Intellectual Output_O1:
EMERALD e-book for developing of biomimetic mechatronic systems

MODULE 8
Intelligent (Smart) Materials

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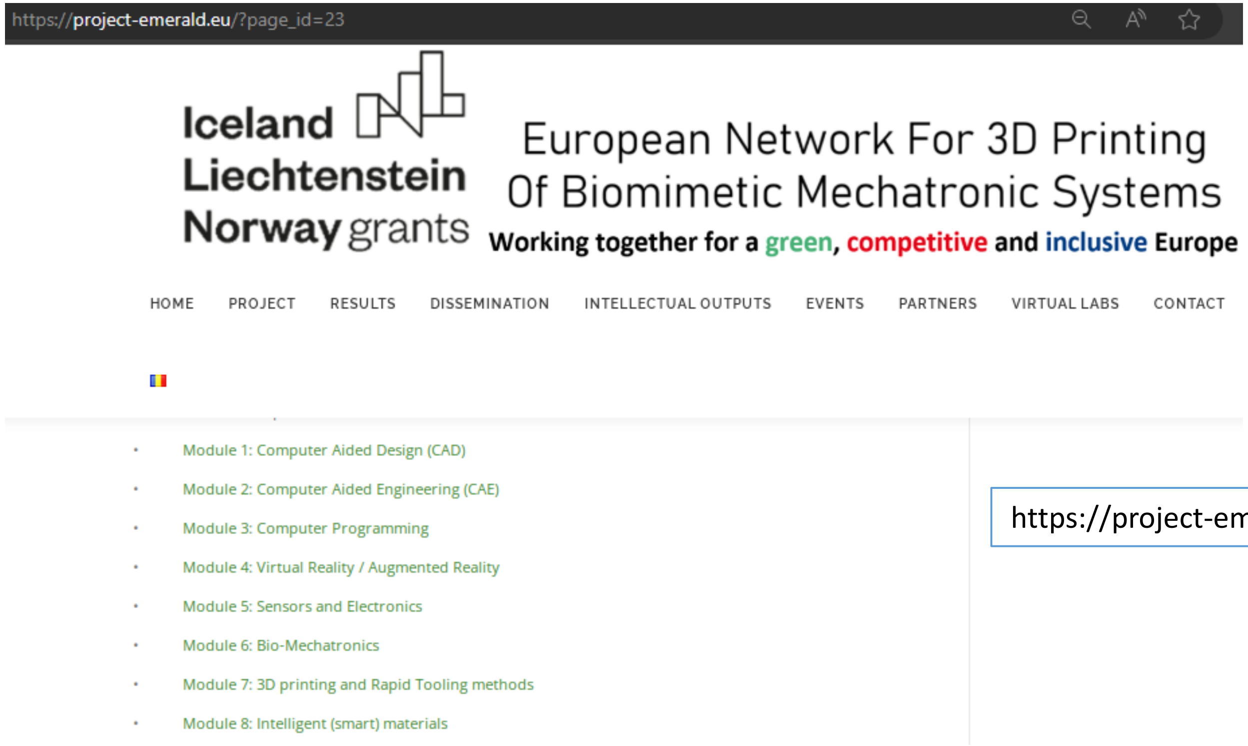

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European Network For 3D Printing Of Biomimetic Mechatronic Systems

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- Module 1: Computer Aided Design (CAD)
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- Module 6: Bio-Mechatronics
- Module 7: 3D printing and Rapid Tooling methods
- Module 8: Intelligent (smart) materials

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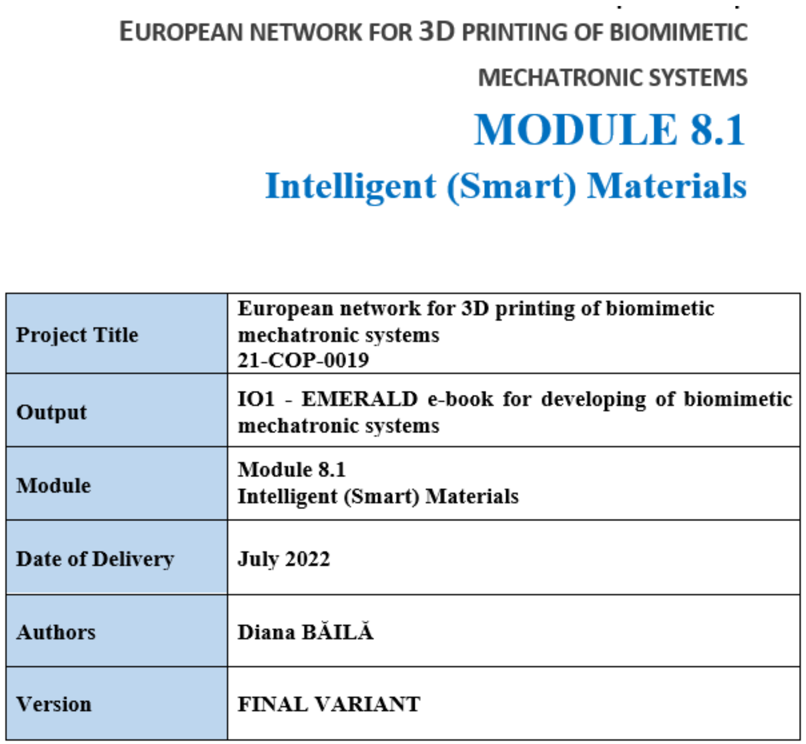

EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC
MECHATRONIC SYSTEMS

MODULE 8.1

Intelligent (Smart) Materials

Project Title	**European network for 3D printing of biomimetic mechatronic systems 21-COP-0019**
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Introduction in Additive Manufacturing technologies

Additive Prototyping Technologies (AM) differ fundamentally from material removal processing technologies (cutting, EDM, laser processing) and redistribution processing technologies material (casting, injection, forging, stamping) by the fact that the parts are obtained by adding layer by layer material using a CAD file.

These technologies have emerged grace a result of the achievements and advances made in the field of fine mechanics, numerical control, laser technology, computers, software, and the new materials development.

These new Additive Manufacturing technologies have started to grow in importance due to the efforts of manufacturers to reduce design times up to marketing, as well as the costs of assimilating and manufacturing new products.

