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METAL ADDITIVE MANUFACTURING: A REVIEW OF MECHANICAL PROPERTIES (POSTPRINT)

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Case Western Reserve University

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14. ABSTRACT ***(Maximum 200 words)***
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Metal Additive Manufacturing: A Review of Mechanical Properties

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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, EBF^3). 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

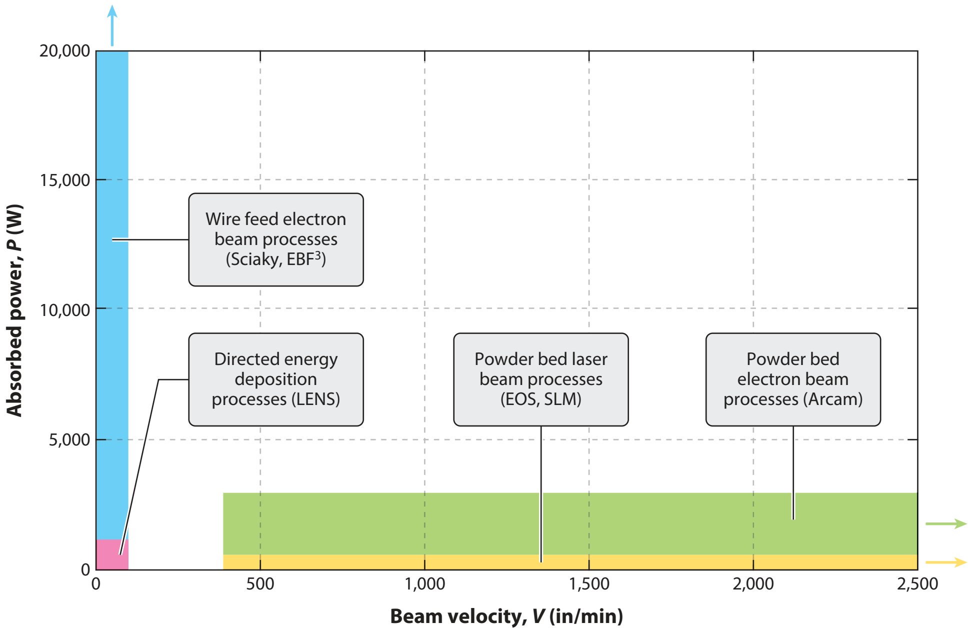

Figure 1

Typical combinations of power (P) and velocity (V) in various metal AM processes. Abbreviations: EBF^3, electron beam freeform fabrication; LENS, laser-engineered net shaping; SLM, selective laser melting. Adapted with permission from Reference 10.

