^{-3}$ inch,
 R_z 1.49 – 1.96 $\times 10^{-3}$ inch

- after polishing

R_z up to < 1 μm
 R_z up to < 0.04 $\times 10^{-3}$ inch

Volume rate [4]

- Parameter set MP1_Surface 1.0 / default job
CC20_MP1_020_default.job (20 μm layer thickness)
- Parameter set MP1_Performance 1.0 / default job
CC20_MP1_040_default.job (40 μm layer thickness)
- Parameter set MP1_Performance 1.0 for M 280 / 400 W
(40 μm layer thickness)
- Parameter set MP1_Speed 1.0 / for M 280 / 400 W
(50 μm layer thickness)

1.6 mm^3/s (5.1 cm^3/h)
0.35 in^3/h

3.2 mm^3/s (11.5 cm^3/h)
0.70 in^3/h

4.2 mm^3/s (15.1 cm^3/h)
0.92 in^3/h

5.5 mm^3/s (19.8 cm^3/h)
1.21 in^3/h

Material data sheet

- [1] Based on users' experience of dimensional accuracy for typical geometries, e.g. $\pm 20 \mu\text{m}$ (0.8×10^3 inch) when parameters can be optimized for a certain class of parts or $\pm 50 \mu\text{m}$ (2×10^3 inch) when building a new kind of geometry for the first time. For larger parts the accuracy can be improved by post-process stress-relieving at 1150°C (2100°F) for 6 hours. Part accuracy is subject to appropriate data preparation and post-processing, in accordance with EOS training.
- [2] Mechanical stability is dependent on geometry (wall height etc.) and application
- [3] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to number of layers) and other factors such as DMLS-Start settings.

Physical and chemical properties of parts

Material composition	Co (60 - 65 wt-%) Cr (26 - 30 wt-%) Mo (5 - 7 wt-%) Si (≤ 1.0 wt-%) Mn (≤ 1.0 wt-%) Fe (≤ 0.75 wt-%) C (≤ 0.16 wt-%) Ni (≤ 0.10 wt-%)
Relative density	approx. 100 %
Density	approx. 8.3 g/cm^3 approx. 0.30 lb/in^3

Material data sheet

Mechanical properties of parts at 20 °C (68 °F)

	As built	Stress relieved [5]
Tensile strength [6]		
- in horizontal direction (XY)	1350 ± 100 MPa 196 ± 15 ksi	1100 ± 100 MPa 160 ± 15 ksi
- in vertical direction (Z)	1200 ± 150 MPa 174 ± 22 ksi	1100 ± 100 MPa 160 ± 15 ksi
Yield strength (Rp 0.2 %) [6]		
- in horizontal direction (XY)	1060 ± 100 MPa 154 ± 15 ksi	600 ± 50 MPa 87 ± 7 ksi
- in vertical direction (Z)	800 ± 100 MPa 116 ± 15 ksi	600 ± 50 MPa 87 ± 7 ksi
Elongation at break [6]		
- in horizontal direction (XY)	(11 ± 3) %	min. 20 %
- in vertical direction (Z)	(24 ± 4) %	min. 20 %
Modulus of elasticity [6]		
- in horizontal direction (XY)	200 ± 20 GPa 29 ± 3 Msi	200 ± 20 GPa 29 ± 3 Msi
- in vertical direction (Z)	190 ± 20 GPa 28 ± 3 Msi	200 ± 20 GPa 29 ± 3 Msi
Fatigue life [7]		
- max. stress to reach 10 million cycles		approx. 560 MPa, 81 ksi
- max. stress to reach 1 million cycles		approx. 660 MPa, 96 ksi
Hardness [8]		approx. 35 - 45 HRC

[5] High temperature stress relieved, 6 hours at 1150 °C (2100 °F) under inert argon atmosphere

[6] Tensile testing according to ISO 6892-1:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5mm (0.2 inch), original gauge length 25mm (1 inch).

[7] Testing according to ASTM E466:1996, using vertical samples, as built, under 250 MPa (36.3 ksi) stress amplitude and 44 Hz testing frequency

[8] Rockwell C (HRC) hardness measurement according to EN ISO 6508-1 on polished surface. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

Material data sheet

Thermal properties of parts

	As built
Coefficient of thermal expansion	
- over 20 - 500 °C (68 - 932 °F)	typ. 13.6×10^{-6} m/m °C typ. 7.6×10^{-6} in/in °F
- over 500 – 1000 °C (932-1832 °F)	typ. 15.1×10^{-6} m/m °C typ. 8.4×10^{-6} in/in °F
Thermal conductivity	
- at 20 °C (68 °F)	typ. 13 W/m °C typ. 90 Btu in/(h ft ² °F)
- at 300 °C (572 °F)	typ. 18 W/m °C typ. 125 Btu in/(h ft ² °F)
- at 500 °C (932 °F)	typ. 22 W/m °C typ. 153 Btu in/(h ft ² °F)
- at 1000 °C (1832 °F)	typ. 33 W/m °C typ. 229 Btu in/(h ft ² °F)
Maximum operating temperature	approx. 1150 °C approx. 2100 °F
Melting range	1350 - 1430 °C 2460 - 2600 °F

Abbreviations

typ.	typical
min.	minimum
approx.	approximately
wt	weight

Material data sheet

Notes

The data are valid for the combinations of powder material machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request. Unless otherwise specified, the data refer to the parameter set MP1_Surface 1.0 or the equivalent default job CC20_MP1_020_default.job. The corresponding data for the parameter set MP1_Performance 1.0 or the equivalent default job CC20_MP1_040_default.job are approximately the same except where otherwise specified.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS, EOSINT and DMLS are registered trademarks of EOS GmbH.

2011 EOS GmbH – Electro Optical Systems. All rights reserved.



Copper C18150

DIRECT METAL LASER SINTERING MATERIAL SPECIFICATIONS

Highlights

- Chromium Zirconium Copper (CuCr1Zr)
- Excellent electrical and thermal conductivity
- Mechanical and material properties stable up to 700°F
- Age Hardenable

Applications:

- Excellent thermal and electrical conductivity
- Conformal induction coils
- Regeneratively cooled nozzles
- Plastic mold components

TYPICAL PHYSICAL PROPERTIES

MECHANICAL PROPERTIES (Z AXIS)	AS BUILT	SR	SR + HIP	SR + HIP + SHT	SR + HIP + SHT + PHT
Yield Strength	22 ksi	27 ksi	16 ksi	17 ksi	36 ksi
Ultimate Tensile Strength	30 ksi	34.6 ksi	36.3 ksi	37 ksi	55 ksi
Modulus	103 GPa	96 GPa	117 GPa	110 GPa	124 GPa
Elongation	31%	14%	47%	48%	31%
Hardness	90 Rockwell B	108 Rockwell B	80 Rockwell B	94 Rockwell B	87 Rockwell B

HEAT TREATMENT OPTIONS

- Stress Relief (SR)
- SR + Hot Isostatic Press (HIP)
- SR + HIP + Solution Anneal (SHT)
- SR + HIP + SHT + Precipitation Strengthening (PHT)

COPPER C18150 COMPOSITION*

ELEMENT	TYPICAL PERCENTAGE
Chromium (Cr)	0.5 Min & 1.5 Max
Nitrogen (N)	0.1 max
Oxygen (O)	0.1 max
Zirconium (Zr)	0.05 Min & 0.20 Max
Other	0.3 Max

*UNS C18150, AMS, and/or additional industry standards and designations

The information presented represents typical values intended for reference and comparison purposes only. It should not be used for design specifications or quality control purposes. End-use material performance can be impacted (+/-) by, but not limited to, part design, end-use conditions, test conditions, color etc. Actual values will vary with build conditions. Product specifications are subject to change without notice. *Chemical analysis for specific lots available upon request.

The performance characteristics of these materials may vary according to application, operating conditions, or end use. Each user is responsible for determining that the material is safe, lawful, and technically suitable for the intended application. Stratasys makes no warranties of any kind, express or implied, including, but not limited to, the warranties of merchantability, fitness for a particular use, or warranty against patent infringement.

Material data sheet

EOS Maraging Steel MS1

EOSMaragingSteelMS1 is a steel powder which has been optimized especially for processing on EOSINT M systems.

This document provides information and data for parts built using EOS MaragingSteelMS1 powder (EOS art.-no.9011-0016) on the following system specifications:

- EOSINT™ 270 Installation Mode Standard
with PSW 3.3 or 3.4 and default job MS1_020_default.job or MS1_040_default.job
- EOSINT™ 270 Dual Mode
with PSW 3.5 and EOSOriginalParameterSet MS1_Surface1.0 or MS1_Performance2.0
- EOSINT™ 280
with PSW 3.5 and EOSOriginalParameterSet MS1_Performance1.0 or MS1_Speed 1.0

Description

Parts built in EOSMaragingSteel MS1 have a chemical composition corresponding to US classification 18%Ni Maraging 300, European 1.2709 and German X3NiCoMoTi8-9-5. This kind of steel is characterized by having very good mechanical properties, and being easily heat-treatable using a simple thermal age-hardening process to obtain excellent hardness and strength.

Parts built from EOSMaragingSteelMS1 are easily machinable after the building process and can be easily post-hardened to more than 50HRC by age-hardening at 490°C (914°F) for 6 hours. In both as-built and age-hardened states the parts can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required. Due to the layerwise building method, the parts have a certain anisotropy, which can be reduced or removed by appropriate heat treatment - see Technical Data for examples.

Material data sheet

Technical data

General process data

Typical achievable part accuracy [1]

- small parts (< 80 x 80 mm)	approx \pm 20 μm approx \pm 0.8 x 10 ³ inch
- large parts	approx \pm 50 μm approx \pm 0.002 inch

Age hardening shrinkage [2]

approx. 0.08 %

Min. wall thickness [3]

approx. 0.3 - 0.4 mm
approx. 0.012 - 0.016 inch

Surface roughness (approx.) [4]

- as manufactured	
MS1 Surface (20 μm)	R_a 4 μm ; R_z 20 μm R_a 0.16 x 10 ³ inch, R_z 0.78 x 10 ³ inch
MS1 Performance (40 μm)	R_a 5 μm ; R_z 28 μm R_a 0.19 x 10 ³ inch, R_z 1.10 x 10 ³ inch
MS1 Speed (50 μm)	R_a 9 μm ; R_z 50 μm R_a 0.47 x 10 ³ inch, R_z 2.36 x 10 ³ inch
- after shot-peening	R_a 4 - 6.5 μm ; R_z 20 - 50 μm R_a 0.16 - 0.26 x 10 ³ inch R_z 0.78 - 1.97 x 10 ³ inch
- after polishing	R_z up to < 0.5 μm R_z up to < 0.02 x 10 ³ inch (can be very finely polished)

Material data sheet

Volume rate [5]

- Parameter set MS1_Surface 1.0 / default job MS1_020_default.job (20 µm layer thickness)	1.6 mm ³ /s (5.8 cm ³ /h) 0.35 in ³ /h
- Parameter set MS1_Performance 2.0 / default job MS1_040_default.job (40 µm layer thickness)	3 mm ³ /s (10.8 cm ³ /h) 0.66 in ³ /h
- Parameter set MS1_Performance 1.0 / for M 280 / 400 W (40 µm layer thickness)	4.2 mm ³ /s (15.1 cm ³ /h) 0.92 in ³ /h
- Parameter set MS1_Speed 1.0 / for M 280 / 400 W (50 µm layer thickness)	5.5 mm ³ /s (19.8 cm ³ /h) 1.21 in ³ /h

- [1] Based on users' experience of dimensional accuracy for typical geometries, as built. Part accuracy is subject to appropriate data preparation and post-processing, in accordance with EOS training.
- [2] Ageing temperature 490 °C (914 °F), 6 hours, air cooling
- [3] Mechanical stability is dependent on geometry (wall height etc.) and application
- [4] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [5] Volume rate is a measure of build speed during laser exposure of hatched areas. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other geometry- and machine setting-related factors.

Material data sheet

Physical and chemical properties of parts

Material composition	Fe (balance) Ni (17 - 19 wt-%) Co (8.5 - 9.5 wt-%) Mo (4.5 - 5.2 wt-%) Ti (0.6 - 0.8 wt-%) Al (0.05 - 0.15 wt-%) Cr, Cu (each \leq 0.5 wt-%) C (\leq 0.03 wt-%) Mn, Si (each \leq 0.1 wt-%) P, S (each \leq 0.01 wt-%)
Relative density	approx. 100 %
Density	8.0 - 8.1 g/cm ³ 0.289 - 0.293 lb/in ³

Material data sheet

Mechanical properties of parts at 20 °C (68°F)

	As built	After age hardening [2]
Tensile strength [6]		min. 1930 MPa min. 280 ksi
- in horizontal direction (XY)	typ. 1100 ± 100 MPa typ. 160 ± 15 ksi	typ. 2050 ± 100 MPa
- in vertical direction (Z)	typ. 1100 ± 100 MPa typ. 160 ± 15 ksi	typ. 297 ± 15 ksi
Yield strength (Rp 0.2 %) [6]		min. 1862 MPa min. 270 ksi
- in horizontal direction (XY)	typ. 1050 ± 100 MPa typ. 152 ± 15 ksi	typ. 1990 ± 100 MPa
- in vertical direction (Z)	typ. 1000 ± 100 MPa typ. 145 ± 15 ksi	typ. 289 ± 15 ksi
Elongation at break [6]		min. 2 %
- in horizontal direction (XY)	typ. (10 ± 4) %	typ. (4 ± 2) %
- in vertical direction (Z)	typ. (10 ± 4) %	
Modulus of elasticity [6]		
- in horizontal direction (XY)	typ. 160 ± 25 GPa typ. 23 ± 4 Msi	typ. 180 ± 20 GPa
- in vertical direction (Z)	typ. 150 ± 20 GPa typ. 22 ± 3 Msi	typ. 26 ± 3 Msi
Hardness [7]	typ. 33 - 37 HRC	typ. 50 - 56 HRC
Ductility (Notched Charpy impact test)	typ. 45 ± 10 J	typ. 11 ± 4 J

[6] Tensile testing according to ISO 6892:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5mm (0.2 inch), original gauge length 25mm (1 inch).

[7] Rockwell C (HRC) hardness measurement according to EN 6508-1 on polished surface. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

Material data sheet

Thermal properties of parts

	As built	After age hardening [2]
Thermal conductivity	typ. $15 \pm 0.8 \text{ W/m}^\circ\text{C}$ typ. $104 \pm 6 \text{ Btu in/(h ft}^2 {^\circ}\text{F)}$	typ. $20 \pm 1 \text{ W/m}^\circ\text{C}$ typ. $139 \pm 7 \text{ Btu in/(h ft}^2 {^\circ}\text{F)}$
Specific heat capacity	typ. $450 \pm 20 \text{ J/kg}^\circ\text{C}$ typ. $0.108 \pm 0.005 \text{ Btu/(lb }^\circ\text{F)}$	typ. $450 \pm 20 \text{ J/kg}^\circ\text{C}$ typ. $0.108 \pm 0.005 \text{ Btu/(lb }^\circ\text{F)}$
Maximum operating temperature		approx. $400 \text{ }^\circ\text{C}$ approx. $750 \text{ }^\circ\text{F}$

Abbreviations

typ.	typical
min.	minimum
approx.	approximately
wt	weight

Notes

The data are valid for the combinations of powder material machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request. Unless otherwise specified, the data refer to the default job MS1_040_default.job or the equivalent parameter set MS1_Performance 2.0. The corresponding data for the default job MS1_020_default.job or the equivalent parameter set MS1_Surface 1.0 are approximately the same except where otherwise specified.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS, EOSINT and DMLS are registered trademarks of EOS GmbH.

2011 EOS GmbH – Electro Optical Systems. All rights reserved.

Material data sheet

EOS NickelAlloy IN625

EOS NickelAlloy IN625 is a heat and corrosion resistant nickel alloy powder which has been optimized especially for processing on EOSINT M systems.

This document provides information and data for parts built using EOS NickelAlloy IN625 powder (EOS art.-no. 9011-0022) on the following system specifications:

EOSINT M 270 Dual Mode
with PSW 3.5 and EOS Original Parameter Set IN625_Surface 1.0

Description

Parts built from EOS NickelAlloy IN625 have chemical composition corresponding to UNS N06625, AMS 5666F, AMS 5599G, W.Nr 2.4856, DIN NiCr22Mo9Nb. This type of alloy is characterized by having high tensile, creep and rupture strength. Conventionally cast or wrought components in this type of nickel alloy have typically excellent fatigue and thermal-fatigue properties combined with good oxidation resistance.

EOS NickelAlloy IN625 is expected to have good corrosion resistance in various corrosive environments. Especially sea-water applications require high pitting and crevice corrosion resistance, stress-corrosion resistance against chloride-ions, high tensile and corrosion-fatigue strength. However, corrosion resistance has not been verified yet and therefore it is recommended to conduct relevant corrosion tests and studies prior to use in specific corrosive environment.

Parts built from EOS NickelAlloy IN625 can be heat treated and material properties can be varied within specified range. Parts can be machined, spark-eroded, welded, micro shot-peened, polished and coated in both as-built and in heat treated conditions. Due to the layerwise building method, the parts have a certain anisotropy - see Technical Data for examples.

Material data sheet

Technical data

General process data

Typical achievable part accuracy [1]

- small parts	approx. $\pm 40 - 60 \mu\text{m}$ approx. $\pm 1.6 - 2.4 \times 10^{-3} \text{ inch}$
---------------	--

- large parts	$\pm 0.2 \%$
---------------	--------------

Min. wall thickness [2]	approx. 0.3 - 0.4 mm approx. 0.012 - 0.016 inch
-------------------------	--

Surface roughness [3]

- after shot-peening	R_a 4 - 6.5 μm , R_z 20 - 50 μm R_a 0.16 - 0.26 $\times 10^{-3}$ inch, R_z 0.78 - 1.97 $\times 10^{-3}$ inch
- after polishing	R_z up to < 0.5 μm R_z up to < 0.02 $\times 10^{-3}$ inch (can be very finely polished)

Volume rate [4]	2 mm^3/s (7.2 cm^3/h) 0.44 in^3/h
-----------------	---

- [1] Based on users' experience of dimensional accuracy for typical geometries, e.g. $\pm 40 \mu\text{m}$ (0.0016 inch) when parameters can be optimized for a certain class of parts or $\pm 60 \mu\text{m}$ (0.0024 inch) when building a new kind of geometry for the first time. Part accuracy is subject to appropriate data preparation and post-processing, in accordance with EOS training.
- [2] Mechanical stability is dependent on geometry (wall height etc.) and application
- [3] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other factors such as DMLS-Start settings.

Material data sheet

Physical and chemical properties of parts

Material composition	Ni (balance \geq 58.00 wt-%) Cr (20.00 - 23.00 wt-%) Mo (8.00 - 10.00 wt-%) Nb (3.15 - 4.15 wt-%) Fe (\leq 5.00 wt-%) Ti (\leq 0.40 wt-%) Al (\leq 0.40 wt-%) Co (\leq 1.0 wt-%) C (\leq 0.10 wt-%) Ta (\leq 0.05 wt-%) Si, Mn (each \leq 0.50 wt-%) P, S (each \leq 0.015 wt-%)
Relative density	approx. 100 %
Density	min. 8.4 g/cm ³ min. 0.30 lb/in ³

Material data sheet

Mechanical properties of parts at 20 °C (68 °F)

	As built	Stress relieved [6]
Tensile strength [5]		
- in horizontal direction (XY)	typ. 990 ± 50 MPa typ. 144 ± 7 ksi	min. 827 MPa (120 ksi) typ. 1040 ± 100 MPa (151 ± 15 ksi)
- in vertical direction (Z)	typ. 900 ± 50 MPa typ. 131 ± 7 ksi	min. 827 MPa (120 ksi) typ. 930 ± 100 MPa (135 ± 15 ksi)
Yield strength, Rp0.2% [5]		
- in horizontal direction (XY)	typ. 725 ± 50 MPa typ. 105 ± 7 ksi	min. 414 MPa (60 ksi) typ. 720 ± 100 MPa (104 ± 15 ksi)
- in vertical direction (Z)	typ. 615 ± 50 MPa typ. 89 ± 7 ksi	min. 414 MPa (60 ksi) typ. 650 ± 100 MPa (94 ± 15 ksi)
Modulus of elasticity [5]		
- in horizontal direction (XY)	typ. 170 ± 20 GPa typ. 25 ± 3 Msi	typ. 170 ± 20 GPa typ. 25 ± 3 Msi
- in vertical direction (Z)	typ. 140 ± 20 GPa typ. 20 ± 3 Msi	typ. 160 ± 20 GPa typ. 23 ± 3 Msi
Elongation at break [5]		
- in horizontal direction (XY)	typ(35 ± 5) %	min. 30 %, typ. (35 ± 5) %
- in vertical direction (Z)	(42 ± 5) %	min. 30 %, typ. (44 ± 5) %
Hardness [7]		
		approx. 30 HRC (287 HB)

[5] Tensile testing according to ISO 6892-1:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5mm (0.2 inch), original gauge length 25mm (1 inch).

[6] Stress relieve: anneal at 870 °C (1600 °F) for 1 hour, rapid cooling

[7] Rockwell C (HRC) hardness measurement according to EN ISO 6508-1 on polished surface. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

Material data sheet

Thermal properties of parts

Maximum operating temperature for parts under load	approx. 650 °C approx. 1200 °F
Oxidation resistance to [8]	980 °C 1800 °F

[8] Based on literature of conventional Ni-alloy with identical chemistry

Abbreviations

typ.	typical
min.	minimum
approx.	approximately
wt	weight

Notes

The data are valid for the combinations of powder material machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS, EOSINT and DMLS are registered trademarks of EOS GmbH.

2011 EOS GmbH – Electro Optical Systems. All rights reserved.

Material data sheet

EOS NickelAlloy IN718

EOS NickelAlloy IN718 is a heat and corrosion resistant nickel alloy powder which has been optimized especially for processing on EOS M systems.

This document provides information and data for parts built using EOS NickelAlloy IN718 powder (EOS art.-no. 9011-0020) on the following system specifications:

EOSINT M280 400W System with PSW3.6 and Parameter Set IN718_Performance 1.0

EOS M290 400W System with EOSPRINT 1.0 and Parameter Set IN718_Performance 1.0

Description

Parts built from EOS NickelAlloy IN718 have chemical composition corresponding to UNS N07718, AMS 5662, AMS 5664, W.Nr 2.4668, DIN NiCr19Fe19NbMo3. This kind of precipitation-hardening nickel-chromium alloy is characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700 °C (1290 °F).

This material is ideal for many high temperature applications such as gas turbine parts, instrumentation parts, power and process industry parts etc. It also has excellent potential for cryogenic applications.

Parts built from EOS NickelAlloy IN718 can be easily post-hardened by precipitation-hardening heat treatments. In both as-built and age-hardened states the parts can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required. Due to the layerwise building method, the parts have a certain anisotropy - see Technical Data for examples.

Material data sheet

Technical data

General process data

Typical achievable part accuracy [1], [11]

- small parts	approx. \pm 40 – 60 μm approx. \pm 1.6 – 2.4 $\times 10^{-3}$ inch
- large parts	\pm 0.2 %

Min. wall thickness [2], [11]	typ. 0.3 - 0.4 mm typ. 0.012 – 0.016 inch
-------------------------------	--

Surface roughness [3], [11]

- after shot-peening	R_a 4 – 6.5 μm , R_z 20 - 50 μm R_a 0.16 – 0.25 $\times 10^{-3}$ inch, R_z 0.78 – 1.97 $\times 10^{-3}$ inch
- after polishing	R_z up to < 0.5 μm R_z up to < 0.02 $\times 10^{-3}$ inch (can be very finely polished)

Volume rate [4]

- Parameter Set IN718_Performance (40 μm)	4 mm^3/s (14.4 cm^3/h) 0.88 in^3/h
---	--

- [1] Based on users' experience of dimensional accuracy for typical geometries, e.g. \pm 40 μm (1.6×10^{-3} inch) when parameters can be optimized for a certain class of parts or \pm 60 μm (2.4×10^{-3} inch) when building a new kind of geometry for the first time. Part accuracy is subject to appropriate data preparation and post-processing, in accordance with EOS training.
- [2] Mechanical stability is dependent on geometry (wall height etc.) and application#
- [3] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other factors such as DMLS-Start settings.

Material data sheet

Physical and chemical properties of parts

Material composition	Ni (50 - 55 wt-%) Cr (17.0 - 21.0 wt-%) Nb (4.75 - 5.5 wt-%) Mo (2.8 - 3.3 wt-%) Ti (0.65 - 1.15 wt-%) Al (0.20 - 0.80 wt-%) Co (\leq 1.0 wt-%) Cu (\leq 0.3 wt-%) C (\leq 0.08 wt-%) Si, Mn (each \leq 0.35 wt-%) P, S (each \leq 0.015 wt-%) B (\leq 0.006 wt-%) Fe (balance)
Relative density	approx. 100 %
Density	min. 8.15 g/cm ³ min. 0.294 lb/in ³

Material data sheet

Mechanical properties of parts at 20 °C (68 °F)

	As built	Heat treated per AMS 5662 [5]	Heat treated per AMS 5664 [6]
Tensile strength [7]			
- in horizontal direction (XY)	typ. 1060 ± 50 MPa (154 ± 7 ksi)		
- in vertical direction (Z)	typ. 980 ± 50 MPa (142 ± 7 ksi)	min. 1241 MPa (180 ksi) typ. 1400 ± 100 MPa (203 ± 15 ksi)	min. 1241 MPa (180 ksi) typ. 1380 ± 100 MPa (200 ± 15 ksi)
Yield strength (Rp 0.2 %) [7]			
- in horizontal direction (XY)	typ. 780 ± 50 MPa (113 ± 7 ksi)		
- in vertical direction (Z)	typ. 634 ± 50 MPa (92 ± 7 ksi)	min. 1034 MPa (150 ksi) typ. 1150 ± 100 MPa (167 ± 15 ksi)	min. 1034 MPa (150 ksi) typ. 1240 ± 100 MPa (180 ± 15 ksi)
Elongation at break [7]			
- in horizontal direction (XY)	typ. (27 ± 5) %		
- in vertical direction (Z)	typ. (31 ± 5) %	min. 12 % typ. (15 ± 3) %	min. 12 % typ. (18 ± 5) %
Modulus of elasticity [7]			
- in horizontal direction (XY)	typ. 160 ± 20 GPa (23 ± 3 Gsi)		
- in vertical direction (Z)		170 ± 20 GPa 24.7 ± 3 Gsi	170 ± 20 GPa 24.7 ± 3 Gsi
Hardness [8]			
	approx. 30 HRC approx. 287 HB	approx. 47 HRC approx. 446 HB	approx. 43 HRC approx. 400 HB

[5] Heat treatment procedure per AMS 5662:

1. Solution Anneal at 980 °C (1800 °F) for 1 hour, air (/argon) cool.
2. Ageing treatment; hold at 720 °C (1330 °F) 8 hours, furnace cool to 620 °C (1150 °F) in 2 hours, hold at 620 °C (1150 °F) 8 hours, air (/argon) cool.