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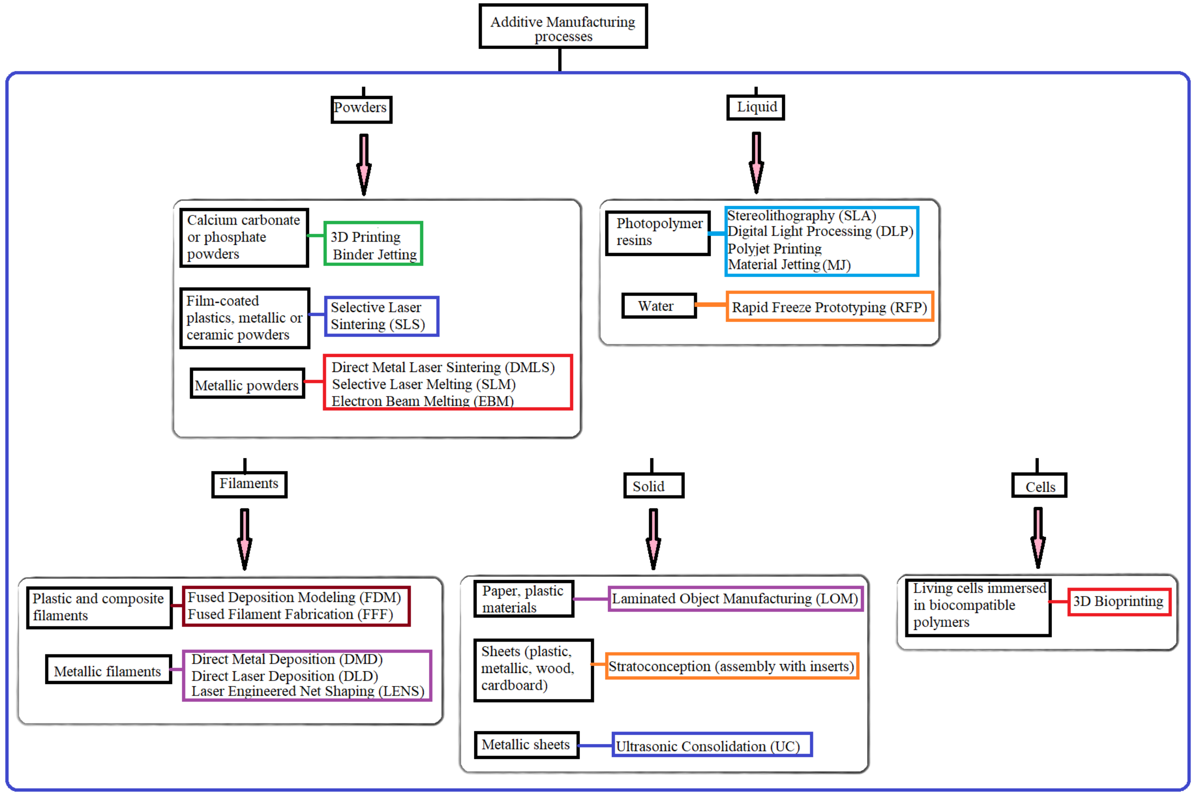
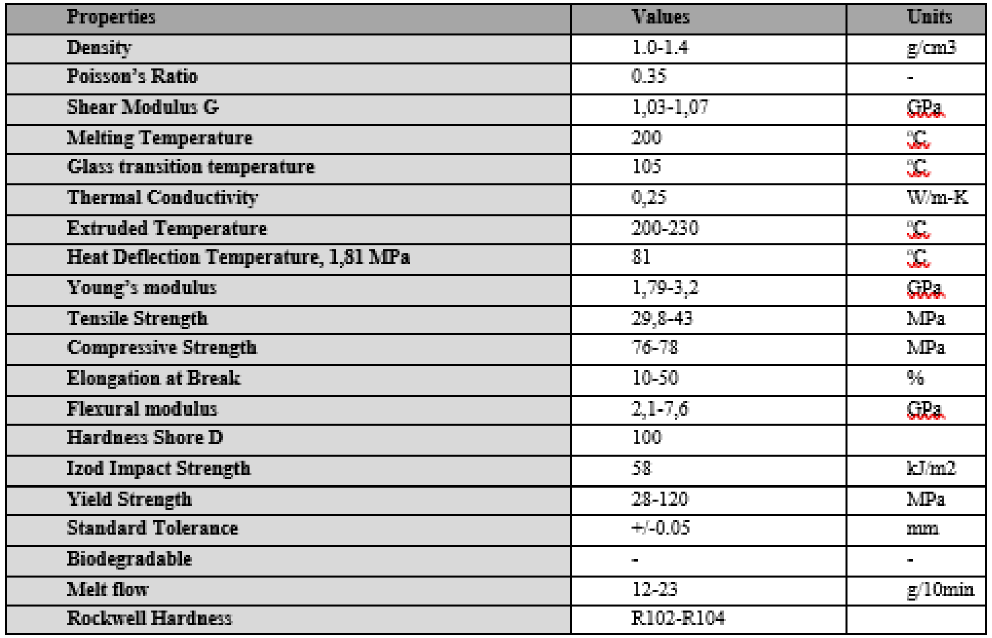


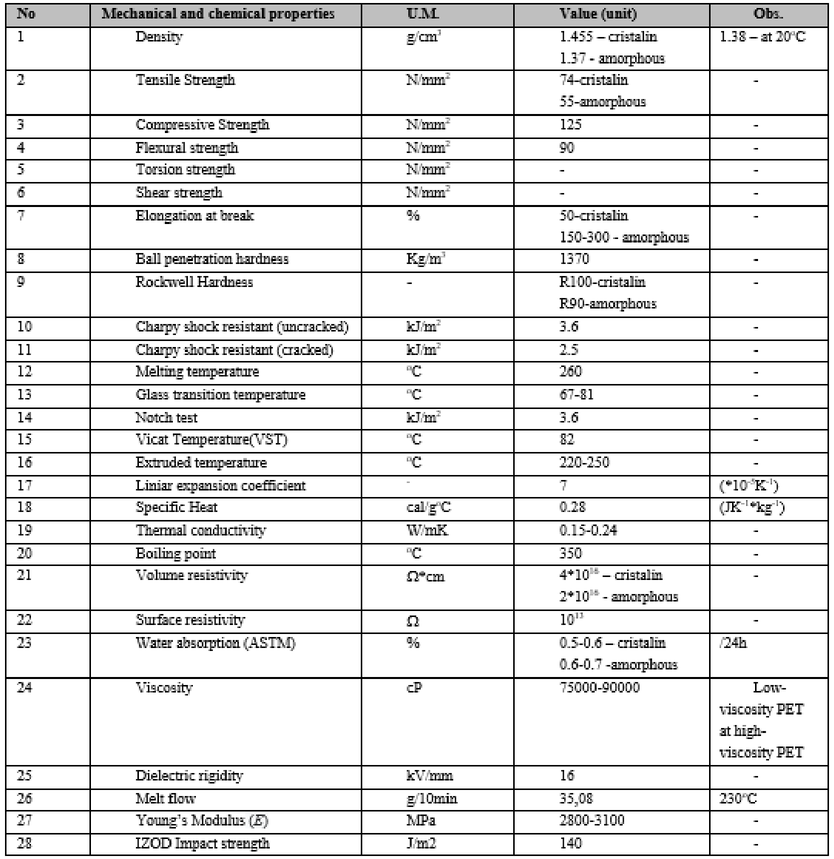
Classification of additive manufacturing technologies according to the materials used

Table 1. The mechanical properties of Acrylonitrile Butadiene Styrene (ABS)



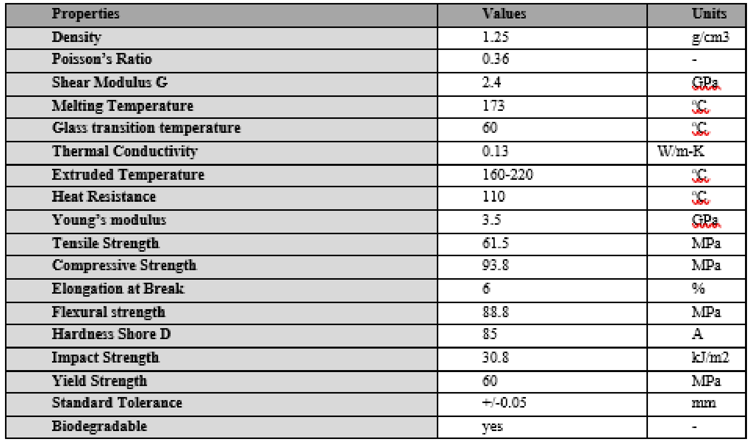
Properties	Values	Units
Density	1.0-1.4	g/cm3
Poisson's Ratio	0.35	-
Shear Modulus G	1,03-1,07	GPa
Melting Temperature	200	°C
Glass transition temperature	105	°C
Thermal Conductivity	0,25	W/m-K
Extruded Temperature	200-230	°C
Heat Deflection Temperature, 1,81 MPa	81	°C
Young's modulus	1,79-3,2	GPa
Tensile Strength	29,8-43	MPa
Compressive Strength	76-78	MPa
Elongation at Break	10-50	%
Flexural modulus	2,1-7,6	GPa
Hardness Shore D	100	
Izod Impact Strength	58	kJ/m2
Yield Strength	28-120	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	-	-
Melt flow	12-23	g/10min
Rockwell Hardness	R102-R104	

Table 2. The mechanical properties of Polyethylene Terephthalate PET (C$_{10}$H$_8$O$_4$)$_n$



