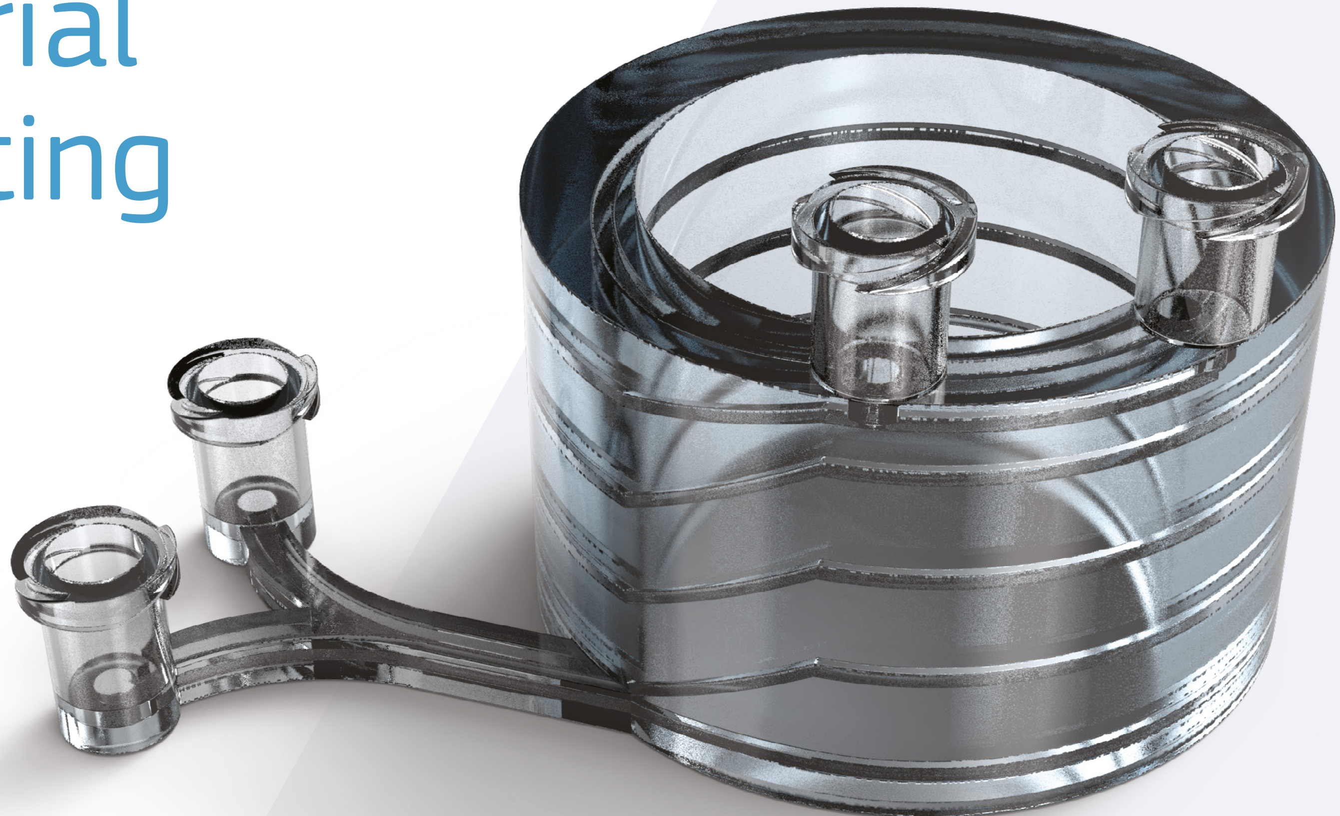
Materials Matter: Selecting the Right Material for 3D Printing



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All values shown in this guide are accurate at the date of publication.

To confirm the latest valid values (in case any update occured), please refer to the Material Data Sheets you can find in the Protolabs website under the Materials section.

Materials must be suited to the application in order to have successful results. The properties of any material become increasingly important as a product progresses from concept and functional prototyping to production.

However, material properties can only be evaluated when the manufacturing process is considered. It is the combination of the material and the process that dictates the characteristics. For example, an alloy processed by die casting has different properties when it is metal injection moulded. Likewise, a thermoplastic will have different properties if it is injection moulded or CNC machined.

Additive manufacturing (AM), or 3D printing, is unique. It is different from all other manufacturing processes, so the material properties and characteristics of parts that it produces are different, even when using a nearly identical alloy or thermoplastic. In terms of material properties, it is not a matter of being better or worse; it is simply important to recognise that the results will be different.

Recognising that there is a difference, the following information will aid in the characterisation, and ultimately the selection, of materials from three widely used industrial 3D printing processes: direct metal laser sintering (DMLS), selective laser sintering (SLS) and stereolithography (SL).

MATERIAL ADVANCEMENTS

The materials used in 3D printing have been improving, as would be expected. These advancements have allowed the technology to move beyond models and prototypes to functional parts for testing, shop floor use and production.

And while the output of 3D printing is different from that of other manufacturing processes, it can offer a suitable alternative when seeking a direct replacement. Yet, its advantages increase when users experiment with the possibilities that it offers.

However, experimentation is a bit challenging because of 3D printing's differences that extend beyond, but are related to, material properties.

For example, additive materials lack the rich set of performance data that characterize a material over a range of conditions. Instead, 3D printing users are presented with a single data sheet that contains a limited set of values. Those values are also likely to present a best case scenario based on testing of virgin material (unrecycled powders, for example).

Another complication is that 3D printing produces anisotropic properties where the values differ predominately in the X and Y (draw plane) vs. the Z orientation. The degree of anisotropism varies with each additive technology – direct metal laser sintering is the closest to isotropic, for example – but it should always be a consideration.

However, the material suppliers may not publish material specifications that document the change in properties from one axis to another, as the data behind these specifications can vary greatly by material, process and even type of machine.