Material data sheet

- [6] Heat treatment procedure per AMS 5664:
 1. Solution Anneal at 1065 °C (1950 °F) for 1 hour, air (/argon) cool.
 2. Ageing treatment; hold at 760 °C (1400 °F) 10 hours, furnace cool to 650 °C (1200 °F) in 2 hours, hold at 650 °C (1200 °F) 8 hours, air (/argon) cool
- [7] Tensile testing according to ISO 6892 -1:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5 mm (0.2 inch), original gauge length 25 mm (1 inch).
- [8] Rockwell C (HRC) hardness measurement according to EN ISO 6508-1 on polished surface. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

Material data sheet

Mechanical properties of parts at high temperature (649 °C, 1200 °F) [11]

	Heat treated per AMS 5662 [5]	Heat treated per AMS 5664 [6]
Tensile Strength (Rm) [9]		
- in vertical direction (Z)	min. 965 MPa (140 ksi) typ. 1170 ± 50 MPa (170 ± 7 ksi)	typ. 1210 ± 50 MPa (175 ± 7 ksi)
Yield strength (Rp 0.2 %) [9]		
- in vertical direction (Z)	min. 862 MPa (125 ksi) typ. 970 ± 50 MPa (141 ± 7 ksi)	typ. 1010 ± 50 MPa (146 ± 7 ksi)
Elongation at break [9]		
- in vertical direction (Z)	min. 6 % typ. (16 ± 3) %	typ. (20 ± 3) %
Stress-Rupture Properties [10]		
- in vertical direction (Z)	min. 23 hours at stress level 689 MPa (100 ksi)	51 ± 5 hours (final applied stress to rupture 792.5 MPa / 115 ksi) 81 ± 10 hours (final applied stress to rupture 861.5 MPa / 125 ksi)

[9] Elevated temperature tensile testing at 649 °C (1200 °F) in accordance with EN 10002-5 (92)

[10] Testing at 649 °C (1200 °F) in accordance with ASTME139 (2006), smooth specimens. Test method as described in AMS 5662 (3.5.1.2.3.3): "The load required to produce an initial axial stress of 689 MPa (100 ksi) shall be used to rupture or for 23 hours, whichever occurs first. After the 23 hours and at intervals of 8 hours minimum, thereafter, the stress shall be increased in increments of 34.5 MPa (5 ksi)."

[11] Hint: these properties were determined on an EOSINT M 270 IM Xtended and EOSINT M 280-400W. Test parts from following machine types EOSINT M 270 Dual Mode, EOSINT M 280-200W and EOS M 290-400W correspond with these data.

Material data sheet

Thermal properties of parts

Heat treated per AMS 5662 [4]	
Coefficient of thermal expansion	
- over 25 - 200 °C (36 - 390 °F)	approx. $12.5 - 13.0 \times 10^{-6}$ m/m°C approx. $6.9 - 7.2 \times 10^{-6}$ in/in°F
- over 25 - 750 °C (36 - 930 °F)	approx. $16.6 - 17.2 \times 10^{-6}$ m/m°C approx. $9.2 - 9.6 \times 10^{-6}$ in/in°F
Maximum operating temperature for parts under load	approx. 650 °C approx. 1200 °F
Oxidation resistance up to [11]	approx. 980 °C approx. 1800 °F

[12] Based on literature of conventional Ni-alloy with identical chemistry

Abbreviations

typ.	typical
min.	minimum
approx.	approximately
wt	weight

Notes

The data are valid for the combinations of powder material machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS, EOSINT and DMLS are registered trademarks of EOS GmbH.

2014 EOS GmbH – Electro Optic Systems. All rights reserved.

Material data sheet

EOS StainlessSteel 316L

EOS StainlessSteel 316L is a corrosion resistant iron based alloy which has been optimized especially for processing on EOSINT M280 systems.

This document provides information and data for parts built using EOS StainlessSteel 316L powder (EOS art.- no. 9011-0032) on the following system specifications:

- EOSINT M280 400W System with PSW3.6 and Parameter Set 316L_Surface 1.0
- EOSINT M280 200W System with PSW3.6 and Parameter Set 316L_Surface 1.0

Description

The parts built from EOS StainlessSteel 316L have chemical composition corresponding to ASTM F138 "Standard Specification for Wrought 18Cr-14Ni-2.5Mo Stainless Steel Bar and Wire for Surgical Implants (UNS S31673)". This kind of stainless steel is characterized having a good corrosion resistance and evidence that there are no leachable substances in cytotoxic concentrations.

This material is ideal in

- Lifestyle/Consumer - watches, other jewellery, spectacle frames, decorations, functional elements in electronic housing and accessories
- Automotive/Industrial – non-corroding common material, food and chemical plants
- Aerospace/Turbine industry – entry-level material for Laser Sintering Technology, mounting parts, brackets, heat exchangers

Parts built from EOS StainlessSteel 316L can be machined, shot-peened and polished in as-built or stress relieved (AMS2759) states if required. Solution annealing is not necessary because the mechanical properties of as-built state are showing desired values (ASTM A403). Parts are not ideal in temperature range 427°C - 816°C where precipitation of chromium carbides occurs. Due to layer-wise building method, the parts have a certain anisotropy which could be seen from mechanical properties.

Material data sheet

Technical data

General process data

EOS StainlessSteel 316L	
Typical achievable part accuracy [1]	
- small parts	approx. $\pm 20\text{-}50 \mu\text{m}$ ($\pm 0.0008 \text{ - } 0.002 \text{ inch}$)
- large parts	approx. $\pm 0.2 \%$
Min. wall thickness [2]	approx. $0.3 \text{ - } 0.4 \text{ mm}$ ($0.012 \text{ - } 0.016 \text{ inch}$)
Layer thickness	$20 \mu\text{m}$ ($0.8 \times 10^{-3} \text{ inch}$)
Surface roughness [3]	
- as-manufactured	$R_a 13 \pm 5 \mu\text{m}; R_z 80 \pm 20 \mu\text{m}$ $R_a 0.5 \pm 0.2 \times 10^{-3} \text{ inch}; R_z 3.1 \pm 0.8 \times 10^{-3} \text{ inch}$
- after shot-peening	$R_a 5 \pm 2 \mu\text{m}; R_z 30 \pm 10 \mu\text{m}$ $R_a 0.2 \pm 0.08 \times 10^{-3} \text{ inch}; R_z 1.2 \pm 0.4 \times 10^{-3} \text{ inch}$
- after polishing	R_z up to $< 1 \mu\text{m}$ R_z up to $< 0.04 \times 10^{-3} \text{ inch}$ (can be very finely polished)
Volume rate [4]	$2 \text{ mm}^3/\text{s}$ ($7.2 \text{ cm}^3/\text{h}$) $0.44 \text{ in}^3/\text{h}$

- [1] Based on users' experience of dimensional accuracy for typical geometries, e.g. $\pm 40 \mu\text{m}$ when parameters can be optimized for a certain class of parts or $\pm 60 \mu\text{m}$ when building a new kind of geometry for the first time. Part accuracy is subject to appropriate data preparation and postprocessing.
- [2] Mechanical stability is dependent on geometry (wall height etc.) and application
- [3] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for vertical surfaces.
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other factors such as contour and Up-/DownSkin parameters.

Material data sheet

Physical and chemical properties of parts

EOS StainlessSteel 316L			
Material composition	Element	Min	Max
	Fe	balance	
	Cr	17.00	19.00
	Ni	13.00	15.00
	Mo	2.25	3.00
	C	0.030	
	Mn	2.00	
	Cu	0.50	
	P	0.025	
	S	0.010	
	Si	0.75	
	N	0.10	
Relative density with standard parameters	approx. 100 %		
Density with standard parameters	min. 7.9 g/cm ³ min. 0.285 lb/in ³		

Material data sheet

Mechanical properties of parts (at room temperature)

As built	
Ultimate tensile strength [5]	
- in horizontal direction (XY)	640 ± 50 MPa
- in vertical direction (Z)	540 ± 55 MPa
Yield strength, Rp0.2% [5]	
- in horizontal direction (XY)	530 ± 60 MPa
- in vertical direction (Z)	470 ± 90 MPa
Young's modulus [5]	
- in horizontal direction (XY)	typ. 185 GPa
- in vertical direction (Z)	typ. 180 GPa
Elongation at break [5]	
- in horizontal direction (XY)	40 ± 15 %
- in vertical direction (Z)	50 ± 20 %
Hardness [6]	typ. 85 HRB

[5] Machining and testing of the test bars according to ISO 6892 / ASTM E8M, proportional test pieces, diameter of the neck area 5 mm (0.2 inch), gauge length 4D = 20.0mm (0.79 inch), stress rate 10MPa/s, strain speed in plastic region 0.375 1/min.

[6] Rockwell hardness (HRB) measurement according to EN ISO 6508-1 on polished surface.

Material data sheet

Abbreviations

typ.	typical
min.	minimum
approx.	approximately
wt	weight

The quoted values refer to the use of these materials with EOSINT M 280 systems according to current specifications (including the latest released process software PSW and any hardware specified for the relevant material) and operating instructions. All values are approximate. Unless otherwise stated, the quoted mechanical and physical properties refer to standard building parameters and test samples built in vertical orientation. They depend on the building parameters and strategies used, which can be varied by the user according to the application.

The data are based on our latest knowledge and are subject to changes without notice. They are provided as an indication and not as a guarantee of suitability for any specific application.

EOS®, EOSINT®, DMLS®, DirectTool® and DirectPart® are registered trademarks of EOS GmbH.

© 2014 EOS GmbH – Electro Optical Systems. All rights reserved.

Material data sheet

EOS StainlessSteel GP1 for EOSINT M 270

A number of different materials are available for use with EOSINT M systems, offering a broad range of eManufacturing applications. EOSStainlessSteelGP1 is a stainless steel powder which has been optimized especially for EOSINTM 270 systems. Other materials are also available for EOSINTM systems, and further materials are continuously being developedplease refer to the relevantmaterial data sheets for details.

This document provides a brief description of the principle applications, and a table of technical data. For details of the system requirements please refer to the relevant information quote.

Description, application

EOS StainlessSteelGP1 is a pre-alloyed stainless steel in fine powder form. Its composition corresponds to US classification 17-4 and European 1.4542. This kind of steel is characterized by having good corrosion resistance and mechanical properties, especially excellent ductility in a-sier processed state, and is widely used in a variety of engineering applications.

This material is ideal for many part-building applications (DirectPart) such as functional metal prototypes, small series products, individualised products or spare parts. Standard processing parameters use full melting of the entire geometry with 20µm layer thickness, but it is also possible to useSkin & Core building style to increase the build speed. Using standard parameters the mechanical properties are fairly uniform in all directions. Parts made from EOS StainlessSteelGP1 can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required. Unexposed powder can be reused.

Typical applications:

- engineering applications including functional prototypes, small series products, individualised products or spare parts.
- parts requiring high corrosion resistance, sterilisability, etc.
- parts requiring particularly high toughness and ductility.

Material data sheet

Technical data

General process and geometric data

Minimum recommended layer thickness	20 µm 0.8 mil
Typical achievable part accuracy [1]	
- small parts	± 20 – 50 µm 0.8 – 2.0 mil
- large parts [2]	± 0.2 %
Min. wall thickness [3]	
	0.3 - 0.4 mm 0.012 - 0.016 in
Surface roughness	
- after shot peening	R _a 2.5 - 4.5 µm, R _y 15 - 40 µm R _a 0.1 - 0.2 , R _y 0.6 - 1.6 mil
- after polishing	R _z up to < 0.5 µm (can be very finely polished)
Volume rate [4]	
- standard parameters (20 µm layers, full density)	2 mm ³ /s 0.44 in ³ /h
- Innercore parameters (Skin & Corestyle, full density)	4 mm ³ /s 0.88 - 1.1 in ³ /h

- [1] Based on users' experience of dimensional accuracy for typical geometries, e.g. ± 20 µm when parameters can be optimized for a certain class of parts or ± 50 µm when building a new kind of geometry for the first time.
- [2] For larger parts the accuracy can be improved by post-process stressrelieving at 650°C for 1 hour
- [3] Mechanical stability is dependent on geometry (wall height etc.) and application
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other factors such as DMLS - Start settings.

Material data sheet

Physical and chemical properties of parts

Material composition	steel including alloying elements Cr (15 – 17.5 wt-%) Ni (3 - 5 wt-%) Cu (3 - 5 wt-%) Mn (max. 1 wt-%) Si (max. 1 wt-%) Mo (max. 0.5 wt-%) Nb (0.15 - 0.45 wt-%) C (max. 0.07 wt-%)
Relative density with standard parameters	approx. 100 %
Density with standard parameters	7.8 g/cm ³ 0.28 lb/in ³

Mechanical properties of parts [5]

	As manufactured	Stress relieved (1 hour at 650 °C)
Ultimate tensile strength		
- in horizontal direction (XY)	min 850 MPa (123 ksi) typical 930 ± 50 MPa (135 ± 7 ksi)	typical 1100 MPa (160 ksi)
- in vertical direction (Z)	min 850 MPa (123 ksi) typical 960 ± 50 MPa (139 ± 7 ksi)	typical 980 MPa (142 ksi)
Yield strength		
(R _{eL} , Lower yield strength)		
- in horizontal direction (XY)	min 530 MPa (77 ksi) typical 586 ± 50 MPa (85 ± 7 ksi)	typical 590 MPa (86 ksi)
- in vertical direction (Z)	min 530 MPa (77 ksi) typical 570 ± 50 MPa (83 ± 7 ksi)	typical 550 MPa (80 ksi)
(R _{eH} , Upper yield strength)		
- in horizontal direction (XY)	min 595 MPa (86 ksi) typical 645 ± 50 MPa (94 ± 7 ksi)	typical 634 MPa (92 ksi)
- in vertical direction (Z)	min 580 MPa (84 ksi) typical 630 ± 50 MPa (91 ± 7 ksi)	typical 595 MPa (86 ksi)

Material data sheet

Young's modulus	$170 \pm 30 \text{ GPa}$ ($25 \pm 4 \text{ msi}$)	typical 180 GPa (26 msi)
Elongation at break		
- in horizontal direction (XY)	min 25 % typical $31 \pm 5 \%$	typical 29 %
- in vertical direction (Z)	min 25 % typical $35 \pm 5 \%$	typical 31 %
Hardness [6]		
- as built	approx. $230 \pm 20 \text{ HV1}$	
- ground & polished[7]	approx 250 - 400 HV1	

- [5] Mechanical testing according to ISO 6892:1998(E) Annex C, proportional test pieces, Diameter of the neck area 5 mm, original gauge length 25mm
- [6] Vickers hardness measurement (HV) according to DINEN ISO 6507-1. Note that depending on the measurement method used, the measured hardness value can be dependent on the surface roughness and can be lower than the real hardness. To avoid inaccurate results, hardness should be measured on a polished surface.
- [7] Due to work-hardening effect

Thermal properties of parts

Coefficient of thermal expansion	
- over 20- 600 °C (68 - 1080 °F)	$14 \times 10^{-6} \text{ m/m°C}$ $7.8 \times 10^{-6} \text{ in/in°F}$
Thermal conductivity	
- at 20 °C (68 °F)	13 W/m°C $90 \text{ Btu/(h ft}^2 \text{ °F/in)}$
- at 100 °C (212 °F)	14 W/m°C $97 \text{ Btu/(h ft}^2 \text{ °F/in)}$
- at 200 °C (392 °F)	15 W/m°C $104 \text{ Btu/(h ft}^2 \text{ °F/in)}$
- at 300 °C (572 °F)	16 W/m°C $111 \text{ Btu/(h ft}^2 \text{ °F/in)}$
Maximum operating temperature	550 °C 1022 °F

Material data sheet

The quoted values refer to the use of these materials with EOSINT M 270 systems according to current specifications (including the latest released process software PSW and any hardware specified for the relevant material) and operating instructions. All values are approximate. Unless otherwise stated, the quoted mechanical and physical properties refer to standard building parameters and test samples built in horizontal orientation. They depend on the building parameters and strategies used, which can be varied by the user according to the application. Measurements of the same properties using different test methods (e.g. specimen geometries) can give different results. The data are based on our latest knowledge and are subject to changes without notice. They are provided as an indication and not as a guarantee of suitability for any specific application.

EOS[®], EOSINT[®], DMLS[®] and DirectPart[®] are registered trademarks of EOS GmbH.

© 2009 EOS GmbH– Electro OpticalSystems. All rights reserved.

Material data sheet

EOS Titanium Ti64

EOS Titanium Ti64 is a titanium alloy powder which has been optimized especially for processing on EOSINT M systems.

This document provides information and data for parts built using EOS Titanium Ti64 powder (EOS art.-no. 9011-0014) on the following system specifications:

- EOSINT M 270 Installation Mode Xtended
with PSW 3.4 and default job Ti64_30_030_default.job
- EOSINT M 270 Dual Mode
with PSW 3.5 and Original EOS Parameter Set Ti64_Performance 2.0
- EOSINT M 280
with PSW 3.5 and Original EOS Parameter Set Ti64_Speed 1.0

Description

Parts built in EOS Titanium Ti64 have a chemical composition corresponding to ISO 5832-3, ASTM F1472 and ASTM B348.

This well-known light alloy is characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight and biocompatibility.

This material is ideal for many high-performance engineering applications, for example in aerospace and motor racing, and also for the production of biomedical implants (note: subject to fulfilment of statutory validation requirements where appropriate).

Due to the layerwise building method, the parts have a certain anisotropy, which can be reduced or removed by appropriate heat treatment - see Technical Data for examples.

Material data sheet

Technical data

General process and geometric data

Typical achievable part accuracy [1]	$\pm 50 \mu\text{m}$
Min. wall thickness [2]	approx. 0.3 – 0.4 mm approx. 0.012 – 0.016 inch
Surface roughness, as built [3]	
Ti64_30_030_default.job Ti64 Performance (30 µm)	R_a 9 – 12 µm, R_z 40 – 80 µm R_a 0.36 – 0.47 $\times 10^3$ inch, R_z 1.6 – 3.2 $\times 10^3$ inch
Ti64 Speed 1.0 (60 µm)	R_a 6 – 10 µm, R_z 35 – 40 µm R_a 0.23 – 0.39 $\times 10^3$ inch, R_z 1.37 – 1.57 $\times 10^3$ inch
Volume rate [4]	
Ti64_30_030_default.job Ti64 Performance (30 µm)	3.75 mm ³ /s (13.5 cm ³ /h) 0.82 in ³ /h
Ti64 Speed 1.0 (60 µm)	9 mm ³ /s (32.4 cm ³ /h) 1.98 in ³ /h

- [1] Based on users' experience of dimensional accuracy for typical geometries. Part accuracy is subject to appropriate data preparation and post-processing, in accordance with EOS training.
- [2] Mechanical stability is dependent on geometry (wall height etc.) and application
- [3] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other factors such as DMLS-Start settings.

Material data sheet

Physical and chemical properties of parts

Material composition	Ti (balance) Al (5.5 – 6.75 wt.-%) V (3.5 – 4.5 wt.-%) O (< 2000 ppm) N (< 500 ppm) C (< 800 ppm) H (< 150 ppm) Fe (< 3000 ppm)
Relative density	approx. 100 %
Density	4.41 g/cm ³ 0.159 lb/in ³

Material data sheet

Mechanical properties of parts

	As built	Heat treated [6]
Tensile strength [5]		
- in horizontal direction (XY)	typ. 1230 ± 50 MPa typ. 178 ± 7 ksi	min. 930 MPa (134.8 ksi) typ. 1050 ± 20 MPa (152 ± 3 ksi)
- in vertical direction (Z)	typ. 1200 ± 50 MPa typ. 174 ± 7 ksi	min. 930 MPa (134.8 ksi) typ. 1060 ± 20 MPa (154 ± 3 ksi)
Yield strength ($R_{p0.2}$) [5]		
- in horizontal direction (XY)	typ. 1060 ± 50 MPa typ. 154 ± 7 ksi	min. 860 MPa (124.7 ksi) typ. 1000 ± 20 MPa (145 ± 3 ksi)
- in vertical direction (Z)	typ. 1070 ± 50 MPa typ. 155 ± 7 ksi	min. 860 MPa (124.7 ksi) typ. 1000 ± 20 MPa (145 ± 3 ksi)
Elongation at break [5]		
- in horizontal direction (XY)	typ. (10 ± 2) %	min. 10 % typ. (14 ± 1) %
- in vertical direction (Z)	typ. (11 ± 3) %	min. 10 % typ. (15 ± 1) %
Modulus of elasticity [5]		
- in horizontal direction (XY)	typ. 110 ± 10 GPa typ. 16 ± 1.5 GPa	typ. 116 ± 10 GPa typ. 17 ± 1.5 GPa
- in vertical direction (Z)	typ. 110 ± 10 GPa typ. 16 ± 1.5 GPa	typ. 114 ± 10 GPa typ. 17 ± 1.5 GPa
Hardness [7]	typ. 320 ± 12 HV5	

- [5] Tensile testing according to ISO 6892-1:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5 mm (0.2 inch), original gauge length 25 mm (1 inch).
- [6] Specimens were treated at 800 °C (1470 °F) for 4 hours in argon inert atmosphere. Mechanical properties are expressed as minimum values to indicate that mechanical properties exceed the minimum requirements of material specification standards. ASTM F1472-08. By fulfilling these minimum values, also the specifications of standards ASTM B348-09 and ISO 5832-3:2000 are meet.
- [7] Vickers hardness measurement (HV) according to EN ISO 6507-1 on polished surface. Note that measured hardness can vary significantly depending on how the specimen has been prepared.

Material data sheet

Thermal properties of parts

Maximum long-term operating temperature	approx. 350 °C approx. 660 °F
---	----------------------------------

Abbreviations

typ.	typical
min.	minimum
wt.	weight
approx.	approximately

Notes

The data are valid for the combinations of powder material machine and parameter sets referred to on page 1, when used in accordance with the relevant Operating Instructions (including Installation Requirements and Maintenance) and Parameter Sheet. Part properties are measured using defined test procedures. Further details of the test procedures used by EOS are available on request.

The data correspond to our knowledge and experience at the time of publication. They do not on their own provide a sufficient basis for designing parts. Neither do they provide any agreement or guarantee about the specific properties of a part or the suitability of a part for a specific application. The producer or the purchaser of a part is responsible for checking the properties and the suitability of a part for a particular application. This also applies regarding any rights of protection as well as laws and regulations. The data are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS, EOSINT and DMLS are registered trademarks of EOS GmbH.

2011 EOS GmbH – Electro Optical Systems. All rights reserved.

Material data sheet

EOS NickelAlloy HX

EOS NickelAlloy HX is a heat and corrosion resistant metal alloy powder intended for processing on EOS M 290 systems.

This document provides information and data for parts built using EOS NickelAlloy HX powder (EOS art.-no. 9011-0023) on the following system specifications:

- EOS M 290 400W with EOSPRINT 1.x and EOS Parameter set HX_Performance 2.0

Description, application

EOS NickelAlloy HX raw material is a nickel-chromium-iron-molybdenum alloy in fine powder form. Its composition corresponds to UNS N06002. While the wrought and cast versions of the alloy generally are solution annealed, the laser melted material manufactured of this powder has a high strength and good elongation already in the as-built condition. Solution annealing of the laser sintered material will homogenize the microstructure, relax internal stresses and increase the elongation, while slightly decreasing the strength.

This type of alloy is characterized by having high strength and oxidation resistance also at elevated temperatures, and is often used up to 1200°C. Therefore its applications can be found in aerospace technology, gas turbine parts, etc.

Standard laser processing parameters results in full melting of the entire geometry, typically with 40 µm layer thickness. Parts built from EOS NickelAlloy HX can be heat treated and material properties can be varied within specified range. In both as-built and solution heat treated states the parts can be machined, spark-eroded, welded, micro shot-peened, polished, and coated if required. Unexposed powder can be reused.

EOS - Material data sheet

Technical data

General process data

EOS NickelAlloy HX	
Typical achievable part accuracy [1]	
- small parts	approx. $\pm 50\text{-}80 \mu\text{m}$ ($\pm 0.0020\text{-}0.0031 \text{ inch}$)
- large parts	approx. $\pm 0.2 \%$
Min. wall thickness [2]	typ. $0.4\text{-}0.5 \text{ mm}$ ($0.016\text{-}0.020 \text{ inch}$)
Layer thickness	$40 \mu\text{m}$
Surface roughness [3]	
- after shot-peening (horizontal / vertical)	$R_a 3\text{-}6.5 \mu\text{m}$, $R_z 10\text{-}30 \mu\text{m}$ $R_a 0.12\text{-}0.25 \times 10^{-3} \text{ inch}$, $R_z 0.39\text{-}1.18 \times 10^{-3} \text{ inch}$
- after polishing	R_z up to $< 0.5 \mu\text{m}$ R_z up to $< 0.02 \times 10^{-3} \text{ inch}$ (can be very finely polished)
Volume rate [4]	$4.2 \text{ mm}^3/\text{s}$ ($15.2 \text{ cm}^3/\text{h}$) $0.93 \text{ in}^3/\text{h}$

- [1] Based on users' experience of dimensional accuracy for typical geometries, e.g. $\pm 50 \mu\text{m}$ when parameters can be optimized for a certain class of parts or $\pm 80 \mu\text{m}$ when building a new kind of geometry for the first time. Part accuracy is subject to appropriate data preparation and postprocessing.
- [2] Mechanical stability is dependent on geometry (wall height etc.) and application
- [3] Due to the layerwise building, the surface structure depends strongly on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect. The values also depend on the measurement method used. The values quoted here give an indication of what can be expected for horizontal (up-facing) or vertical surfaces.
- [4] Volume rate is a measure of build speed during laser exposure. The total build speed depends on the average volume rate, the recoating time (related to the number of layers) and other factors such as DMLS-Start settings.

EOS - Material data sheet

Physical and chemical properties of parts

EOS NickelAlloy HX			
Material composition	Element	Min	Max
	Ni	balance	
	Cr	20.5	23.0
	Fe	17.0	20.0
	Mo	8.0	10.0
	W	0.2	1.0
	Co	0.5	2.5
	C	--	0.1
	Si	--	1.0
	Mn	--	1.0
	S	--	0.03
	P	--	0.04
	B	--	0.01
	Se	--	0.0050
	Cu	--	0.5
	Al	--	0.5
	Ti	--	0.15
Relative density with standard parameters		approx. 100 %	
Density with standard parameters		min. 8.2 g/cm ³ min. 0.296 lb/in ³	

EOS - Material data sheet

Mechanical properties of parts (at room temperature)

As built	
Ultimate tensile strength [5]	
- in horizontal direction (XY)	typ. 820 ± 50 MPa
- in vertical direction (Z)	typ. 675 ± 50 MPa
Yield strength, Rp0.2% [5]	
- in horizontal direction (XY)	typ. 630 ± 50 MPa
- in vertical direction (Z)	typ. 545 ± 50 MPa
Young's modulus [5]	
- in horizontal direction (XY)	typ. 195 ± 20 GPa
- in vertical direction (Z)	typ. 175 ± 20 GPa
Elongation at break [5]	
- in horizontal direction (XY)	typ. 27 ± 8 %
- in vertical direction (Z)	typ. 39 ± 8 %

[5] Tensile testing according to ISO 6892-1:2009 (B) Annex D, proportional test pieces, diameter of the neck area 5 mm (0.2 inch), original gauge length 25 mm (1 inch).

Abbreviations

typ.	typical
min.	minimum
approx.	approximately
wt	weight



EOS - Material data sheet

The quoted values refer to the use of these materials with EOS M 290 systems according to current specifications (including the latest released process software PSW and any hardware specified for the relevant material) and operating instructions. All values are approximate. Unless otherwise stated, the quoted mechanical and physical properties refer to standard building parameters and test samples built in vertical orientation. They depend on the building parameters and strategies used, which can be varied by the user according to the application.