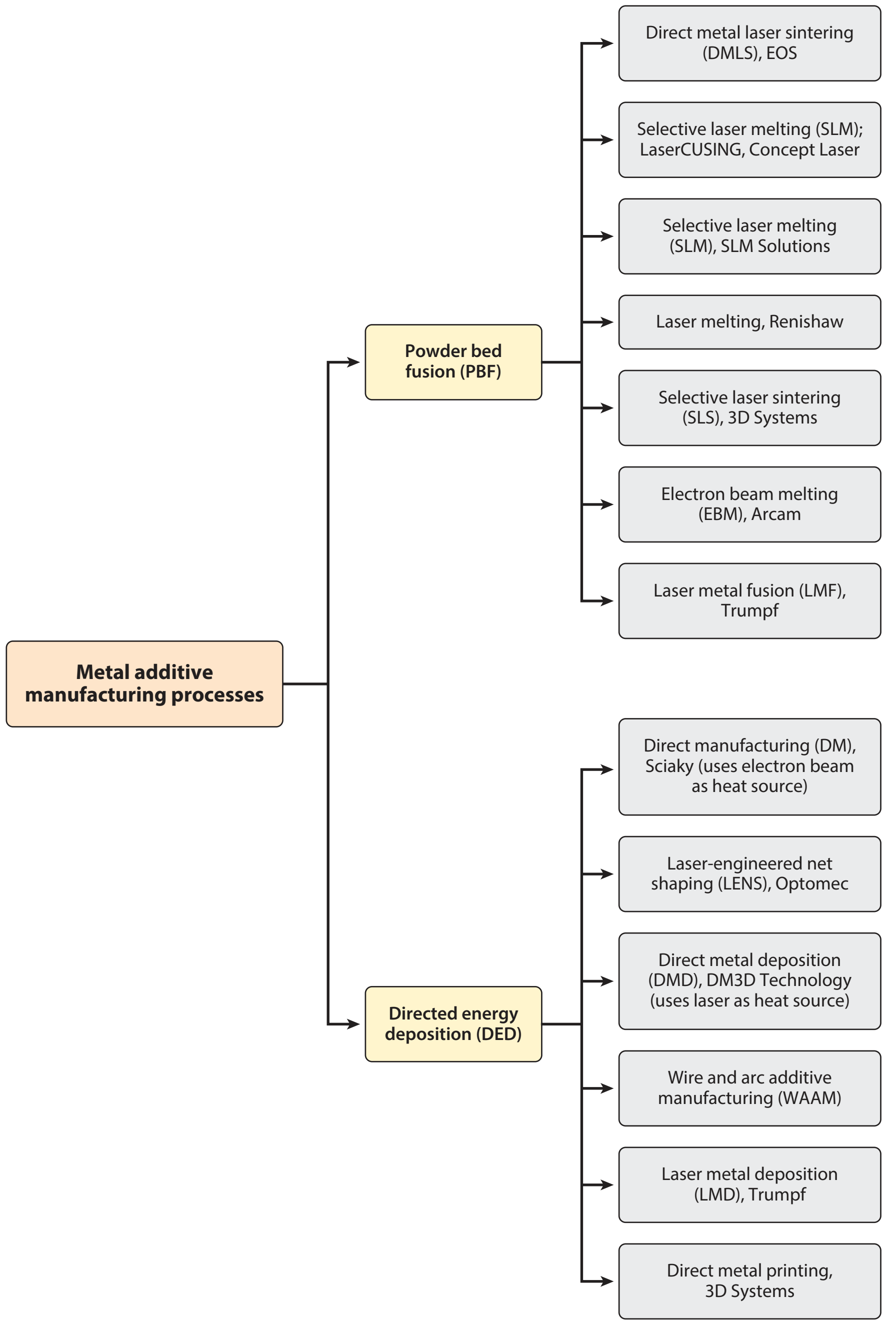

Figure 2

Summary of metal additive manufacturing processes, along with their commercial machine supplier names.

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

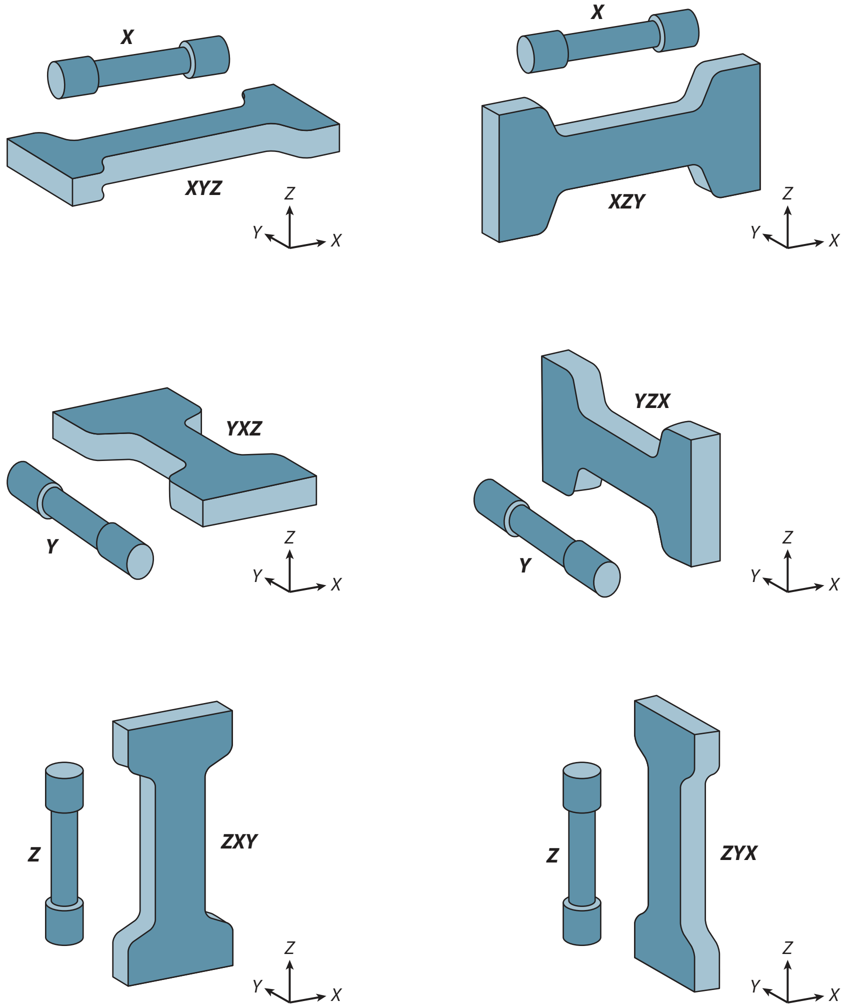

Figure 3

Orientation designations for mechanical testing of 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 insight into part/component quality in different locations and orientations.