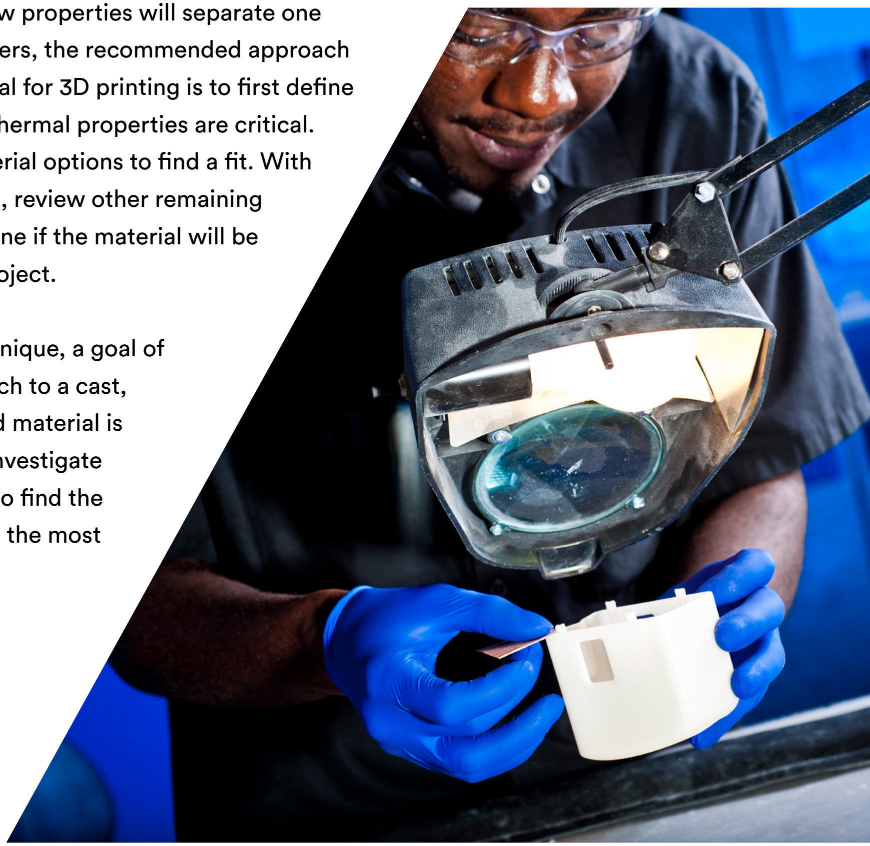
By designing specifically for the 3D printing process, and adjusting the build orientation, anisotropism or inadequate material properties can be overcome. To achieve this, designers can leverage the experiences from past projects (or that of a qualified service organisation) to fill in the data gaps that exist because of the limited material properties data. When performance is critical, also consider independent lab testing of additive materials. While success is dependent on material properties, they are not the only considerations. Each additive material and build process will also dictate characteristics such as maximum part size, dimensional accuracy, feature resolution, surface finish, production time and part cost. So it is advised to select a suitable material and then evaluate its ability to meet expectations and requirements related to time, cost and quality.

MATERIAL SELECTION

Generally, one or two material properties distinguish an additive material from all others. For example, if seeking the average tensile strength of polyamide (PA) 11, a stereolithography photopolymer maybe be a better option than a selective laser sintering PA. Conversely, if the heat deflection temperature (HDT) of an ABS is needed, the best option would be a sintered nylon.

Recognising that a few properties will separate one material from the others, the recommended approach for selecting a material for 3D printing is to first define what mechanical or thermal properties are critical. Then review the material options to find a fit. With the options narrowed, review other remaining properties to determine if the material will be acceptable for the project.

Since 3D printing is unique, a goal of finding a perfect match to a cast, moulded or machined material is ill-advised. Instead, investigate the material options to find the material that satisfies the most critical requirements.



DIRECT METAL LASER SINTERING (DMLS)

DMLS uses pure metal powders to produce parts with properties that are generally accepted to be equal or better than those of wrought materials. Because there is rapid melting and solidification in a small, constantly moving spot, DMLS may yield differences in grain size and grain boundaries that impact mechanical performance. Research is ongoing to characterise the grain structures, which can change with the laser parameters, post-build heat treatment and hot isostatic pressing. However, the results are not widely available. Ultimately, this difference will become an advantage when grain structure can be manipulated to offer varying mechanical properties in a part.

Of the three additive manufacturing processes discussed here, DMLS produces parts with material properties that approach an isotropic state. However, there will be some property variance when measured along different axes. For a visual comparison of DMLS material properties, see Chart 1 for tensile strength, Chart 2 for elongation and Chart 3 for hardness.

