Influence of process parameters and part orientation on mechanical properties for DMLS manufactured Stainless steel AISI 316L

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Abstract

The paper is dedicated to test campaign of stainless steel AISI316L (14404) samples manufactured by direct metal laser sintering technology (DMLS). DMLS represents cutting edge manufacturing technology of dimensionally complicated components. In recent years, this technology is implemented into the civilian sector of products with high added value, i.e. molding, aviation and medical industry. Commercialization of this technology is limited by high investment cost and lack of confidence in the quality of printed products. Test build composed of tensile test bars and V-notched impact specimens was designed and manufactured in order to verify materials properties. Attention was also paid to surface roughness, geometry, uniformity of microhardness and internal structure. The spatial anisotropy of mechanical properties dependence was revealed. Laser focusing level towards the level of melting offset (focus move) and its impact on tensile properties were investigated.

Key words: additive manufacturing, direct metal laser sintering, stainless steel, tensile test, notched bar impact testing, anisotropy

1. Introduction

Additive manufacturing has great potential in the production of functional prototypes and serial production of complex shaped components such as channels for conformal cooled molds, nozzles, made to measure implants and airfoils. Production speed-up or even cost reduction of products currently manufactured in complicated assemblies - brazed or welded parts can be obtained by the introduction of additive laser manufacturing.

All materials used in aircraft and medical industry have to pass extensive certification and their safety and operational reliability must always be verified. Very little additive components is actually introduced into operation for these reasons and many of them still remains in the stage of prototyping. [1]

In other less pioneering industries parts usually do not have to undergo so extensive testing. Despite the potential of weight reduction, shorter lead times, structural optimization and maybe cost reduction additive manufacturing was not yet fully implemented. There is a need to consider DMLS advantages and technology limitation early at the design stage of the product. Technological, materials and mechanical properties of DMLS products can differ from conventionally produced material (forging, casting, etc.)

Mechanical properties of DMLS produced test samples made of AISI 316L stainless steel was investigated below.

2. Stainless steel CL 20ES

Stainless steel powder labeled Concept Laser CL20ES is commercially available and designed for LaserCUSING 3D printers of the same manufacturer. CL 20ES is an austenitic stainless steel with chemical composition according to: 1.4404, X 2 CrNiMo 17 13 2, 316L. CL20ES is low carbon stainless steel suitable for welding and subsequent heat treatment due to sensitization resistance.

For elimination of internal stresses following heat treatment is prescribed: heat up to 550°C/3 hours; dwell time 6 hours; slow cooling in the oven or at ambient atmosphere. [2]

Table 1. *Chemical composition.*

Component	Indicative value (%)
Fe	Balance
Cr	16,5 – 18,5
Ni	10 – 13
Mo	2 – 2,5
Mn	0 – 2,0
Si	0 – 1,0
P	0 – 0,045
C	0 – 0,030
S	0 – 0,030

Table 2. *Mechanical and physical properties. [2], [3]*

Property	CL20ES data sheet	Conventional material (min.)
Yield point Re [N/mm^2]	[1] 470	205
Tensile Strength Rm [N/mm^2]	[1] 570	515-
Elongation A [%]	[1), 2)] >15	40
Young's modulus E [N/mm^2]	[3] approx.. 200.10^3	200.10^3

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Thermal conductivity λ [W/mK]	[3] approx.. 15	14
Hardness	[4] 20 HRC	<215 HB
[1] Tensile test at 20°C according to DIN EN 50125 [2] By using a special heat treatment a higher elongation can be achieved. [3] Specification according to the material manufacturer's data sheet. [4] Hardness test according to DIN EN ISO 6508		

3. Design of experiment

3.1. Build parameters

Concept Laser M2 Cusing machine was used for test build manufacturing. M2 Cusing is middle-class machine with 250x250x280 mm build envelop. Experimental build was performed at Misan s.r.o. (CL official Czech reseller). Process parameters of test build was as follows:

Table 3. *Process parameters.*

Layer thickeness	30 µm
Exposition of plane	200 W, 800 mm/s
Exposition of contour	180 W, 1600 mm/s
Beam diameter	0,15 mm
Beam overlapp	0,15x0,15 = 0,225 mm^2
Focus level (variable)	**- 3 mm / 0 mm**

3.2. Geometry of test samples

Tensile test specimen geometry fully respects gage section according to ASTM E8 (Standard Test Methods for Tension Testing of Metallic Materials). 6 mm diameter round bars with gage length five times the diameter was proposed. Central cylindrical part was extended from 30 to 45 mm in order to have enough space for reflex strips of laser extensometer (Fig. 1)

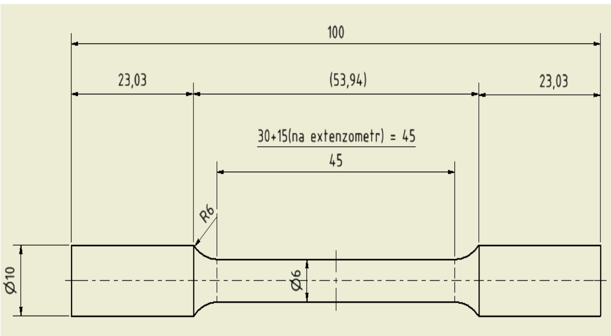

Fig. 1. *Tensile test bar – ASTM E8 modification.*

V-notched impact test samples were printed as block 10x10x55 mm with additional stock per surface. Test samples were subsequently machined (notch, functional surfaces) in order to meet dimensions, roughness and GPS requirements of ČSN ISO 148-1.