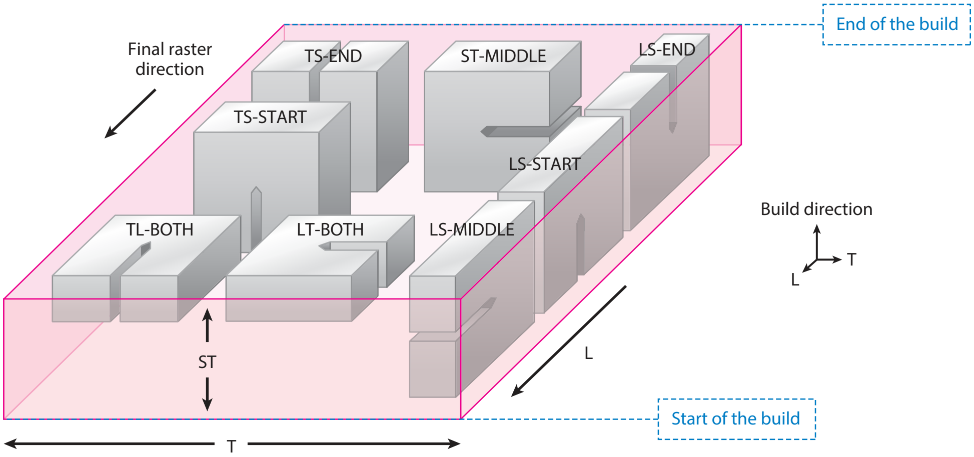

Figure 4

Possible designations for AM fracture and fatigue 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. In addition, **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, A2X, 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 A2X 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	*XY*	NA	876 ± 12.5	978 ± 9.5	13.5 ± 1.5	NA	
Arcam S12	As built	*XY*	NA	982 ± 5.7	1,029 ± 7	12.2 ± 0.8	372 ± 7.2	145
		Z	NA	984 ± 8.5	1,032 ± 12.9	9 ± 2.9	367 ± 8.3	
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	9.9 ± 1.02	NA	
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	NA	117 ± 4	795 ± 10	870 ± 10	13.7 ± 1	NA	
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.
[a]ELI (extra low interstitial) powder was used.

α + β 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 α + β 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
	HIP				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	*E* (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