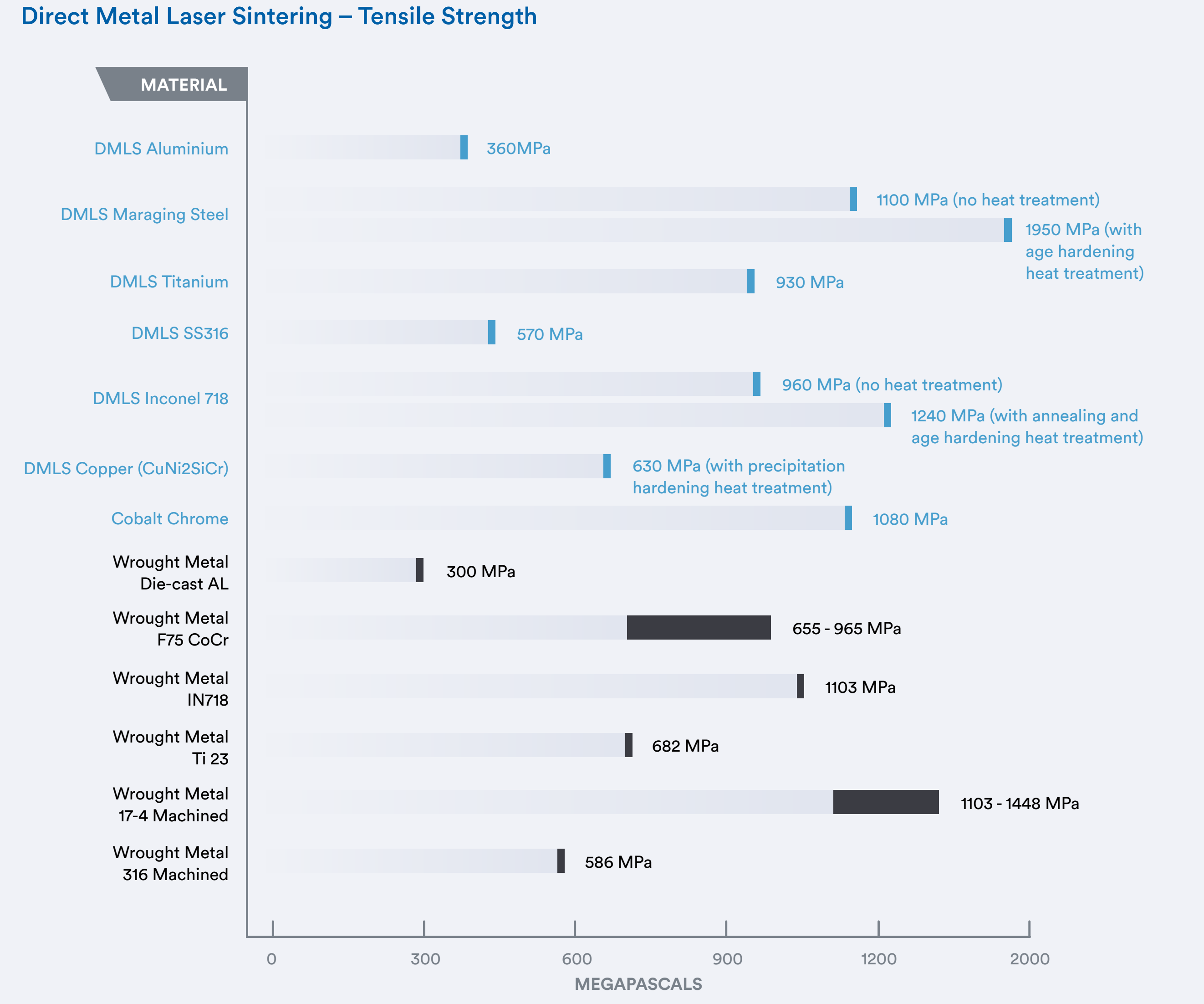


Chart 1

Stainless steel is a commonly used DMLS material and is available from Protolabs in 316L, which hasexcellent elongation, offering 40% at break, making it very malleable. 316L offers acid & corrosion resistance and is more temperature resistant than most other materials in its stress relieved state.

DMLS aluminium (Al) is comparable to a 3000 series alloy that is used in casting and die casting processes. Its composition is AlSi10Mg. Al has an excellent strength-to-weight ratio, good temperature and corrosion resistance, and good fatigue, creep and rupture strength.

Compared to die-cast 3000 series aluminium, the Al properties for tensile strength (360 MPa +/- 30 MPa) and yield strength (240 MPa +/- 30MPa) far exceed the average values. However, elongation at break (EB) is significantly lower (6% vs. 11%) when compared to the average for 3000 series aluminiums.

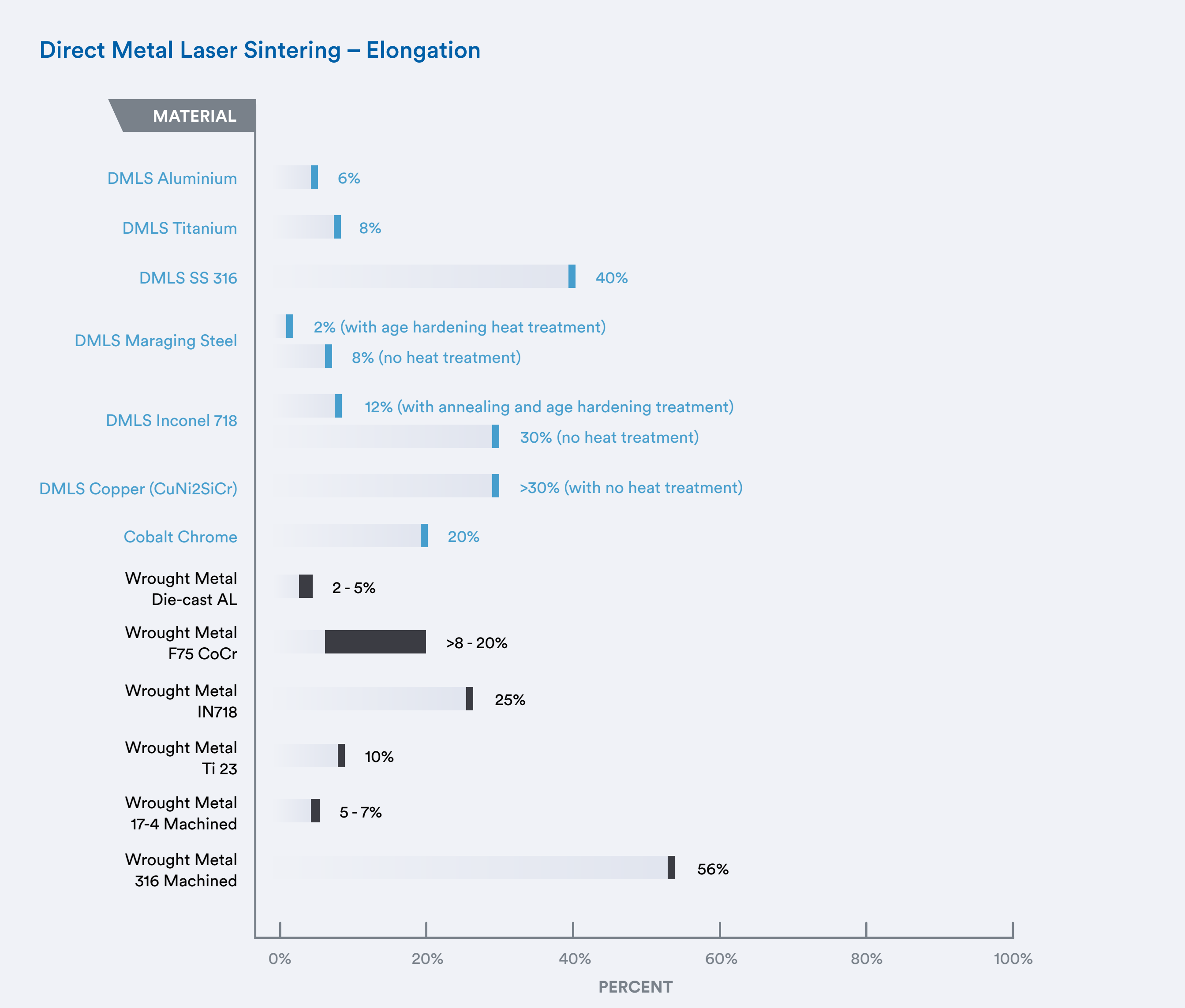


Chart 2

DMLS titanium (Ti6Al4V) is most commonly used for medical applications due to its strength-to-weight ratio, temperature resistance and acid/corrosion resistance. Versus Ti grade 23 annealed, the mechanical properties are nearly identical with a tensile strength of 930 MPa, elongation at break of 10% and hardness of 33 HBW.

Maraging steel is known for possessing superior strength and toughness without losing malleability. It is a special class of low-carbon ultra-high-strength steels that derive their strength not from carbon, but from precipitation of intermetallic compounds. It is curable up to 37 HRC with high temperature resistance. Its uniform with its uniform expansion and easy machinability before aging makes maraging steel useful in high-wear components of assembly lines and dies.

