Any shape. Anytime. Anywhere.

Whitepaper

Mechanical Testing of DMLS Parts

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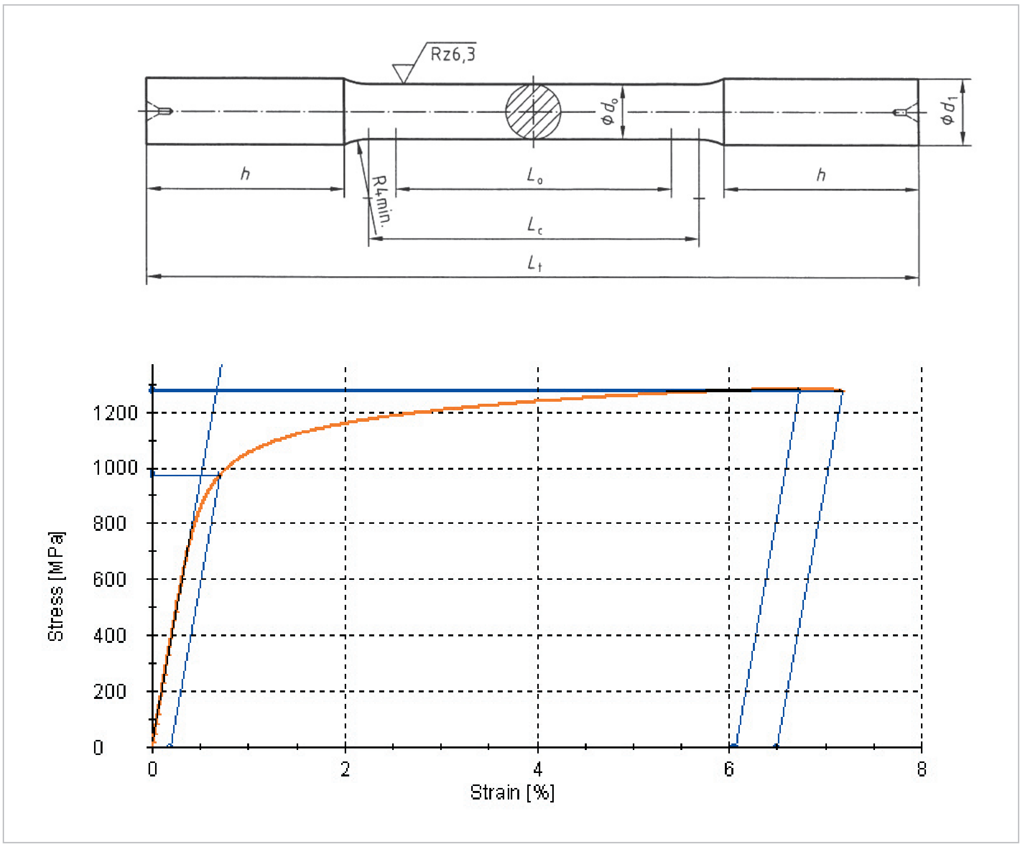

e-Manufacturing Solutions

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1. Direct Metal Laser-Sintering (DMLS)

Laser-sintering is a generative layer manufacturing technology and is the key technology for e-Manufacturing – the fast, flexible, and cost effective production directly from electronic data. Even highly complex three-dimensional geometries can be built efficiently and fully automatically, without requiring any tools or laborious milling path programming. The laser-sintering process allows for the simultaneous production of many different parts in one single build job. Laser-sintering can be used in every phase of the product lifecycle from rapid prototyping via series manufacturing to the production of spare parts. For further details on e-Manufacturing by laser-sintering visit www.eos.info.

Direct metal laser-sintering (DMLS) is a production method for creating metal parts. It works by taking 3D geometry data such as a CAD file or scan data, which are sliced into layers by software. From this layer data, laser exposure vectors are calculated for each layer of the build process. In the production machine, very thin (typically between 20 and 60 µm) layers of metal powder are applied onto a powder bed, the surface of which is selectively exposed using a scanned, focussed laser beam. The energy of the laser beam melts the powder in the exposed areas, creating a metallic bond to the surrounding exposed material including the previous layer. The process of applying and exposing layers is repeated, thereby creating solid metal parts additively, layer by layer, from the powder material.