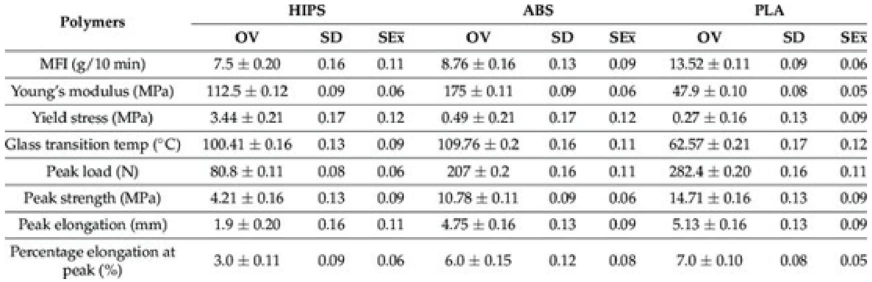
No	Mechanical and chemical properties	U.M.	Value (unit)	Obs.
1	Density	g/cm^3	1.455 – cristalin 1.37 - amorphous	1.38 – at 20°C
2	Tensile Strength	N/mm^2	74-cristalin 55-amorphous	-
3	Compressive Strength	N/mm^2	125	-
4	Flexural strength	N/mm^2	90	-
5	Torsion strength	N/mm^2	-	-
6	Shear strength	N/mm^2	-	-
7	Elongation at break	%	50-cristalin 150-300 - amorphous	-
8	Ball penetration hardness	Kg/m^3	1370	-
9	Rockwell Hardness	-	R100-cristalin R90-amorphous	-
10	Charpy shock resistant (uncracked)	kJ/m^2	3.6	-
11	Charpy shock resistant (cracked)	kJ/m^2	2.5	-
12	Melting temperature	°C	260	-
13	Glass transition temperature	°C	67-81	-
14	Notch test	kJ/m^2	3.6	-
15	Vicat Temperature(VST)	°C	82	-
16	Extruded temperature	°C	220-250	-
17	Liniar expansion coefficient	-	7	(*10^{-5}K^{-1})
18	Specific Heat	cal/g°C	0.28	(JK^{-1}*kg^{-1})
19	Thermal conductivity	W/mK	0.15-0.24	-
20	Boiling point	°C	350	-
21	Volume resistivity	Ω*cm	4*10^{16} – cristalin 2*10^{16} - amorphous	-
22	Surface resistivity	Ω	10^{13}	-
23	Water absorption (ASTM)	%	0.5-0.6 – cristalin 0.6-0.7 -amorphous	/24h
24	Viscosity	cP	75000-90000	Low-viscosity PET at high-viscosity PET
25	Dielectric rigidity	kV/mm	16	-
26	Melt flow	g/10min	35,08	230°C
27	Young's Modulus (*E*)	MPa	2800-3100	-
28	IZOD Impact strength	J/m2	140	-

Table 3. The mechanical properties of PLA (Polylactic Acid)



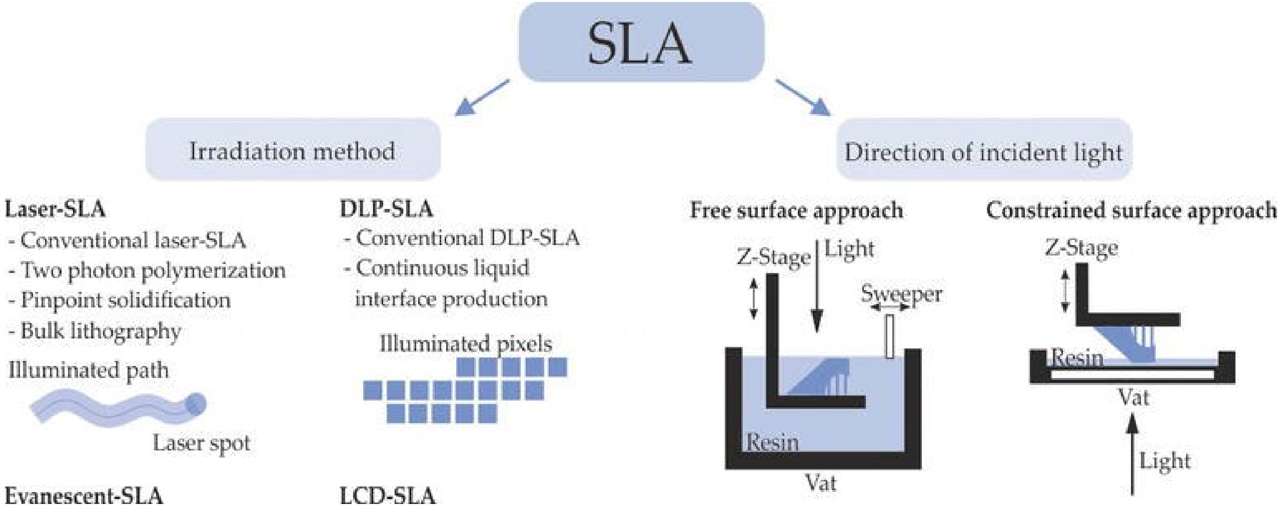
Properties	Values	Units
Density	1.25	g/cm3
Poisson's Ratio	0.36	-
Shear Modulus G	2.4	GPa
Melting Temperature	173	°C
Glass transition temperature	60	°C
Thermal Conductivity	0.13	W/m-K
Extruded Temperature	160-220	°C
Heat Resistance	110	°C
Young's modulus	3.5	GPa
Tensile Strength	61.5	MPa
Compressive Strength	93.8	MPa
Elongation at Break	6	%
Flexural strength	88.8	MPa
Hardness Shore D	85	A
Impact Strength	30.8	kJ/m2
Yield Strength	60	MPa
Standard Tolerance	+/-0.05	mm
Biodegradable	yes	-

Table 4. Comparison concerning mechanical properties between the common materials used in FDM technology, PLA, ABS and HIPS

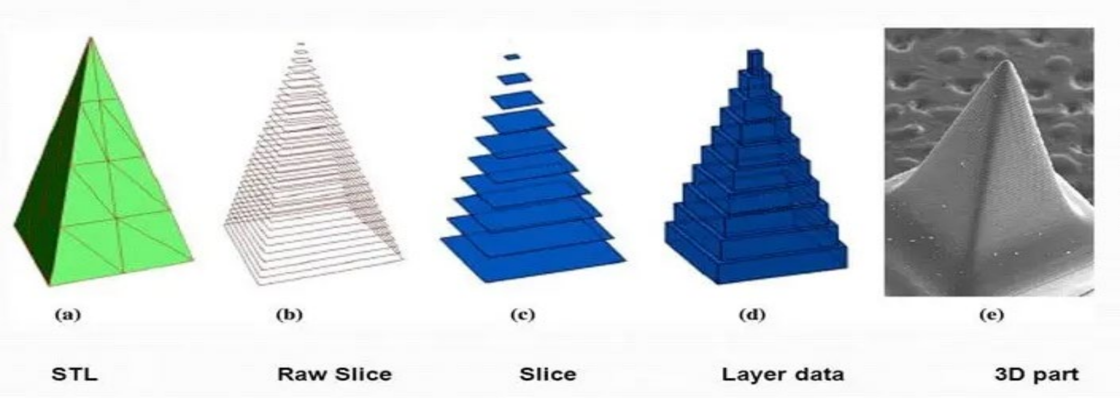


Polymers	HIPS			ABS			PLA		
	OV	SD	SEx	OV	SD	SEx	OV	SD	SEx
MFI (g/10 min)	7.5 ± 0.20	0.16	0.11	8.76 ± 0.16	0.13	0.09	13.52 ± 0.11	0.09	0.06
Young's modulus (MPa)	112.5 ± 0.12	0.09	0.06	175 ± 0.11	0.09	0.06	47.9 ± 0.10	0.08	0.05
Yield stress (MPa)	3.44 ± 0.21	0.17	0.12	0.49 ± 0.21	0.17	0.12	0.27 ± 0.16	0.13	0.09
Glass transition temp (°C)	100.41 ± 0.16	0.13	0.09	109.76 ± 0.2	0.16	0.11	62.57 ± 0.21	0.17	0.12
Peak load (N)	80.8 ± 0.11	0.08	0.06	207 ± 0.2	0.16	0.11	282.4 ± 0.20	0.16	0.11
Peak strength (MPa)	4.21 ± 0.16	0.13	0.09	10.78 ± 0.11	0.09	0.06	14.71 ± 0.16	0.13	0.09
Peak elongation (mm)	1.9 ± 0.20	0.16	0.11	4.75 ± 0.16	0.13	0.09	5.13 ± 0.16	0.13	0.09
Percentage elongation at peak (%)	3.0 ± 0.11	0.09	0.06	6.0 ± 0.15	0.12	0.08	7.0 ± 0.10	0.08	0.05

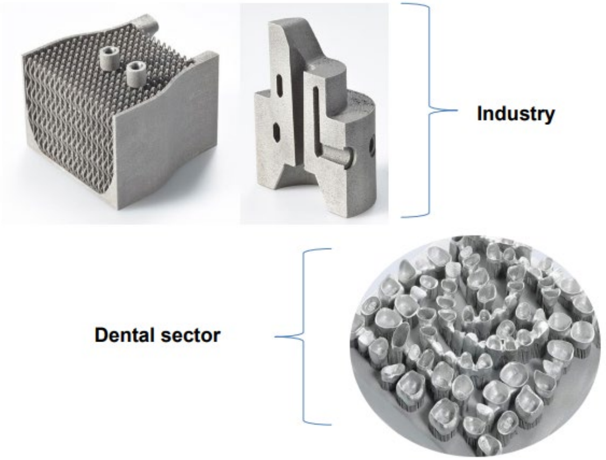
Transparent resins used in dental domain manufactured by SLA