Inconel 718 (IN718) is a nickel chromium superalloy used in high service temperature applications, such as aircraft engine components or gas turbine parts. DMLS IN718 parts have an impressive operating temperature range of -252°C to 704°C, coupled with excellent corrosion resistance and good fatigue, creep and rupture strength.

Copper (CuNi2SiCr) is a low alloyed Copper-Material which combines good mechanical properties with high thermal and electrical conductivity. It is usually used in more rough environements where pure copper is not feasible.

Cobalt Chrome is a superalloy comprised primarily of cobalt and chromium, and is known for its high strength-to-weight ratio, excellent creep and corrosion resistance. Parts built in CoCr are according to ASTM F75.

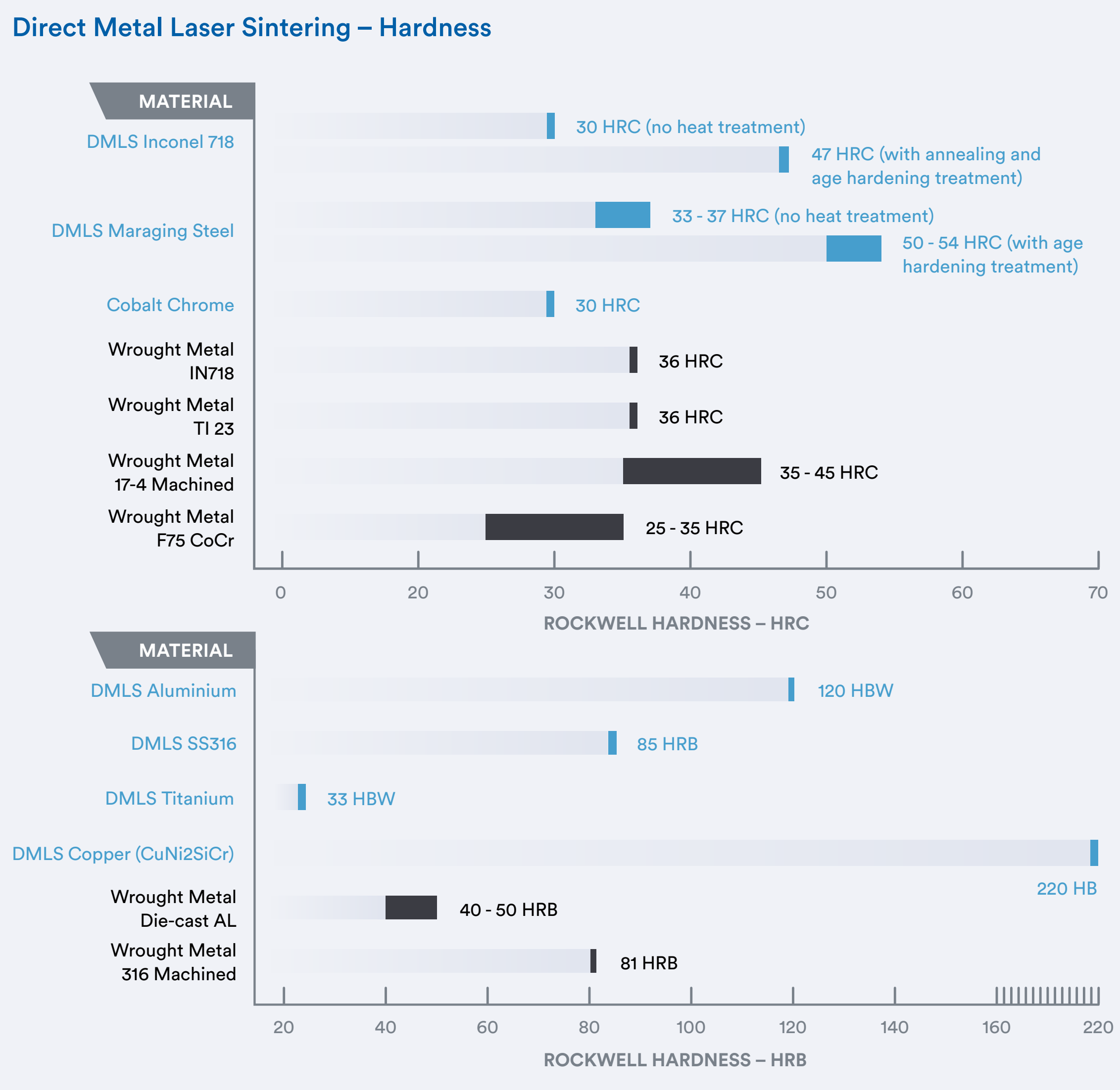


Chart 3

SELECTIVE LASER SINTERING (SLS)

SLS uses thermoplastic powders, predominantly polyamide(PA), to make functional parts that have greater toughness and higher impact strength than parts produced through stereolithography (SL), as well as high HDTs (157°c to 188°c). The tradeoffs are that SLS lacks the surface finish and fine feature details available with SL.

Generally, SLS PAs, when compared with the average values of their injection moulded counterparts, have similar HDT values but lower values for the mechanical properties. In a few instances, SLS PAs report properties that document the degree of anisotropism. For a visual comparison of SLS mineral properties, see Chart 4 for heat deflection, Chart 5 for elongation at break and Chart 6 for tensile strength.