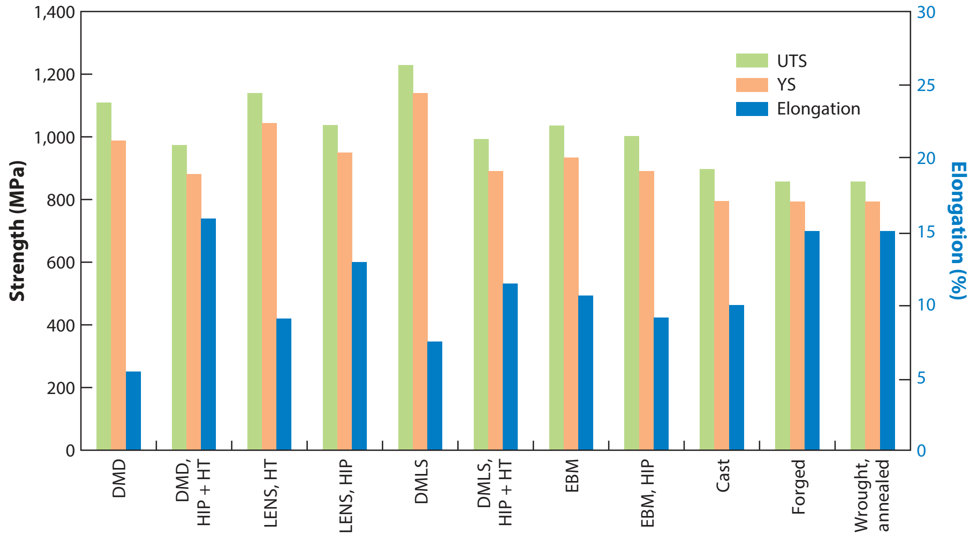

Figure 5

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$\sqrt{m}$) 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 (Optomec)	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; LF^3, 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			
EBM	TiAl	Heat treated (compression)		54	544	1,800	40	NA	172
SLM	316L	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
EOS M270	15-5 PH (precipitation-hardening stainless steel)				1,100	1,470	15		
EOS M250	4340	Stress relieved	*XY*	213.7	1,303	1,372	16–17	462–495 (Hv)	86
SLM250 Realizer	316L	As built	*XY*	NA	220–270	520–680	40–45	NA	93
Arcam S12	IN625	As built	*Z*	NA	410	750	44	14 (HRC)	102
		HIP			330	770	69	8 (HRC)	
EOS M280	IN718	Heat treated	*Z*	NA	1,034	1,309	27	NA	105
			XY		1,068	1,344	27		
SLM	IN718	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		66 ± 5		399 ± 7		152 ± 5 (Hv)	
SLM250 HL	Al-12Si	As built	NA	NA	220.5 ± 9.4	418.9 ± 9.3	3.91 ± 0.3	NA	115
		Heat treated			202.2 ± 4.3	369.3 ± 3.4	4.38 ± 0.16		
SLM	Al-12Si	As built	NA	NA	223.5	355.1	4.2	NA	174
SLM	Al-Si-10Mg	As built	*Z*	70.7 ± 1.3	168.8 ± 1.3	272.8 ± 2.9	8.2 ± 0.3	NA	124
			XY	70.2 ± 1.2	169 ± 1	267	9.1 ± 0.5		
SLM	Al-Si-10Mg	As built	NA	NA	207.8	367.7	4	NA	174
SLM	Al-12Si	As built	*XY*	NA	224 ± 7	368 ± 11	4.8 ± 0.6	NA	175
SLM100 Realizer	Al-12Si	As built	*XY*	NA	240	360	4	NA	176
		Heat treated			110	190	5		
SLM Concept Laser M2	Al-Si-10Mg	As built	*XY*	NA	~250	~330	~1.2	NA	177
			Z		~240	~320	~1		
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)	
SLM Concept Laser M1	Al-Si-10Mg	As built	*XY*	68 ± 3	NA	391 ± 6	5.55 ± 0.4	127 (HV)	179
			Z			398 ± 8	3.47 ± 0.6		
SLM	CoCrMo	As built	*XY*	NA	738 ± 9.9	1,050 ± 12.2	5.2 ± 0.3	39.7 ± 1.2 (HRC)	180
			Z		685.3 ± 10.5	970 ± 9.8	3.9 ± 0.2	34.3 ± 1.2	
EBM	CoCrMo	As built	*XY*	NA	717	1,110	5	NA	181
			Z		786	869	0.8		
		HIP +heat treated	*XY*		586	1,145	30		
			Z		586	1,151	30		
SLM	CoCrMo	As built	NA	NA	1,050 ± 150	1,300 ± 150	>6	42 ± 4 (HRC)	182
EBM	Niobium	As built	*Z*	NA	141	225	34.25	NA	183
SLM	AZ91D	As built	*XY*	NA	254	296	~1	100 (Hv)	184

NA denotes data not available.

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	*Y*	NA	474 ± 17	549 ± 23	0.5	NA	185
			Z		424 ± 30	488 ± 50	0.5		
DMD	4340	Stress relieved	*XY*	NA	1,398.65	NA	1.665	NA	95
DLD (LENS)	316L	As built	*Z*	NA	405–415	620–660	34–40	NA	225
		Heat treated	*Z*	NA	325–355	600–620	42–43	NA	
SMD	IN718	As built	*XY*	NA	473 ± 6	828 ± 8	28 ± 2	NA	186
DLD	IN718	As built	*Z*	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	*XY*	159	580	910	22	NA	189
EBF[3]	IN718	As built	*XY*	138	655	978	NA	NA	99
			YX	194	699	936			
		Heat treated	*XY*	174	986	1,114			
			YX	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	*X*	NA	114 ± 4.8	263 ± 0.5	18 ± 0.5	NA	127
			Y		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_{Ic} 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*		52.4 ± 3.48	193
	EOS M280	As built	*XY*		37.5 ± 5	194
		HIP			57.8 ± 5	
		Heat treated			86.3	
PBF(EBM)	Arcam A1	As built	*XY*		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*	3PB	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 μCT, and many of 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,