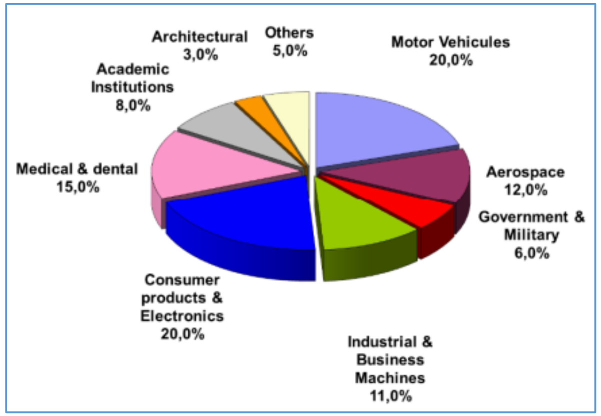


The principle of manufacturing for both technologies: SLA and DLP

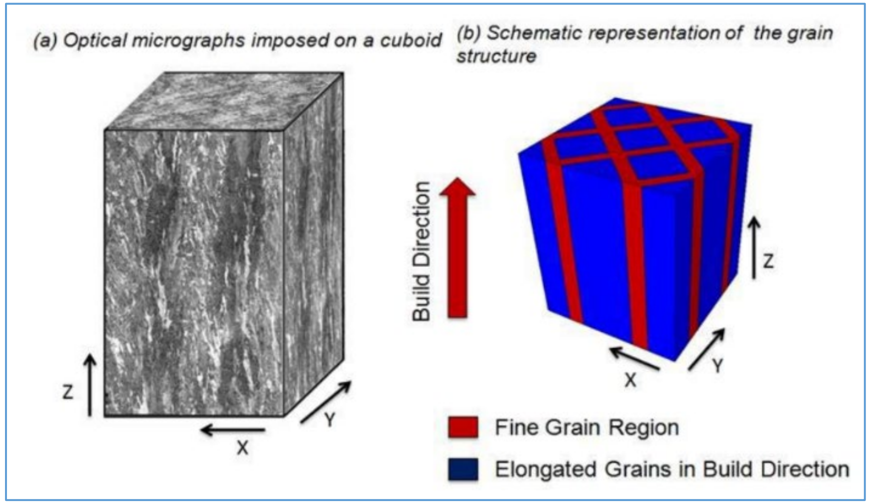


The general processing principle of Additive Laser Manufacturing technologies

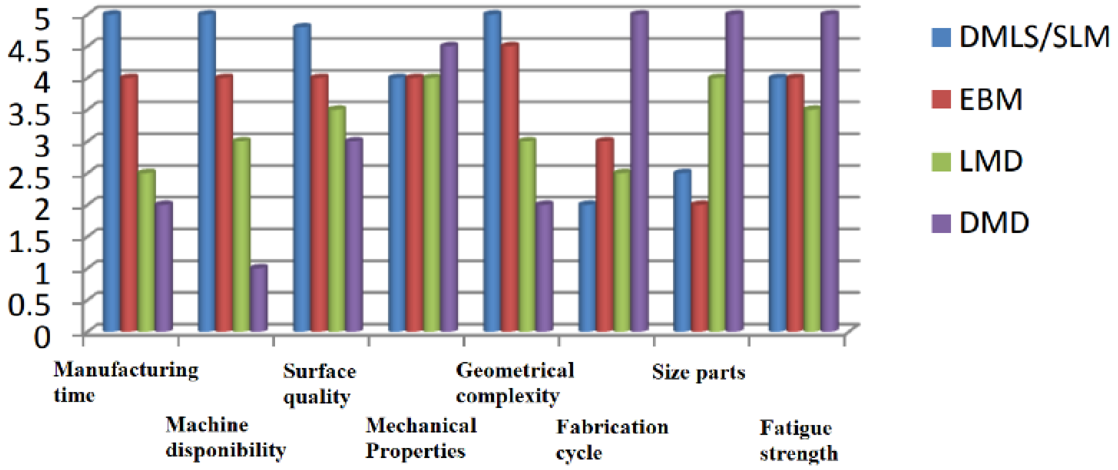




Applications domain of Additive Laser Manufacturing

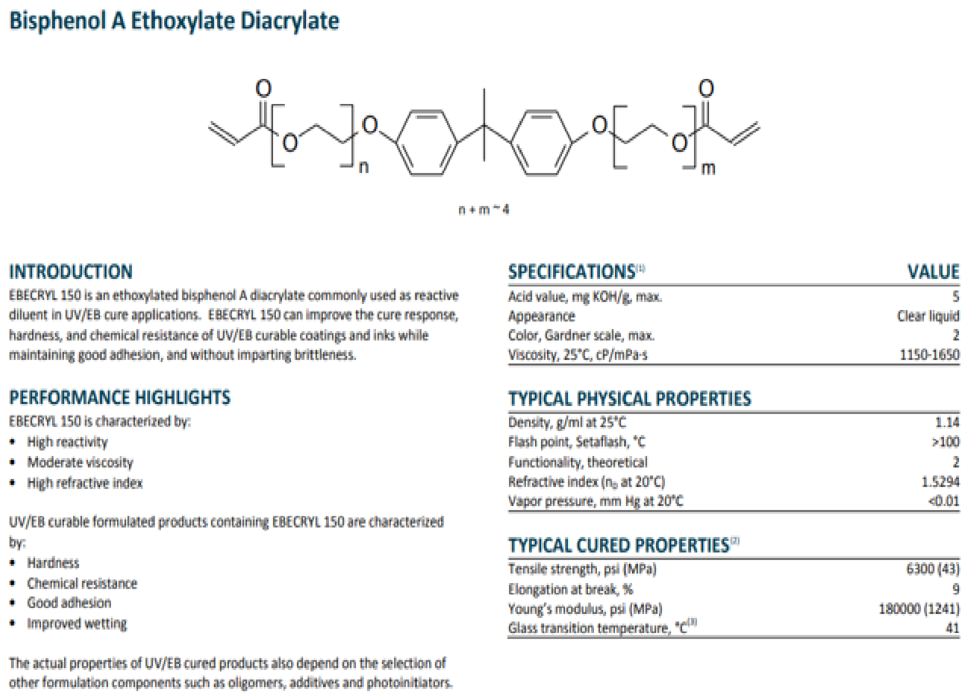


Anisotropy of the microstructure of parts built by SLM



Comparison between the Additive Laser Technologies

Table 5. The mechanical properties of Bisphenol A Ethoxylate Diacrylate



Bisphenol A Ethoxylate Diacrylate

n + m ~ 4

INTRODUCTION

EBECRYL 150 is an ethoxylated bisphenol A diacrylate commonly used as reactive diluent in UV/EB cure applications. EBECRYL 150 can improve the cure response, hardness, and chemical resistance of UV/EB curable coatings and inks while maintaining good adhesion, and without imparting brittleness.

PERFORMANCE HIGHLIGHTS

EBECRYL 150 is characterized by:

- High reactivity
- Moderate viscosity
- High refractive index

UV/EB curable formulated products containing EBECRYL 150 are characterized by:

- Hardness
- Chemical resistance
- Good adhesion
- Improved wetting

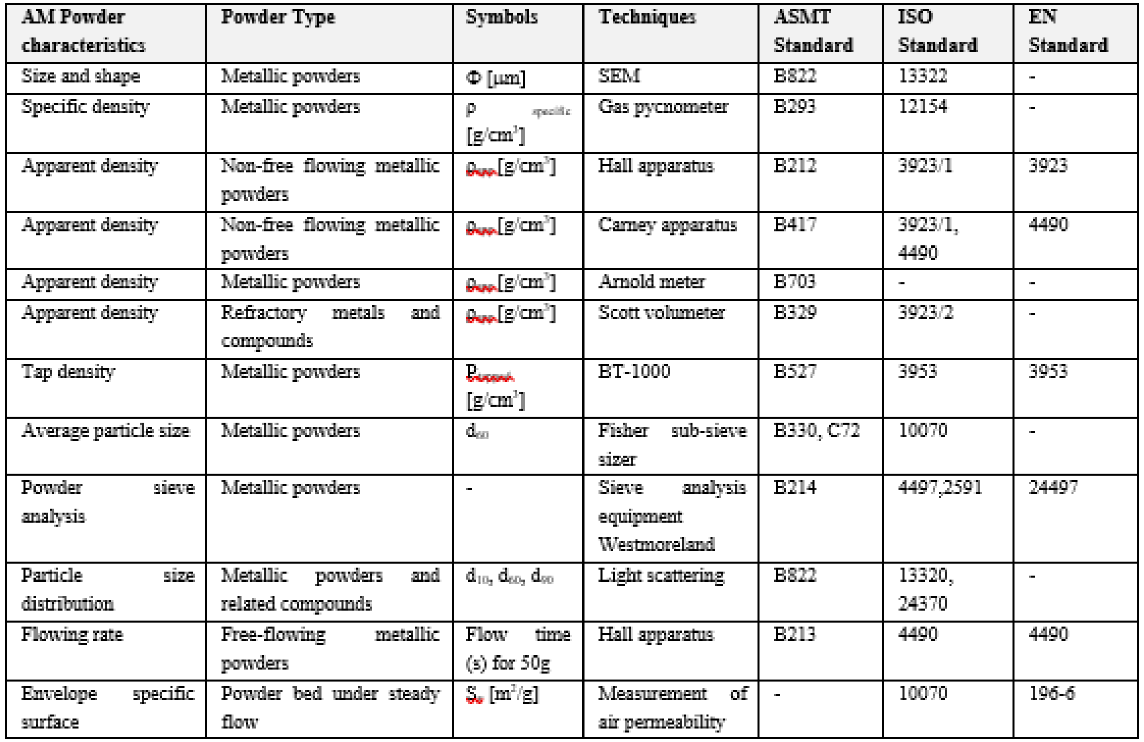
The actual properties of UV/EB cured products also depend on the selection of other formulation components such as oligomers, additives and photoinitiators.

SPECIFICATIONS(1)	VALUE
Acid value, mg KOH/g, max.	5
Appearance	Clear liquid
Color, Gardner scale, max.	2
Viscosity, 25°C, cP/mPa·s	1150-1650

TYPICAL PHYSICAL PROPERTIES	
Density, g/ml at 25°C	1.14
Flash point, Setaflash, °C	>100
Functionality, theoretical	2
Refractive index (n_D at 20°C)	1.5294
Vapor pressure, mm Hg at 20°C	<0.01

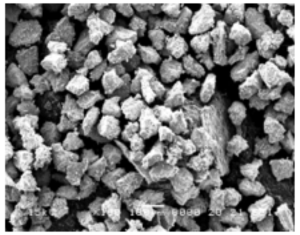
TYPICAL CURED PROPERTIES(2)	
Tensile strength, psi (MPa)	6300 (43)
Elongation at break, %	9
Young's modulus, psi (MPa)	180000 (1241)
Glass transition temperature, °C(3)	41

Table 6. Standards (ASTM, ISO, EN) for powder properties used in additive manufacturing [86]

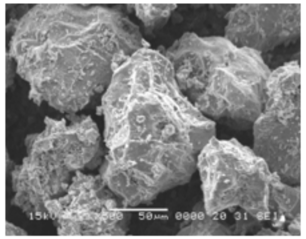


AM Powder characteristics	Powder Type	Symbols	Techniques	ASMT Standard	ISO Standard	EN Standard
Size and shape	Metallic powders	Φ [μm]	SEM	B822	13322	-
Specific density	Metallic powders	$\rho_{specific}$ [g/cm^3]	Gas pycnometer	B293	12154	-
Apparent density	Non-free flowing metallic powders	ρ[illegible][g/cm^3]	Hall apparatus	B212	3923/1	3923
Apparent density	Non-free flowing metallic powders	ρ[illegible][g/cm^3]	Carney apparatus	B417	3923/1, 4490	4490
Apparent density	Metallic powders	ρ[illegible][g/cm^3]	Arnold meter	B703	-	-
Apparent density	Refractory metals and compounds	ρ[illegible][g/cm^3]	Scott volumeter	B329	3923/2	-
Tap density	Metallic powders	P[illegible] [g/cm^3]	BT-1000	B527	3953	3953
Average particle size	Metallic powders	d_{60}	Fisher sub-sieve sizer	B330, C72	10070	-
Powder sieve analysis	Metallic powders	-	Sieve analysis equipment Westmoreland	B214	4497,2591	24497
Particle size distribution	Metallic powders and related compounds	d_{10}, d_{60}, d_{90}	Light scattering	B822	13320, 24370	-
Flowing rate	Free-flowing metallic powders	Flow time (s) for 50g	Hall apparatus	B213	4490	4490
Envelope specific surface	Powder bed under steady flow	S_w [m^2/g]	Measurement of air permeability	-	10070	196-6

The Co-Cr alloy powder (ST2724G) used for DMLS manufacturing presents the chemical composition: 54.31 %Co; 23.08%Cr; 11.12% Mo, 7.85% W, 3.35% Si, and Mn, Fe < 0.1%.

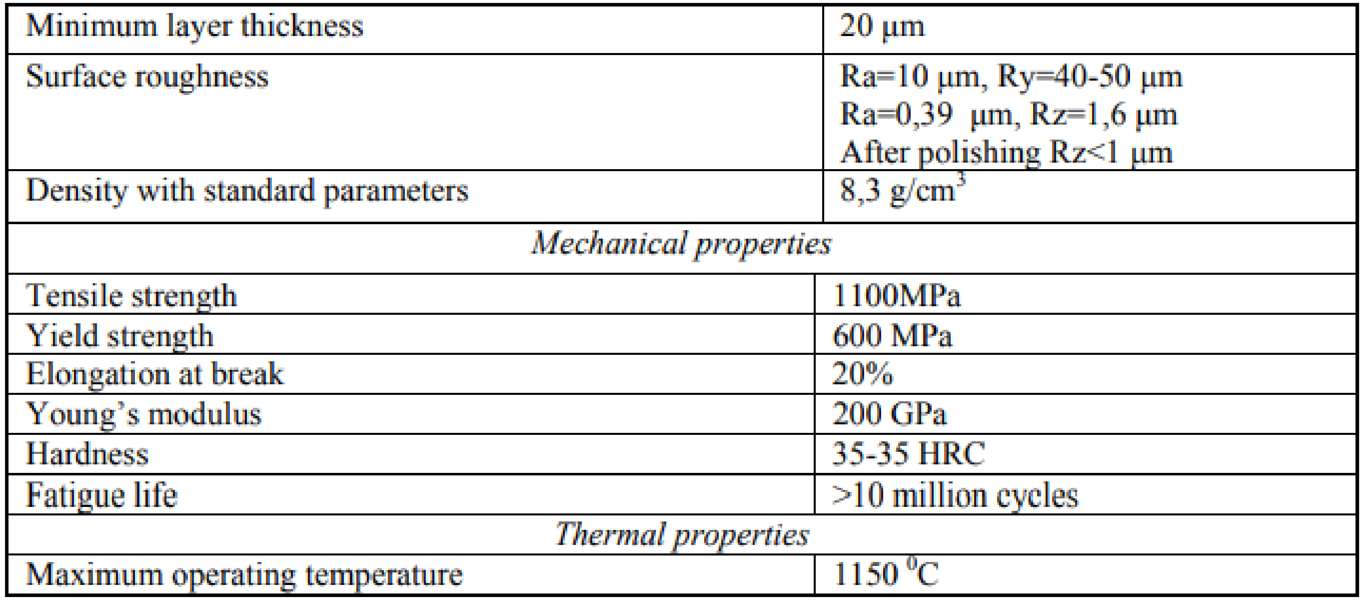


Ti6Al4V powder obtained by hydride-dehydride

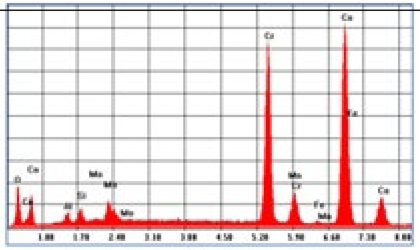


Compact and irregular Ti6Al4V grains

Table 7. Mechanical characteristics of Co-Cr powder

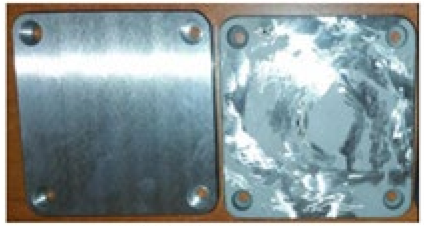


Minimum layer thickness	20 µm
Surface roughness	Ra=10 µm, Ry=40-50 µm Ra=0,39 µm, Rz=1,6 µm After polishing Rz<1 µm
Density with standard parameters	8,3 g/cm^3
Mechanical properties	
Tensile strength	1100MPa
Yield strength	600 MPa
Elongation at break	20%
Young's modulus	200 GPa
Hardness	35-35 HRC
Fatigue life	>10 million cycles
Thermal properties	
Maximum operating temperature	1150 ^{0}C