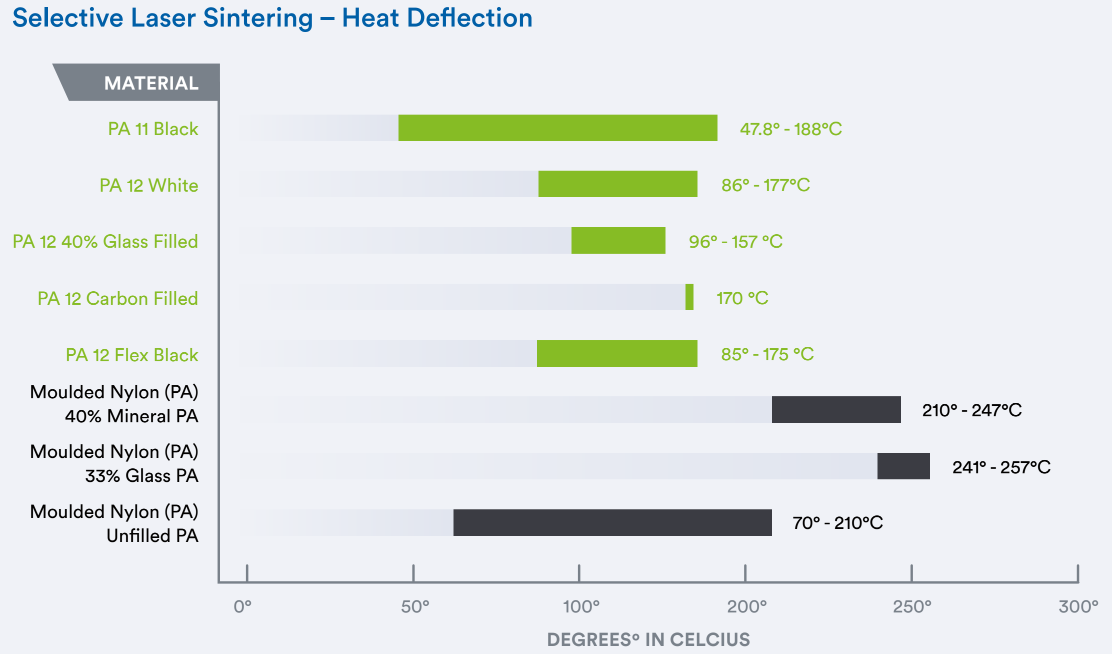


Chart 4

PA 11 Black delivers ductility and flexibility with a tensile modulus of 48 MPa and EB of 30% in XY direction, all without sacrificing tensile strength (49 MPa) and temperature resistance (HDT of 188°c). These characteristics make PA 850 a popular general-purpose material and the best solution for making living hinges for limited trials.

When compared to the averages for injection-moulded PA 11, PA 11 Black has a higher HDT (188°c vs 140°c) with similar tensile strength and stiffness. However, its EB, while the highest of all AM plastics, is 60% less than that for a moulded PA 11.

Another factor that distinguishes PA 11 Black is its uniform, deep-black colour. Black has high contrast, which makes features pop standout, and it hides dirt, grease and grime. Black is also desirable for optical applications due to low reflectivity.

PA 12 White is a balanced, economical, go-to material for general-purpose applications. PA 12 White is stiffer than PA 11 black (tensile modulus of 1650 MPa vs 1560 MPa) and has a similar tensile strength (48 MPa vs 42 - 48 MPa). While its EB is less than half that of PA 11 black, at 18% it's still one of the top performers in terms of ductility. PA 12 White is loosely comparable to the average properties for an injection moulded PA 12. It has similar stiffness but roughly half the tensile strength and EB. However, its HDT is significantly higher: 188°c vs. 138°c.

PA 12 40% Glass Filled is a polyamide powder loaded with glass spheres that make it stiff and dimensionally stable. However, the glass filler makes it brittle, significantly decreasing impact and tensile strengths. The glass spheres also make PA 12 40% Glass Filled parts much heavier than those made with any other AM material. PA 12 40% Glass Filled is a good choice when stiffness and temperature resistance are required.

Selective Laser Printing – Elongation At Break

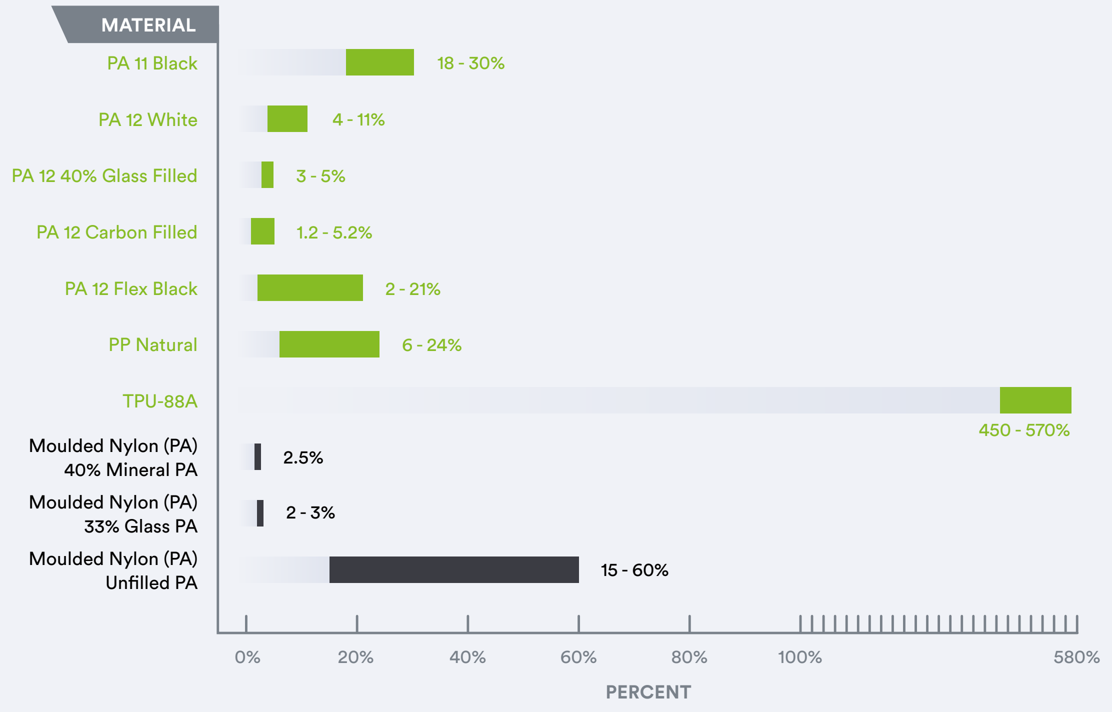


Chart 5

PA 12 Carbon Filled is an anthracite grey nylon characterised by extreme stiffness and high temperature resistance, coupled with electric conductivity properties and light weight. Carbon-fibre filler provides different mechanical properties based on the considered three axis direction.

PA 12 Flex Black is a black/ anthracite nylon characterised by excellent flexibility and impact resistance. PA 12 Flex black combines positive properties of PA12 and PP. Strength and stiffness is similar to PA 12 with tensile strength of 48MPa. The elongation is comparable to that of unfilled PP with EB of 2-21% vs. 6-24%

PP Natural is real polypropylene, one of the most commonly used plastics worldwide. The material shows high durability and is both tough and flexible. Other important characteristics are its low weight compared to other plastic materials, together with excellent chemical resistance and electrical insulation. The material also has low moisture absorption.