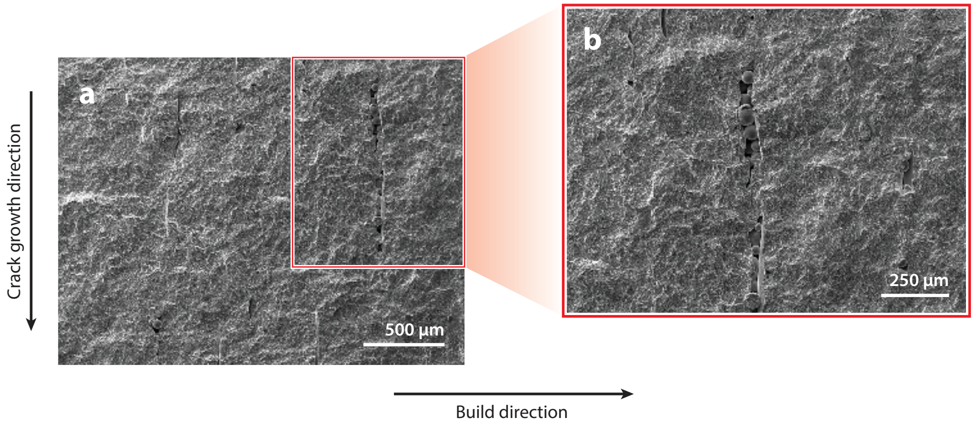

Figure 6

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

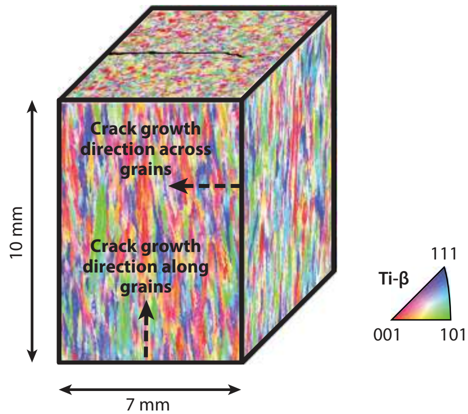

Figure 7

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.