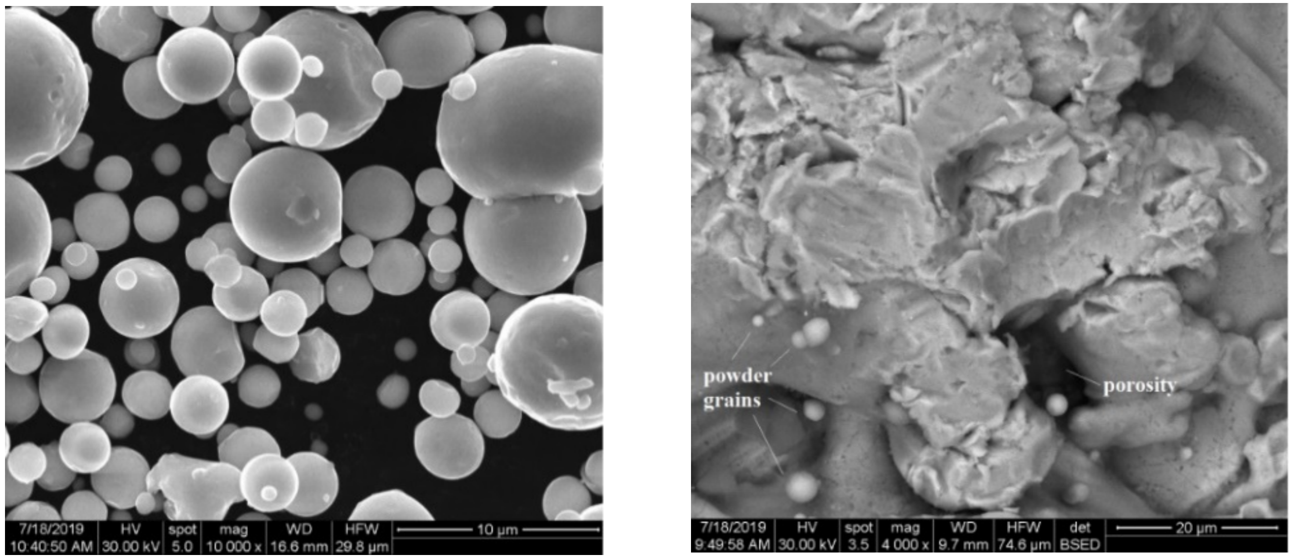


EDAX analysis of Co-Cr alloy powder

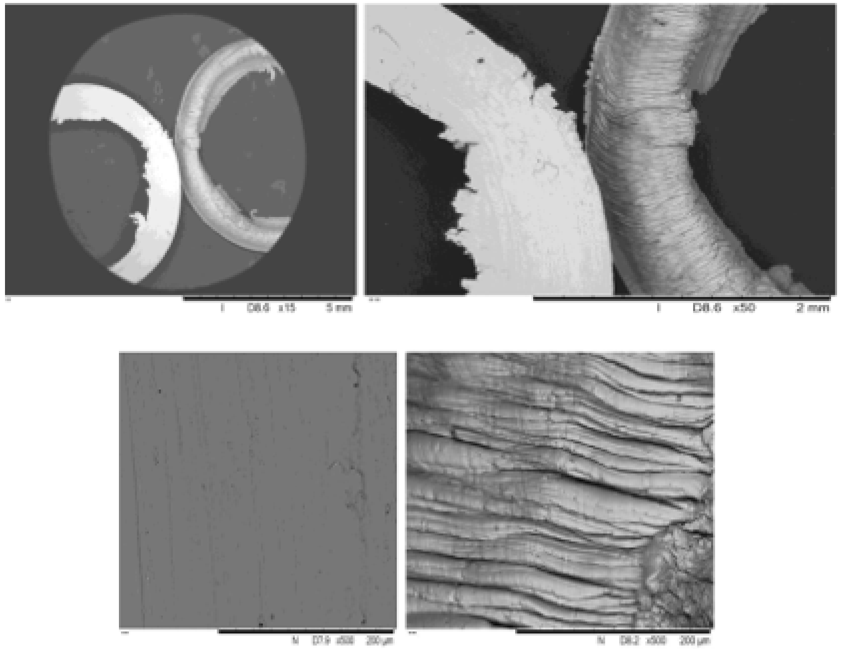
. Analogue dental implants manufactured by DMLS



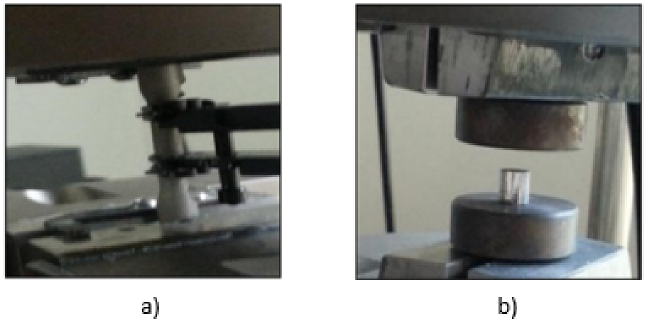
The platen of sintering machine



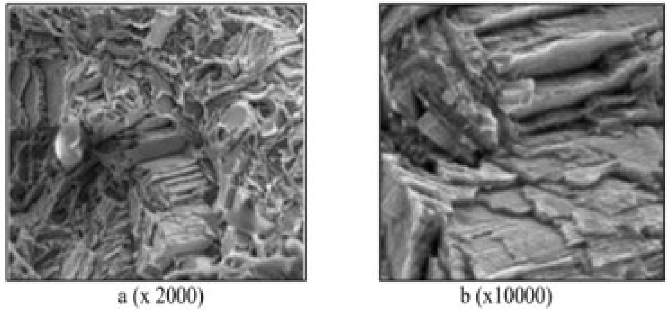
SEM analysis of a) Co-Cr powder; **b) DMLS sintered structure**



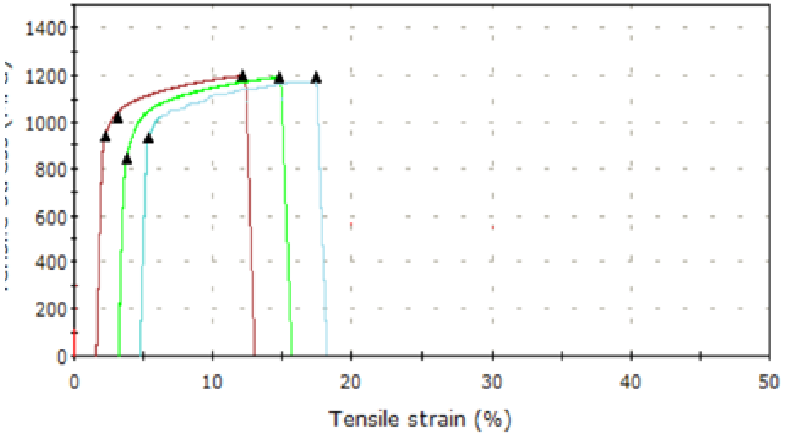
SEM analysis of Co-Cr alloy chips and stainless-steel martensitic Fe-15%Cr of the platen of the machine



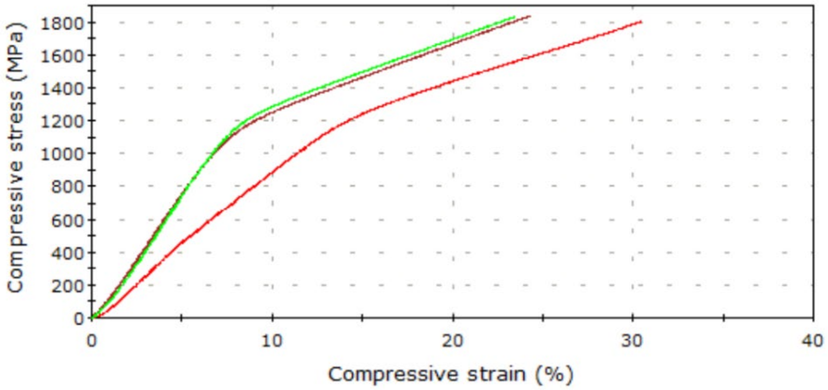
a) Traction and b) Compression tests of Co-Cr alloy manufacturing by DMLS, using INSTRON 8810 machine