TPU-88A is a thermoplastic polyurethane (TPU) that combines rubber-like elasticity and elongation with good abrasion and impact resistance. EB for TPU-88A is 450-570%

Selective Laser Sintering – Tensile Strength

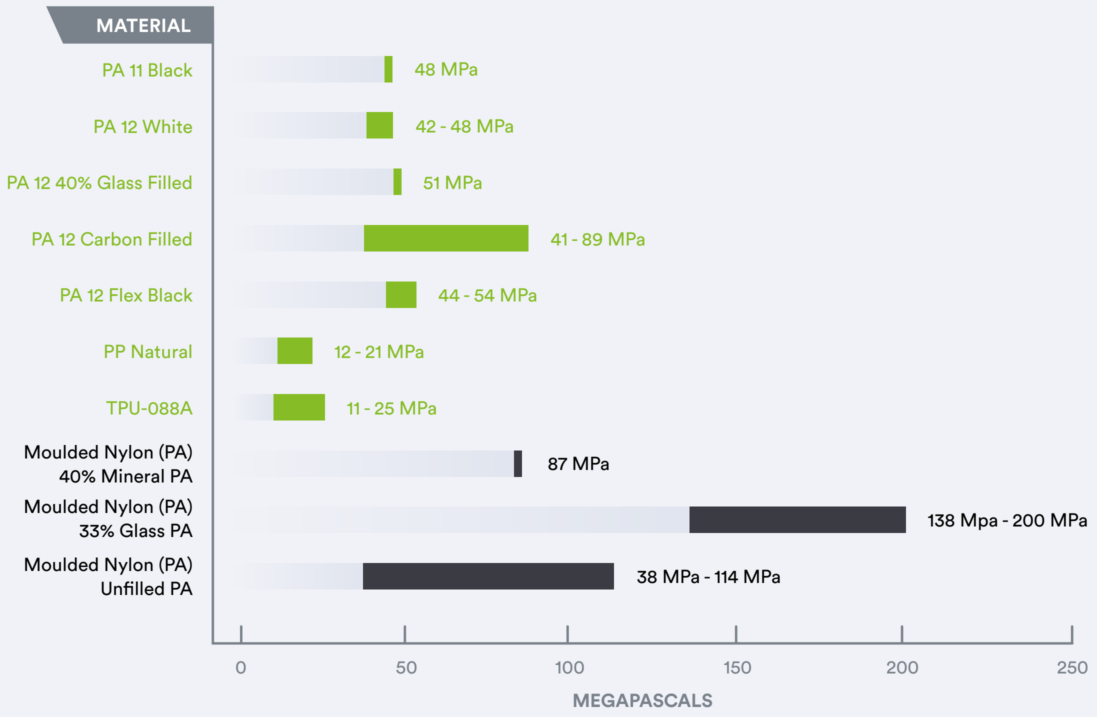


Chart 6

STEREOLITHOGRAPHY (SL)

SL uses photopolymers, thermoset resins cured with ultraviolet (UV) light. It offers the broadest material selection with a large range of tensile strengths, tensile and flexural moduli, and EBs. Note that the impact strengths and HDTs are generally much lower than those of common injection-moulded plastics. The range of materials also offers options for colour and opacity. Combined with good surface finish and high feature resolution, SL can produce parts that mimic injection moulding in terms of performance and appearance.

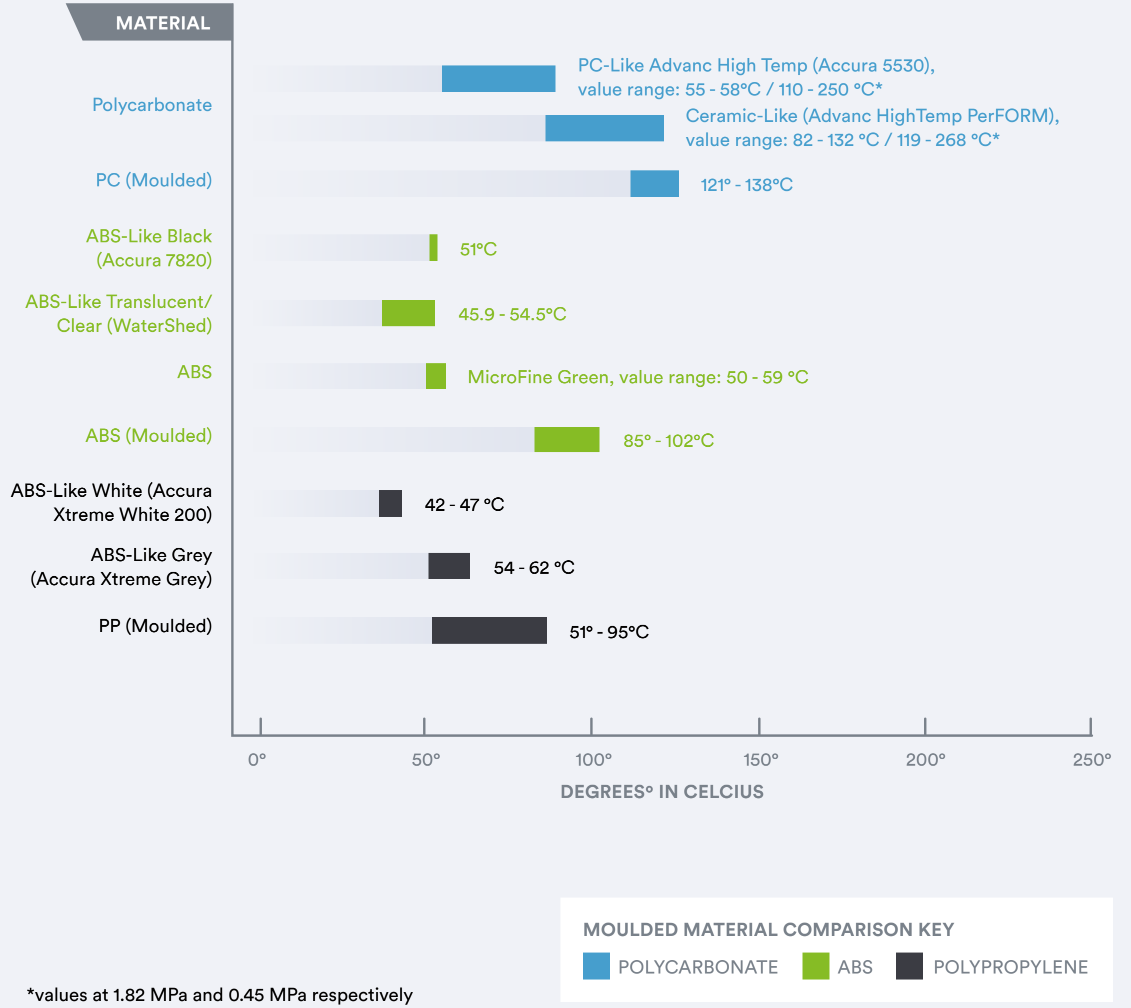
The photopolymers are hygroscopic and UV sensitive, which may alter the dimensions and performance of the part over time. Exposure to moisture and UV light will alter the appearance, size and mechanical properties. For a visual comparison of SL material properties, see Chart 7 for heat deflection, Chart 8 for elongation at break and Chart 9 for tensile strength.