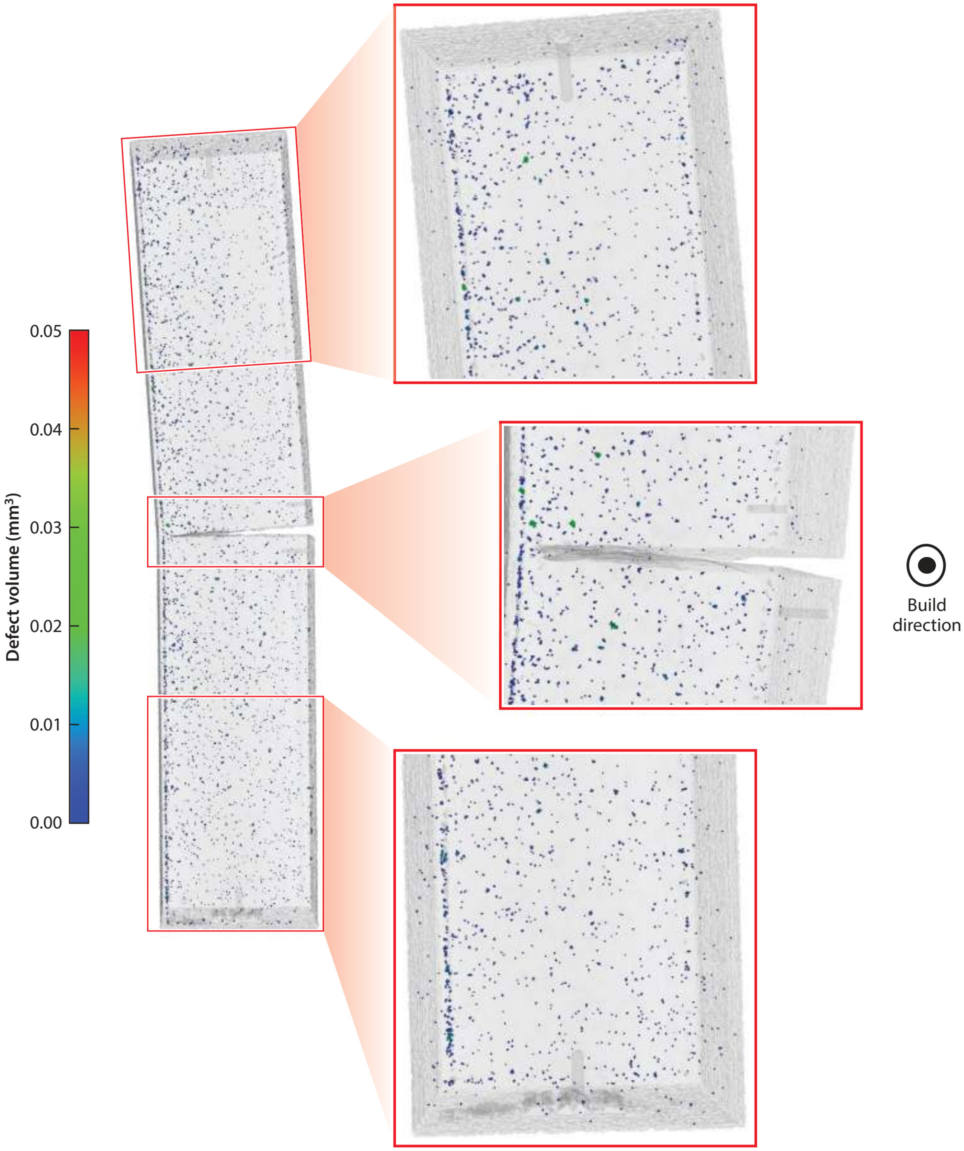

Figure 8

μCT images of a 10 × 20 × 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

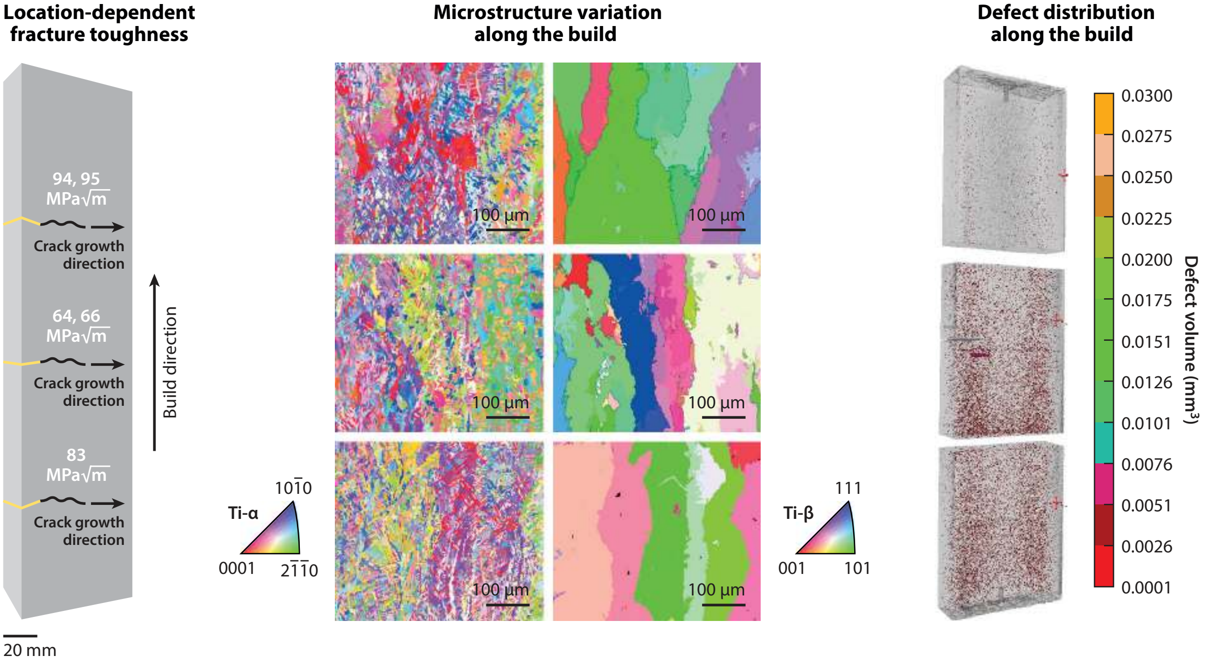

Figure 9

Illustration of location-dependent toughness values in an as-built PBF (EBM) Ti-6Al-4V sample. Variations in microstructure (prior β grains and α + β 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 γTi-Al 4822 fracture toughness for EBM PBF