SEM analysis of the samples of Co-Cr superalloy after the traction tests

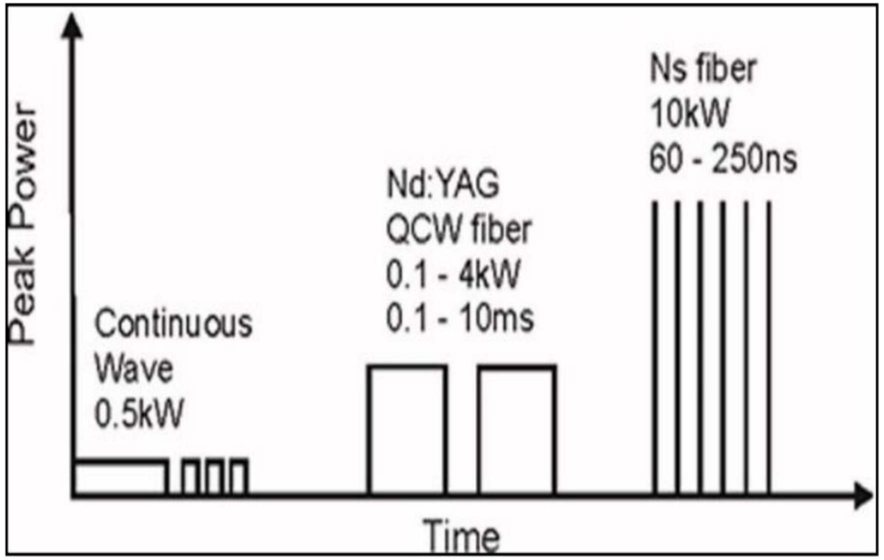


Traction curves obtained for the Co-Cr alloy manufactured by DMLS

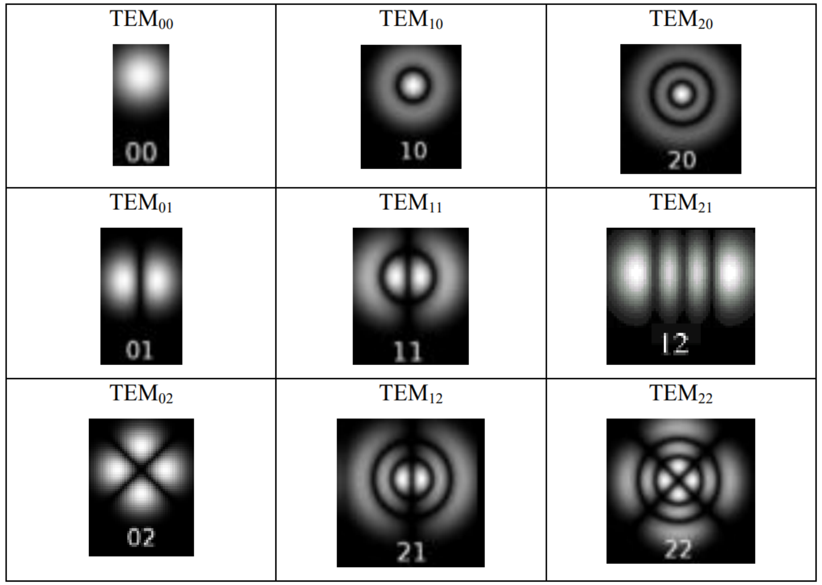


Compression curves obtained for the Co-Cr alloy manufactured by DMLS

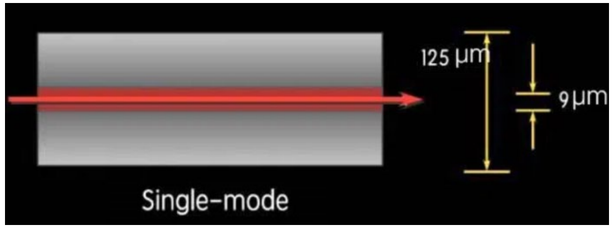
Laser types used in Additive Manufacturing



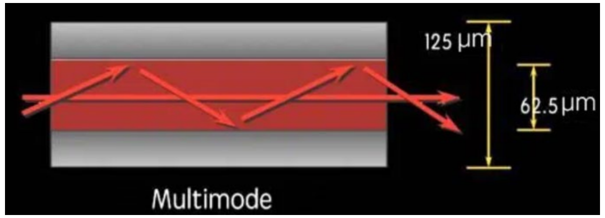
Differences between YAG and fibers lasers



Different laser modes



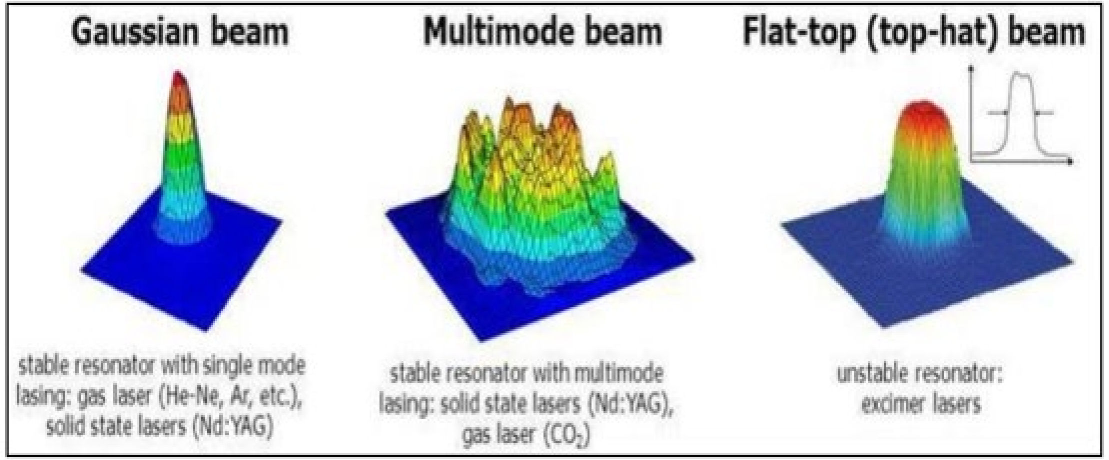
Monomodal laser fibers



Multimodal laser fibers

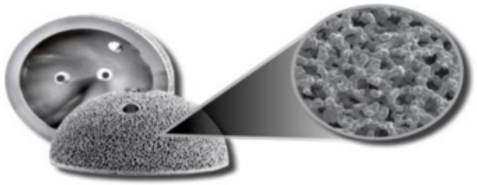
Phenix Systems – PM100 system

TrumaForm LF250 system



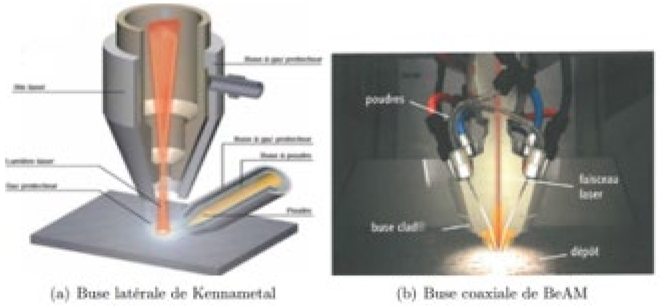
Laser beam profiles Nd:YAG:.a) Gaussian beam; b) Multimode beam; c)flat-top (top-hat) beam

Trabecular Lattice structures for enhanced osseointegration



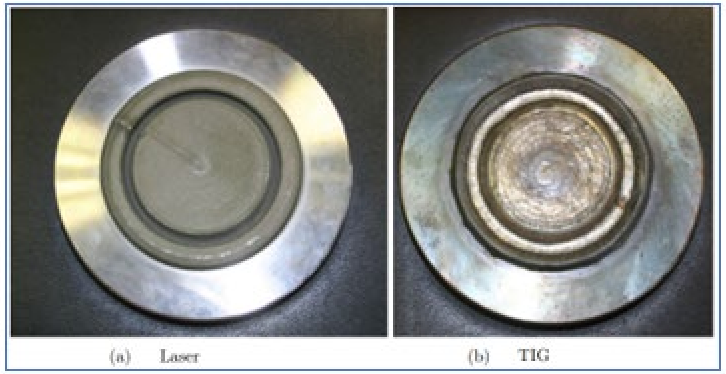
Acetabular cups, manufactured by EBM technology, for hip replacements, with trabecular structure, Courtesy Arcam

Metallic powders and filaments used in Laser Metal Deposition and Direct Metal Deposition