ABS-Like White (Accura Xtreme White 200) is a widely used SL material. In terms of flexibility and strength, it falls between polypropylene and ABS, which makes it a good choice for snap fits, master patterns and demanding applications. Xtreme is a durable SL material; it has a very high impact strength (64 J/M.) and a high EB (20%) while mid-range in strength and stiffness. However, its HDT (47°c) is the lowest of the SL materials.

Compared to the average value for injection-moulded ABS, Xtreme can have a slightly higher tensile strength (45 MPa - 50 MPa) but slightly lower EB (20% vs. 30%).Under a flexing load, Xtreme is 26% less rigid, and its impact strength is 70% lower.

Chart 7

Stereolithography – Heat Deflection



*values at 1.82 MPa and 0.45 MPa respectively

Stereolithography – Elongation At Break

*after additional thermal post cure

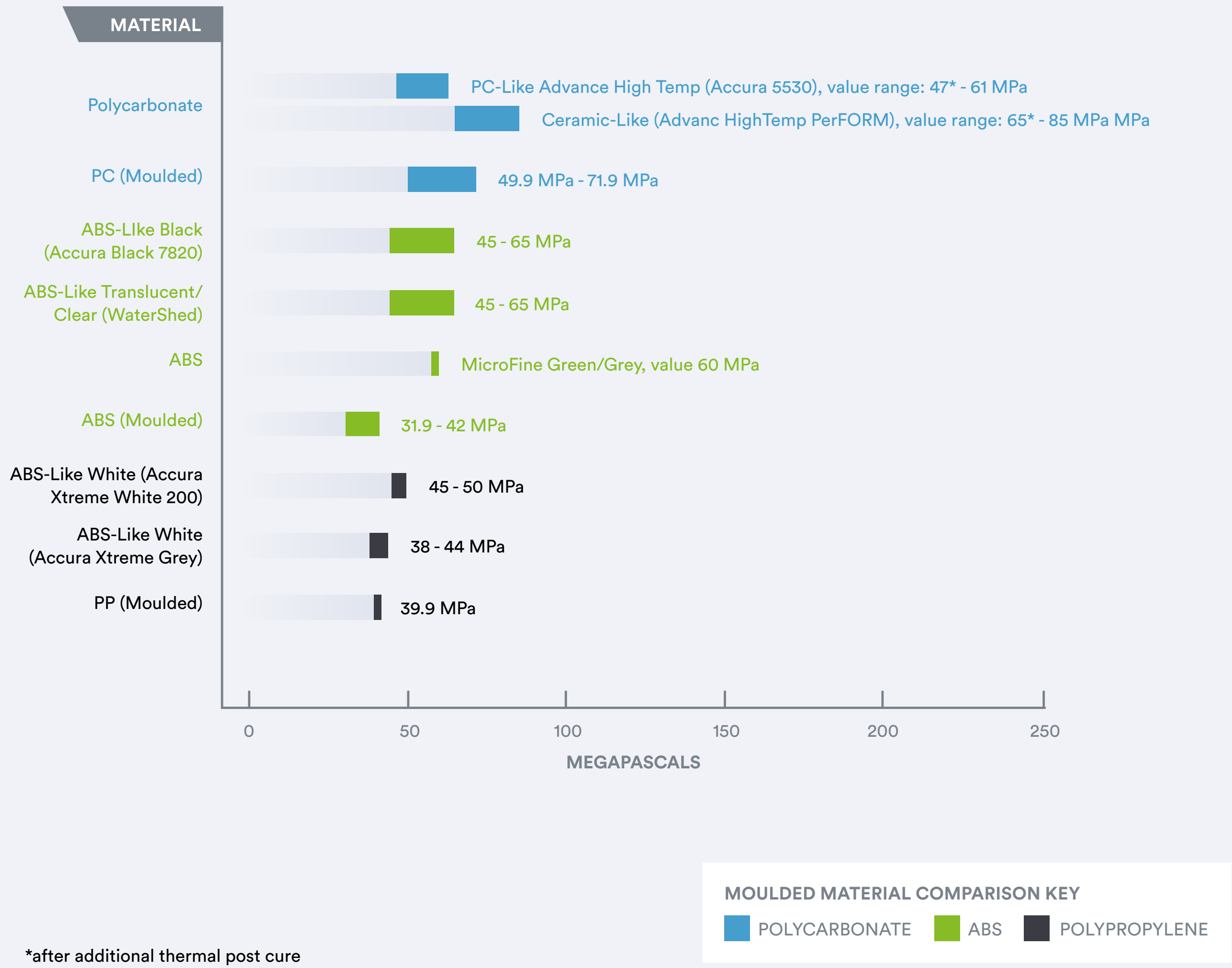
Chart 8

ABS-Like Grey (Accura Xtreme Grey) is similar to polypropylene (PP)/ABS and is a tough, durable material. It is very suitable for snap fits, assemblies and demanding applications and it is characterized by its grey colour.

ABS-Like Translucent/ Clear (WaterShed) offers a unique combination of low moisture absorption (0.35%) and near-colourless transparency – secondary operations will be required to get the material completely clear, and it will also retain a very light blue hue a erward. While good for general-purpose applications and pattern-making, WaterShed is the best choice for flow-visualisation models, light pipes and lenses.

Watershed's tensile strength and EB are among the highest of 3D-printed, thermoplastic-like materials, which makes it tough and durable. Compared to average injection-moulded ABS values, Watershed offers a slightly higher tensile strength (53.6 MPa vs 42 MPa), but falls short in EB (15.5% vs. 30%) and HDT at 50 °C -> 54 °C.

Stereolithography – Tensile Strength



*after additional thermal post cure

Chart 9

ABS-Like Black (Accura Black 7820) is another alternative when prototyping injection-moulded ABS parts. It not only mimics ABS's mechanical properties, its deep black colour and glossy up-facing surfaces in a top profile offer the appearance of a moulded part, while layer lines may be visible in a side profile. It offers a large working envelope of physical properties, high EB (6-13%) and impact strength suitable for building concept models, and functional prototype parts.