As with all production methods, it is important for designers to have sufficient information and understanding of the mechanical properties of the resulting parts, in order to design for the required part performance. The purpose of this white paper is to provide recommendations for suitable test procedures for DMLS parts and hints about how to use the results. All results reported are from EOSINT M 270 systems.

2. Mechanical test standards and their applicability

2.1. Static tensile testing

A common procedure to characterize the mechanical properties of a material is tensile testing. This method applies stresses to the sample in defined intervals and records the response of the material in terms of strain. Typical curves are plotted using technical diagrams which contain all relevant data. The parameters to evaluate the mechanical applicability are as following.

» **Young´s modulus E [GPa]:** Calculated from the slope of the stress/strain curve in the elastic region. Measure of the stiffness of a material (the higher E the more resistant a material behaves towards an external stress).

» **Upper (ReH)/lower (ReL) yield strength or yield strength Rp0.2 [MPa]:** Defines the limit of the elastic range. Loading beyond this region will result in plastic deformation. Depending on the course of plastic deformation, one can define an upper and lower limit or a yield strength determined by a parallel line starting at a remaining plastic strain of 0.2%.

» **Ultimate tensile strength UTS or Rm [MPa]:** This quantity equals the maximum stress reached in the stress/strain diagram related to the start cross section. UTS is a very typical parameter used for mechanical evaluation. Nonetheless it is a critical one too, because it relates to the start cross section and not to the narrowed one after plastic deformation.

» **Elongation at break At [%]:** Describes the deformation-ability of a material. The remaining elongation at break is related to the starting length.

All relevant quantities are marked in the stress-strain diagram in Figure 1, where the curve shows example results for EOS CobaltChrome MP1.

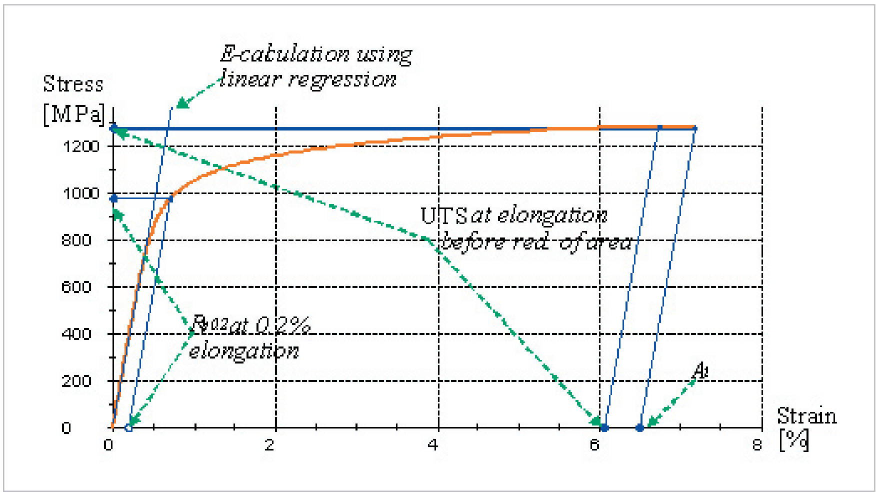


Figure 1
Tensile stress-strain diagram

To be able to compare the mechanical properties of DMLS parts with metal parts produced by other processes such as casting, forging etc., standard procedures should be applied which are accepted and commonly used for metal parts in general. For tensile testing EOS uses the international standard ISO 6892 : 1998 -03 and the european/german standards DIN EN 10002-1 : 2001-12 and DIN 50125 : 2009-07, which are typically used by industry and constitute the definition of sample geometry, speed of testing as well as the interpretation of results and requirements of the testing machine. In accordance with these standards, EOS has selected as standard for tensile testing proportional cylindrical tensile bars with 5mm diameter and 25mm length of the test section, and cylindrical (non-threaded) ends for clamping, as shown in Figure 2.