The data are based on our latest knowledge and are subject to changes without notice. They are provided as an indication and not as a guarantee of suitability for any specific application.

EOS[®], EOSINT[®], DMILS[®], DirectTool[®] and DirectPart[®] are registered trademarks of EOS GmbH.

© 2015 EOS GmbH – Electro Optical Systems. All rights reserved.



Material data sheet

EOS NickelAlloy IN625

EOS NickelAlloy IN625 is a heat and corrosion resistant nickel alloy powder which has been optimized especially for processing on EOSINT M systems.

This document provides information and data for parts built using EOS NickelAlloy IN625 powder (EOS art.-no. 9011-0022) on the following system specifications:

- EOS DMLS™ system: EOS M290
- HSS recoating blade (2200-4073)
- Argon atmosphere
- Grid nozzle (2200-5501)
- IPCM M sieving module with 63µm mesh recommended (9044-0032)
- Software: EOSYSTEM v.2.5 or newer
- EOS Parameter set IN625 Performance 2.0

Description

Parts built from EOS NickelAlloy IN625 have chemical composition corresponding to UNS N06625, AMS 5666F, AMS 5599G, W.Nr 2.4856, DIN NiCr22Mo9Nb. This type of alloy is characterized by having high tensile, creep and rupture strength. Conventionally cast or wrought components in this type of nickel alloy have typically excellent fatigue and thermal-fatigue properties combined with good oxidation resistance. EOS NickelAlloy IN625 is expected to have good corrosion resistance in various corrosive environments. Especially sea-water applications require high pitting and crevice corrosion resistance, stress-corrosion resistance against chloride-ions, high tensile and corrosion-fatigue strength. However, corrosion resistance has not been verified yet and therefore it is recommended to conduct relevant corrosion tests and studies prior to use in specific corrosive environment.

Parts built from EOS NickelAlloy IN625 can be heat treated and material properties can be varied within specified range. Parts can be machined, spark-eroded, welded, micro shot-peened, polished and coated in both as-built and in heat-treated conditions. Due to the layerwise building method, the parts have certain anisotropy.



Material data sheet

Quality Assurance

The quality of the EOS NickelAlloy IN625 powder lots is ensured by the Quality Assurance procedures. The procedures include sampling (ASTM B215), PSD analysis (ISO 13320), chemical analyses (ASTM E2371, ASTM E1409, ASTM E1941, ASTM E1447), and mechanical testing (ISO 6892-1).

The results of the quality assurance tests are given in the lot specific Mill Test Certificates (MTC) according to EN 10204 type 3.1.

Material data sheet

Technical Data

Powder properties

Material composition [wt.%]	Element	Min	Max
	Cr	20.00	23.00
	Mo	8.00	10.00
	Nb	3.15	4.15
	Fe	-	5.00
	Ti	-	0.40
	Al	-	0.40
	Co	-	1.00
	Si	-	0.50
	Mn	-	0.50
	C	-	0.10
	Ta	-	0.05
	P	-	0.015
	S	-	0.015
	Ni	58.00	bal.

Particle size

d50 [1]	35 ± 6 µm
---------	-----------

[1] Particle size distribution analysis according to ISO 13320

Material data sheet

General process data

Layer thickness	40 µm
Volume rate [2]	4.2 mm ³ /s (15.2 cm ³ /h)

- [2] The volume rate is a measure of build speed during laser exposure of the skin area. The total build speed depends on this volume rate and many other factors such as exposure parameters of contours, supports, up and downskin, recoating time, Home-In or LPM settings.

Physical properties of parts

Part density [3]	8.4 g/cm ³
Surface roughness after shot peening [4]	typ. R _a 1–5 µm; R _z 3–10 µm
Hardness as built [5]	typ. 27 HRC

- [3] Weighing in air and water according to ISO 3369.
- [4] The numbers were measured at the horizontal (up-facing) and all vertical surfaces of test cubes. Due to the layerwise building the roughness strongly depends on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect.
- [5] Hardness measurement according to standard EN ISO 6508-1:2005

Material data sheet

Tensile data at room temperature [6,7]

	As built [9]	Heat treated [8,9]
Ultimate tensile strength, Rm		
- in horizontal direction (XY)	Mean 980 MPa StDev. 5 MPa	Mean 1000 MPa StDev. 10 MPa
- in vertical direction (Z)	Mean 870 MPa StDev. 10 MPa	Mean 890 MPa StDev. 10 MPa
Yield strength, Rp0.2%		
- in horizontal direction (XY)	Mean 720 MPa StDev. 5 MPa	Mean 680 MPa StDev. 5 MPa
- in vertical direction (Z)	Mean 630 MPa StDev. 5 MPa	Mean 640 MPa StDev. 5 MPa
Elongation at break, A		
- in horizontal direction (XY)	Mean 33 % StDev. 2 %	Mean 34 % StDev. 2 %
- in vertical direction (Z)	Mean 48 % StDev. 2 %	Mean 49 % StDev. 2 %

- [6] The numbers are average values and are determined from samples with horizontal and vertical orientation.
- [7] Tensile testing according to ISO 6892-1 B10, proportional test pieces, diameter of the neck area 5 mm (0.2 inch), original gauge length 20 mm (0,79 inch).
- [8] Heat treatment procedure: anneal at 870 °C (1600 °F) for 1 hour, rapid cooling.
- [9] The values are subject to variations depending on samples orientation on a building platform.



Material data sheet

Abbreviations

min. minimum
max. maximum
wt. weight
typ. typical
StDev. standard deviation

The quoted values refer to the use of this material with above specified EOS DMLS system, EOSYSTEM software version, parameter set and operation in compliance with parameter sheet and operating instructions. All measured values are average numbers. Part properties are measured with specified measurement methods using defined test geometries and procedures and. Further details of the test procedures used by EOS are available on request. Any deviation from these standard settings may affect the measured properties.

The data correspond to EOS knowledge and experience at the time of publication and they are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS does not warrant any properties or fitness for a specific purpose, unless explicitly agreed upon. This also applies regarding any rights of protection as well as laws and regulations.

EOS®, EOSINT®, DMLS®, DirectTool® and DirectPart® are registered trademarks of EOS GmbH.

©2017 EOS GmbH – Electro Optical Systems. All rights reserved.

17-4PH Stainless Steel



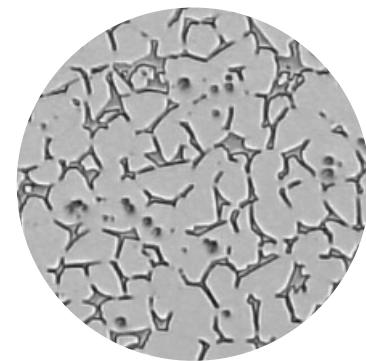
Typical Material Properties

Material Properties	Test Method	17-4PH H900
Tensile Strength		
Ultimate Strength		X & Y: 1070 - 1310 MPa Z: 1070 - 1310 MPa
Yield Strength (0.2% offset)		X & Y: 970 - 1030 MPa Z: 970 - 1020 MPa
Elongation	ASTM E8	X & Y: 4%- 12% Z: 4% - 11%
Elastic Modulus		X & Y: 180 -190 GPa Z: 180 - 200 GPa
Hardness	ASTM E18	35 - 41 HRC
Impact	ASTM E23	55 - 75 J
Poisson's Ratio		0.28 - 0.30
Relative Density		96 - 99%
Density		7.5 - 7.7 g/cc
Surface Roughness		3 - 12 µm Ra



17-4PH Printed Part

Material Composition			
Iron	bal	Niobium + Tantalum	0.15-0.45%
Nickel	3-5%	Manganese	1.0% max
Chromium	15.5-17.5%	Silicon	1.0% max
Carbon	0.07% max		
Copper	3-5%		



Microstructure

ExOne disclaims all warranties and liabilities for the content hereof and makes no representations as to its accuracy or fitness for use for any purpose. Any tradenames, trademarks, or service marks of others appearing herein are used strictly nominatively and are not to be construed as implying any affiliation, connection, association, sponsorship, or approval of the owners thereof for ExOne, its products, or the content hereof.

316L Stainless Steel



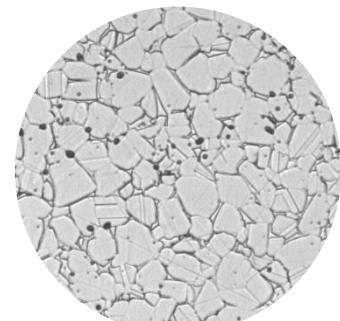
Typical Material Properties

Material Properties	Test Method	316L
Tensile Strength		
Ultimate Strength	ASTM E8	X & Y: 450 - 580 MPa Z: 450 - 520 MPa
Yield Strength (0.2% offset)		X & Y: 140 - 220 MPa Z: 140 - 220 MPa
Elongation		X & Y: 40 - 55% Z: 40 - 50%
Elastic Modulus		X & Y: 190 - 220 GPa Z: 180 - 190 GPa
Hardness		67 - 71 HRB
Impact		55 - 75 J
Poisson's Ratio		0.28 - 0.30
Relative Density		96 - 99%
Density		7.6 - 7.9 g/cc
Surface Roughness		3 - 12 µm Ra



316L Printed Part

Material Composition			
Iron	bal	Molybdenum	2-3%
Nickel	10-14%	Manganese	2.0% max
Chromium	16-18%	Silicon	1.0% max
Carbon	0.03% max		



Microstructure

ExOne disclaims all warranties and liabilities for the content hereof and makes no representations as to its accuracy or fitness for use for any purpose. Any tradenames, trademarks, or service marks of others appearing herein are used strictly nominatively and are not to be construed as implying any affiliation, connection, association, sponsorship, or approval of the owners thereof for ExOne, its products, or the content hereof.

Material Properties

Table displays the average tested values

Tensile Data

Ultimate Strength	X & Y: 1310 MPa Z: 1331 MPa
Yield Strength	X & Y: 1069 MPa Z: 1076 MPa
Elongation	X & Y: 15% Z: 15%
Elastic Modulus	X & Y: 193 GPa Z: 193 GPa
Hardness	41 HRC
Impact	12.2 J
Poisson's Ratio	0.29
Relative Density	99.2%
Density	8.13 g/cc
Surface Roughness	3.6 µm Ra

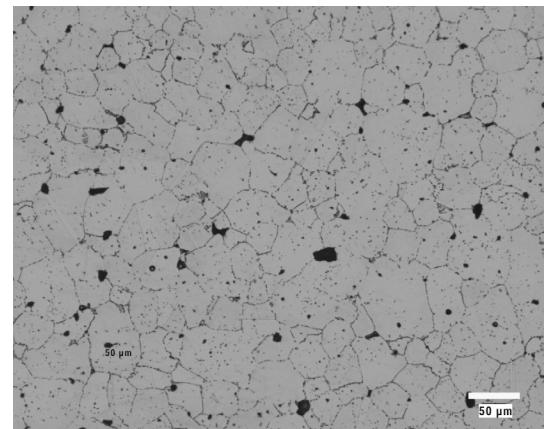
Table displays the average tested values. Material properties tested after solution annealing and aging heat treatments. Heat treating profile in accordance with AMS 5662.

Material Composition	UNS N07718 ASTM B637-18 (wt%)
Nickel	50.0 - 55.0
Chromium	17.0 - 21.0
Iron	Balance
Niobium+ Tantalum	4.75 - 5.50
Molybdenum	2.80 - 3.30
Titanium	0.65 - 1.15
Aluminum	0.20 - 0.80
Carbon	0.04 - 0.13*
Cobalt	1.00 max
Manganese	0.35 max
Silicon	0.35 max
Copper	0.30 max
Phosphorus	0.015 max
Sulfur	0.015 max
Boron	0.006 max

* The wt% of carbon in the as-sintered state is < 0.08%. Final carbon results are dependent upon the secondary heat treating conditions



Inconel 718 Printed Parts



Microstructure

ExOne disclaims all warranties and liabilities for the content hereof and makes no representations as to its accuracy or fitness for use for any purpose. Any trademarks, service marks, or service marks of others appearing herein are used strictly nominatively and are not to be construed as implying any affiliation, connection, association, sponsorship, or approval of the owners thereof for ExOne, its products, or the content hereof.

304L Stainless Steel

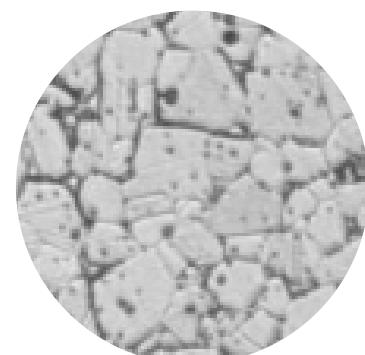
Typical Material Properties

Material Properties	Test Method	304L Stainless Steel
Tensile Strength		
Ultimate Strength		X & Y: 450 - 570 MPa Z: 450 - 570 MPa
Yield Strength (0.2% offset)		X & Y: 140 - 200 MPa Z: 140 - 200 MPa
Elongation	ASTM E8	X & Y: 40 - 60% Z: 40 - 55%
Elastic Modulus		X & Y: 190 - 220 GPa Z: 190 - 200 GPa
Hardness	ASTM E18	67 - 75 HRB
Impact	ASTM E23	35 - 45 J
Relative Density		96 - 99%
Density		7.6 - 7.9 g/cc
Surface Roughness		3 - 12 µm Ra



304L Stainless Steel Printed Part

Material Composition			
Iron	bal	Sulfur	0.03% max
Nickel	8-12%	Manganese	2.0% max
Chromium	18-20%	Silicon	1.0% max
Carbon	0.03% max		
Phosphorus	0.045% max		



304L Stainless Steel Microstructure

ExOne disclaims all warranties and liabilities for the content hereof and makes no representations as to its accuracy or fitness for use for any purpose. Any tradenames, trademarks, or service marks of others appearing herein are used strictly nominatively and are not to be construed as implying any affiliation, connection, association, sponsorship, or approval of the owners thereof for ExOne, its products, or the content hereof.



Review in Advance first posted online
on April 21, 2016. (Changes may
still occur before final publication
online and in print.)

Metal Additive Manufacturing: A Review of Mechanical Properties

John J. Lewandowski and Mohsen Seifi

Department of Materials Science and Engineering, Case Western Reserve University (CWRU),
Cleveland, Ohio 44106; email: JJL3@case.edu, mohsen.seifi@case.edu

Annu. Rev. Mater. Res. 2016. 46:14.1–14.36

The *Annual Review of Materials Research* is online at
matsci.annualreviews.org

This article's doi:
10.1146/annurev-matsci-070115-032024

Copyright © 2016 by Annual Reviews.
All rights reserved

Keywords

metal additive manufacturing, mechanical properties, fracture, fatigue,
toughness, tensile

Abstract

This article reviews published data on the mechanical properties of additively manufactured metallic materials. The additive manufacturing techniques utilized to generate samples covered in this review include powder bed fusion (e.g., EBM, SLM, DMLS) and directed energy deposition (e.g., LENS, EBF³). Although only a limited number of metallic alloy systems are currently available for additive manufacturing (e.g., Ti-6Al-4V, TiAl, stainless steel, Inconel 625/718, and Al-Si-10Mg), the bulk of the published mechanical properties information has been generated on Ti-6Al-4V. However, summary tables for published mechanical properties and/or key figures are included for each of the alloys listed above, grouped by the additive technique used to generate the data. Published values for mechanical properties obtained from hardness, tension/compression, fracture toughness, fatigue crack growth, and high cycle fatigue are included for as-built, heat-treated, and/or HIP conditions, when available. The effects of test orientation/build direction on properties, when available, are also provided, along with discussion of the potential source(s) (e.g., texture, microstructure changes, defects) of anisotropy in properties. Recommendations for additional work are also provided.

INTRODUCTION

A number of metal additive manufacturing (AM) processes are currently available (1), depending on the heat source (2, 3), such as electron beam (2–7), laser, or arc (2, 3, 8, 9), and on how the raw material is supplied. Materials supply can occur via powder or wire feed, whereby selected regions are melted at different combinations of absorbed power (P) and beam velocity (V) (10), as shown in **Figure 1**, and then solidified. Cooling rates during and after solidification are affected and controlled by the P - V combinations utilized and by any preheating of the substrate. These variables, along with the subsequent thermal cycles that occur during such layered manufacturing as well as any postprocessing (e.g., heat treatment, HIP), affect the resulting microstructures, as reviewed previously (10) and in another contribution to this journal's keynote topic on AM (11). Nonequilibrium microstructures and defects can result in as-built materials, depending on the processing conditions and materials employed, whereas postprocessing via heat treatment and/or HIP can be used to change some of the microstructural features and to reduce or eliminate defects and any residual stresses. These changes affect both the orientation dependence of mechanical properties and their magnitude, as this article documents. A broader review on materials qualification needs for metal AM is provided elsewhere (10).

The recent reviews of the metal AM processes by Frazier (2) and Dutta & Froes (3) highlight some of the differences between the various processes. **Figure 2** provides the two major metal AM process categories reviewed in this article, powder bed fusion (PBF) and directed energy deposition (DED). **Figure 2** also includes designations for the technologies currently available within each major process category [e.g., direct metal laser melting (DMLM), selective laser melting (SLM), selective laser sintering (SLS), direct metal deposition (DMD)] and current commercial machine

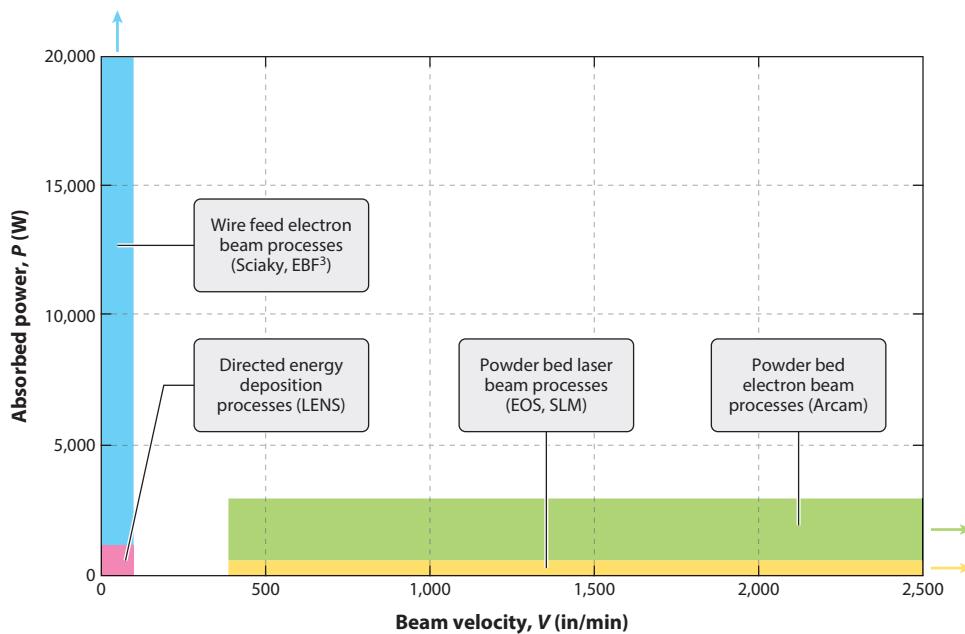
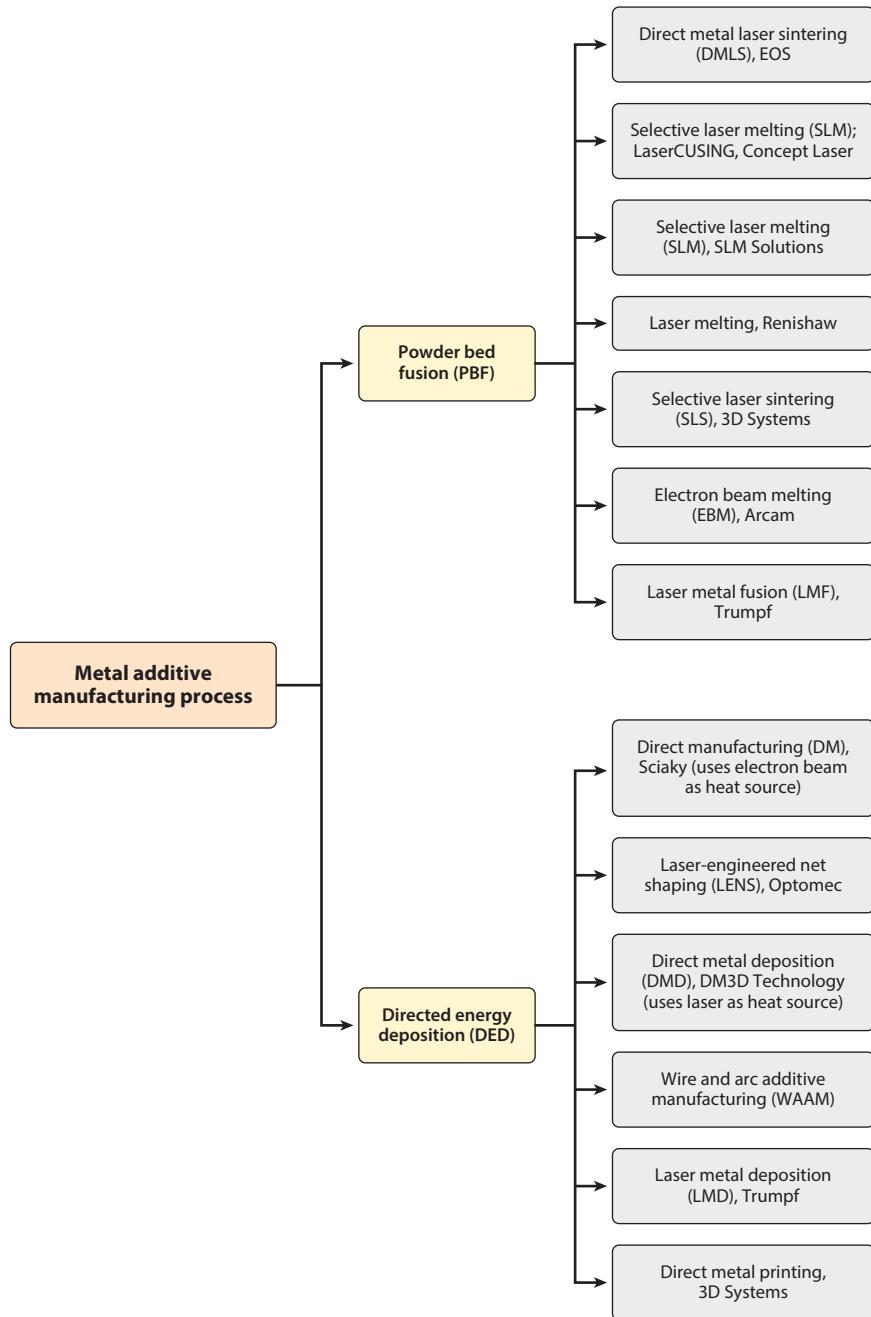


Figure 1

Typical combinations of power (P) and velocity (V) in various metal AM processes. Abbreviations: EBF³, electron beam freeform fabrication; LENS, laser-engineered net shaping; SLM, selective laser melting. Adapted with permission from Reference 10.

**Figure 2**

Summary of metal additive manufacturing processes.

Table 1 Summary of various alloys used in different process categories, along with references

	PBF		DED				
	EBM (powder)	Laser (powder)	EBM (wire; Sciaky)	EBM (powder)	Laser (wire)	Laser (powder; LENS)	WAAM (wire)
Titanium alloys	12–48	49–71			72–79	80–83	74
TiAl (intermetallics)	199, 203–222	171, 172, 223, 224					
Steel alloys		84–93	94		95		96
Nickel alloys	97–102	103–110			111, 112		
Aluminum alloys		113–124	125				126, 127
High-entropy alloys	128	129					

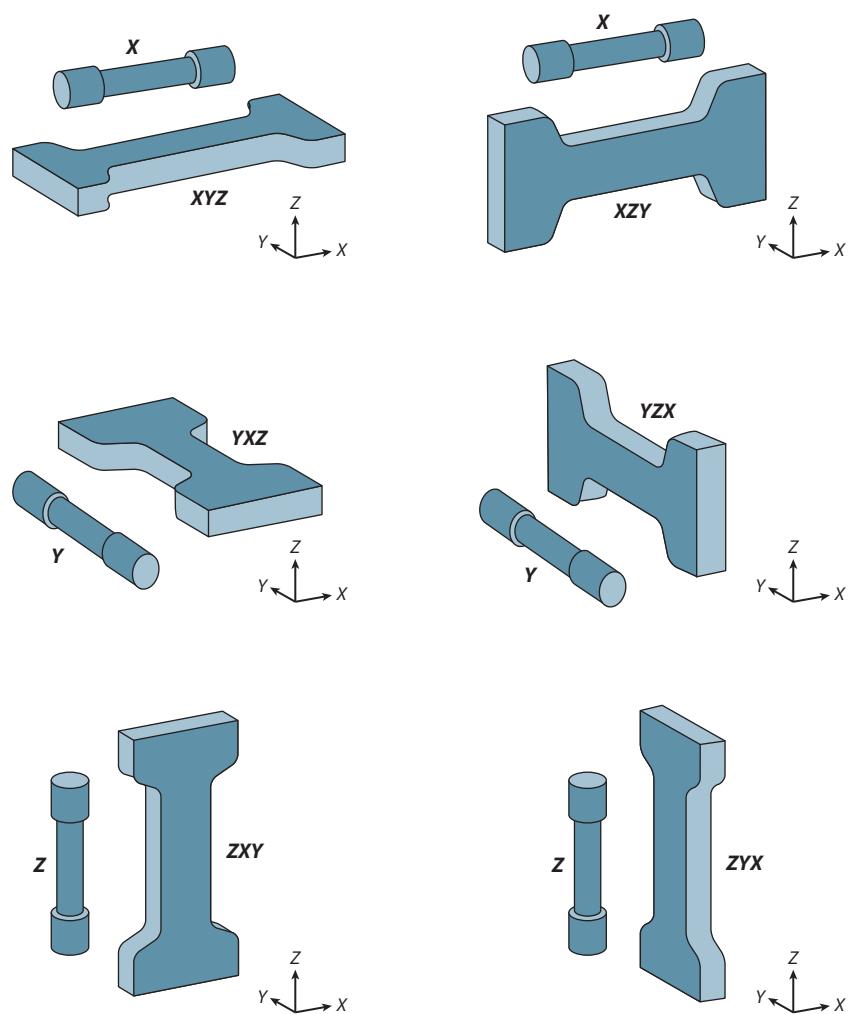
suppliers. To systematically review the published values for mechanical properties obtained for materials manufactured by these different techniques, this review begins with a compilation of the most widely utilized AM alloy systems along with the process category (e.g., PBF, DED) and energy source for fusion [e.g., electron beam melting (EBM), laser, and wire and arc additive manufacturing (WAAM)]. Individual tables and/or figures for each alloy, energy source, and/or mechanical property are then provided for as-built, heat-treated, and/or HIP conditions and document the test orientation and build direction when available.

ADDITIVELY MANUFACTURED ALLOY SYSTEMS

As indicated in previous reviews (2, 3), at present there is only a limited number of alloy systems for which mechanical properties are published. **Table 1** summarizes the existing alloy classes and references to published data, along with the process category and source of fusion. These categories provide the basis for the remainder of this review.