MicroFine Green/Grey is custom formulated at Protolabs to deliver the highest level of detail – 0.07 mm features are possible – and tightest tolerance available from any SL material. The material is used to make micro to small parts, generally less than 25 × 25 × 25 mm³.

In terms of mechanical properties, MicroFine Green/Grey falls in the mid-range of SL materials for tensile strength and modulus (60 MPa and 2600 MPa respectively) and on the low end for impact strength and EB (0.23 J/cm and 8% respectively).

MicroFine Green has a stiffness and tensile strengths similar to injection-moulded ABS, however, it does have a lower HDT than ABS (59 °C vs 102°C).

PC-Like Advanc HighTemp (Accura 5530) provides a strong, stiff part with high temperature resistance. Furthermore, a thermal post-cure option can increase HDT from 85°C up to 250 °C (at 0.45 MPa). 5530 has one of the highest tensile and flexural moduli of all the unfilled SL materials and the second highest tensile strength (61 MPa). However, the postcure does make 5530 less durable, resulting in an impact strength of only 21 J/m and an EB of 2.9%. Without the thermal post-cure, 5530 retains its tensile strength and becomes more flexible. Also, EB increases by about 50%.

When compared to injection-moulded thermoplastics, a 10% glass-filled polycarbonate is the closest match. With the thermal post-cure, 5530 has similar tensile strength and flexural modulus (compared to the average values) with 66% higher HDT. However, impact strength and EB are much lower for 5530 (81% and 72% lower, respectively).

Ceramic-Like (Advanc HighTemp PerFORM) is the ideal material for creating strong, stiff parts with excellent high heatresistance. An additional thermal post-cure option can increase HDT from 132°C up to 268 °C (at 0.45 MPa), i.e. to the highest value among all SLA materials. Typical material usage includes production of tooling and wind tunnel testing applications

CONCLUSION

Spanning metals, thermoplastics and thermosets, 3D printing provides many different materials that can simulate, if not replace, those that are processed through conventional means. While an exact match is not possible, since the fundamental processes are different, the material breadth means that there is a strong likelihood that the important material characteristics are satisfied.

The key to success is being open to, and cognizant of, the differences. With the support of an informed, qualified 3D printing resource that can fill in the data gaps, this mindset opens the door to leveraging the unique advantages that 3D printing technology can offer.

Sources

matweb.com, ulprospector.com, vendor datasheets and protolabs.co.uk

DECISION TREE: DMLS MATERIAL

METAL

ATTRIBUTES	DMLS
STRENGTH	Inconel 718 Titanium Ti64 Maraging Steel Cobalt Chrome
LIGHTWEIGHT	Aluminium Titanium Ti6Al4V
TEMPERATURE RESISTANCE	Inconel 718 Titanium Ti6Al4V
CORROSION RESISTANCE	Stainless Steel 316L Inconel 718 Titanium Ti6Al4V Cobalt Chrome
STRENGTH-TO-WEIGHT RATIO	Aluminium
THERMAL CONDUCTIVITY	Copper (CuNi2SiCr)
ELECTICAL CONDUCTIVITY	Copper (CuNi2SiCr)

DIRECT METAL LASER SINTERING (DMLS)

Stainless Steel TS: 570 MPa Elongation: 40% Hardness: 85 HRB	**Aluminium** TS: 360 MPa Elongation: 6% Hardness: 120 HBW
Titanium TS: 930 MPa Elongation: >10% Hardness: 33 HBW	**Maraging Steel*** TS: 1100 MPa / 1950 MPa Elongation: 8% / 2% Hardness: 33 - 37 HRC / 50 - 54 HRC
Inconel 718* TS: 960 MPa / >1240 MPa Elongation: 30% / >12% Hardness: 30 HRC / 47 HRC	**Copper CuNi2SiCr*** TS: 250 MPa / 630 MPa Elongation: >30% / 10% Hardness: -- / 220 HB
Cobalt Chrome TS: 1080 MPa Elongation: 20% Hardness: 30 HRC	

*values without / with optional heat treatment

KEY

TS - TENSILE STRENGTH

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DECISION TREE: SL AND SLS MATERIAL

STEREOLITHOGRAPHY (SL)

AABS-Like (Accura Xtreme White 200) HD: 42 - 47°C EB: 7 - 20% TS: 45 - 50 MPa	**ABS-Like Grey (Accura Xtreme Grey)** HT: 54 - 62°C EB: 14 - 22% TS: 38 - 44 MPa	**ABS-Like Translucent/ Clear (Watershed)** HD: 45.9 - 54.5°C EB: 11 - 20% TS: 47.1 - 53.6 MPa
ABS-Like Black (Accura Black 7820) HD: 51°C EB: 6 - 13% TS: 45 - 47 MPa	**MicroFine Green/ Grey** HD: 50 - 59°C EB: 6.1% TS: 44.9 MPa	**PC-Like Advanc High Temp (Accura 5530)** HD: 55 - 85°C /// 110 - 250°C* EB: 1.3* - 4.4% TS: 47* - 61 MPa
Ceramic-Like (Advance HighTemp PerFORM) HD: 82 - 268°C EB: 1 - 1.2% TS: 68* - 80 MPa		

*after additional thermal post cure

SELECTIVE LASER SINTERING (SLS)

PA 11 Black Similar to: Nylon 11 HD: 48 - 188°C EB: 18 - 30% TA: 48 MPa	**PA 12 White** Material Type: Nylon 12 HD: 86 - 177°C EB: 4 - 11% TS: 42 - 48 MPa	**PA 12 40% Glass Filled** Material Type: 40% GF Nylon 12 HD: 96 - 157 °C EB: 3 - 5% TS: 51 MPa

KEY

HD - HEAT DEFLECTION
EB - ELONGATION AT BREAK
TS - TENSILE STRENGTH

All shown values are at 1.82 MPa and 0.45 MPa respectively

PLASTIC

ATTRIBUTES	SL / SLS
STRENGTH	Accura Xtreme Accura Extreme White PA 12 White
TRANSPARENCY	Somos WaterShed XC 11122
TEMPERATURE RESISTANCE	Somos PerFORM Accura SL 5530 PA 12 White
HIGH RESOLUTION	Accura Black Somos WaterShed XC 11122 Accura Xtreme White 200
MICRO RESOLUTION	MicroFine Green
DURABILITY	PA 12 White PA 11 Black PA 12 40% Glass Filled
STIFFNESS	Somos PerFORM Accura Xtreme PA 12 White PA 12 40% Glass Filled
IMPACT RESISTANCE	Accura Black 7820 Accura Xtreme White 200 PA 12 White