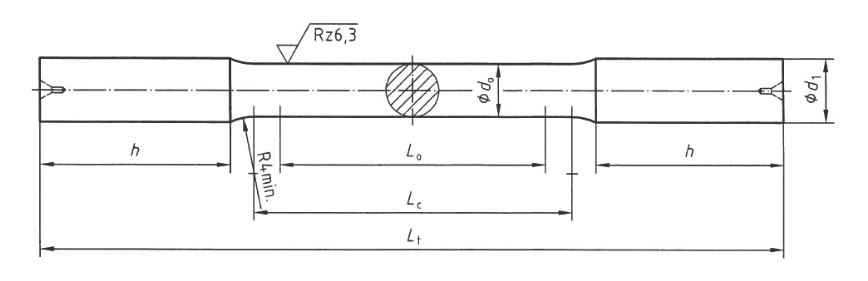


Figure 2
Recommended tensile test sample for DMLS according to ISO 6892, DIN EN 10002-1 and DIN 50125, using Lt=80mm, Lc=40mm, L0=25mm, d0=5mm, d1=6mm, h=20mm

The reasons for selecting this geometry as standard for DMLS are as follows:

- cylindrical sample geometry ensures a homogenous distribution of stress.
- cylindrical sample geometry is easy and efficient to produce, and also easier to post-machine with high tolerances (if desired) compared to e.g. flat specimens.
- the results are also comparable to ASTM E 8M-04, because the dimensional guidelines correlate to ISO 6892, DIN EN 10002-1 and DIN 50125 by a factor of 0.8333.
- 5mm diameter provides better good reliability of results (smaller is less reliable, 4mm is the smallest permitted by the standards) combined with cost-effective production (larger sizes mean longer build times and higher costs).

Note: modifications to the clamping areas are allowed if necessary for the testing machine and so long as they do not affect the testing region. For example, threaded ends can be used, although these are not recommended unless necessary because they increase the production time and cost of the specimens.

For the mechanical testing, EOS normally uses its own "Zwick/Roell Z050" machine with a maximum load of 50kN. Digital control and analysis of results is done via the software "Testexpert II". Loading rates are chosen in accordance with the standards and depending on the material being tested. Some typical values are 20MPa s-1 in the elastic and 0.008s-1 in the plastic region.

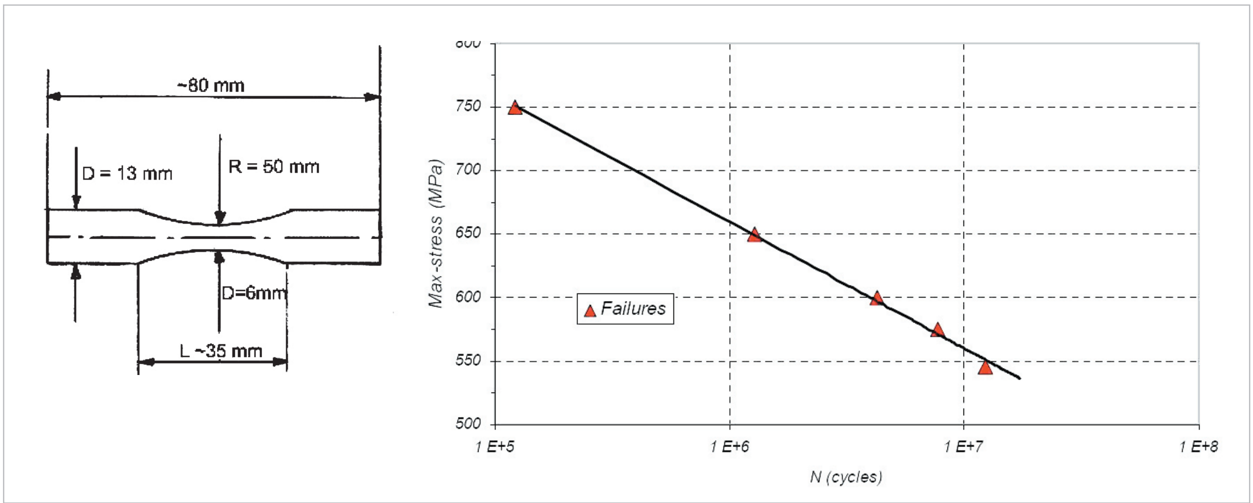
It is important to decide in advance whether the specimens will be machined or not. Some example results from both are given with discussion in section 3.1. If they are to be machined, then sufficient machining stock must be added before building and adapted to the build strategy (e.g. use no contours, or make sure they are completely machined away). In the case of horizontal samples, typically more stock may be needed to allow for stress-induced warpage which can occur when building the long thin specimens (whether and to what extent warpage occurs will depend on the material, the build parameters used and whether or not post-build stress-relieving is applied).