MECHANICAL PROPERTIES OF ADDITIVELY MANUFACTURED METALLIC MATERIALS

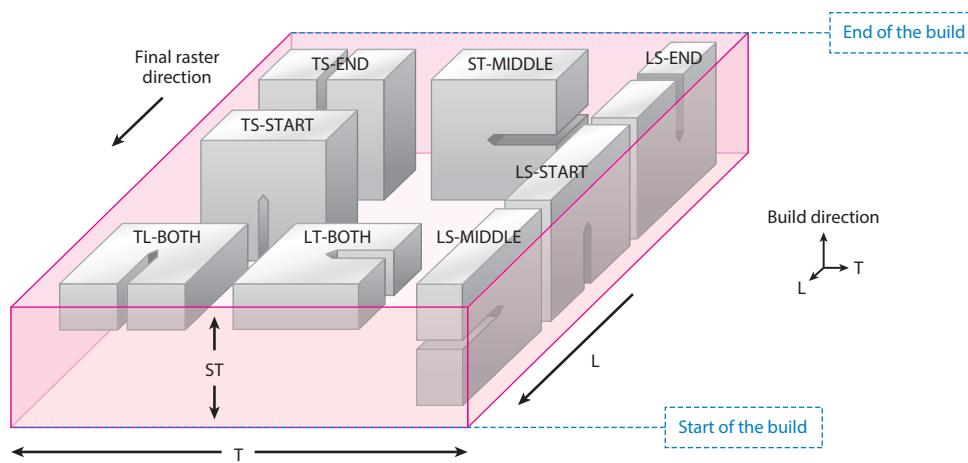
Although most of the published mechanical property measurements have been reported for Ti-6Al-4V, tables and/or figures summarizing data for each of the alloy classes shown in **Table 1** are provided, when available. Review of the literature also reveals that most of the published work has focused on tension/compression testing, with more recent work on fracture-critical properties. In the tables, the effects of specimen or build orientation on tensile properties are documented using the *X*, *Y*, *Z* designation according to the ASTM standard (130) shown in **Figure 3**, when documented in the published work. Rectangular and nonsymmetric test coupons thus require three letters (*X*, *Y*, *Z*) to provide a complete orientation designation. In this terminology, *Z* designates the build direction. The *X* axis is parallel to the front of the machine and is perpendicular to *Z*. The *Y* axis is perpendicular to both the *Z* and *X* axes, with a positive direction defined to make a right-hand set of coordinates. The first letter designates the axis parallel to the longest overall dimension. The second letter designates the second-longest overall dimension, followed by the third letter, which designates the third-longest overall dimension of the coupon. For example, a specimen with XYZ designation has its longest dimension parallel to *X*, its second-longest dimension parallel to *Y*, and its shortest overall dimension parallel to *Z*. **Figure 3** also illustrates that only one letter

**Figure 3**

Orientation designations for AM materials.

is required for cylindrically symmetric samples. Unfortunately, not all of the published works reviewed herein followed these ASTM/ISO rules. In some cases, only one letter was used for nonsymmetric samples. The tables also document any postprocessing (e.g., heat treatment, HIP) that was used.

ASTM committee F42 (131) is reviewing potential modifications to the orientation designation scheme for fracture toughness and fatigue crack growth, as shown in **Figure 4** (48). These modifications to the evolving ASTM standards for AM materials may be necessary to document the unique orientation- and location-dependent properties that can be produced both within and between builds in AM-processed materials (10, 48) due to differences in the microstructure, texture, residual stresses, and/or defects. These types of samples could also serve as witness samples deposited along with components in the same build to provide input on part/component quality in different locations and orientations.

**Figure 4**

Possible designations for AM mechanical testing based on existing ASTM standards. There are eight different orientation and direction combinations. Abbreviations: L, longitudinal; S, short; T, transverse. Adapted from References 48 and 131 with permission.

QUASI-STATIC PROPERTIES: TENSILE AND FRACTURE TOUGHNESS

Tables 2 and **3** compile published tensile properties for Ti-6Al-4V produced via PBF EBM and laser techniques, respectively, and include hardness data when available along with literature references. **Tables 2** and **3** show the machine type and powder [e.g., conventional versus ELI (extra low interstitial)] utilized; show the specimen orientation using the X, Y, Z scheme presented in **Figure 3**; and specify whether the material was tested in the as-built, heat-treated, and/or HIP condition. **Figure 5** captures some of the key early observations on AM tensile properties for Ti-6Al-4V, and the tables and figures contained herein provide updated details along with many additional references.

The summary in **Table 2** for PBF (EBM) reveals orientation-dependent values for yield strength, ultimate tensile strength (UTS), and elongation to failure that are also affected by postprocessing heat treatments and/or HIP. Because of differences in the sample gauge lengths between the different investigations, the reported elongations to failure are difficult to compare directly. However, properties reported for all of the conditions (as built, heat treated, and/or HIP) often approach and exceed those reported for conventionally processed Ti-6Al-4V (3). EBM machine type (e.g., Arcam A1, A2, A2xx, S12, S400) appears to affect the reported properties, although property variations have also been documented on samples manufactured within one machine type. The source(s) of these variations could be explored by conducting round robin activities like those organized by NIST/ASTM (132, 133) for PBF (laser), and the source(s) of the orientation-dependent properties is starting to receive additional attention from the AM community. Orientation-dependent differences in the microstructure, texture, and defects contribute to some of these tensile property differences but become more important in the fracture-critical properties (e.g., HCF, fatigue crack growth, fracture toughness) reviewed below. Postprocessing (e.g., heat treatment and/or HIP) can be used to produce more desirable microstructures and to reduce or eliminate process-induced defects [e.g., lack of fusion (LoF), isolated porosity] but affects the cost-effectiveness of the process. In general, the use of preheated powder beds in the EBM process reduces the cooling rate during and after the AM process, typically producing

Table 2 Summary of EBM PBF AM Ti-6Al-4V tensile properties

Machine type	Condition	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness (Hv)	Reference
Arcam	Heat treated	ZX	NA	869 ± 7	965 ± 5	6 ± 0	NA	141
Arcam A1	As built	XY	NA	783 ± 15	833 ± 22	2.7 ± 0.4	NA	142
		ZX		812 ± 12	851 ± 19	3.6 ± 0.9		
Arcam	As built	XY	NA	870 ± 8.1	971 ± 3.1	12.1 ± 0.9	NA	12
		Z		879 ± 12.5	953 ± 8.8	13.8 ± 0.9		
	HIP	XY		866 ± 6.4	959 ± 8.2	13.6 ± 0.6		
		Z		868 ± 2.9	942 ± 2.6	12.9 ± 0.8		
Arcam ELI ^a	As built	XY	NA	817 ± 4.3	918 ± 1.0	12.6 ± 0.8	NA	
		Z		802 ± 7.9	904 ± 6.0	13.8 ± 0.9		
	HIP	XY		814 ± 2.4	916 ± 2.5	13.6 ± 1.2		
		Z		807 ± 8.4	902 ± 8.7	14.8 ± 0.5		
Arcam A2xx ELI ^a	As built	XY	NA	851.8 ± 5.8	964 ± 0.3	16.3 ± 0.8	NA	143
Arcam A2 ELI ^a	As built	Z	NA	928 ± 13.3	1,011 ± 14.8	13.6 ± 1.4	NA	31
	HIP	Z	NA	813 ± 14.3	908 ± 3.2	17.7 ± 0.9	NA	
Arcam S12	As built	XY	NA	975	1,033	16.78	NA	144
Arcam	As built	XY	NA	881 ± 12.5	978 ± 11.5	10.7 ± 1.5	NA	33
		HIP		876 ± 12.5	978 ± 9.5	13.5 ± 1.5		
Arcam S12	As built	XY	NA	982 ± 5.7	1,029 ± 7	12.2 ± 0.8	372 ± 7.2	145
		Z		984 ± 8.5	1,032 ± 12.9	9 ± 2.9		
Arcam S400	As built	XY	NA	899 ± 4.7	978 ± 3.2	9.5 ± 1.2	NA	39
		ZX		869 ± 7.2	928 ± 9.8	9.9 ± 1.7		
Arcam S400	As built	XY	104 ± 2.3	844 ± 21.6	917 ± 30.53	8.8 ± 1.42	NA	40
		Z		101 ± 2.5	782 ± 5.1	842 ± 13.84		
Arcam S400 ELI ^a	As built	Z	NA	1,150	1,200	16	380	146
Arcam	As built	NA	118 ± 5	830 ± 5	915 ± 10	13.1 ± 0.4	NA	16
		HIP		117 ± 4	795 ± 10	870 ± 10		
Arcam A2 ELI ^a	As built	Z	93 ± 2	735 ± 28	775 ± 26	2.3 ± 0.8	369 ± 2	29

(Continued)



Table 2 (Continued)

Machine type	Condition	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness (Hv)	Reference
Arcam ELI ^a	HIP	XY	NA	841	938	20	NA	14
	As built	Z	NA	856	924	15	NA	
	HIP	Z	NA	800	876	16	NA	
Arcam	As built	NA	114 ± 6	1,135 ± 12	NA	NA	NA	147
Arcam S400	As built	Z	109 ± 2.1	1,098 ± 15	1,237 ± 13	8.8 ± 0.6	NA	148
Arcam	As built	NA	128	880	930	>10%	NA	149

NA denotes data not available.

^aELI (extra low interstitial) powder was used.

$\alpha + \beta$ lamellar microstructures [with prior β grain sizes that can be affected or controlled by the combinations of P and V utilized in the process (134–140)]. EBM AM materials typically possess lower levels of residual stresses in the as-built condition than do materials made by laser-based techniques that typically use no preheat; the faster cooling rates typically produce highly nonequilibrium microstructures [e.g., martensite in PBF (laser) Ti-6Al-4V] and much higher levels of residual stress that require subsequent stress relief treatments, as described below. Chemistry control in the PBF (EBM) process can also become an issue in Ti-6Al-4V due to the preferential loss of Al during EBM of powders in high vacuum.

Table 3 illustrates that PBF (laser) of Ti-6Al-4V exhibited features (e.g. orientation-dependent properties, machine effects (132, 133), postprocessing improvements to properties) similar to those shown for PBF (EBM) in **Table 2**. Highly nonequilibrium microstructures (e.g., martensite), along with substantial residual stresses that increase the strength and decrease the elongation values, are possible in as-built Ti-6Al-4V. Postprocessing has been used to increase the elongation to failure while reducing the yield strength, UTS, and residual stress values.

Table 4, which summarizes DED (laser) tensile properties, shows similar general characteristics of orientation- and machine-dependent properties, with values for as-built yield strength, UTS, and elongation to failure generally between the values exhibited in **Tables 2** and **3** for PBF (EBM) and PBF (laser), respectively. The combinations of P and V shown in **Figure 1** for DED generally produce $\alpha + \beta$ lamellar microstructures, with prior β grain sizes somewhat larger than those obtained from PBF (laser) due to the slower cooling rates typically present in DED (57, 59, 134–137). **Table 4** also shows that HIP can result in significant increases to the elongation-to-failure values via the elimination of process-induced defects. These process-induced defects are particularly detrimental to the high cycle fatigue behavior, as discussed below.

Table 5 summarizes the more limited published work on tensile properties for all of the other alloys in **Table 1** manufactured using PBF techniques. The limited published tensile properties for 316L PBF (laser) reveal properties in the range of commercially produced 316L. HIP of 316L produced via SLM increased elongation, likely due to the elimination of process-induced defects. Both Al-12Si and Al-Si-10Mg are alloys typically processed via commercial casting techniques (e.g., sand, gravity die). Strength levels in PBF (laser)-processed versions of Al-12Si and Al-Si-10Mg are in the range of data produced via sand and die casting techniques, whereas the somewhat higher elongation values arise due to the microstructure refinement provided by the faster cooling

Table 3 Summary of laser-melted PBF AM Ti-6Al-4V tensile properties

Machine type	Condition	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
EOS	As built	XZY	91.8 ± 0.5	938 ± 7.7	1,140 ± 5	NA	NA	150
	Stress relieved		98.2 ± 1.2	862 ± 3.1	936 ± 3.6			
	HIP		106.8 ± 1.3	835 ± 3.8	910 ± 2.9			
SLM	As built	XY	NA	1,093 ± 64	1,279 ± 13	6 ± 0.7	NA	151
		ZX		1,125 ± 22	1,216 ± 8	6 ± 0.4		
	Stress relieved	XY		1,145 ± 17	1,187 ± 10	7 ± 2.7		
		ZX		1,132 ± 13	1,156 ± 13	8 ± 0.4		
	Heat treated	XY		973 ± 8	996 ± 10	3 ± 0.4		
		ZX		964 ± 7	998 ± 14	6 ± 2		
EOS M280	As built	ZX	NA	1,017 ± 7	1,096 ± 7	12 ± 0.5	NA	141
SLM	As built	NA	110	736	1,051	11.9	360 (Hv)	152
	HIP		115.4	885	973	19	351 (Hv)	
	Heat treated		117.4	1,051	1,115	11.3	321 (Hv)	
Renishaw MTT250	As built	XY	NA	910 ± 9.9	1,035 ± 29	3.3 ± 0.76	NA	153
SLM250	As built	ZX	NA	NA	1,314 ± 15.6	4 ± 1.2	NA	154
					1,088 ± 26.3	13.8 ± 1.3		
	Heat treated				1,228 ± 32.4	8 ± 15		
Renishaw AM250	As built	XZ	115 ± 6	978 ± 5	1,143 ± 6	11.8 ± 0.5	NA	155
		ZX	119 ± 7	967 ± 10	117 ± 3	8.9 ± 0.4		
		XY	113 ± 5	1,075 ± 25	1,199 ± 49	7.6 ± 0.5		
	Stress relieved	XZ	113 ± 9	958 ± 6	1,057 ± 8	12.4 ± 0.7		
		ZX	117 ± 6	937 ± 9	1,052 ± 11	9.6 ± 0.9		
		XY	112 ± 6	974 ± 7	1,065 ± 21	7.0 ± 0.5		
SLM250	As built	ZX	NA	1,008	1,080	1.6	NA	9
	HIP			962	1,080	5		
	Heat treated			912	1,005	8.3		
Realizer	As built	ZX	119 ± 7	967 ± 10	117 ± 3	8.9 ± 0.4	NA	64
SLM50	Stress relieved		117 ± 6	937 ± 9	1,052 ± 11	9.6 ± 0.9		
EOS M270	As built	ZX	NA	1,143 ± 30	1,219 ± 20	4.89 ± 0.6	NA	39
		XY		1,195 ± 19	1,269 ± 9	5 ± 0.5		

(Continued)

Table 3 (*Continued*)

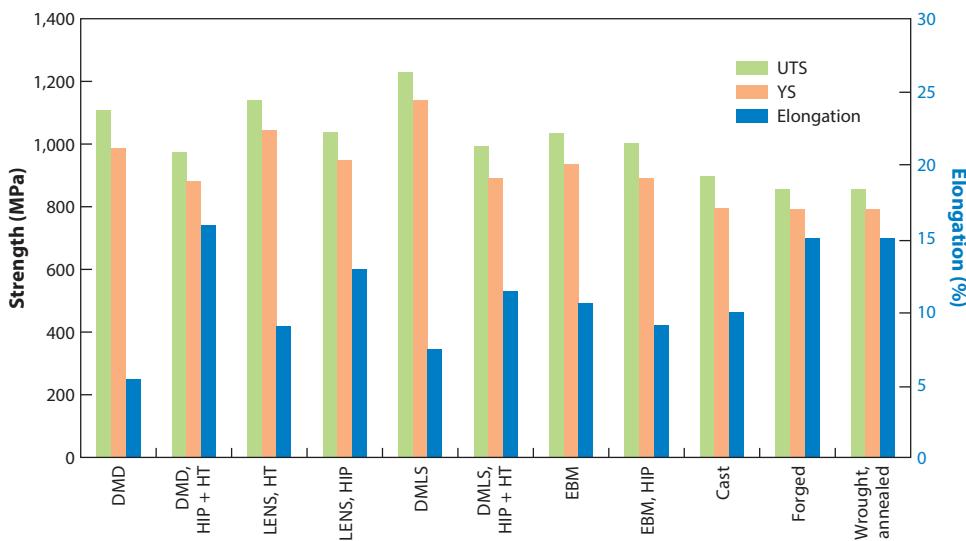
Machine type	Condition	Specimen orientation	<i>E</i> (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
SLM	As built	XY	109.2 ± 3.1	1,110 ± 9	1,267 ± 5	7.28 ± 1.12	NA	156
EOS M270	As built	NA	110 ± 5	990 ± 5	1,095 ± 10	8.1 ± 0.3	NA	51
	Heat treated		NA	1,040 ± 10	1,140 ± 10	8.2 ± 0.3	NA	
EOS M270	As built	ZX	111	1,120	1,257	8.0	37 (HRC)	148
EOS M27	As built	Z	NA	1,333	1,407	4.54	NA	157
SLM (Trumpf)	As built	XY	105 ± 5	1,137 ± 20	1,206 ± 8	7.6 ± 2	NA	158
		ZX	102 ± 7	962 ± 47	1,166 ± 25	1.7 ± 0.3		
	Heat treated	XY	103 ± 11	944 ± 8	1,036 ± 30	8.5 ± 1		
		ZX	98 ± 3	925 ± 14	1,040 ± 40	7.5 ± 2		
SLM	As built	NA	94	1,125	1,250	6	NA	159
Renishaw MTT	As built	X	NA	1,166 ± 6	1,321 ± 6	2.0 ± 0.7	NA	160
DLF	As built	X	118 ± 2.3	1,100 ± 12	1,211 ± 31	6.5 ± 0.6	NA	161
Concept Laser M2	As built	X	NA	1,070 ± 50	1,250 ± 50	5.5 ± 1	NA	162
		Z		1,050 ± 40	1,180 ± 30	8.5 ± 1.5		

NA denotes data not available.

rates in the PBF (laser) processes used. The very limited published tension data on CoCrMo reveal that PBF (laser) exhibits somewhat higher strengths and lower elongation to failure than does PBF (EBM) in the as-built condition; these data also indicate orientation-dependent properties in the PBF (EBM) material. HIP and heat treatment of PBF (EBM) CoCrMo removed the orientation effects on properties and significantly increased the elongation to failure, consistent with HIP elimination of process-induced defects. There are not enough published data on the other alloy systems listed in **Table 5** to make sensible comparisons at this time.

Table 6 summarizes the evolving database for DED, focusing on Inconel 718 (IN718). Properties are shown for both as-built and heat-treated conditions for a variety of machine types using either laser melting or EBM. Although there are not enough data reported within one machine type to make sensible comparisons, **Table 6** shows significant differences between the properties obtained on IN718 processed across the different machine types and energy sources used for melting.

Whereas there has been extensive research to determine the range of uniaxial tensile properties possible for PBF (EBM, laser) and DED (laser) reported in **Tables 2–6**, much less published research is available for the fracture-critical properties (e.g., toughness, fatigue) of Ti-6Al-4V, and very few published data exist for the fracture properties of the other alloy systems listed in **Table 1**. **Table 7** summarizes fracture toughness properties of Ti-6Al-4V for both PBF (laser)- and PBF (EBM)-processed materials, again using the X, Y, Z nomenclature shown in **Figure 3**. Candidate fracture toughness numbers, K_q , are provided in **Table 7** because thickness requirements for valid fracture toughness (i.e., K_{Ic}) measurements are not met in PBF (EBM) Ti-6Al-4V (48) and are not

**Figure 5**

Summary of Ti-6Al-4V AM tensile properties. Abbreviations: DMD, direct metal deposition; DMLS, direct metal laser sintering; EBM, electron beam melting; HT, heat treated; LENS, laser-engineered net shaping; UTS, ultimate tensile strength; YS, yield stress. Adapted from Reference 3.

reported for PBF (laser) Ti-6Al-4V (151). Again, directly comparing toughness numbers between various works is difficult because few of the published values were obtained on samples sufficiently thick to provide valid K_{Ic} (i.e., plane strain) measurements and because non-plane strain conditions (i.e., thinner samples) inflate toughness numbers due to plane stress conditions. Nonetheless, PBF (laser)-processed Ti-6Al-4V exhibits toughness values well below those of conventionally processed Ti-6Al-4V (48, 140, 196) and exhibits orientation-dependent values and significant effects of machine type and postprocessing conditions. In general, the as-built PBF (laser) Ti-6Al-4V exhibits the lowest toughness in the as-built condition, likely due to a combination of highly nonequilibrium microstructures, significant residual stresses, and process-induced defects. Stress relief, heat treatment, and/or HIP postprocessing appear to improve the toughness values reported in **Table 7** by reducing harmful residual stresses, by generating more favorable microstructures, and by minimizing defects in the as-built PBF (laser) material. The highest published toughness for the PBF (laser) Ti-6Al-4V reported in **Table 7** belongs to the EOS M280 processed material ($K_q = 86.3$ MPa/m) after a postprocessing heat treatment (194), whereas the as-built and/or HIP versions exhibited significantly lower toughness values.

In contrast, **Table 7** reveals significantly higher toughness values from preliminary studies on PBF (EBM) Ti-6Al-4V (48, 140) in both as-built and HIP-processed material, although machine-, orientation-, and location-dependent toughness values were exhibited. More recent work (10) suggested that both microstructure and texture variations and defect population vary with different build orientations, locations, and machines, thereby affecting the magnitude of toughness. **Figure 6** shows the fracture surface of an as-built PBF (EBM) Ti-6Al-4V toughness sample tested in the LT-BOTH orientation (10) shown in **Figure 4**. The various LoF defects that are evident perpendicular to the build direction in this LT-BOTH sample likely contribute to the orientation-dependent toughness values, although microstructural differences along and perpendicular to the build can also contribute (10), as suggested in **Figure 7**.

Table 4 Summary of laser-fusion DED AM Ti-6Al-4V tensile properties

Machine type	Condition	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
LENS (Optomec)	Stress relieved	X	116	1,065	1,109	4.9	NA	58
		Y	116	1,066	1,112	5.5		
		Z	112	832	832	0.8		
	HIP	X	118	946	1,005	13.1		
		Y	118	952	1,007	13.0		
		Z	114	899	1,002	11.8		
DLD (Trumpf)	As built	X	NA	950 ± 2	1,025 ± 10	12 ± 1	NA	72
		Z		950 ± 2	1,025 ± 2	5 ± 1		
	HIP	NA		850 ± 2	920 ± 1	17 ± 2		
LMD	As built	X	NA	976 ± 24	1,099 ± 2	4.9 ± 0.1	NA	163
LSF	As built	Z	NA	1,070	1,140	6	NA	164
LF ³	As built	X	NA	892 ± 10	911 ± 10	6.4 ± 0.6	NA	165
	As built	Z		522	797 ± 27	1.7 ± 0.3		
	As built (machined)	X		984 ± 25	1,069 ± 19	5.4 ± 1		
	As built (machined)	Z		958 ± 14	1,026 ± 17	3.8 ± 0.9		
	Heat treated	X		681 ± 35	750 ± 20	4.8 ± 1.6		
	Heat treated	Z		637 ± 13	717 ± 12	3.4 ± 1.0		
	Heat treated (machined)	X		870 ± 37	953 ± 18	11.8 ± 1.3		
	Heat treated (machined)	Z		930 ± 15	942 ± 13	9.7 ± 2.2		
DMD	As built	X	NA	1,105 ± 19	1,163 ± 22	4 ± 1	NA	166
	Heat treated	X		975 ± 15	1,053 ± 18	7.5 ± 1		
IPG YLR	As built	X	NA	960 ± 26	1,063 ± 20	10.9 ± 1.4	NA	80
		Z		958 ± 19	1,064 ± 26	14 ± 1		

(Continued)



Table 4 (Continued)

Machine type	Condition	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
LENS (Op-tomec)	As built (low power)	X	NA	1,005	1,103	4	NA	167
	Heat treated (low power)			1,000	1,073	9		
	As built (high power)			990	1,042	7		
	Heat treated (high power)			991	1,044	10		
Laser forming	Heat treated	NA	NA	839	900	12.3	NA	168
DLF	Heat treated	NA	NA	958	1,027	6.2	NA	169
LENS	Heat treated	NA	NA	827–965	896–1,000	1–16	NA	170
LENS	As built	Z	119	908	1,038	3.8	NA	226
	Annealed		112	959	1,049	3.7		
	Heat treated		118	957	1,097	3.4		

NA denotes data not available. Other abbreviations: DLD, direct laser fabrication; DMD, direct metal deposition; LMD, laser metal deposition; LSF, laser solid forming; LF³, laser freeform fabrication.

Figure 8 shows µCT analyses revealing process-induced defects in a large (i.e., 10 × 20 × 100 mm) as-built PBF (EBM) LT-BOTH Ti-6Al-4V fracture toughness sample that was tested to failure. Interestingly, although µCT analyses showed that HIP minimized or eliminated the defects present in **Figure 8**, **Table 7** and recently published work (10) report lower toughness values for HIP PBF (EBM) Ti-6Al-4V in comparison to the as-built material. Ongoing work is examining the details of the crack path and microstructure interactions to determine the source(s) of this reduction in toughness observed in the defect-free HIP versions (197).

The competition between microstructure-dominated (e.g., **Figure 7**) and defect-dominated (e.g., **Figures 6** and **8**) contributions to toughness may be responsible for these apparently conflicting observations in which defect-free PBF (EBM) HIP Ti-6Al-4V samples exhibit lower toughness than do their defect-containing as-built counterparts. **Figure 9** summarizes location-dependent toughness values along a tall, as-built PBF (EBM) Ti-6Al-4V sample, in addition to microstructure variations and significant differences in defect density along the build. Although HIP eliminates process-induced defects, location-dependent toughness values remain,

Table 5 Summary of tensile properties of all other alloys listed in Table 2 and additively manufactured using PBF

Machine type	Alloy	Condition	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
SLM250HL	TNM (Ti-Al-Nb-Mo)	As built (compression)	NA	NA	1,620–1,651	1,816–1,903	NA	NA	171
		Heat treated (compression)			886–1,071	1,428–1,671			
		Heat treated (compression)		54	544	1,800	40	NA	172
EBM	TiAl	As built	NA	NA	NA	600.2 ± 2.2	55 ± 2.5	NA	154
		Heat treated				617.9 ± 1.4	54.1 ± 1.6		
		HIP				586.6 ± 2.4	64.4 ± 2.9		
SLM Concept Laser M1	316L	As built	NA	NA	640	760	30	NA	173
					1,100	1,470	15		
	EOS M270	15-5 PH (precipitation-hardening stainless steel)							
EOS M250	4340	Stress relieved	XY	213.7	1,303	1,372	16–17	462–495 (HV)	86
	316L	As built	XY	NA	220–270	520–680	40–45	NA	93
	Realizer	As built	Z	NA	410	750	44	14 (HRC)	102
EOS M280	IN625				330	770	69	8 (HRC)	
	Arcaim S12				1,034	1,309	27	NA	105
	IN718	Heat treated	Z	NA	1,068	1,344	27		
SLM		As built	XY	NA	816 ± 24	1,085 ± 11	19.1 ± 0.7	35 (HRC)	104
			Z		737 ± 4	1,010 ± 10	20.6 ± 2.1	30 (HRC)	
		Heat treated	XY		1,227 ± 1	1,447 ± 10	101 ± 0.6	45 (HRC)	
			Z		1,136 ± 16	1,357 ± 5	13.6 ± 0.2	45 (HRC)	

SLM	Al-Si-10Mg	As built	NA	68 ± 3	NA	396 ± 8	NA	136 ± 9 (HV)	118
		Heat treated	NA	66 ± 5	399 ± 7	399 ± 7	NA	152 ± 5 (HV)	115
SLM250 HL	Al-12Si	As built	NA	220.5 ± 9.4	418.9 ± 9.3	3.91 ± 0.3	NA	NA	115
		Heat treated	NA	202.2 ± 4.3	369.3 ± 3.4	4.38 ± 0.16	NA	NA	115
SLM	Al-12Si	As built	NA	223.5	355.1	4.2	NA	NA	174
		Z	70.7 ± 1.3	168.8 ± 1.3	272.8 ± 2.9	8.2 ± 0.3	NA	NA	124
SLM	Al-Si-10Mg	As built	NA	70.2 ± 1.2	169 ± 1	267	9.1 ± 0.5	NA	174
		XY	NA	207.8	367.7	4	NA	NA	174
SLM	Al-12Si	As built	NA	224 ± 7	368 ± 11	4.8 ± 0.6	NA	NA	175
		XY	NA	240	360	4	NA	NA	176
SLM100 Realizer	Al-12Si	As built	NA	110	190	5	NA	NA	175
		Heat treated	NA	~250	~330	~1.2	NA	NA	177
SLM	Al-Si-10Mg Concept Laser M2	As built	NA	~240	~320	~1	NA	NA	177
		Z	NA	243 ± 7	330 ± 3	6.2 ± 0.3	105 ± 2 (HV)	178	178
EOS M270	Al-Si-10Mg	As built	XY	73 ± 1	243 ± 7	330 ± 3	6.2 ± 0.3	105 ± 2 (HV)	178
		Z	72 ± 1	231 ± 3	329 ± 2	4.1 ± 0.2	108 ± 3 (HV)	178	178
SLM	Al-Si-10Mg Concept Laser M1	As built	XY	68 ± 3	NA	391 ± 6	5.55 ± 0.4	127 (HV)	179
		Z	NA	738 ± 9.9	1,050 ± 12.2	5.2 ± 0.3	39.7 ± 1.2 (HRC)	NA	180
SLM	CoCrMo	As built	XY	NA	685.3 ± 10.5	970 ± 9.8	3.9 ± 0.2	34.3 ± 1.2	NA
		Z	NA	717	1,110	5	NA	NA	181
EBM	CoCrMo	As built	XY	NA	786	869	0.8	NA	NA
		Z	NA	586	1,145	30	NA	NA	NA
SLM	CoCrMo	As built	XY	NA	1,050 ± 150	1,300 ± 150	>6	42 ± 4 (HRC)	182
		Z	NA	141	225	34.25	NA	NA	183
EBM	Niobium	As built	XY	NA	254	296	~1	100 (HV)	184
SLM	AZ91D	As built	XY	NA	NA	NA	NA	NA	NA

NA denotes data not available.