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

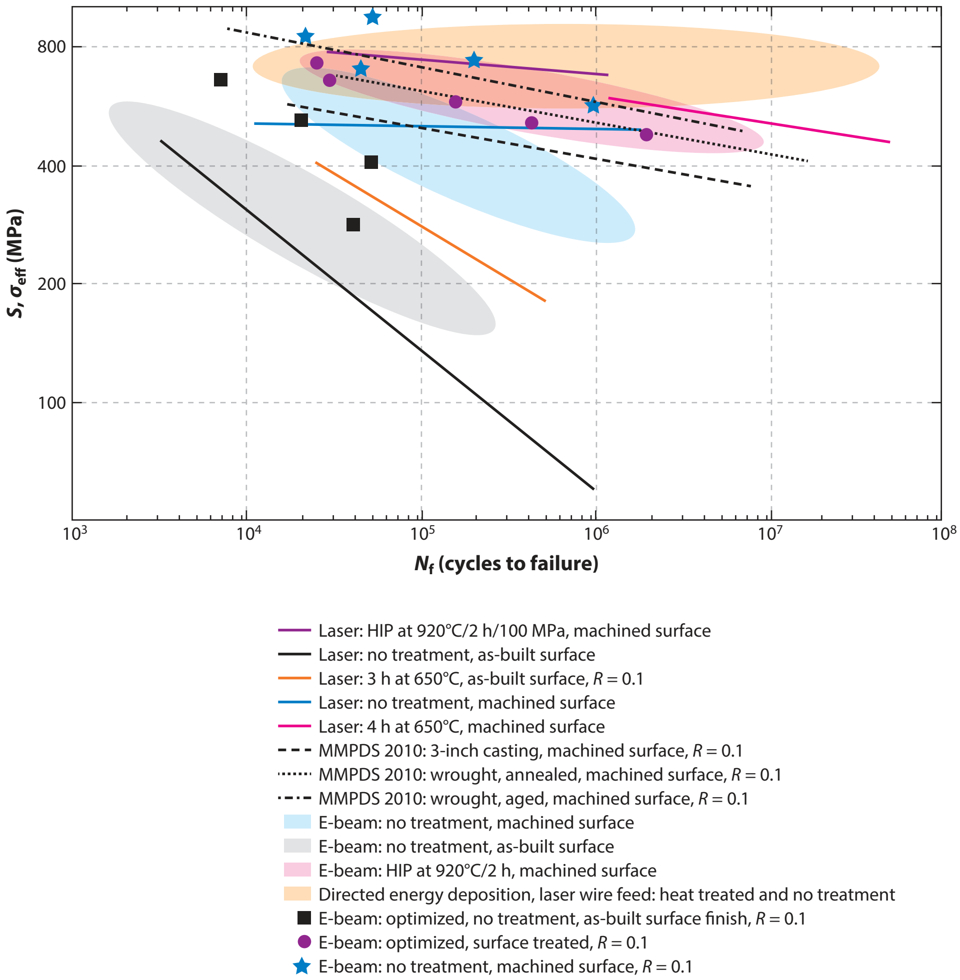

Figure 10

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} ($MPa\sqrt{m}$)	Paris slope	C (m/cycle)	K_c ($MPa\sqrt{m}$)	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		
	Stress relieved	*XY*				5.84	9.93E-15		
		XZ				3.24	1.16E-11		
		ZX				3.35	8.85E-12		
	Heat treated	*XY*				3.83	2.04E-12		
		XZ				3.11	1.71E-11		
		ZX				2.94	2.58E-11		
	As built	*XY*	CT (10 Hz)	0.1	6.3 ± 0.7	2.6 ± 0.3	1.2E-7	37 ± 4.3	192
		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	
	As built	*ZX*	CT (10 Hz)	0.1	NA	3.38	5E-12	NA	193
EBM	As built	*XYZ*	3PB (20 Hz)	0.1	3.8	2.9	NA	91	140
		XZY: start			5.7	4.1		96	
		XZY: end			4.2	3.5		53	
		XYZ		0.3	3.8, 3.9	2.4, 2.3, 2.7		83, 88, 96	48
		XZY: start		0.3	3.6	2.1		87	
		XZY: end		0.3	4.9	2.4		71	
		ZXY: middle		0.3	3.8	2.6		69	
		XYZ		0.7	3.4	1.9		78	
		XZY: start		0.7	3.5	1.4		77	
		XZY: end		0.7	3.7	1.6		63	

NA denotes data not available.