2.2 Fatigue testing

Dynamic properties of a material are mainly recorded by fatigue testing. Here, the material is subjected to cyclic loading until a localized crack is initiated. Plotting the cyclic stress or strain against the cycles to failure in logarithmic scale gives a material-dependent diagram, which can be used to estimate part lifetime at certain load conditions. Different fatigue testing modes can be used, most importantly **axial** and r**otating bend fatigue** (RBF) testing, and either stress or strain controlled. Stress controlled experiments are applied when investigating the high cycle fatigue behavior (**HCF**: 103 to 108 cycles), e.g. according to ISO 1099. The resulting graph is known as Wöhler curve. For higher stress amplitudes the material reaction becomes more sensitive. Thus strain controlled experiments record low cycle fatigue behavior (**LCF**: less than 103 cycles) with high plastic deformation, e.g. according to ISO 12106. Note that test results from different testing modes, sample types, load set-ups, etc cannot easily be compared with each other. Also, fatigue results scatter widely, so enough statistical data is needed for drawing clear conclusions.

When choosing a specimen geometry and testing standard, the same factors should be considered as for static tensile testing. It should be kept in mind that results of fatigue tests typically depend more strongly than for static tests on axiality of the stress-condition, sample geometry, surface quality, post-treatment, grain size, residual stresses, porosities, inclusions, environment and temperature. To obtain the most meaningful results, it is normally recommended to use stress-relieved (via heat treatment) and polished specimens. ISO 1099 and ISO 12106 contain relevant data about the dimensions of test specimen, production, experimental setup and presentation of results. EOS has also used ASTM E446 for fatigue testing, as shown for example in Figure 3. This shows a fatigue lifetime for this material of approximately 1 million cycles at 650 MPa load and 1o million cycles at 550 MPa load.

Figure 3
Axial fatigue testing of EOS CobaltChrome MP1:
(a) left: specimen geometry according to ASTM E466
(b) results of testing at 44Hz with R = 0.1



2.3 Hardness testing

The mechanical resistance of a sample surface towards penetration of a defined test body is known as the material´s hardness. The value of hardness is mostly used as a parameter to indirectly indicate the abrasion behaviour of a material (as opposed to direct measurements of wear rate such as the pin-on-disk method). Different measurement methods exist, so an appropriate method should be chosen depending on the hardness range of the sample and what reference data is to be compared to.

The **Vickers hardness** (HV) according to DIN EN ISO 6507 uses a diamond pyramid as test body and is applied for hard and/or hardened parts. The **Rockwell hardness C** (HRC) according to ISO 6508-1 and DIN EN 10109 uses a cone-shaped diamond test body with a rounded top. This method is very fast and useful for hard samples but not applicable for geometries which show elasticity (i.e. rings, pipes). For softer metals the **Brinell hardness** according to DIN EN ISO 6506-1 is applied. Depending on the material, a metallic sphere is pressed into the sample surface by a defined testing force and time.