14.15

Table 6 Summary of tensile properties of other alloys additively manufactured by DED

Machine type	Alloy	Condition (as built, HIP, or heat treated)	Specimen orientation	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
GTAW	TiAl	As built	<i>Y</i>	NA	474 ± 17	549 ± 23	0.5	NA	185
			<i>Z</i>		424 ± 30	488 ± 50	0.5		
DMD	4340	Stress relieved	<i>XY</i>	NA	1,398.65	NA	1.665	NA	95
DLD (LENS)	316L	As built	<i>Z</i>	NA	405–415	620–660	34–40	NA	225
		Heat treated	<i>Z</i>	NA	325–355	600–620	42–43	NA	
SMD	IN718	As built	<i>XY</i>	NA	473 ± 6	828 ± 8	28 ± 2	NA	186
DLD	IN718	As built	<i>Z</i>	NA	650	1,000	NA	NA	187
		Heat treated			1,257	1,436			
Laser	IN718	As built	NA	NA	590	845	11	NA	188
		Heat treated			1,133	1,240	9		
EBF ³	IN718	As built	<i>XY</i>	159	580	910	22	NA	189
EBF ³	IN718	As built	<i>XY</i>	138	655	978	NA	NA	99
			<i>YX</i>	194	699	936			
		Heat treated	<i>XY</i>	174	986	1,114			
			<i>YX</i>	192	998	1,162			
DLD	IN718	Heat treated	NA	NA	1,097.6	1,321	9.8	NA	111
DLD	IN718	Heat treated	NA	NA	1,034	1,276	12	NA	190
Laser/wire	IN718	Heat treated	NA	NA	1,079	1,314	20.4	NA	191
WAAM	AA2319	As built	<i>X</i>	NA	114 ± 4.8	263 ± 0.5	18 ± 0.5	NA	127
			<i>Y</i>		106 ± 0.8	258 ± 2.2	15.5 ± 1		

NA denotes data not available.

suggesting that subtle detrimental changes to the microstructure may be responsible. More work is clearly needed to resolve these issues, and testing of much thicker samples is necessary to obtain valid K_{lc} measurements.

The relatively high toughness values obtained for the as-built PBF (EBM) Ti-6Al-4V shown in **Table 7** appear promising from a damage tolerance perspective. However, the presence of process-induced defects significantly reduces HCF properties, as discussed below.

Table 8 provides K_q toughness values for PBF (EBM) Ti-Al 4822 (198, 199) in both the as-built and HIP conditions. Although only very limited data exist, the toughness values were similar to those previously obtained for as-cast Ti-Al 4822 (200). However, the scale and homogeneity of the microstructures of the as-built and HIP PBF (EBM) TiAl were very different from one another and from those of the as-cast TiAl (200). The presence of process-induced defects in the

Table 7 Summary of AM Ti-6Al-4V PBF (laser/EBM) fracture toughness

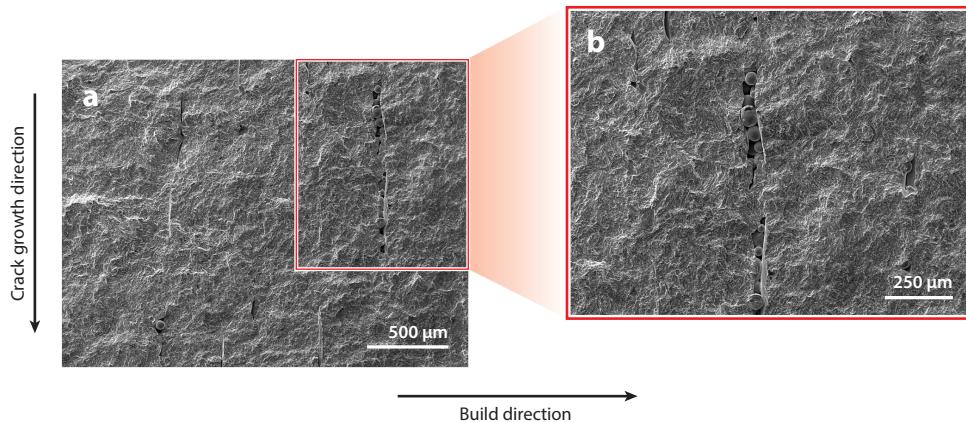
Process category	Machine type	Condition	Specimen orientation	Specimen type	K_q (MPa \sqrt{m})	Reference
PBF(laser)	SLM	As built	XY	CT	28 ± 2	151
			XZ		23 ± 1	
			ZX		16 ± 1	
		Stress relieved	XY		28 ± 2	
			XZ		30 ± 1	
			ZX		31 ± 2	
		Heat treated	XY		41 ± 2	
			XZ		49 ± 2	
			ZX		49 ± 1	
	SLM MTT250	As built	XY		66.9 ± 2.6	192
			XZ		64.8 ± 16.9	
			YZ		41.8 ± 1.7	
	SLM	As built	ZX	CT	52.4 ± 3.48	193
	EOS M280	As built	XY		37.5 ± 5	194
		HIP	XY		57.8 ± 5	
		Heat treated	XY		86.3	
PBF(EBM)	Arcam A1	As built	XY	3PB	110 ± 8.9	142
			ZX		102 ± 7.4	
	Arcam	As built	XY		96.9	195
			ZX		78.1	
		HIP	XY		99.0	
			ZX		83.1	
	Arcam A2	As built	XYZ		68, 80	48
			XZY		76	
			ZXY: middle		65, 66	
			ZXY: near start		79	140
			ZXY: near end		100	

as-built PBF (EBM) TiAl was confirmed by μ CT, and these defects were eliminated with HIP. This produced less scatter in the toughness data reported, again suggesting a competition between microstructure-dominated and defect-dominated contributions to toughness.

HIGH CYCLE FATIGUE AND FATIGUE CRACK GROWTH

As discussed above, process-induced AM defects (e.g., Figures 6, 8, and 9) and microstructure variation/changes (e.g., Figures 7 and 9) can affect the tensile and toughness properties. However, such defects, along with surface roughness and residual stresses, can dominate the cyclic behavior,

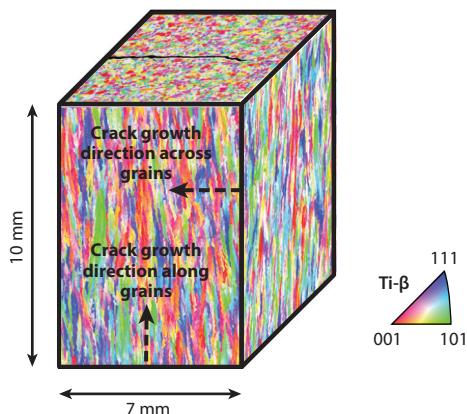


**Figure 6**

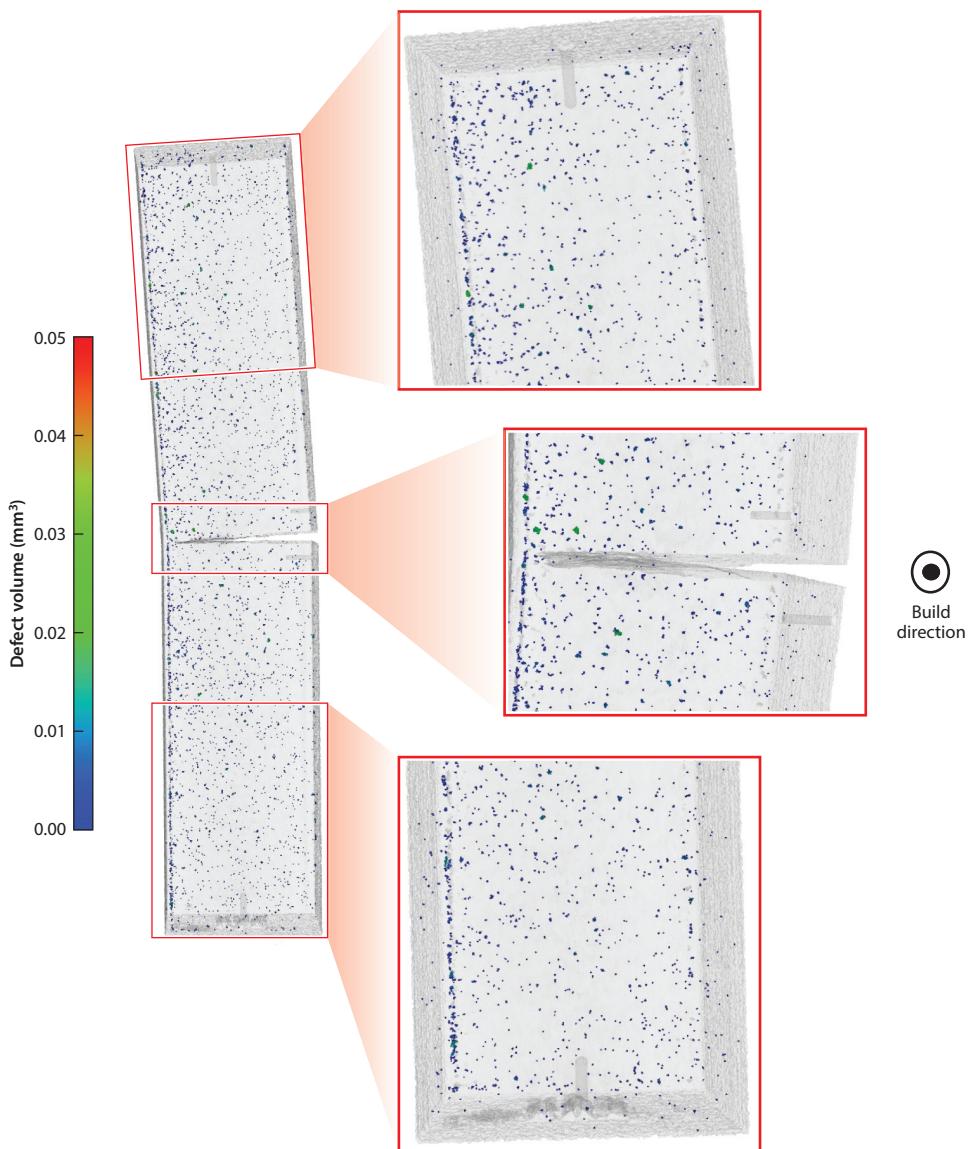
Lack-of-fusion (LoF) defects evident on the fracture surface of a PBF (EBM) as-built Ti-6Al-4V toughness sample tested in the LT-BOTH orientation shown in **Figure 4**. LoF defects are perpendicular to the build direction. (a) Low magnification. (b) Higher magnification.

can obscure microstructural effects, and can severely degrade the high cycle fatigue performance by providing potent fatigue initiation sites along with superimposed harmful residual stresses. These features can overwhelm any microstructural effects, as is shown below.

Although the early fatigue work of Kobryn & Semiatin (58) on LENS-processed (i.e., DED) Ti-6Al-4V exhibited HCF behavior that exceeded cast properties and was in the scatter band for cast + HIP and wrought-annealed Ti-6Al-4V (58), that work also revealed orientation-dependent fatigue life. More recent work (81) on LENS-processed Ti-6Al-4V documented defect-dominated fatigue behavior with fracture initiation from surface cracks and unmelted particles at the surface, as well as subsurface fatigue initiation from unmelted particles. Unmelted particles at the surface reduced the fatigue lifetime by an order of magnitude in comparison to subsurface crack initiation from unmelted particles in the bulk. However, when surface defects were suppressed by optimization

**Figure 7**

Large-area EBSD of an as-built PBF (EBM) Ti-6Al-4V sample showing crack growth across versus along reconstructed β grains. Adapted with permission from Reference 10.

**Figure 8**

μCT images of a $10 \times 20 \times 100$ mm as-built LT-BOTH PBF (EBM) Ti-6Al-4V toughness sample tested to failure in bending. Isolated defects (dark spots) are evident throughout the sample. Notch, fatigue precrack, cracked regions, and direct current potential drop lead holes are also shown. Build direction is out of page.

of the LENS process parameters (81), both as-deposited and simulated repair conditions could produce a fatigue life that exceeded the lower bound for wrought, annealed Ti-6Al-4V and that was in the upper-bound regions of cast + HIP material.

A very recent review (201) summarized the stress-controlled fatigue behavior of PBF (laser)-processed, PBF (EBM)-processed, and DED-processed Ti-6Al-4V, along with the effects of surface roughness (e.g., as built versus machined) and defects (e.g., as built versus HIP) in comparison

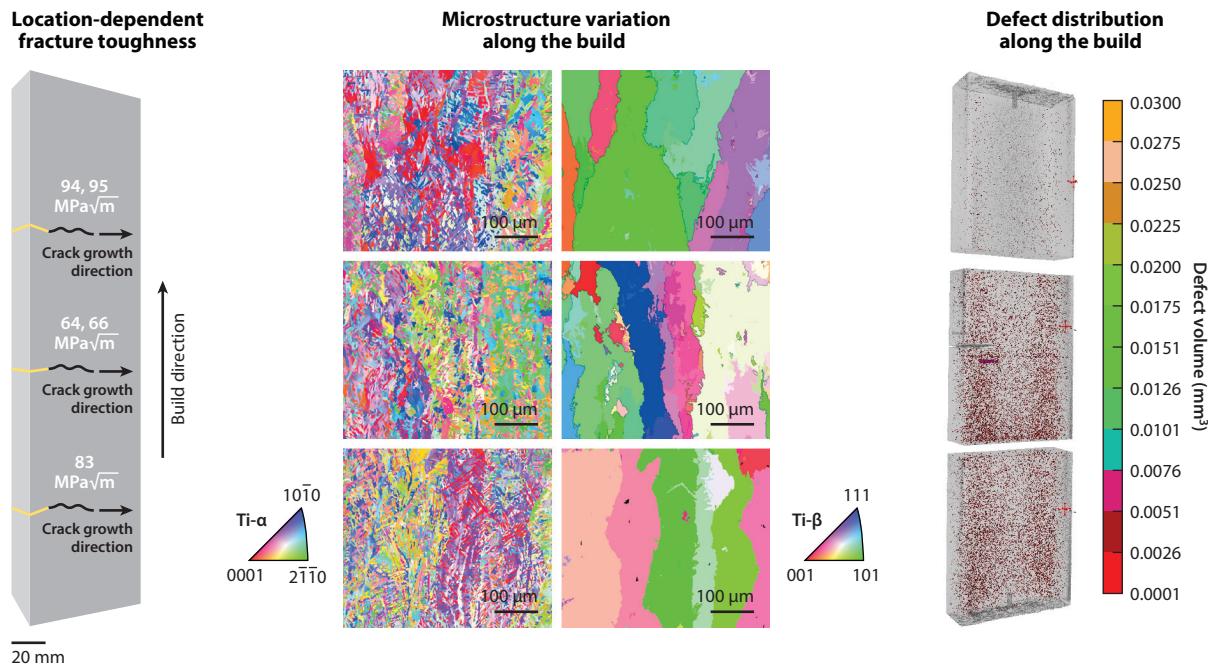
**Figure 9**

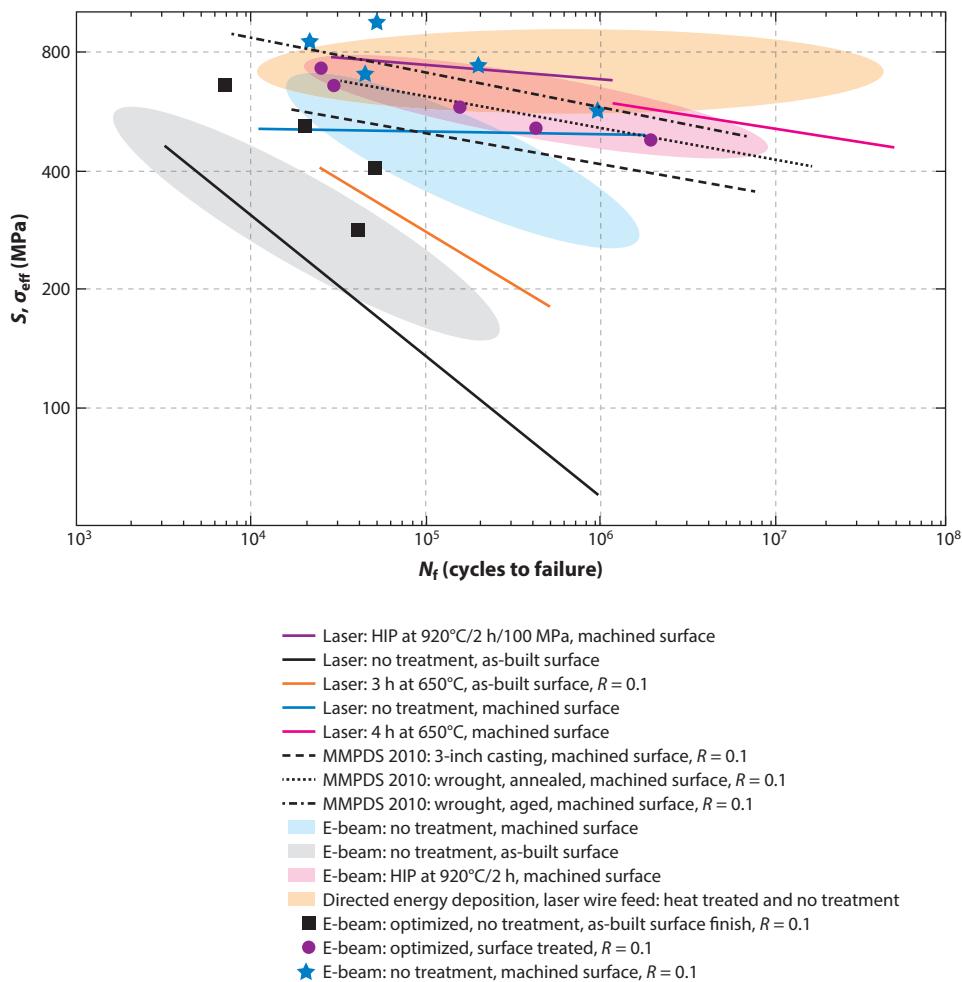
Illustration of location-dependent toughness values in an as-built PBF (EBM) Ti-6Al-4V sample. Variations in microstructure (prior β grains and $\alpha + \beta$ microstructure) and defect density were detected along the same as-built sample.

to as-cast and wrought Ti-6Al-4V tested with machined surfaces. **Figure 10** includes data from that work (201) in addition to a recent similar study on PBF (EBM) Ti-6Al-4V (202) conducted under strain control to capture the essence of the observations to date (201).

Figure 10 shows summary data replotted (from Reference 201) of PBF (laser) $S-N$ fatigue behavior for Ti-6Al-4V tested at $R = 0.1$, along with Metallic Materials Properties Development and Standardization (MMPDS) data obtained for cast (3-inch-thick) and wrought (annealed and aged) material with machined surfaces in addition to data obtained from Reference 202. Although orientation-dependent fatigue behavior was found and some property improvements were achieved with machined and polished surfaces, the very poor performance in comparison to the other data summarized in this plot was assumed to result from process-induced defects. Reference 201 indicates that the significantly improved fatigue data that were obtained by machining the as-built surfaces after optimization of the PBF (laser) process for Ti-6Al-4V support this hypothesis. However, this review (201) indicated that variations in laser process parameters created either a martensitic microstructure or a fine α microstructure. Fine α microstructure resulted in fatigue

Table 8 Summary of AM γ Ti-Al 4822 fracture toughness for EBM PBF

Machine type	Alloy	Condition	Specimen orientation	Specimen type	K_q (MPa $\sqrt{\text{m}}$)	Reference
Arcam A2X	Ti4822	As built	Z	3PB	24.1 ± 6.5	198
		HIP			27.8 ± 0.4	

**Figure 10**

Summary of stress (S) versus cycles to failure (N) (S - N) data for PBF (laser), PBF (EBM), and wire (DED) at $R = 0.1$. Metallic Materials Properties Development and Standardization (MMPDS) data for cast, wrought machined data are shown for comparison. Data were obtained from a variety of sources, including References 12, 201, and 202. Adapted from Reference 201.

performance superior to that of MMPDS reference data for cast + HIP material, whereas the martensitic microstructure's performance was below that of the MMPDS reference data. Heat treatment at 650°C/3 h marginally improved fatigue behavior with the as-built rough surfaces, and cracking again appeared to initiate from the (rough) surfaces. Heat treatment at 650°C/4 h along with machined/EDM/shot-peened/sand-blasted surfaces produced fatigue performance that approached the fatigue performance of cast + HIP MMPDS data.

HIP of the PBF (laser) Ti-6Al-4V at 920°C/2 h/100 MPa, combined with surface machining, produced further improvements to the fatigue data in **Figure 10** via elimination of process-induced defects (201). However, although HIP at 1,050°C/4 h/100 MPa similarly eliminated process-induced defects, the associated microstructure coarsening at this HIP temperature reduced the fatigue performance. These results again emphasize the competition between defect-dominated

and microstructure-dominated contributions to properties. Although the presence of process-induced defects dominates high cycle fatigue performance and obscure microstructural effects, the removal of these defects via HIP or process optimization requires optimization of microstructural features to continue to improve performance.

Figure 10 also includes data (from References 201 and 202) of PBF (EBM) and wire (DED) S-N fatigue behavior for Ti-6Al-4V tested at $R = 0.1$. The PBF (EBM)-processed samples tested with as-built (i.e., rough) surfaces reveals performance only slightly better than that of the worst-performing PBF (laser) samples shown. Some improvement in performance is provided by machining as-built surfaces (12), with more significant improvement reported recently on machined samples (202). However, the high cycle fatigue performance of the early work (12) on machined samples is well below that of the MMPDS cast Ti-6Al-4V data and is likely compromised by premature crack initiation at process-induced defects such as porosity. However, machining + HIP at 920°C/2 h/100 MPa (12) produced results comparable to MMPDS wrought data, again consistent with the HIP elimination of process-induced defects.

Figure 10 also summarizes wire-fed DED fatigue performance. The good fatigue performance of DED-processed Ti-6Al-4V is attributed to the general lack of process-induced defects, whereas differences in the fatigue performance of the laser wire-fed and tungsten inert gas wire-fed Ti-6Al-4V were attributed to differences in microstructural scale (201).

Table 9 summarizes the limited fatigue crack growth data reported for PBF (laser) and PBF (EBM) Ti-6Al-4V. Despite the generally low toughness values of the PBF (laser) Ti-6Al-4V summarized in **Table 7**, **Table 9** reveals Paris slope values at $R = 0.1$ in the range of 3–6, which is typical for metallic materials, and overload K_c values in the range of the toughness values reported in **Table 7** for PBF (laser) Ti-6Al-4V. The higher-toughness PBF (EBM) Ti-6Al-4V exhibits much higher K_c at overload in fatigue and similarly low Paris slope values and fatigue thresholds in the range of conventional Ti-6Al-4V. However, location- and orientation-dependent fatigue crack growth is evident in **Table 9** and is likely affected by the competition between microstructure-dependent and defect-dependent contributions to fatigue crack growth, which is somewhat similar to that proposed in **Figure 9** for toughness.