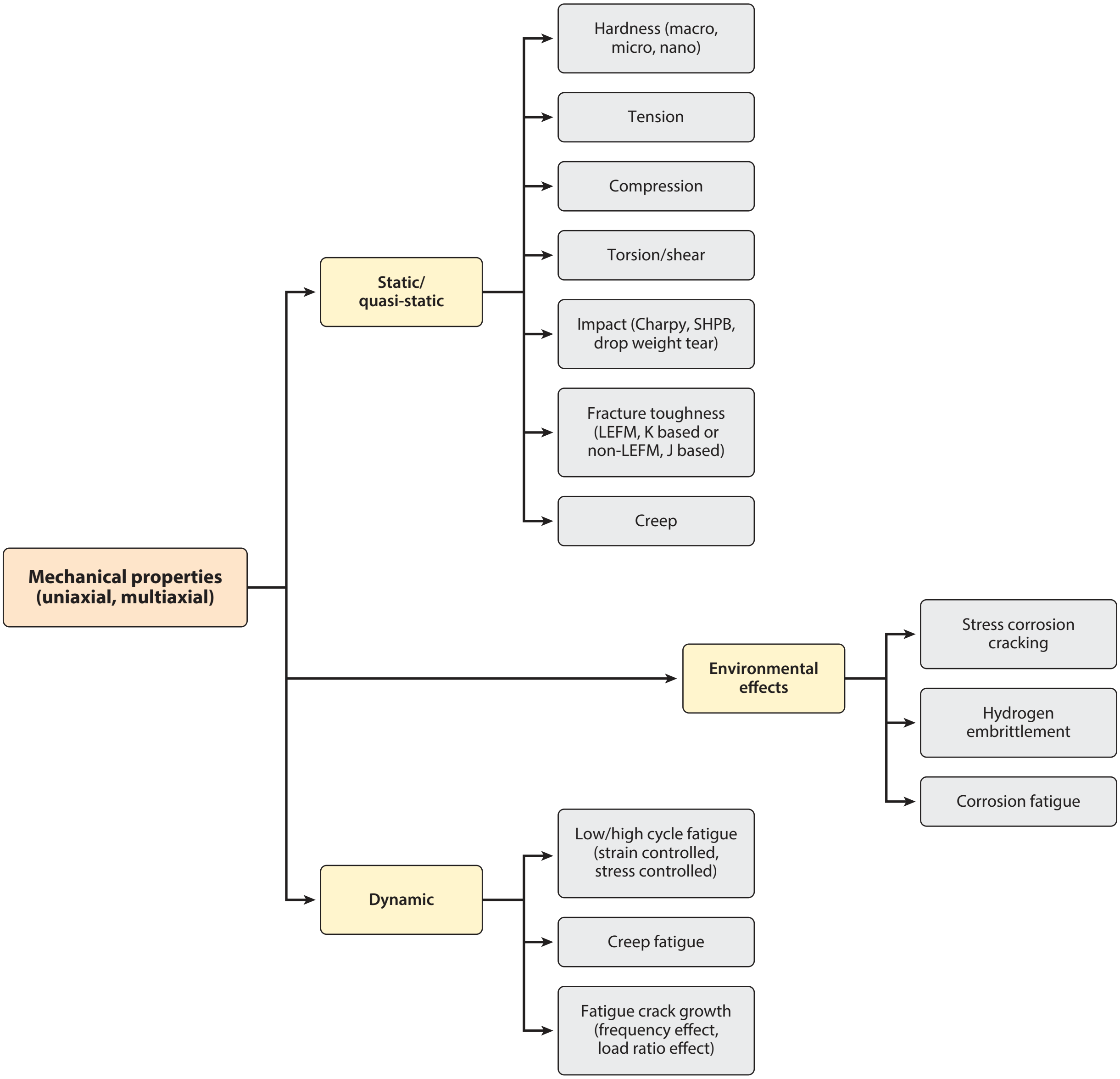

Figure 11

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

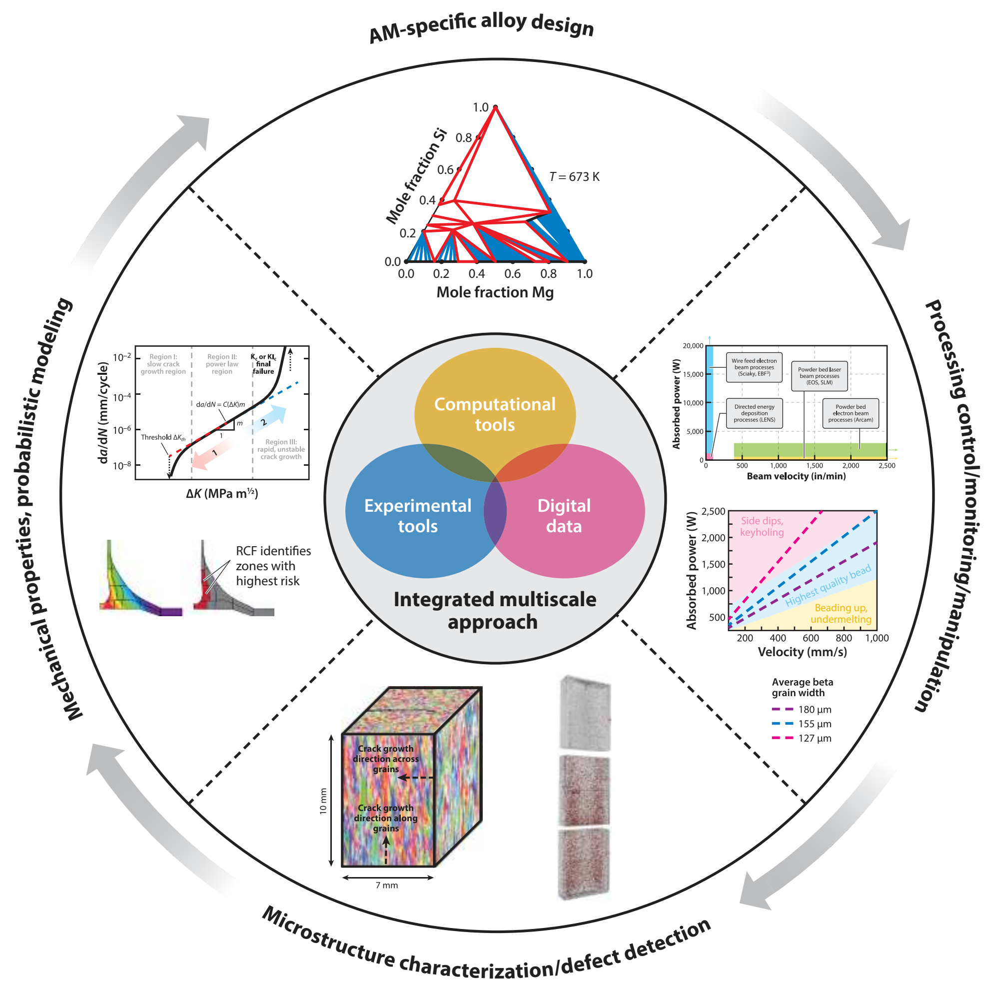

Figure 12

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.

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