EOS recommends using Vickers or Rockwell testing for DMLS parts, although Brinell can be used for the softer DirectMetal 20 material. Surface roughness can significantly affect the results of hardness measurements (i.e. give misleading results), so in general it is recommended to only used ground or polished surfaces. It should be considered whether bulk or surface hardness is to be measured, and preparation methods chosen accordingly, e.g. either completely removing or completely leaving the contour region.

Hardness data is a relative measurement, so only results measured with the same method can be directly compared to each other. Tables exist for converting between different hardness methods but these are not considered to give precise data, so it should always be stated whether a value is directly measured or converted using a table.

3. Example results of DMLS mechanical testing[1]

3.1 Influence of specimen geometry, surface finish and build orientation

Figure 4 shows the effect on the Young´s modulus E (as a representative example of mechanical properties) of laser-sintered EOS Titanium Ti64 depending on the specimen geometry, build orientation and surface finish. The following trends can be seen:

- flat specimens (DIN 50125) have in every case both lower value and higher standard deviation than the corresponding cylindrical samples (DIN 50125)
- machined specimens have in every case both higher value and lower standard deviation than the corresponding unmachined (as built) samples

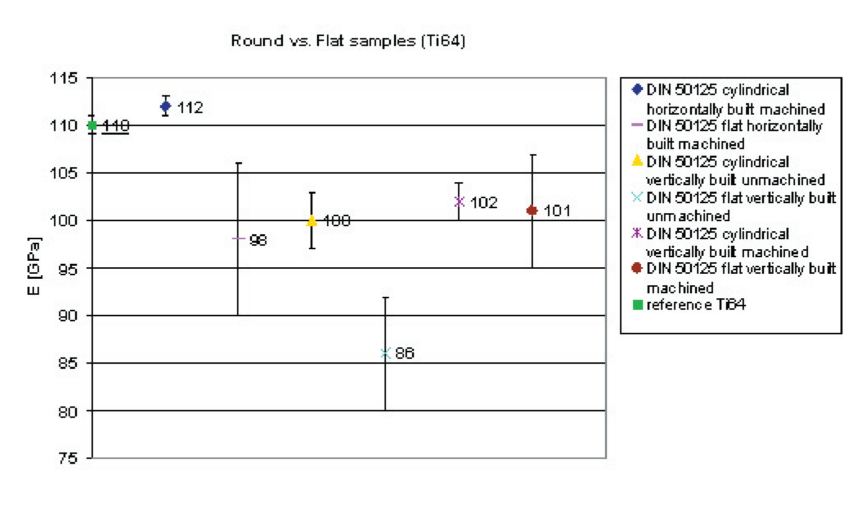


Figure 4
Comparison of Young´s modulus (mean and standard deviation) for EOS Titanium Ti64 depending on:
(i) specimen geometry (cylindrical vs. flat);
(ii) build orientation (vertical vs. horizontal);
(iii) surface finish (as-built vs. machined)

These results confirm that more consistent and reliable results are to be expected when using machined cylindrical specimens.

Regarding the influence of the build orientation (horizontal vs. vertical), the results are inconclusive, with the horizontal values being somewhat higher for cylindrical and slightly lower for flat samples. The effect of orientation is material-dependent. Figure 5 gives some results comparing the mechanical properties of horizontal and vertical specimens (according to EOS standard) in EOS MaragingSteel MS1 (1.2709) and EOS Titanium Ti64 (Ti6Al4V). These show that EOS MaragingSteel MS1 has slightly better properties in the horizontal direction, whereas EOS Titanium Ti64 has significantly better yield strength and elongation at break in the vertical direction. However in most cases the differences are relatively small, showing that anisotropic effects often do not have a very significant effect.