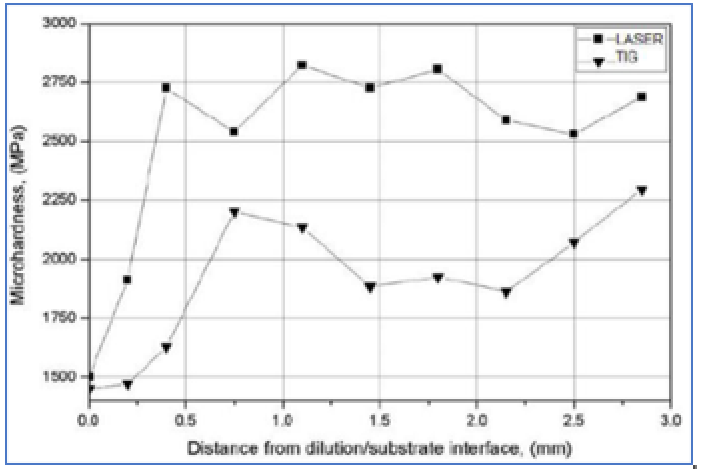


(a) Buse latérale de Kennametal (b) Buse coaxiale de BeAM

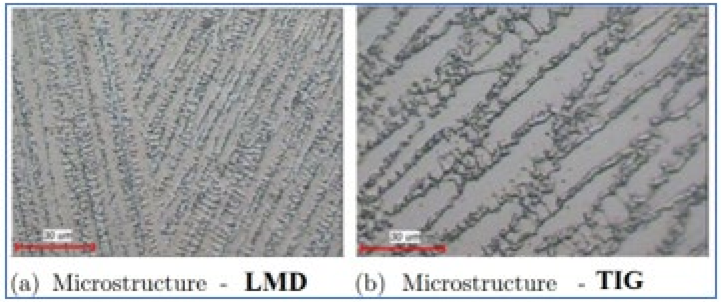
a) Laterally Kennametal buse; b) Coaxially BeAM buse


(a) Laser (b) TIG

Geometry resulting from LMD process and TIG welding

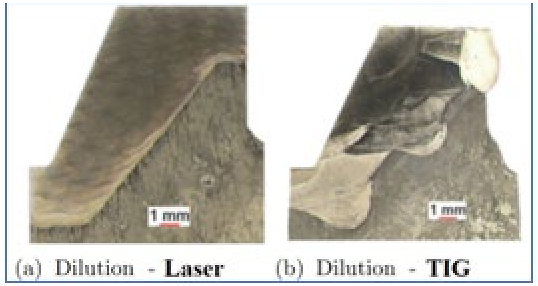


Evolution of the microhardness as a function of the distance to the hardened zone for an Inconel 625 coating added by laser or TIG



(a) Microstructure - **LMD** (b) Microstructure - **TIG**

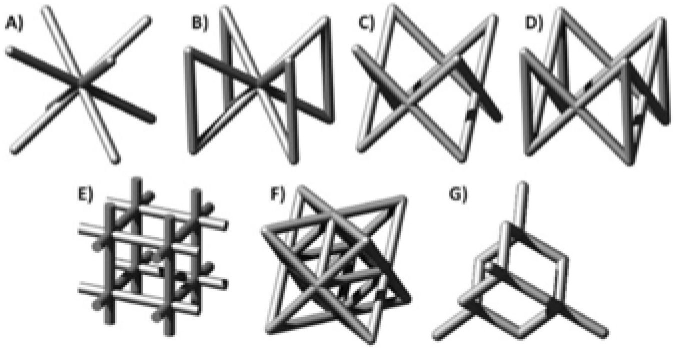
Microstructure after: a)LMD process and b)welding TIG



(a) Dilution - **Laser** (b) Dilution - **TIG**

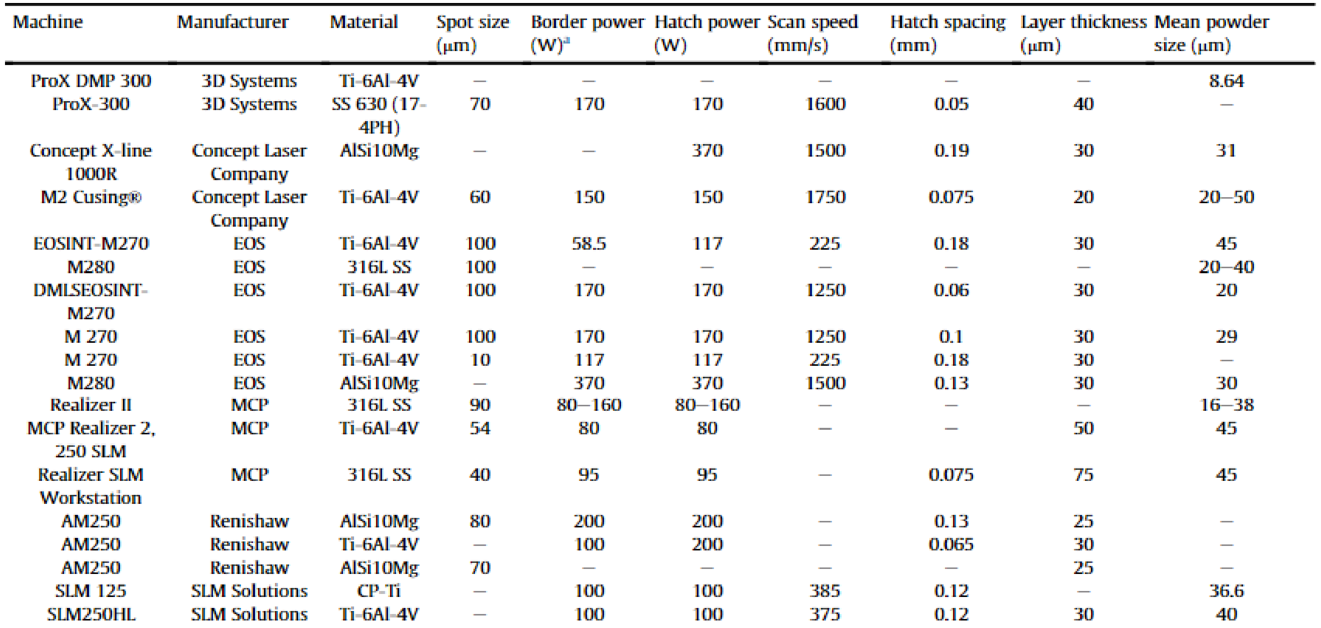
ZAT after: a)LMD process and b)welding TIG

Architectural materials manufactured by SLM



Strut-based lattice structures: BCC (A), BCCZ (B), FCC (C), FCCZ (D), cubic (E), Octet-truss (F), and diamond (G)

Table 8 SLM processing parameters



Machine	Manufacturer	Material	Spot size (μm)	Border power (W)[a]	Hatch power (W)	Scan speed (mm/s)	Hatch spacing (mm)	Layer thickness (μm)	Mean powder size (μm)
ProX DMP 300	3D Systems	Ti-6Al-4V	–	–	–	–	–	–	8.64
ProX-300	3D Systems	SS 630 (17-4PH)	70	170	170	1600	0.05	40	–
Concept X-line 1000R	Concept Laser Company	AlSi10Mg	–	–	370	1500	0.19	30	31
M2 Cusing®	Concept Laser Company	Ti-6Al-4V	60	150	150	1750	0.075	20	20–50
EOSINT-M270	EOS	Ti-6Al-4V	100	58.5	117	225	0.18	30	45
M280	EOS	316L SS	100	–	–	–	–	–	20–40
DMLSEOSINT-M270	EOS	Ti-6Al-4V	100	170	170	1250	0.06	30	20
M 270	EOS	Ti-6Al-4V	100	170	170	1250	0.1	30	29
M 270	EOS	Ti-6Al-4V	10	117	117	225	0.18	30	–
M280	EOS	AlSi10Mg	–	370	370	1500	0.13	30	30
Realizer II	MCP	316L SS	90	80–160	80–160	–	–	–	16–38
MCP Realizer 2, 250 SLM	MCP	Ti-6Al-4V	54	80	80	–	–	50	45
Realizer SLM Workstation	MCP	316L SS	40	95	95	–	0.075	75	45
AM250	Renishaw	AlSi10Mg	80	200	200	–	0.13	25	–
AM250	Renishaw	Ti-6Al-4V	–	100	200	–	0.065	30	–
AM250	Renishaw	AlSi10Mg	70	–	–	–	–	25	–
SLM 125	SLM Solutions	CP-Ti	–	100	100	385	0.12	–	36.6
SLM250HL	SLM Solutions	Ti-6Al-4V	–	100	100	375	0.12	30	40