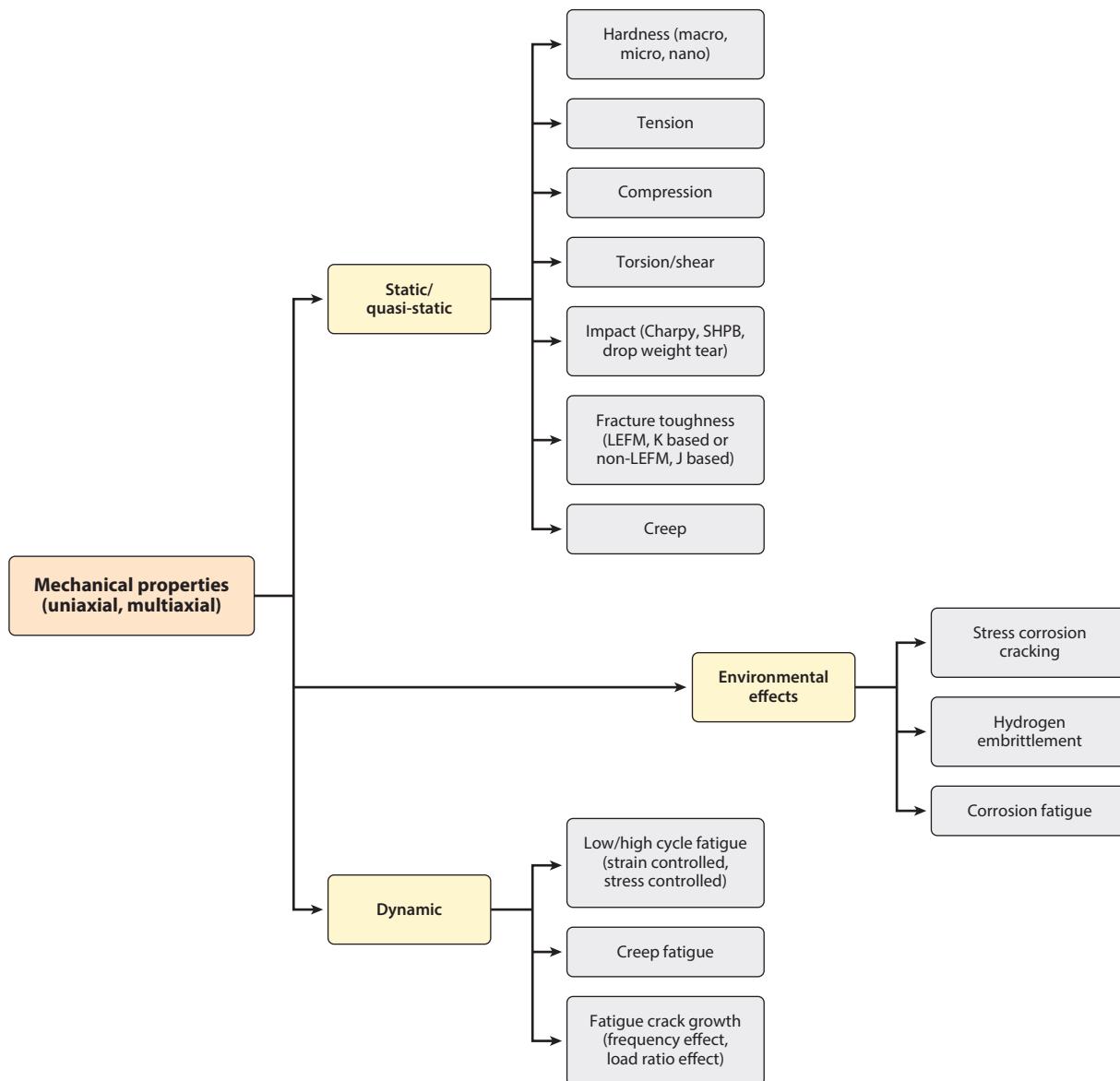
CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVE

Figure 11 summarizes the range of mechanical properties typically generated in the mechanical characterization of metallic structural materials depending on their intended application. In that regard, this review summarizes published data currently available for AM metallic materials across the range of currently available PBF and DED process categories. Although the breadth of published mechanical properties has not covered the whole range of those shown in **Figure 11**, some of the mechanical properties reported for some of the metallic systems approach, and sometimes exceed, properties obtained on similar materials processed conventionally (e.g., casting, extrusion, forging). However, relatively few published data exist on standard samples, and little to no published work exists for low cycle fatigue, fatigue crack growth, fracture toughness, impact, creep, creep fatigue, multiaxial testing, or environmental effects. Furthermore, the current variability of properties (controlled by microstructure, residual stress, defects, etc.) within and between builds in one machine and across different machines and techniques, as well as the presence of process-induced defects and location/orientation-dependent properties, limits the more widespread use of these processing techniques for fracture-critical applications. The source(s), detection, and elimination of process-induced defects remain areas requiring additional focus to determine the microstructural features that will control properties with these processing techniques. These goals can be accomplished only by a better understanding of the fundamental

Table 9 Summary of PBF AM Ti-6Al-4V fatigue crack growth properties

Process category	Condition	Specimen orientation	Specimen type	Load ratio (R)	ΔK_{th} (MPa $\sqrt{\text{m}}$)	Paris slope	C (m/cycle)	K_c (MPa/m)	Reference
Laser melting	As built	XY	CT(5 Hz)	0.1	NA	3.37	5.79E-12	NA	151
		XZ				4.17	7.51E-12		
		ZX				4.41	2.08E-12		
		XY				5.84	9.93E-15		
	Stress relieved	XZ				3.24	1.16E-11		
		ZX				3.35	8.83E-12		
		XY				3.83	2.04E-12		
	Heat treated	XZ				3.11	1.71E-11		
		ZX				2.94	2.58E-11		
		XY	CT(10 Hz)	0.1	6.3 ± 0.7	2.6 ± 0.3	1.2E-7	37 ± 4.3	192
EBM	As built	XZ			5.8 ± 0.8	2.3 ± 0.3	5.8E-8	40 ± 25.1	
		YZ			5.9 ± 1.0	2.4 ± 0.6	1.6E-7	37.11 ± 4	
		ZX	CT (10 Hz)	0.1	NA	3.38	5E-12	NA	193
		XYZ	3PB(20 Hz)	0.1	3.8	2.9	NA	91	140
	XZZ: start	XZZ: end			5.7	4.1		96	
		XZZ: start			4.2	3.5		53	
		XZZ: end			0.3	3.8, 3.9	2.4, 2.3, 2.7	83, 88, 96	48
	XYZ: start	XYZ: middle			0.3	3.6	2.1	87	
		XYZ: start			0.3	4.9	2.4	71	
		XYZ: end			0.3	3.8	2.6	69	

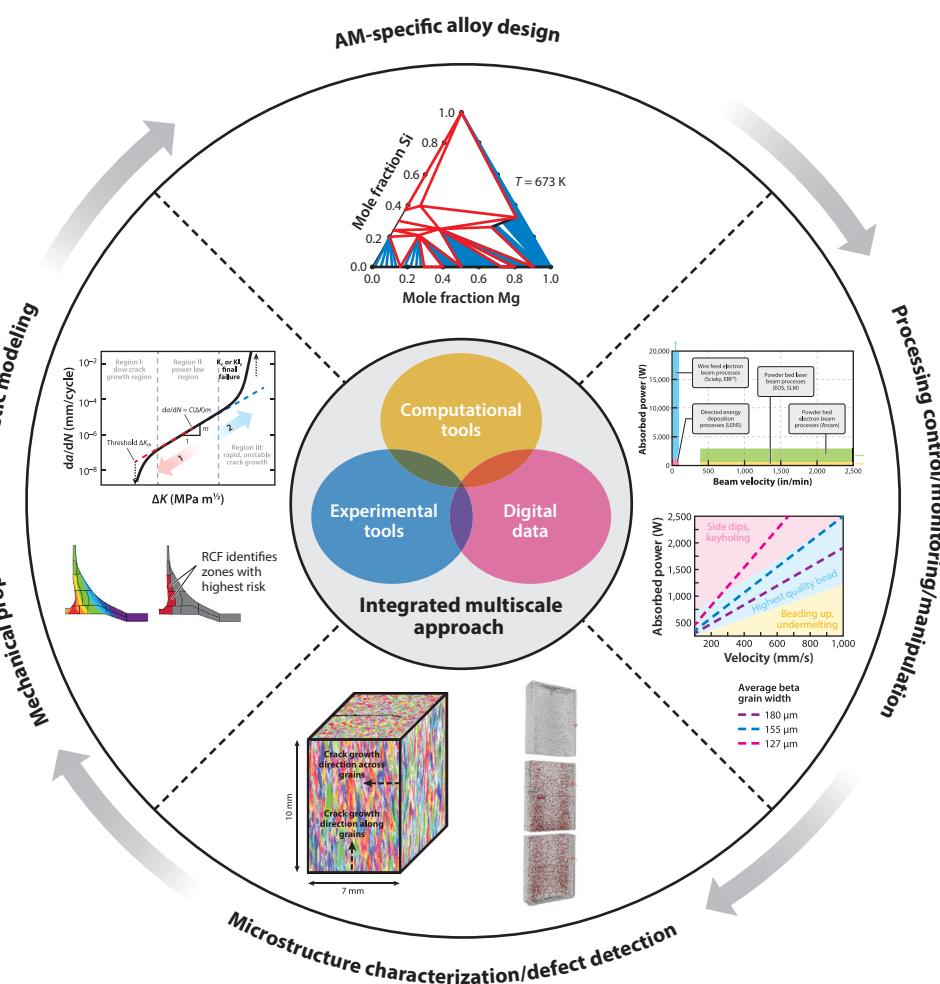
NA denotes data not available.

**Figure 11**

The range of mechanical properties typically generated for structural materials. The specific properties of interest depend on the intended application. Abbreviations: LEFM, linear elastic fracture mechanics; SHPB, split-Hopkinson pressure bar.

processing-structure-property relationships possible with this emerging technology. A more complete review of the evolving processing-microstructure-property relationships is in progress (203).

One approach that has recently been proposed (10) and that is summarized in **Figure 12** is to utilize Integrated Computation Materials (Science) and Engineering [ICM(S)E] to begin to address the multitude of issues that include development strategies for new alloys/microstructures

**Figure 12**

Integrated multiscale approach for the development of additively manufactured alloys for structural applications.

specifically designed to take advantage of AM as well as the lack of detailed process-structure-property understanding both within and across different machines that do not provide open source access. Some of the various challenges that have been summarized in more detail elsewhere (10) include lack of computationally efficient tools, lack of in situ commercial monitoring systems, lack of material/testing standards, feedstock and recyclability/reusability issues, surface roughness and residual stress management/control, process feedback and control, postprocessing via alternate heat treatments and/or HIP conditions, big data generation and handling issues, and probabilistic modeling of fracture-critical properties. Addressing these challenges in a cost-effective manner will require the integration of fundamental and applied approaches by various science and engineering disciplines at academic, industrial, and government institutions.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

The time spent gathering the information and generating some of the data reported in this article was partly supported by America Makes, the National Additive Manufacturing Innovation Institute, under project 4009, “Rapid Qualification Methods for Powder Bed Direct Metal Additive Manufacturing Processes,” through contract FA8650-12-2-7230, and such support is highly appreciated. Additional support was provided by two ASTM International scholarship awards (M. Seifi) and by the Arthur P. Armington Professorship (J.J. Lewandowski). Mechanical testing and analyses at CWRU were conducted in the Advanced Manufacturing and Mechanical Reliability Center. M. Seifi appreciates various discussions with ASTM F42/E08/E07 committee members as well as significant interactions with YXLON, a division of Comet technologies, and GE inspection technologies regarding μ CT results. Authors also appreciate fruitful collaboration with Materials Resources LLC for microstructural quantification/analyses.

LITERATURE CITED

1. Kruth J-P, Leu MC, Nakagawa T. 1998. Progress in additive manufacturing and rapid prototyping. *CIRP Ann. Manuf. Technol.* 47(1):525–40
2. Frazier WE. 2014. Metal additive manufacturing: a review. *J. Mater. Eng. Perform.* 23(6):1917–28
3. Dutta B, Froes FHS. 2014. Additive manufacturing of titanium alloys. *Adv. Mater. Res.* 1019(Oct.):19–25
4. Facchini L, Magalini E, Robotti P, Molinari A. 2009. Microstructure and mechanical properties of Ti-6Al-4V produced by electron beam melting of pre-alloyed powders. *Rapid Prototyp. J.* 15(3):171–78
5. Parthasarathy J, Starly B, Raman S, Christensen A. 2010. Mechanical evaluation of porous titanium (Ti6Al4V) structures with electron beam melting (EBM). *J. Mech. Behav. Biomed. Mater.* 3(3):249–59
6. Murr LE, Gaytan SM, Ramirez DA, Martinez E, Hernandez J, et al. 2012. Metal fabrication by additive manufacturing using laser and electron beam melting technologies. *J. Mater. Sci. Technol.* 28(1):1–14
7. Collins PC, Haden CV, Ghamarian I, Hayes BJ, Ales T, et al. 2014. Progress toward an integration of process-structure-property-performance models for ‘three-dimensional (3-D) printing’ of titanium alloys. *JOM* 66(7):1299–309
8. Yu J, Rombouts M, Maes G, Motmans F. 2012. Material properties of Ti6Al4V parts produced by laser metal deposition. *Phys. Procedia* 39:416–24
9. Leuders S, Thöne M, Riemer A, Niendorf T, Tröster T, et al. 2013. On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: fatigue resistance and crack growth performance. *Int. J. Fatigue* 48:300–7
10. Seifi M, Salem A, Beuth J, Harrysson O, Lewandowski JJ. 2016. Overview of materials qualification need for metal additive manufacturing. *JOM* 68(3):747–64
11. Collins PC, Brice DA, Samimi P, Ghamarian I, Fraser HL. 2016. Microstructural control of additively manufactured materials. *Annu. Rev. Mater. Res.* 46:in press
12. Ackelid U, Svensson M. 2009. Additive manufacturing of dense metal parts by electron beam melting. In *Proceedings of Materials Science and Technology Conference (MS&T)*, pp. 2711–19. Novelty, OH: ASM Int.
13. Chang Y, McLouth T, Pozuelo M, Chang C, Wooten J. 2015. The micro-mechanical behavior of electron beam melted Ti-6Al-4V alloy. In *TMS Proceedings*, pp. 211–18. Warrendale, PA/Hoboken, NJ: TMS/Wiley
14. Christensen A, Kircher R, Lippincott A. 2007. Qualification of electron beam melted (EBM) Ti6Al4V-ELI for orthopaedic applications. In *Proceedings from the Materials & Processes for Medical Devices Conference*, pp. 48–53. Novelty, OH: ASM Int.



15. Devika D, Dass SS, Kumar Chaudhary S. 2015. Characterization and corrosion behaviour study on biocompatible Ti-6Al-4V component fabricated by electron beam melting. *J. Biomimetics Biomater. Biomed. Eng.* 22:63–75
16. Facchini L, Magalini E, Robotti P, Molinari A. 2009. Microstructure and mechanical properties of Ti-6Al-4V produced by electron beam melting of pre-alloyed powders. *Rapid Prototyp. J.* 15(3):171–78
17. Gong H, Rafi K, Gu H, Starr T, Stucker B. 2014. Analysis of defect generation in Ti-6Al-4V parts made using powder bed fusion additive manufacturing processes. *Addit. Manuf.* 1–4:87–98
18. Gong X, Anderson T, Chou K. 2012. Review on powder-based electron beam additive manufacturing technology. In *Proceedings of the ASME International Symposium on Flexible Automation*, pp. 507–15. New York: ASME
19. Gong X, Lydon J, Cooper K, Chou K. 2013. Microstructural characterization and modeling of beam speed effects on Ti-6Al-4V by electron beam additive manufacturing. In *Solid Freeform Fabrication Proceedings*, pp. 459–69. Austin: Univ. Tex.
20. Gong X, Lydon J, Cooper K, Chou K. 2014. Beam speed effects on Ti-6Al-4V microstructures in electron beam additive manufacturing. *J. Mater. Res.* 29(17):1–9
21. Guo C, Ge W, Lin F. 2015. Effects of scanning parameters on material deposition during electron beam selective melting of Ti-6Al-4V powder. *J. Mater. Process. Technol.* 217:148–57
22. Hrabe N, Quinn T. 2013. Effects of processing on microstructure and mechanical properties of a titanium alloy (Ti-6Al-4V) fabricated using electron beam melting (EBM). Part 1. Distance from build plate and part size. *Mater. Sci. Eng. A* 573:264–70
23. Ikeo N, Ishimoto T, Serizawa A, Nakano T. 2014. Control of mechanical properties of three-dimensional Ti-6Al-4V products fabricated by electron beam melting with unidirectional elongated pores. *Metall. Mater. Trans. A* 45(10):4293–301
24. Jamshidinia M, Kovacevic R. 2015. The influence of heat accumulation on the surface roughness in powder-bed additive manufacturing. *Surf. Topogr. Metrol. Prop.* 3(1):014003
25. Juechter V, Scharowsky T, Singer RF, Körner C. 2014. Processing window and evaporation phenomena for Ti-6Al-4V produced by selective electron beam melting. *Acta Mater.* 76:252–58
26. Kalinyuk AN, Trigub NP, Semiatin SL. 2003. Microstructure, texture, and mechanical properties of electron-beam melted Ti-6Al-4V. *Mater. Sci. Eng. A* 346:178–88
27. Karlsson J, Norell M, Ackelid U, Engqvist H, Lausmaa J. 2015. Surface oxidation behavior of Ti-6Al-4V manufactured by Electron Beam Melting (EBM®). *J. Manuf. Process.* 17:120–26
28. Koike M, Greer P, Owen K, Lilly G, Murr LE, et al. 2011. Evaluation of titanium alloys fabricated using rapid prototyping technologies—electron beam melting and laser beam melting. *Materials* 4(12):1776–92
29. Koike M, Martinez K, Guo L, Chahine G, Kovacevic R, Okabe T. 2011. Evaluation of titanium alloy fabricated using electron beam melting system for dental applications. *J. Mater. Process. Technol.* 211(8):1400–8
30. Kok Y, Tan X, Tor S, Chua CK. 2015. Fabrication and microstructural characterisation of additive manufactured Ti-6Al-4V parts by electron beam melting. *Virtual Phys. Prototyp.* 10(1):13–21
31. Lu SL, Tang HP, Ning YP, Liu N, StJohn DH, Qian M. 2015. Microstructure and mechanical properties of long Ti-6Al-4V rods additively manufactured by selective electron beam melting out of a deep powder bed and the effect of subsequent hot isostatic pressing. *Metall. Mater. Trans. A* 46(9):3824–34
32. Markl M, Ammer R, Rüde U, Körner C. 2015. Numerical investigations on hatching process strategies for powder-bed-based additive manufacturing using an electron beam. *Int. J. Adv. Manuf. Technol.* 78(1–4):239–47
33. Mohammadhosseini A, Fraser D, Masood SH, Jahedi M. 2013. Microstructure and mechanical properties of Ti-6Al-4V manufactured by electron beam melting process. *Mater. Res. Innov.* 17(Suppl. 2):106–12
34. Murr LE. 2014. Metallurgy of additive manufacturing: examples from electron beam melting. *Addit. Manuf.* 5:40–53
35. Murr LE, Gaytan SM, Lopez MI, Martinez E, Medina F, Wicker RB. 2009. Metallographic characterization of additive-layer manufactured products by electron beam melting of Ti-6Al-4V powder. *Pract. Metallogr.* 46(9):442–53



- REVIEWS**
- AR**
- ADVANCE**
36. Hrabe N, Kircher R, Quinn T. 2012. Effects of processing on microstructure and mechanical properties of Ti-6Al-4V fabricated using electron beam melting (EBM): orientation and location. In *Solid Freeform Fabrication Proceedings*, pp. 1045–58. Austin: Univ. Tex.
 37. Ponader S, Vairaktaris E, Heinl P, Wilmowsky CV, Rottmair A, et al. 2008. Effects of topographical surface modifications of electron beam melted Ti-6Al-4V titanium on human fetal osteoblasts. *J. Biomed. Mater. Res. A* 84(4):1111–19
 38. Puebla K. 2012. Effect of melt scan rate on microstructure and macrostructure for electron beam melting of Ti-6Al-4V. *Mater. Sci. Appl.* 3(5):259–64
 39. Rafi HK, Karthik NV, Gong H, Starr TL, Stucker BE. 2013. Microstructures and mechanical properties of Ti6Al4V parts fabricated by selective laser melting and electron beam melting. *J. Mater. Eng. Perform.* 22(12):3872–83
 40. Rafi K, Karthik N, Starr TL, Stucker BE. 2012. Mechanical property evaluation of Ti-6Al-4V parts made using electron beam melting. In *Solid Freeform Fabrication Proceedings*, pp. 526–35. Austin: Univ. Tex.
 41. Saifdar A, He HZ, Wei L-Y, Snis A, De Paz LEC. 2012. Effect of process parameters settings and thickness on surface roughness of EBM produced Ti-6Al-4V. *Rapid Prototyp. J.* 18(5):401–8
 42. Saifdar A, Wei L-Y, Snis A, Lai Z. 2012. Evaluation of microstructural development in electron beam melted Ti-6Al-4V. *Mater. Charact.* 65:8–15
 43. Scharowsky T, Juechter V, Singer RF, Körner C. 2015. Influence of the scanning strategy on the microstructure and mechanical properties in selective electron beam melting of Ti-6Al-4V. *Adv. Eng. Mater.* 17(11):1573–78
 44. Svensson M. 2013. Influence of interstitials on material properties of Ti-6Al-4V fabricated with Electron Beam Melting (EBM®). In *Proceedings from the Materials and Processes for Medical Devices Conference*, pp. 119–24. Novelty, OH: ASM Int.
 45. Svensson M, Ackelid U, Ab A. 2010. Titanium alloys manufactured with electron beam melting mechanical and chemical properties. In *Proceedings of Materials & Processes for Medical Devices Conference*, pp. 189–94. Novelty, OH: ASM Int.
 46. Wang X, Gong X, Chou K. 2015. Scanning speed effect on mechanical properties of Ti-6Al-4V alloy processed by electron beam additive manufacturing. *Procedia Manuf.* 1:287–95
 47. Zhao H, Antonysamy AA, Meyer J, Ciuea O, Williams ST, Prangnell PB. 2015. Automated multi-scale microstructure heterogeneity analysis of selective electron beam melted Ti-6Al-4V components. In *TMS Proceedings*, pp. 429–36. Warrendale, PA/Hoboken, NJ: TMS/Wiley
 48. Seifi M, Dahar M, Aman R, Harrysson O, Beuth J, Lewandowski JJ. 2015. Evaluation of orientation dependence of fracture toughness and fatigue crack propagation behavior of as-deposited ARCAM EBM Ti-6Al-4V. *JOM* 67(3):597–607
 49. Behrendt U, Shellabear M. 1995. The EOS rapid prototyping concept. *Comput. Ind.* 28(1):57–61
 50. Challis VJ, Xu X, Zhang LC, Roberts AP, Grotowski JF, Sercombe TB. 2014. High specific strength and stiffness structures produced using selective laser melting. *Mater. Des.* 63:783–88
 51. Facchini L, Magalini E, Robotti P, Molinari A, Höges S, Wissenbach K. 2010. Ductility of a Ti-6Al-4V alloy produced by selective laser melting of prealloyed powders. *Rapid Prototyp. J.* 16(6):450–59
 52. Fu CH, Guo YB. 2014. Three-dimensional temperature gradient mechanism in selective laser melting of Ti-6Al-4V. *J. Manuf. Sci. Eng.* 136(6):061004
 53. Gong H, Gu H, Dilip JJS, Pal D, Stucker B, et al. 2014. Melt pool characterization for selective laser melting of Ti-6Al-4V pre-alloyed powder. In *Solid Freeform Fabrication Proceedings*. Austin: Univ. Tex.
 54. Grimm T, Wiora G, Witt G. 2015. Characterization of typical surface effects in additive manufacturing with confocal microscopy. *Surf. Topogr. Metrol. Prop.* 3(1):014001
 55. Hanzl P, Zetek M, Bakša T, Kroupa T. 2015. The influence of processing parameters on the mechanical properties of SLM parts. *Procedia Eng.* 100:1405–13
 56. Khaing MW, Fuh JYH, Lu L. 2001. Direct metal laser sintering for rapid tooling: processing and characterisation of EOS parts. *J. Mater. Process. Technol.* 113(1–3):269–72
 57. Kobry PA, Semiatin SL. 2001. The laser additive manufacture of Ti-6Al-4V. *JOM* 53(9):40–42
 58. Kobry PA, Semiatin SL. 2001. Mechanical properties of laser-deposited Ti-6Al-4V. In *Solid Freeform Fabrication Proceedings*, pp. 179–86. Austin: Univ. Tex.

59. Kobryn P, Semiatin S. 2003. Microstructure and texture evolution during solidification processing of Ti-6Al-4V. *J. Mater. Process. Technol.* 135(2–3):330–39
60. Schnitzer M, Lisý M, Hudák R, Živ J. 2015. Experimental measuring of the roughness of test samples made using DMLS technology from the titanium alloy Ti-6Al-4V. In *IEEE International Symposium on Applied Machine Intelligence and Informatics*, 13th, pp. 31–36
61. Simchi A. 2006. Direct laser sintering of metal powders: mechanism, kinetics and microstructural features. *Mater. Sci. Eng. A* 428(1–2):148–58
62. Simchi A, Petzoldt F, Pohl H. 2003. On the development of direct metal laser sintering for rapid tooling. *J. Mater. Process. Technol.* 141(3):319–28
63. Simonelli M, Tse YY, Tuck C. 2012. Further understanding of Ti-6Al-4V selective laser melting using texture analysis. In *Solid Freeform Fabrication Proceedings*, pp. 480–91. Austin: Univ. Tex.
64. Simonelli M, Tse YY, Tuck C. 2014. The formation of $\alpha + \beta$ microstructure in as-fabricated selective laser melting of Ti-6Al-4V. *J. Mater. Res.* 29(17):2028–35
65. Thijss L, Verhaeghe F, Craeghs T, Van Humbeeck J, Kruth J-P. 2010. A study of the microstructural evolution during selective laser melting of Ti-6Al-4V. *Acta Mater.* 58(9):3303–12
66. Thombansen U, Abels P. 2015. Process observation in selective laser melting (SLM). *Proc. SPIE* 9356:93560R
67. Wauthle R, Vrancken B, Beynaerts B, Jorissen K, Schrooten J, et al. 2015. Effects of build orientation and heat treatment on the microstructure and mechanical properties of selective laser melted Ti6Al4V lattice structures. *Addit. Manuf.* 5:77–84
68. Wu X, Sharman R, Mei J, Voice W. 2004. Microstructure and properties of a laser fabricated burn-resistant Ti alloy. *Mater. Des.* 25(2):103–9
69. Wu X, Liang J, Mei J, Mitchell C, Goodwin PS, Voice W. 2004. Microstructures of laser-deposited Ti-6Al-4V. *Mater. Des.* 25(2):137–44
70. Xu W, Brandt M, Sun S, Elambasseril J, Liu Q, et al. 2015. Additive manufacturing of strong and ductile Ti-6Al-4V by selective laser melting via in situ martensite decomposition. *Acta Mater.* 85:74–84
71. 2001. EOS takes fine approach to laser sintering. *Met. Powder Rep.* 56(3):18
72. Qiu C, Ravi GA, Dance C, Ranson A, Dilworth S, Attallah MM. 2015. Fabrication of large Ti-6Al-4V structures by direct laser deposition. *J. Alloys Compd.* 629:351–61
73. Hofmann DC, Roberts S, Otis R, Kolodziejska J, Dillon RP, et al. 2014. Developing gradient metal alloys through radial deposition additive manufacturing. *Sci. Rep.* 4:5357
74. Wang F, Williams S, Colegrove P, Antonysamy AA. 2012. Microstructure and mechanical properties of wire and arc additive manufactured Ti-6Al-4V. *Metall. Mater. Trans. A* 44(2):968–77
75. Brandl E, Baufeld B, Leyens C, Gault R. 2010. Additive manufactured Ti-6Al-4V using welding wire: comparison of laser and arc beam deposition and evaluation with respect to aerospace material specifications. *Phys. Procedia* 5:595–606
76. Qian L, Mei J, Liang J, Wu X. 2005. Influence of position and laser power on thermal history and microstructure of direct laser fabricated Ti-6Al-4V samples. *Mater. Sci. Technol.* 21(5):597–605
77. Kobryn PA, Moore EH, Semiatin SL. 2000. Effect of laser power and traverse speed on microstructure, porosity, and build height in laser-deposited Ti-6Al-4V. *Scr. Mater.* 43(4):299–305
78. Brandl E, Leyens C, Palm F. 2011. Mechanical properties of additive manufactured Ti-6Al-4V using wire and powder based processes. *IOP Conf. Ser. Mater. Sci. Eng.* 26:012004
79. Kottman M, Zhang S, McGuffin-Cawley J, Denney P, Narayanan BK. 2015. Laser hot wire process: a novel process for near-net shape fabrication for high-throughput applications. *JOM* 67(3):622–28
80. Carroll BE, Palmer TA, Beese AM. 2015. Anisotropic tensile behavior of Ti-6Al-4V components fabricated with directed energy deposition additive manufacturing. *Acta Mater.* 87:309–20
81. Prabhu AW, Chaudhary A, Zhang W, Babu SS. 2015. Effect of microstructure and defects on fatigue behaviour of directed energy deposited Ti-6Al-4V. *Sci. Technol. Weld. Join.* 20(8):659–69
82. Kelly SM, Kampe SL. 2004. Microstructural evolution in laser-deposited multilayer Ti6Al4V build. Part I. Microstructural characterization. *Metall. Mater. Trans. A* 35(June):1861–67
83. Kelly SM, Kampe SL. 2004. Microstructural evolution in laser-deposited multilayer Ti-6Al-4V builds: Part II. Thermal modeling. *Metall. Mater. Trans. A* 35(6):1869–79