		EOS MaragingSteel MS1		EOS Titanium Ti64	
		horizontal	**vertical**	**horizontal**	**vertical**
Young´s modulus	**[GPa]**	172	160	112	111
Yield strength	**[MPa]**	1085	1076	1043	1088
Ultimate tensile strength	**[MPa]**	1188	1140	1248	1201
Elongation at break	**[%]**	13.3	10.0	8.5	10.6

Figure 5
Comparison of mechanical properties of horizontal and vertical specimens in EOS MaragingSteel MS1 and EOS Titanium Ti64.

3.2 Influence of build position within machine

It is to be expected the process conditions will vary slightly depending on the position in the build area, for example because the shape of the laser spot will change slightly depending on the scan angle. Figure 6 shows the mechanical properties measured from specimens built vertically in EOS StainlessSteel PH1 material according to EOS standard in various positions within the EOSINT M 270 build area, including the extreme positions in the centre and two opposite corners, as well as one edge. It can be seen that there is only minimal variation in the mechanical properties, showing that the build position has negligible effect.

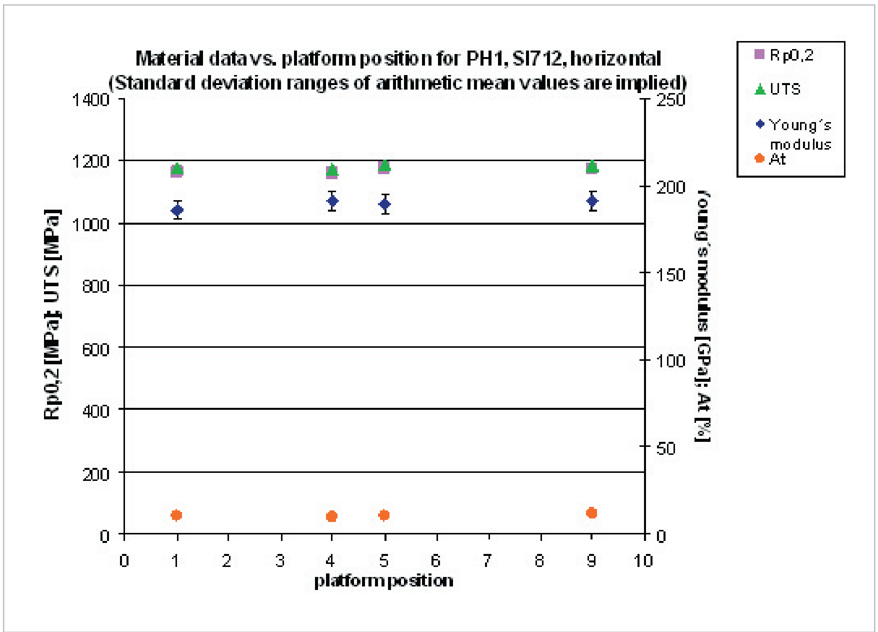


Figure 6
Comparison of mechanical properties for EOS StainlessSteel PH1 built vertically in the following positions in the EOSINT M 270 build area:

1. rear left corner
4. centre left edge
5. centre
9. front right corner

3.3 Reproducibility of properties

An important aspect for production with DMLS is the reproducibility of mechanical properties for identical parts built on different machines and at different times. To assess this, EOS builds a standardized quality assurance job on every EOSINT M 270 system at the end of the production process. This QA job includes tensile specimens which are tested in accordance with the standard procedures described above. Figure 7 shows the results for 37 successively produced EOSINT M 270 machines. It can be seen that all the values show a good reproducibility.