- REVIEWERS
- ABR**
- ADVANCE
84. Buican GR, Oancea G, Lancea C, Pop MA. 2015. Some considerations regarding micro hardness of parts manufactured from 316-L Steel using SLM technology. *Appl. Mech. Mater.* 760:515–20
 85. Zhao X, Wei Q, Song B, Liu Y, Luo X, et al. 2015. Fabrication and characterization of AISI 420 stainless steel using selective laser melting. *Mater. Manuf. Process.* 30(11):1283–89
 86. Jelis E, Clemente M, Kerwien S, Ravindra NM, Hespel MR. 2015. Metallurgical and mechanical evaluation of 4340 steel produced by direct metal laser sintering. *JOM* 67(3):582–89
 87. King WE, Barth HD, Castillo VM, Gallegos GF, Gibbs JW, et al. 2014. Observation of keyhole-mode laser melting in laser powder-bed fusion additive manufacturing. *J. Mater. Process. Technol.* 214(12):2915–25
 88. Jägle EA, Choi P. 2014. Precipitation and austenite reversion behavior of a maraging steel produced by selective laser melting. *J. Mater. Res.* 29(17):2072–79
 89. Kempen K, Vrancken B, Buls S, Thijs L, Van Humbeeck J, Kruth J-P. 2014. Selective laser melting of crack-free high density M2 high speed steel parts by baseplate preheating. *J. Manuf. Sci. Eng.* 136(6):061026
 90. Lebrun T, Tanigaki K, Horikawa K, Kobayashi H. 2014. Strain rate sensitivity and mechanical anisotropy of selective laser melted 17-4 PH stainless steel. *Mech. Eng. J.* 1(5):SMM0049
 91. Abele E, Stoffregen HA, Kniepkamp M, Lang S, Hampe M. 2014. Selective laser melting for manufacturing of thin-walled porous elements. *J. Mater. Process. Technol.* 215:114–22
 92. Riemer A, Leuders S, Thöne M, Richard HA, Tröster T, Niendorf T. 2014. On the fatigue crack growth behavior in 316L stainless steel manufactured by selective laser melting. *Eng. Fract. Mech.* 120:15–25
 93. Tolosa I, Garciandía F, Zubiri F, Zapirain F, Esnaola A. 2010. Study of mechanical properties of AISI 316 stainless steel processed by ‘selective laser melting’, following different manufacturing strategies. *Int. J. Adv. Manuf. Technol.* 51(5–8):639–47
 94. Wanjara P, Brochu M, Jahazi M. 2007. Electron beam freeforming of stainless steel using solid wire feed. *Mater. Des.* 28(8):2278–86
 95. Sun G, Zhou R, Lu J, Mazumder J. 2015. Evaluation of defect density, microstructure, residual stress, elastic modulus, hardness and strength of laser-deposited AISI 4340 steel. *Acta Mater.* 84:172–89
 96. Colegrove PA, Coules HE, Fairman J, Martina F, Kashoob T, et al. 2013. Microstructure and residual stress improvement in wire and arc additively manufactured parts through high-pressure rolling. *J. Mater. Process. Technol.* 213(10):1782–91
 97. You X, Tan Y, Li J, Li P, Dong C, et al. 2015. Effects of solution heat treatment on the microstructure and hardness of Inconel 740 superalloy prepared by electron beam smelting. *J. Alloys Compd.* 638:239–48
 98. List FA, Dehoff RR, Lowe LE, Sames WJ. 2014. Properties of Inconel 625 mesh structures grown by electron beam additive manufacturing. *Mater. Sci. Eng. A* 615:191–97
 99. Tayon WA, Shenoy RN, Redding MR, Bird RK, Hafley RA. 2014. Correlation between microstructure and mechanical properties in an Inconel 718 deposit produced via electron beam freeform fabrication. *J. Manuf. Sci. Eng.* 136(6):061005
 100. Martinez E, Murr LE, Hernandez J, Pan X, Amato K, et al. 2013. Microstructures of niobium components fabricated by electron beam melting. *Metallogr. Microstruct. Anal.* 2(3):183–89
 101. Murr LE, Martinez E, Pan XM, Gaytan SM, Castro JA, et al. 2013. Microstructures of Rene 142 nickel-based superalloy fabricated by electron beam melting. *Acta Mater.* 61(11):4289–96
 102. Murr LE, Martinez E, Gaytan SM, Ramirez DA, Machado BI, et al. 2011. Microstructural architecture, microstructures, and mechanical properties for a nickel-base superalloy fabricated by electron beam melting. *Metall. Mater. Trans. A* 42(11):3491–508
 103. Li S, Wei Q, Shi Y, Zhu Z, Zhang D. 2015. Microstructure characteristics of Inconel 625 superalloy manufactured by selective laser melting. *J. Mater. Sci. Technol.* 31(9):946–52
 104. Strößner J, Terock M, Glatzel U. 2015. Mechanical and microstructural investigation of nickel-based superalloy IN718 manufactured by selective laser melting (SLM). *Adv. Eng. Mater.* 17(8):1099–105
 105. Scott-Emuakpor O, Schwartz J, George T, Holycross C, Cross C, Slater J. 2015. Bending fatigue life characterisation of direct metal laser sintering nickel alloy 718. *Fatigue Fract. Eng. Mater. Struct.* 38(9):1105–17
 106. Harrison NJ, Todd I, Mumtaz K. 2015. Reduction of micro-cracking in nickel superalloys processed by Selective Laser Melting: a fundamental alloy design approach. *Acta Mater.* 94:59–68

107. Kunze K, Etter T, Grässlin J, Shklover V. 2015. Texture, anisotropy in microstructure and mechanical properties of IN738LC alloy processed by selective laser melting (SLM). *Mater. Sci. Eng. A* 620:213–22
108. Carter LN, Martin C, Withers PJ, Attallah MM. 2014. The influence of the laser scan strategy on grain structure and cracking behaviour in SLM powder-bed fabricated nickel superalloy. *J. Alloys Compd.* 615:338–47
109. Kanagarajah P, Brenne F, Niendorf T, Maier HJ. 2013. Inconel 939 processed by selective laser melting: effect of microstructure and temperature on the mechanical properties under static and cyclic loading. *Mater. Sci. Eng. A* 588:188–95
110. Benn RC, Salva RP, Engineering P. 2010. Additively manufactured Inconel alloy 718. In *TMS Superalloy 718 and Derivatives Proceedings*, 7th, pp. 455–69. Warrendale, PA/Hoboken, NJ: TMS/Wiley
111. Zhang Y-N, Cao X, Wanjara P, Medraj M. 2014. Tensile properties of laser additive manufactured Inconel 718 using filler wire. *J. Mater. Res.* 29(17):2006–20
112. Dehoff RR, Sarosi PM, Collins PC, Fraser HL, Mills MJ. 2003. Microstructural evaluation of LENS™ deposited Nb-Ti-Si-Cr alloys. *MRS Proc.* 753:BB2.6
113. Gu D, Wang H, Dai D, Yuan P, Meiners W, Poprawe R. 2015. Rapid fabrication of Al-based bulk-form nanocomposites with novel reinforcement and enhanced performance by selective laser melting. *Scr. Mater.* 96:25–28
114. Weingarten C, Buchbinder D, Pirch N, Meiners W, Wissenbach K, Poprawe R. 2015. Formation and reduction of hydrogen porosity during selective laser melting of AlSi10Mg. *J. Mater. Process. Technol.* 221:112–20
115. Siddique S, Imran M, Wycisk E, Emmelmann C, Walther F. 2015. Influence of process-induced microstructure and imperfections on mechanical properties of AlSi12 processed by selective laser melting. *J. Mater. Process. Technol.* 221:205–13
116. Yan C, Hao L, Hussein A, Young P, Huang J, Zhu W. 2015. Microstructure and mechanical properties of aluminium alloy cellular lattice structures manufactured by direct metal laser sintering. *Mater. Sci. Eng. A* 628:238–46
117. Olakanmi EO, Cochrane RF, Dalgarno KW. 2015. A review on selective laser sintering/melting (SLS/SLM) of aluminium alloy powders: processing, microstructure, and properties. *Prog. Mater. Sci.* 74:401–77
118. Kempen K, Thijs L, Van Humbeeck J, Kruth J-P. 2015. Processing AlSi10Mg by selective laser melting: parameter optimisation and material characterisation. *Mater. Sci. Technol.* 31(8):917–23
119. Krishnan M, Atzeni E, Canali R, Calignano F, Manfredi D, et al. 2014. On the effect of process parameters on properties of AlSi10Mg parts produced by DMLS. *Rapid Prototyp. J.* 20(6):449–58
120. Rometsch PA, Zhong H, Nairn KM, Jarvis T, Wu X. 2014. Characterization of a laser-fabricated hypereutectic Al-Sc alloy bar. *Scr. Mater.* 87:13–16
121. Li Y, Gu D. 2014. Parametric analysis of thermal behavior during selective laser melting additive manufacturing of aluminum alloy powder. *Mater. Des.* 63:856–67
122. Mertens R, Clijsters S, Kempen K, Kruth J-P. 2014. Optimization of scan strategies in selective laser melting of aluminum parts with downfacing areas. *J. Manuf. Sci. Eng.* 136(6):06 1012
123. Aboulkhair NT, Everitt NM, Ashcroft I, Tuck C. 2014. Reducing porosity in AlSi10Mg parts processed by selective laser melting. *Addit. Manuf.* 1–4:77–86
124. Rosenthal I, Stern A, Frage N. 2014. Microstructure and mechanical properties of AlSi10Mg parts produced by the laser beam additive manufacturing (AM) technology. *Metallogr. Microstruct. Anal.* 3(6):448–53
125. Taminger K, Hafley R. 2003. Electron beam freeform fabrication: a rapid metal deposition process. In *Proc. Annu. Automot. Compos. Conf.*, 3rd, pp. 9–10
126. Li X, Reynolds AP, Cong B, Ding J, Williams S. 2015. Production and properties of a wire-arc additive manufacturing part made with friction extruded wire. In *TMS Proceedings*, pp. 445–52. Warrendale, PA/Hoboken, NJ: TMS/Wiley
127. Gu J, Cong B, Ding J, Williams SW, Zhai Y. 2014. Wire+arc additive manufacturing of aluminum. In *Solid Freeform Fabrication Proceedings*, pp. 451–58. Austin: Univ. Tex.



128. Fujieda T, Shiratori H, Kuwabara K, Kato T, Yamanaka K, et al. 2015. First demonstration of promising selective electron beam melting method for utilizing high-entropy alloys as engineering materials. *Mater. Lett.* 159(15):12–15
129. Brif Y, Thomas M, Todd I. 2015. The use of high-entropy alloys in additive manufacturing. *Scr. Mater.* 99:93–96
130. ISO/ASTM. 2013. *Standard terminology for additive manufacturing-coordinate systems and test methodologies*. ASTM/ISO Stand. 52921
131. ASTM. 2015. *Anisotropy effects in mechanical properties of AM parts*. ASTM Work Item WK49229
132. Moylan S, Land J, Possolo A. 2015. Additive manufacturing round robin protocols: a pilot study. In *Solid Freeform Fabrication Proceedings*, pp. 1504–12. Austin: Univ. Tex.
133. Moylan S, Slotwinski J. 2014. Assessment of guidelines for conducting round robin studies in additive manufacturing. In *Proceedings of ASPE Spring Topical Meeting—Dimensional Accuracy and Surface Finish in Additive Manufacturing*, Vol. 57, pp. 82–85. Berkeley, CA: NIST
134. Gockel J, Beuth J, Taminger K. 2014. Integrated control of solidification microstructure and melt pool dimensions in electron beam wire feed additive manufacturing of Ti-6Al-4V. *Addit. Manuf.* 1–4:119–26
135. Beuth J, Fox J, Gockel J, Montgomery C, Yang R, et al. 2013. Process mapping for qualification across multiple direct metal additive manufacturing processes. In *Solid Freeform Fabrication Proceedings*, pp. 655–65. Austin: Univ. Tex.
136. Gockel J, Beuth J. 2013. Understanding Ti-6Al-4V microstructure control in additive manufacturing via process maps. In *Solid Freeform Fabrication Proceedings*, pp. 666–74. Austin: Univ. Tex.
137. Nassar AR, Keist JS, Reutzel EW, Spurgeon TJ. 2015. Intra-layer closed-loop control of build plan during directed energy additive manufacturing of Ti-6Al-4V. *Addit. Manuf.* 6:39–52
138. Soylemez E, Beuth JL, Taminger K. 2010. Controlling melt pool dimensions over a wide range of material deposition rates in electron beam additive manufacturing. In *Solid Freeform Fabrication Proceedings*, pp. 571–82. Austin: Univ. Tex.
139. Montgomery C, Beuth J, Sheridan L, Klingbeil N. 2015. Process mapping of Inconel 625 in laser powder bed additive manufacturing. In *Solid Freeform Fabrication Proceedings*, pp. 1195–204. Austin: Univ. Tex.
140. Seifi M, Christiansen D, Beuth JL, Harrysson O, Lewandowski JJ. 2016. Process mapping, fracture and fatigue behavior of Ti-6Al-4V produced by EBM additive manufacturing. In *Proceedings of World Conference on Titanium, 13th*, pp. 1373–77. Warrendale, PA/Hoboken, NJ: TMS/Wiley
141. Greitemeier D, Dalle Donne C, Syassen F, Eufinger J, Melz T. 2016. Effect of surface roughness on fatigue performance of additive manufactured Ti-6Al-4V. *Mater. Sci. Technol.* In press
142. Edwards P, O’Conner A, Ramulu M. 2013. Electron beam additive manufacturing of titanium components: properties and performance. *J. Manuf. Sci. Eng.* 135(6):061016
143. Tan X, Kok Y, Tan YJ, Descoins M, Mangelinck D, et al. 2015. Graded microstructure and mechanical properties of additive manufactured Ti-6Al-4V via electron beam melting. *Acta Mater.* 97:1–16
144. Rodriguez OL, Allison PG, Whittington WR, Francis DK, Rivera OG, et al. 2015. Dynamic tensile behavior of electron beam additive manufactured Ti6Al4V. *Mater. Sci. Eng. A* 641:323–27
145. Hrabe N, Quinn T. 2013. Effects of processing on microstructure and mechanical properties of a titanium alloy (Ti-6Al-4V) fabricated using electron beam melting (EBM). Part 2. Energy input, orientation, and location. *Mater. Sci. Eng. A* 573:271–77
146. Murr LE, Esquivel EV, Quinones SA, Gaytan SM, Lopez MI, et al. 2009. Microstructures and mechanical properties of electron beam–rapid manufactured Ti-6Al-4V biomedical prototypes compared to wrought Ti-6Al-4V. *Mater. Charact.* 60(2):96–105
147. McLouth T, Chang Y, Wooten J, Yang J. 2015. The effects of electron beam melting on the microstructure and mechanical properties of Ti-6Al-4V and γ -TiAl. *Microsc. Microanal.* 21(588):1177–78
148. Gong H, Rafi K, Gu H, Janaki Ram GD, Starr T, Stucker B. 2015. Influence of defects on mechanical properties of Ti-6Al-4V components produced by selective laser melting and electron beam melting. *Mater. Des.* 86:545–54
149. Morgan L, Lindhe U, Harrysson O. 2003. Rapid manufacturing with electron beam melting (EBM)—a manufacturing revolution? In *Solid Freeform Fabrication Proceedings*, pp. 433–38. Austin: Univ. Tex.

150. Rekeda KD, Liu D. 2015. Fatigue life of selective laser melted and hot isostatically pressed Ti-6Al-4V absent of surface machining. Presented at *AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 56th
151. Cain V, Thijss L, Van Humbeeck J, Van Hooreweder B, Knutsen R. 2015. Crack propagation and fracture toughness of Ti6Al4V alloy produced by selective laser melting. *Addit. Manuf.* 5(1):68–76
152. Kasperovich G, Hausmann J. 2015. Improvement of fatigue resistance and ductility of TiAl6V4 processed by selective laser melting. *J. Mater. Process. Technol.* 220:202–14
153. Edwards P, Ramulu M. 2014. Fatigue performance evaluation of selective laser melted Ti-6Al-4V. *Mater. Sci. Eng. A* 598:327–37
154. Leuders S, Lieneke T, Lammers S, Tröster T, Niendorf T. 2014. On the fatigue properties of metals manufactured by selective laser melting—the role of ductility. *J. Mater. Res.* 29(17):1911–19
155. Simonelli M, Tse YY, Tuck C. 2014. Effect of the build orientation on the mechanical properties and fracture modes of SLM Ti-6Al-4V. *Mater. Sci. Eng. A* 616(10):1–11
156. Vrancken B, Thijss L, Kruth J-P, Van Humbeeck J. 2012. Heat treatment of Ti6Al4V produced by Selective Laser Melting: microstructure and mechanical properties. *J. Alloys Compd.* 541:177–85
157. Murr LE, Quinones SA, Gaytan SM, Lopez MI, Rodela A, et al. 2009. Microstructure and mechanical behavior of Ti-6Al-4V produced by rapid-layer manufacturing, for biomedical applications. *J. Mech. Behav. Biomed. Mater.* 2(1):20–32
158. Vilardo T, Colin C, Bartout JD. 2011. As-fabricated and heat-treated microstructures of the Ti-6Al-4V alloy processed by selective laser melting. *Metall. Mater. Trans. A* 42(10):3190–99
159. Vandenbroucke B, Kruth JP. 2007. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. *Rapid Prototyp. J.* 13(4):196–203
160. Mertens A, Reginster S, Paydas H, Contrepois Q, Dormal T, et al. 2014. Mechanical properties of alloy Ti-6Al-4V and of stainless steel 316L processed by selective laser melting: influence of out-of-equilibrium microstructures. *Powder Metall.* 57(3):184–89
161. Hollander DA, von Walter M, Wirtz T, Sellei R, Schmidt-Rohlfing B, et al. 2006. Structural, mechanical and *in vitro* characterization of individually structured Ti-6Al-4V produced by direct laser forming. *Biomaterials* 27(7):955–63
162. Qiu C, Adkins NJE, Attallah MM. 2013. Microstructure and tensile properties of selectively laser-melted and of HIPed laser-melted Ti-6Al-4V. *Mater. Sci. Eng. A* 578:230–39
163. Yu J, Rombouts M, Maes G, Motmans F. 2012. Material properties of Ti6Al4V parts produced by laser metal deposition. *Phys. Procedia* 39:416–24
164. Zhang S, Lin X, Chen J, Huang W. 2009. Heat-treated microstructure and mechanical properties of laser solid forming Ti-6Al-4V alloy. *Rare Met.* 28(6):537–44
165. Alcristo J, Enriquez A, Garcia H, Hinkson S, Steelman T, et al. 2011. Tensile properties and microstructures of laser-formed Ti-6Al-4V. *J. Mater. Eng. Perform.* 20(2):203–12
166. Dinda GP, Song L, Mazumder J. 2008. Fabrication of Ti-6Al-4V scaffolds by direct metal deposition. *Metall. Mater. Trans. A* 39(12):2914–22
167. Zhai Y, Galarraga H, Lados DA. 2015. Microstructure evolution, tensile properties, fatigue damage mechanisms in Ti-6Al-4V alloys fabricated by two additive manufacturing techniques. *Procedia Eng.* 114:658–66
168. Arcella FG, Froes FH. 2000. Producing titanium aerospace components from powder using laser forming. *JOM* 52(5):28–30
169. Lewis GK, Schlienger E. 2000. Practical considerations and capabilities for laser assisted direct metal deposition. *Mater. Des.* 21(4):417–23
170. Griffith ML, Ensz MT, Puskar JD, Robino CV, Brooks JA, et al. 2000. Understanding the microstructure and properties of components fabricated by Laser Engineered Net Shaping (LENS). *MRS Proc.* 625:9; doi: 10.1557/PROC-625-9
171. Löber L, Schimansky FP, Kühn U, Pyczak F, Eckert J. 2014. Selective laser melting of a beta-solidifying TNM-B1 titanium aluminide alloy. *J. Mater. Process. Technol.* 214(9):1852–60
172. Löber L, Biamino S, Ackelid U, Sabbadini S, Epicoco P, et al. 2011. Comparison of selective laser and electron beam melted titanium aluminides. In *Solid Freeform Fabrication Proceedings*, pp. 547–56. Austin: Univ. Tex.



173. Spierings AB, Starr TL, Ag I. 2013. Fatigue performance of additive manufactured metallic parts. *Rapid Prototyp. J.* 19(2):88–94
174. Sercombe TB, Li X. 2016. Selective laser melting of aluminium and aluminium metal matrix composites: review. *Mater. Technol.* In press
175. Wang XJ, Zhang LC, Fang MH, Sercombe TB. 2014. The effect of atmosphere on the structure and properties of a selective laser melted Al-12Si alloy. *Mater. Sci. Eng. A* 597:370–75
176. Li XP, Wang XJ, Saunders M, Suvorova A, Zhang LC, et al. 2015. A selective laser melting and solution heat treatment refined Al-12Si alloy with a controllable ultrafine eutectic microstructure and 25% tensile ductility. *Acta Mater.* 95:74–82
177. Read N, Wang W, Essa K, Attallah MM. 2015. Selective laser melting of AlSi10Mg alloy: process optimisation and mechanical properties development. *Mater. Des.* 65:417–24
178. Manfredi D, Calignano F, Krishnan M, Canali R, Ambrosio EP, Atzeni E. 2013. From powders to dense metal parts: characterization of a commercial AlSiMg alloy processed through direct metal laser sintering. *Materials* 6(3):856–69
179. Kempen K, Thijs L, Van Humbeeck J, Kruth J-P. 2012. Mechanical properties of AlSi10Mg produced by selective laser melting. *Phys. Procedia* 39:439–46
180. Song C, Yang Y, Wang Y, Wang D, Yu J. 2014. Research on rapid manufacturing of CoCrMo alloy femoral component based on selective laser melting. *Int. J. Adv. Manuf. Technol.* 75(1–4):445–53
181. Kircher R, Christensen A, Wurth K. 2009. Electron Beam Melted (EBM) Co-Cr-Mo alloy for orthopaedic implant applications. In *Solid Freeform Fabrication Proceedings*, pp. 428–36. Austin: Univ. Tex.
182. Tarasova TV, Nazarov AP, Prokof'ev MV. 2015. Effect of the regimes of selective laser melting on the structure and physicomechanical properties of cobalt-base superalloys. *Phys. Met. Metallogr.* 116(6):601–5
183. Terrazas CA, Mireles J, Gaytan SM, Morton PA, Hinojos A, et al. 2016. Fabrication and characterization of high-purity niobium using electron beam melting additive manufacturing technology. *Int. J. Adv. Manuf. Technol.* In press
184. Wei K, Gao M, Wang Z, Zeng X. 2014. Effect of energy input on formability, microstructure and mechanical properties of selective laser melted AZ91D magnesium alloy. *Mater. Sci. Eng. A* 611:212–22
185. Ma Y, Cuiuri D, Hoye N, Li H, Pan Z. 2015. The effect of location on the microstructure and mechanical properties of titanium aluminides produced by additive layer manufacturing using in-situ alloying and gas tungsten arc welding. *Mater. Sci. Eng. A* 631:230–40
186. Baufeld B. 2012. Mechanical properties of INCONEL 718 parts manufactured by shaped metal deposition (SMD). *J. Mater. Eng. Perform.* 21(7):1416–21
187. Blackwell PL. 2005. The mechanical and microstructural characteristics of laser-deposited IN718. *J. Mater. Process. Technol.* 170(1–2):240–46
188. Zhao X, Chen J, Lin X, Huang W. 2008. Study on microstructure and mechanical properties of laser rapid forming Inconel 718. *Mater. Sci. Eng. A* 478(1–2):119–24
189. Bird RK, Hibberd J. 2009. *Tensile properties and microstructure of Inconel 718 fabricated with electron beam freeform fabrication (EBF³)*. Tech. Rep., NASA
190. Qi H, Azer M, Ritter A. 2009. Studies of standard heat treatment effects on microstructure and mechanical properties of laser net shape manufactured INCONEL 718. *Metall. Mater. Trans. A* 40(10):2410–22
191. Cao X, Rivaux B, Jahazi M, Cuddy J, Birur A. 2009. Effect of pre- and post-weld heat treatment on metallurgical and tensile properties of Inconel 718 alloy butt joints welded using 4kW Nd:YAG laser. *J. Mater. Sci.* 44(17):4557–71
192. Edwards P, Ramulu M. 2015. Effect of build direction on the fracture toughness and fatigue crack growth in selective laser melted Ti-6Al-4V. *Fatigue Fract. Eng. Mater. Struct.* 38(10):1228–36
193. Van Hooreweder B, Moens D, Boonen R, Kruth J-P, Sas P. 2012. Analysis of fracture toughness and crack propagation of Ti6Al4V produced by selective laser melting. *Adv. Eng. Mater.* 14(1–2):92–97
194. Becker TH, Beck M, Scheffer C. 2015. Microstructure and mechanical properties of direct metal laser sintered Ti-6Al-4V. *S. Afr. J. Ind. J.* 26:1–10
195. Svensson M. 2009. Ti6Al4V manufactured with electron beam melting (EBM): mechanical and chemical properties. In *Proceedings from the Materials & Processes for Medical Devices Conference*, pp. 189–94. Novelty, OH: ASM Int.

196. Boyer R, Welsch G, Collings EW. 1994. *Materials Properties Handbook: Titanium Alloys*. Novelty, OH: ASM Int.
197. Seifi M, Salem A, Satko D, Lewandowski JJ. 2016. Role of defect and microstructure on fracture resistance and fatigue crack growth behavior of AM Ti-6Al-4V alloy. *Int. J. Fatigue* 91(10):in press
198. Seifi M, Ghamarian I, Samimi P, Collins PC, Lewandowski JJ. 2016. Microstructure and mechanical properties of Ti-48Al-2Cr-2Nb manufactured via electron beam melting. In *Proceedings of World Conference on Titanium, 13th*, pp. 1317–22. Warrendale, PA/Hoboken, NJ: TMS/Wiley
199. Seifi M, Salem A, Satko D, Ackelid U, Lewandowski JJ. 2016. Microstructural inhomogeneity and post processing effects on mechanical properties of Ti-48Al-2Cr-2Nb manufactured by EBM additive manufacturing. *Intermetallics*. Under review
200. Dahir MS, Seifi SM, Bewlay BP, Lewandowski JJ. 2015. Effects of test orientation on fracture and fatigue crack growth behavior of third generation as-cast Ti-48Al-2Nb-2Cr. *Intermetallics* 57:73–82
201. Li P, Warner DH, Fatemi A, Phan N. 2015. Critical assessment of the fatigue performance of additively manufactured Ti-6Al-4V and perspective for future research. *Int. J. Fatigue* 85:130–43
202. Fodran E, Walker K. 2015. *Surface finish enhancement for the electron beam direct digital manufacturing of Ti-6Al-4V alloy structural components*. Tech. Rep., Armament Research, Development and Engineering Center, Weapons Software Engineering Center, Benét Lab.
203. Seifi M, Lewandowski JJ. 2016. Microstructure and mechanical properties of additive manufactured alloys. *Prog. Mater. Sci.* In preparation
204. Filippini M, Beretta S, Içöz C, Patriarca L. 2015. Effect of the microstructure on the fatigue strength of a TiAl intermetallic alloy produced by additive manufacturing. *Mater. Res. Soc. Symp. Proc.* 1:3–8
205. McLouth T, Chang Y, Wooten J, Yang J. 2015. The effects of electron beam melting on the microstructure and mechanical properties of Ti-6Al-4V and γ -TiAl. *Microsc. Microanal.* 21(588):1177–78
206. Seikh A, Mohammad A, Sherif E-S, Al-Ahmari A. 2015. Corrosion behavior in 3.5% NaCl solutions of γ -TiAl processed by electron beam melting process. *Metals* 5(4):2289–302
207. Tang HP, Yang GY, Jia WP, He WW, Lu SL, Qian M. 2015. Additive manufacturing of a high niobium-containing titanium aluminide alloy by selective electron beam melting. *Mater. Sci. Eng. A* 636:103–7
208. Biamino S, Klöden B, Weißgärber T, Kieback B, Ackelid U. 2014. Titanium aluminides for automotive applications processed by electron beam melting. In *Proceedings of Metal Powder Industries Federation (MPIF)*, pp. 96–103. Princeton, NJ: MPIF
209. Filippini M, Beretta S, Patriarca L, Sabbadini S. 2014. Effect of the microstructure on the deformation and fatigue damage in a gamma TiAl produced by additive manufacturing. In *TMS Proceedings*, pp. 189–93. Warrendale, PA/Hoboken, NJ: TMS/Wiley
210. Ge W, Guo C, Lin F. 2014. Effect of process parameters on microstructure of TiAl alloy produced by electron beam selective melting. *Procedia Eng.* 81:1192–97
211. Ge W, Lin F, Guo C. 2014. The effect of scan pattern on microstructure evolution and mechanical properties in electron beam melting Ti47Al2Cr2Nb. In *Solid Freeform Fabrication Proceedings*, pp. 501–13. Austin: Univ. Tex.
212. Schwerdtfeger J, Körner C. 2014. Selective electron beam melting of Ti-48Al-2Nb-2Cr: microstructure and aluminium loss. *Intermetallics* 49:29–35
213. Filippini M, Beretta S, Patriarca L, Pasquero G, Sabbadini S. 2012. Fatigue sensitivity to small defects of a gamma–titanium–aluminide alloy. *J. ASTM Int.* 9(5):104293
214. Terner M, Biamino S, Ugues D, Sabbadini S, Fino P, et al. 2013. Phase transitions assessment on γ -TiAl by thermo mechanical analysis. *Intermetallics* 37:7–10
215. Hernandez J, Murr LE, Gaytan SM, Martinez E, Medina F, Wicker RB. 2012. Microstructures for two-phase gamma titanium aluminide fabricated by electron beam melting. *Metallogr. Microstruct. Anal.* 1(1):14–27
216. Biamino S, Penna A, Ackelid U, Sabbadini S, Tassa O, et al. 2011. Electron beam melting of Ti-48Al-2Cr-2Nb alloy: microstructure and mechanical properties investigation. *Intermetallics* 19(6):776–81
217. Filippini M, Beretta S, Patriarca L, Pasquero G, Sabbadini S. 2011. Defect tolerance of a gamma titanium aluminide alloy. *Procedia Eng.* 10:3677–82



218. Franzen SF, Karlsson J, Dehoff R, Ackelid U, Rios O, et al. 2011. Microstructural properties of gamma titanium aluminide manufactured by electron beam melting. In *TMS Proceedings*, pp. 455–62. Warrendale, PA/Hoboken, NJ: TMS/Wiley
219. Murr LE, Gaytan SM, Ceylan A, Martinez E, Martinez JL, et al. 2010. Characterization of titanium aluminide alloy components fabricated by additive manufacturing using electron beam melting. *Acta Mater.* 58(5):1887–94
220. Patriarca L. 2010. Fatigue crack growth of a gamma titanium aluminide alloy. In *Youth Symposium on Experimental Solid Mechanics, 9th*, pp. 36–39
221. Sabbadini S, Tassa O, Gennaro P, Ackelid U. 2010. Additive manufacturing of gamma titanium aluminide parts by electron beam melting. In *TMS Proceedings*, pp. 267–74. Warrendale, PA/Hoboken, NJ: TMS/Wiley
222. Cormier D, Harrysson O, Mahale T, West H. 2007. Freeform fabrication of titanium aluminide via electron beam melting using prealloyed and blended powders. *Res. Lett. Mater. Sci.* 2007:1–4
223. Li W, Liu J, Wen W, Wei Q, Yan C, Shi Y. 2016. Crystal orientation, crystallographic texture and phase evolution in the Ti–45Al–2Cr–5Nb alloy processed by selective laser melting. *Mater. Charact.* 113:125–33
224. Gussone J, Hagedorn Y-C, Gherekhloo H, Kasperovich G, Merzouk T, Hausmann J. 2015. Microstructure of γ -titanium aluminide processed by selected laser melting at elevated temperatures. *Intermetallics* 66:133–40
225. Yadollahi A, Shamsaei N, Thompson SM, Seely DW. 2015. Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel. *Mater. Sci. Eng. A* 644:171–83
226. Sterling A, Torries B, Shamsaei N, Thompson SM, Seely DW. 2016. Fatigue behavior and failure mechanisms of direct laser deposited Ti-6Al-4V. *Mater. Sci. Eng. A* 655:100–12





GE Additive

Spectra H Titanium Ti6Al4V Grade 5

²²
Ti

Base Parameter for Arcam EBM Spectra H

Data in this material datasheet represents material built with 50µm layer thickness and in an Vacuum atmosphere on a Arcam EBM Spectra H – V1.0. Values listed are typical.



Spectra H – Ti6Al4V – Grade 5

In the Arcam Spectra H-machine the Ti6Al4V - Grade 5 process runs at a powder bed temperature of around 700°C. The elevated powder bed temperature eliminates the need for post-build stress-relieving and allows the building of parts in multiple layers in the Z-direction which further increases productivity. The chosen layer thickness enables both high build speed and high resolution.

Titanium Ti6Al4V

The high strength, low weight ratio and outstanding corrosion resistance inherent to titanium and its alloys has led to a wide and diversified range of successful applications which demand high levels of reliable performance in surgery and medicine as well as in aerospace, automotive, chemical plant, power generation, oil and gas extraction, sports, and other major industries. The biocompatibility of Ti6Al4V is excellent, especially when direct contact with tissue or bone is required. In the majority of other engineering applications, titanium replaces heavier, less serviceable or less cost-effective materials.



Spectra H Ti6Al4V Grade 5

This material is developed as a standard material according to Production level (P-material). It has been fully verified according to Arcam EBM Process Verification, with data available for full build envelope. The process parameters can be further optimized to suit the specific needs for individual applications. The parameters set fulfils ASTM F2924 standard both regards to chemical composition as well as mechanical properties.

POWDER INFORMATION

AP&C Ti6Al4V – Grade 5 powder 45-106 µm particle size distribution. For more information on Ti6Al4V powder, visit <https://www.advancedpowders.com/powders/titanium/ti-6al-4v-5>.

MACHINE CONFIGURATION

- Spectra H – V1.0
- EBM Control 5.5

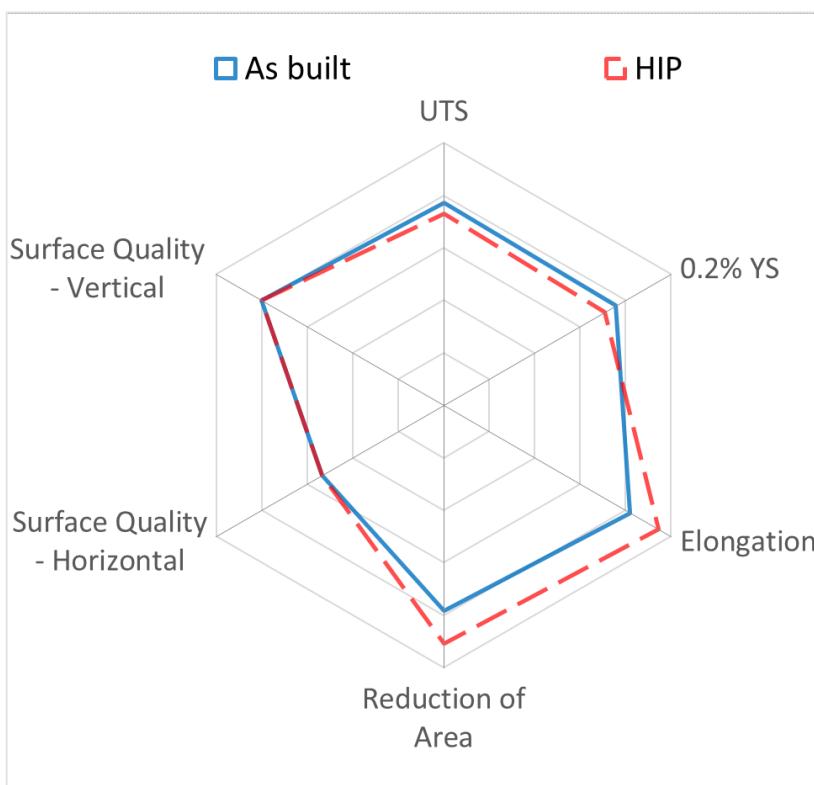
AVAILABLE PARAMETERS

- Spectra H Ti6Al4V Grade 5 Base - 50µm layer thickness

THERMAL TREATMENTS

1. As-Built
2. HIP – 920°C ± 10 °C, 1000bar ± 50bar, 120min ± 30min, cool under inert atmosphere to below 425°C

THERMAL TREATMENT COMPARISON



Spider Plot is generated by normalizing typical material data (containing only vertical data) against a range defined for each material family. For **Titanium Alloys**, the ranges are as follows:
UTS: 0-1300 MPa
0.2%YS: 0-1200 MPa
Elongation: 0-20%
Reduction of Area: 0-60%
Surface Quality (all): 25-40 µm

Surface Roughness
(µm)UpSkin
DownSkin

H	32
V	28

Thermal State	Porosity (% Density)		Hardness (HV30)		Poisson's Ratio	
	H	V	H	V (XZ - YZ)	H	V
1 As-Built	99.8	99.8	350	327 - 326	--	--
2 HIP	--	--	--	--	--	--

TENSILE DATA

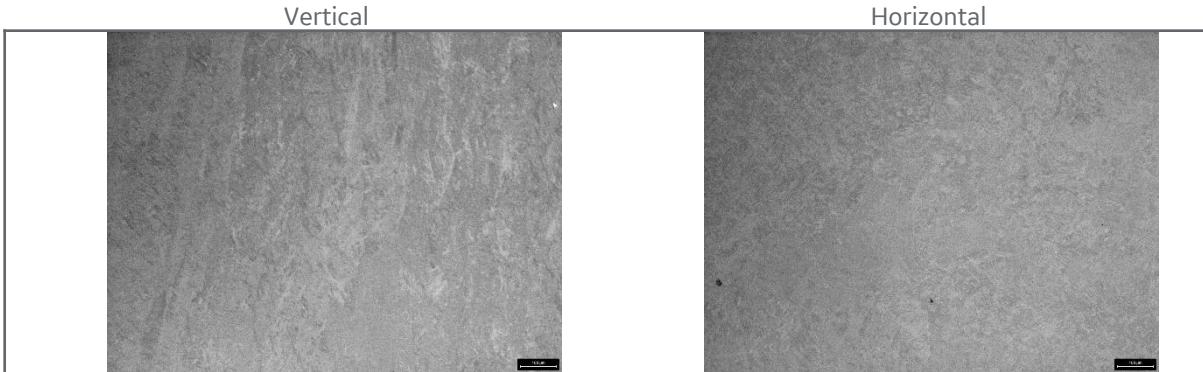
Tensile testing done in accordance with ASTM E8 and ASTM E21

Temperature: RT

Thermal State	Modulus of Elasticity		0.2% YS		UTS		Elongation		Reduction of Area	
	H	V	H	V	H	V	H	V	H	V
1 As-Built	--	--	915	910	1005	1005	14.7	16.4	35.7	43.0
2 HIP	--	--	--	850	--	950	--	18.9	--	50.0

SEM IMAGES

1 As-Built



1 HIP

H: HORIZONTAL (XY) orientation
V: VERTICAL (Z) orientation

* All of the figures contained herein are approximate only. The figures provided are dependent on a number of factors, including but not limited to, process and machine parameters, and the approval is brand specific and/or application specific. The information provided on this material data sheet is illustrative only and cannot be relied on as binding.

Material data sheet - FlexLine

EOS StainlessSteel 316L

EOS StainlessSteel 316L is a stainless steel powder intended for processing on EOS DMLS™ machines.

- EOS DMLS™ EOS M100 system
 - HSS blade (300006274)
 - Argon atmosphere
 - IPCM extra sieving module with 63 µm mesh
 - Hand sieve with 63 µm mesh (300013590) recommended
- EOSYSTEM
 - EOSPRINT v 1.6 or higher
 - Software: HCS 1.8 or higher
- EOS Parameter set: 316L_020_FlexM100_200

Description

EOS StainlessSteel 316L is a corrosion resistant iron based alloy which has been optimized for processing on EOS DMLS systems. EOS StainlessSteel 316L have chemical composition corresponding to ASTM F138 "Standard Specification for Wrought 18Cr-14Ni-2.5Mo Stainless Steel Bar and Wire for Surgical Implants (UNS S31673)". This kind of stainless steel is characterized having a good corrosion resistance and evidence that there are no leachable substances in cytotoxic concentrations.

This material is ideal in

- Lifestyle/Consumer, e.g. watches, other jewellery, spectacle frames, decorations
- Automotive/Industrial, e.g. non-corroding common material, food and chemical plants
- Aerospace/Turbine industry
- Entry-level material for Laser Sintering Technology, e.g. mounting parts, heat exchangers, functional elements in electronic housing and accessories

Parts built from EOS StainlessSteel 316L can be machined, shot-peened and polished in as-built or stress relieved (AMS2759) states if required. Solution annealing is not necessary because the mechanical properties of as-built state are showing desired values (ASTM A403). Parts are not ideal in temperature range 427°C - 816°C where precipitation of chromium carbides occurs. Due to layer-wise building method, the parts have a certain anisotropy which could be seen from mechanical properties.

Material data sheet - FlexLine

Technical Data

Powder properties

The chemical composition of the powder (wt-%):

Material composition	Element	Min	Max
	Fe	Balance	
	Cr	17.00	19.00
	Ni	13.00	15.00
	Mo	2.25	3.00
	C	0.030	
	Mn	2.00	
	Cu	0.50	
	P	0.025	
	S	0.010	
	Si	0.75	
	N	0.10	

Max. particle size

≥ 63µm [1]	Max. 1,0 wt%
------------	--------------

[1] analysis according to ASTM B214.

General process data

Layer thickness	20 µm
Volume rate [2]	1,16 mm ³ /s (4,17 cm ³ /h) 0,25 in ³ /h

[2] The volume rate is a measure of build speed during laser exposure of the skin area. The total build speed depends on this volume rate and many other factors such as exposure parameters of contours, supports, up and downskin, recoating time, Home-In or LPM settings.

Material data sheet - FlexLine

Physical and chemical properties of parts

Part density [3]	min. 7,98 g/ cm ³
Surface roughness after shot peening [4]	R _a < 12 µm; R _z < 62 µm

[3] Weighing in air and water according to ISO 3369.

[4] Measurement according to ISO 4287. The numbers were measured at the horizontal (up-facing) and all vertical surfaces of test cubes. Due to the layerwise building the roughness strongly depends on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect.

Tensile data at room temperature [5, 6]

As built		
	Horizontal	Vertical
Ultimate tensile strength, R _m	650 MPa	590 MPa
Yield strength, R _{p0.2}	535 MPa	490 MPa
Elongation at break, A	35 %	45 %

[5] The numbers are average values of vertical and horizontal orientation.

[6] Tensile testing according to ISO 6892 & ASTM E8M, proportional test pieces, diameter of the neck area 4 mm, original gauge length 4D (16 mm). Tensile test parameters: Stress rate 10MPa/s in elastic range, strain speed in plastic region 0,375 1/min. Results are derived from the validation data made with EOS M100 system and two powder LOTs



Material data sheet - FlexLine

Abbreviations

min. minimum
max. maximum
wt. weight

Legal notes

The quoted values refer to the use of this material with above specified EOS DMLS system, EOSYSTEM software version, parameter set and operation in compliance with parameter sheet and operating instructions. All measured values are average numbers. Part properties are measured with specified measurement methods using defined test geometries and procedures. Further details of the test procedures used by EOS are available on request. Any deviation from these standard settings may affect the measured properties.

The data correspond to EOS knowledge and experience at the time of publication and they are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS does not warrant any properties or fitness for a specific purpose, unless explicitly agreed upon. This also applies regarding any rights of protection as well as laws and regulations.

EOS®, EOSINT®, DMLS®, DirectTool® and DirectPart® are registered trademarks of EOS GmbH.

©2017 EOS GmbH – Electro Optical Systems. All rights reserved.

Material data sheet

EOS StainlessSteel PH1

EOS StainlessSteel PH1 is a metal alloy powder which has been optimized for processing on EOS M systems.

This document provides information and data for parts built using EOS StainlessSteel PH1 powder (EOS art.-no. 9011-0019) on the following specifications:

- DMLS system: M290
 - Ceramic blade (2200-3013), carbon fibre (2200-4366) compatible
 - IPCM sieving module with 63µm mesh size (9044-0032) recommended
 - Nitrogen atmosphere
 - Internal 80µm mesh sieve (1212-0312) possible
- Software: EOSYSTEM 2.4 or newer
- Parameter set: PH1_020_Surface_M291_200

Description

EOS StainlessSteel PH1 is a pre-alloyed stainless steel in fine powder form. The chemistry of EOS StainlessSteel PH1 conforms to the compositions of DIN 1.4540 and UNS S15500.

This kind of steel is characterized by having good corrosion resistance and excellent mechanical properties, especially in the precipitation hardened state. This type of steel is widely used in variety of engineering applications requiring high hardness, strength and corrosion resistance.

This material is ideal for many part-building applications (DirectPart) such as functional metal prototypes, small series products, individualised products or spare parts. Standard processing parameters use full melting of the entire geometry with 20 µm layer thickness. Using standard parameters the mechanical properties are fairly uniform in all directions. Parts made from EOS StainlessSteel PH1 can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required.

Typical applications:

- engineering applications including functional prototypes, small series products, individualised products or spare parts.
- parts requiring high corrosion resistance, sterilisability, etc.
- parts requiring particularly high hardness and strength.

Material data sheet

Technical Data

Powder properties

Material composition

Element	Min [wt.-%]	Max [wt.-%]
Cr	14.0	15.5
Ni	3.5	5.5
Cu	2.5	4.5
Mn		1.00
Si		1.00
C		0.07
Mo		0.5
Nb	0.15	0.45

Max. particle size

Particles \geq 63µm [1] 0.5 wt.-%

[1] Sieve analysis according to DIN ISO 4497 or ASTM B214.

Material data sheet

General process data

Layer thickness	20 µm 0.8 mil.
Typical achievable part accuracy [2]	
- small parts	± 20 – 50 µm 0.8 – 2.0 mil
- large parts	± 0.2 %
Volume rate [3]	~2.0 mm ³ /s (~7.0cm ³ /h) ~0.40 in ³ /h
Min. wall thickness [4]	~ 0.4 mm ~ 0.016 in

- [2] Based on users' experience of dimensional accuracy for typical geometries, e.g. ± 20 µm when parameters can be optimized for a certain class of parts or ± 50 µm when building a new kind of geometry for the first time.
- [3] The volume rate is a measure of build speed during laser exposure of the skin area. The total build speed depends on this volume rate and many other factors such as exposure parameters of contours, supports, up and downskin, recoating time, Home-In or LPM settings.
- [4] Mechanical stability is dependent on geometry (wall height etc.) and application

Material data sheet

Physical and chemical properties of parts

Part density [5]	~7.7 g/cm ³ ~0.27 lb/in ³
Relative density with standard parameters	approx. 100 %
Surface roughness after shot peening [6]	
- after shot-peening	Ra ~ 5.0 µm, Rz ~ 25.0 µm Ra ~ 0.2 mil, Rz ~ 1.0 mil
- after polishing	Rz up to < 0.5 µm (can be very finely polished)

[5] Weighing in air and water according to ISO 3369.

[6] Measurement according to ISO 4287. The numbers were measured at the horizontal (up-facing) and all vertical surfaces of test cubes. Due to the layerwise building the roughness strongly depends on the orientation of the surface, for example sloping and curved surfaces exhibit a stair-step effect.

Material data sheet

Tensile data at room temperature [7]

	As built	Heat treated [9] (mod H900 heat treatment)
Ultimate tensile strength		
- in horizontal direction (XY)	1200 \pm 50 MPa	min. 1350 MPa (typical 1450 \pm 100 MPa)
- in vertical direction (Z)	1200 \pm 50 MPa	min. 1340 MPa (typical 1440 \pm 100 MPa)
Yield strength (Rp 0.2 %)		
- in horizontal direction (XY)	1025 \pm 85 MPa	min. 1250 MPa (typical 1350 \pm 100 MPa)
- in vertical direction (Z)	930 \pm 75 MPa	min. 1200 MPa (typical 1300 \pm 100 MPa)
Elongation at break		
- in horizontal direction (XY)	17 % \pm 4 %	min 10 % (typical 15 % \pm 3 %)
- in vertical direction (Z)	14 % \pm 4 %	min 10 % (typical 13 % \pm 3 %)
Hardness [8]		
- as built	-	min 40 HRC (typical 43 HRC)

- [7] Mechanical testing according to ISO 6892:1998(E) Annex C, proportional test pieces, Diameter of the neck area 5mm, original gauge length 25mm, test pieces built in 20µm layer-thickness.
- [8] Rockwell C (HRC) hardness measurement according to DIN EN ISO 6508-1. Note that depending on the measurement method used, the measured hardness value can be dependent on the surface roughness and can be lower than the real hardness. To avoid inaccurate results, hardness should be measured on a polished surface.
- [9] Mechanical properties are expressed as minimum values to indicate that mechanical properties exceed the min requirements of material specification standards such as ASTM A564-04 (XM12), ASTM A693-06 (XM12). Hardening of EOS StainlessSteel PH1 done using modified H900 heat treatment (soaking time at precipitation hardening temperature 525°C elongated for 4 hours).



Material data sheet

Abbreviations

min. minimum

max. maximum

wt. weight

The quoted values refer to the use of this material with above specified type of EOS DMLS system, EOSYSTEM software version, parameter set and operation in compliance with parameter sheet and operating instructions. Part properties are measured with specified measurement methods using defined test geometries and procedures and. Further details of the test procedures used by EOS are available on request. Any deviation from these standard settings may affect the measured properties.

The data correspond to EOS knowledge and experience at the time of publication and they are subject to change without notice as part of EOS' continuous development and improvement processes.

EOS does not warrant any properties or fitness for a specific purpose, unless explicitly agreed upon. This also applies regarding any rights of protection as well as laws and regulations.

EOS[®], EOSINT[®], DMLS[®], DirectTool[®] and DirectPart[®] are registered trademarks of EOS GmbH.

© 2017 EOS GmbH – Electro Optical Systems. All rights reserved.

Ti6-4

SPECIFICATIONS

EU Ti-6Al-4V

USA UNSR56400

MATERIAL DESCRIPTION

- Titanium alloy with good mechanical properties up to 300°C. Titanium alloy alpha + beta type.

COMPOSITION

% massique

Ti	—————	Balance
Al	—————	6
V	—————	4
O2	—————	0,2
C	—————	<0,08

APPLICATIONS



MATERIAL SHEET

Typical mechanical properties

The data provided in this document represent typical but not guaranteed values.

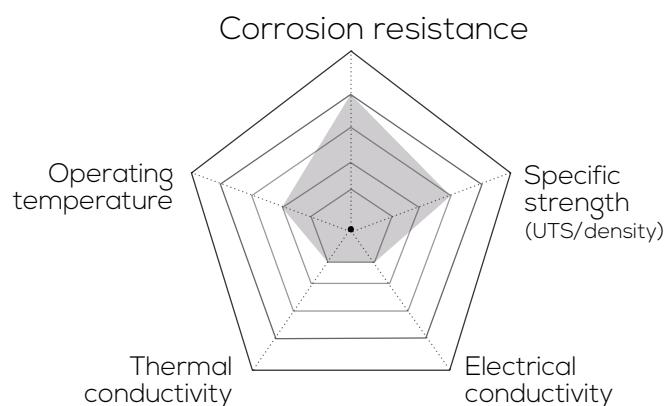
	Stress-relieved	Heat treated*
Ultimate Tensile Strength UTS, MPa	1150	980
Yield Strength YS, MPa	1070	860
Elongation at break E 5D, %	10	15

* Heat treatment: 920°C/2h.

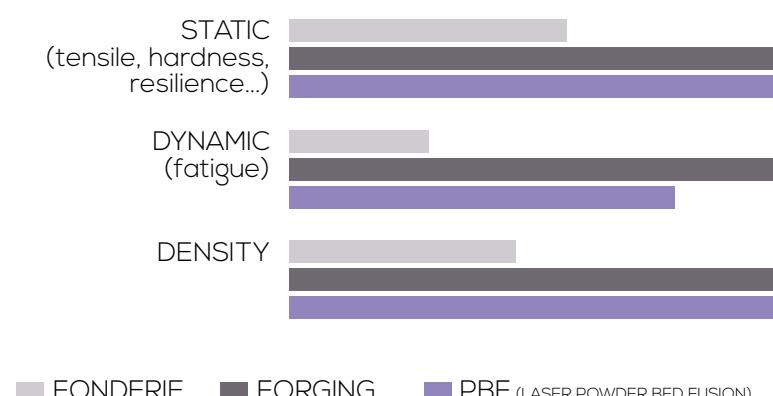
The mechanical characteristics along the Z axis are lowered by about 100 MPa after manufacturing.

The anisotropy is significantly reduced, if not eliminated, after heat treatment.

Physical properties



Qualitative comparison according to processes



Technical data

PARTICLES SIZE :

Available in different granulometries.

SUPPLIERS :

AddUp will provide support with your choice of powder supplier.

Applications, in detail



INDUSTRY

Tubing

Ti6-4 has a very good resistance against corrosion. It can be used in corrosive environments such as water, sea water, or natural streams.

Main applications would be in tubing, nozzles, and valve bodies.



AERONAUTIC

Sub-assembly

Its good mechanical properties and its specific strength (UTS/density) make Ti6-4 commonly used for aeronautic structures like longeron, external doors safety parts or fasteners in ambient or warm atmospheres (<300°C).



POWER GENERATION

Land-based turbine

For land-based turbines, Ti6-4 is used in cold sections (<300°C) to reduce the mass of rotating parts like disks or blades.



LUXURY

Watch

The compromise between lightness and hardness makes Ti6-4 (Titanium grade 5) useful for watch cases and/or wrist strap.

Its low density (4.5) reduces the mass of the watch and while retaining its level of hardness to be scratchresistant.