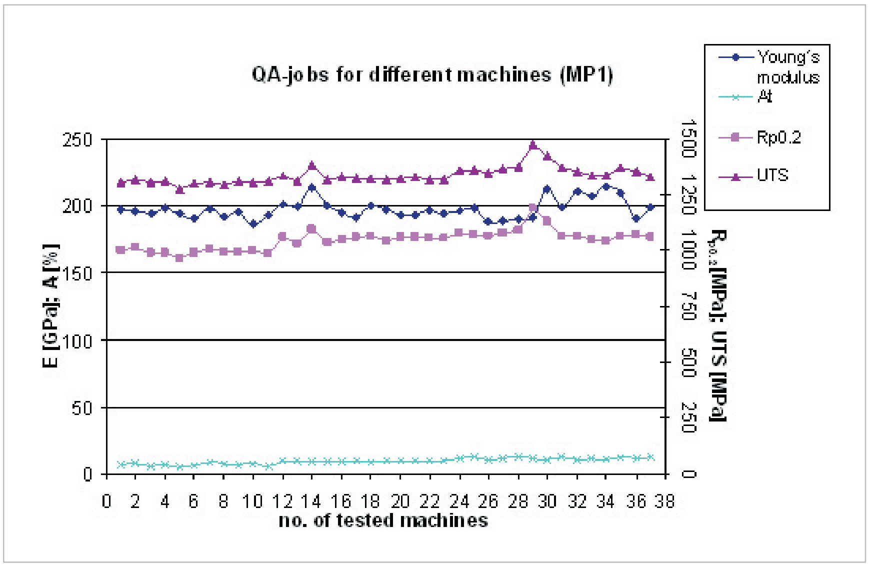


Figure 7
Mechanical properties of quality assurance jobs built in EOS CobaltChrome MP1 on 37 successively produced EOSINT M 270 machines.

4. Discussion

The standard specimen and procedure for static tensile testing described in section 2.1 has proven to be very suitable for DMLS parts, as demonstrated by the results given in section 3. So far, not enough experience has been gathered with fatigue testing to draw conclusions, but this is likely to change soon as more fatigue testing is done. Results of mechanical testing confirm that the values depend on a variety of factors including powder material, technology status of the machine and software, build strategy and process parameters used, build orientation and post-processing applied. Therefore it is important to specify these factors when comparing results.

Due to the layer-building process, horizontally and vertically oriented specimens will normally indicate the range of mechanical properties to be expected in bulk material, so it is recommended to test both. Horizontal specimens need to be built on support structures, so at least in this case post-machining is recommended, for which sufficient machining stock should be added. Vertical specimens can also be built net-shape and tested without post-machining (for example only applying shot-peening). This will typically give a larger scatter of results. As with all manufacturing methods, it should be remembered that the mechanical behaviour of real three-dimensional parts is not only determined by the bulk material properties, but also by surface roughness and other geometric effects, such as stress-concentrations at corners. This is especially relevant for fatigue behaviour.

DMLS is still a young production method compared to casting, machining etc., so the volume of measured mechanical properties data is still comparably small. EOS continues to measure and publish data, especially for new materials and parameter sets. EOS also does its best to gather additional data measured by users of EOSINT machines, in order to continually add to the statistical data base.

References

[1] Note: the data given in the quoted examples are results from specific measurements. For current guidelines and specifications of EOS products, please refer to the valid material data sheets, system manuals etc.

About the authors

Michael Frey studied materials science at University of Augsburg, Germany, where he focussed on solid state physics and solid state chemistry. He gained his Masters degree in materials science and joined EOS in 2008. He works in the DMLS Materials and Process Development group at EOS GmbH, and has performed extensive investigations into mechanical properties of DMLS parts.

Mike Shellabear graduated in mechanical engineering at Loughborough University of Technology, England, where he also gained his Ph.D in vibration analysis using laser interferometry. In 1991 he joined EOS, Germany, as Engineering Manager for 3D Optical Metrology, later taking over responsibility as Market Development Manager and then Assistant to the Management Board. Following that, he was appointed Product Manager for the Direct Metal Laser Sintering (DMLS) technology and became its Vice President in 2006. He has more than 18 years of experience in the Rapid Prototyping & Manufacturing industry.

Lena Thorsson has a Masters degree in metallurgy and materials engineering from the Royal Institute of Technology, Stockholm, Sweden. After working ten years in various R&D environments and mainly within the field of Rapid Prototyping & Manufacturing, she joined EOS in 2008. She now works in the DMLS Materials and Process Development group at EOS Finland.