3.3.Experimental build layout

Altogether 15 pieces tensile round bars and 20 Charpy impact V-notch test samples were manufactured. Orientation a focus level parameter represent the main variables. Stress relieving acc. to CL20ES datasheet was performed in order to eliminate internal stresses. Surface discoloration occurred due to use of atmospheric furnace (Fig. 3)

Table 4. *Test sample roadmap.*

Orientation	**Type**	**Focus level**	**#pcs**
vertical	tensile	- 3	5
vertical	tensile	0	5
45	tensile	-3	5
vertical	charpy	- 3	5
vertical	charpy	0	5
horizontal	charpy	- 3	10

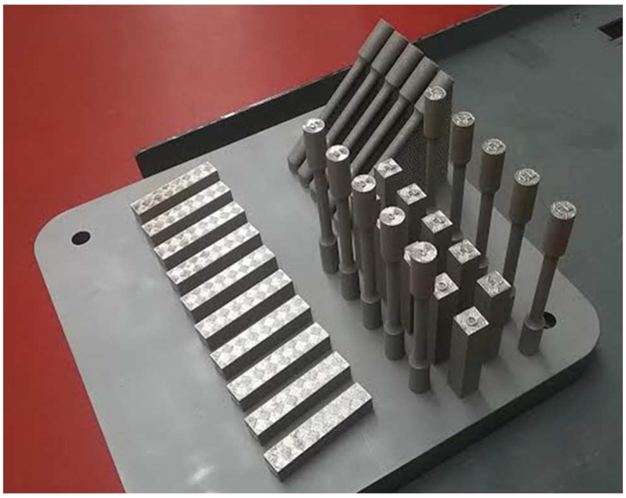

Fig. 2. *Building platform with test samples before annealing.*

4. Experimental analysis

4.1. Surface roughness and GPS

Roughness and contour measurement at a measuring station with MahrSurf *XCR* 20 was used. Straightness of tensile test bar was investigated for vertical and 45° orientation bar on evaluation length of 50 mm. The deterioration was observed in case of building on support structure under 45° angle:

- vertical orientation (FL= -3): 0,11 mm
- 45° angle (FL= -3): 0,16 mm

In terms of profile roughness samples printed horizontally showed the best results. The worst results was achieved in case of tilted surfaces. Surfaces after DMLS are usually subjected to further surface finishing technology otherwise cannot be considered as functional.

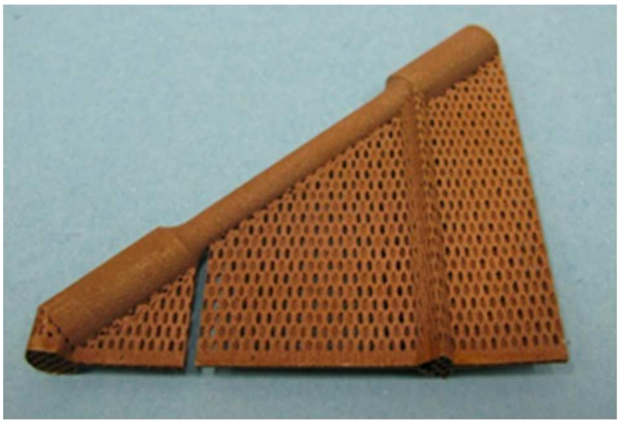

Fig. 3. *Tensile test bar printed under 45°angle before breaking away the supports – surface discoloration after annealing.*

Table 5. *Typical roughness parameters.*

Roughness parameters [µm]						
Orientation	**Ra**	**Rz**	**Rt**	**Rp**	**Rv**	**RSm**
vertical	13,76	88,20	115,14	46,20	42	2854,79
45°	16,09	93,960	126,01	53,68	40,28	303,75
horizontal	12,14	77,99	106,26	40,67	37,32	466,01

4.2. Tensile test

The test was carried out acc. to DIN EN ISO 6892-1. Test specimens are acc. to ASTM E8. The reason for this hybrid solution was cracking in transition radius (neck) when using CSN ISO geometry during previous tests. Therefore the bodies are selected according to ASTM E8, to avoid this. The test was performed on the machine LabTest 5.100SP1. Measurement was done at room temperature t = 20 ° C.

3 sets of samples (Table 4) was subject to tensile test. Scope of the experiment enabled to evaluate anisotropy of the material and effect of focus level move to mechanical properties.

Test samples printed tilted by 45° exhibited:

- higher Rm by 13,5% (689 vs. 607 N/mm^2)
- higher Re by 15,5% (550 vs. 476 N/mm^2)
- lower A by 15,9% (37% vs. 44%)

In case of third group focus level was moved to the level of melting. Following differences against initial focus level -3 mm were revealed:

- higher Rm by 1,2% (615 vs. 607 N/mm^2)
- higher Re by 7,3% (511 vs. 476 N/mm^2)
- lower A by 1,25% (43% vs. 44%)

Effect of orientation of test bar exhibited significantly greater impact on mechanical properties than focus move. For comprehensive summary graph see Fig. 4.

4.3. Charpy impact toughness at room temperature

Three different directions of impact (related to the level of melting and sample orientation) was investigated. The aim of the experiment was detection of impact toughness KCV [J/cm^2] differences. Additional 5 samples was printed vertically using focus level 0 mm to be compared with standard FL -3 mm strategy. KCV [J/cm^2] is defined as absorbed energy [J] divided by surface under the notch. Designation of test samples:

- VERTICAL BUILD; notch axis parallel to the level of melting (Fig. 5)
- HORIZONTAL BUILD; FL -3 mm; notch axis (bottom) lies in particular level of melting (Fig. 6)
- HORIZONTAL BUILD; notch axis (bottom) oriented perpendicularly to melting levels (Fig. 7)

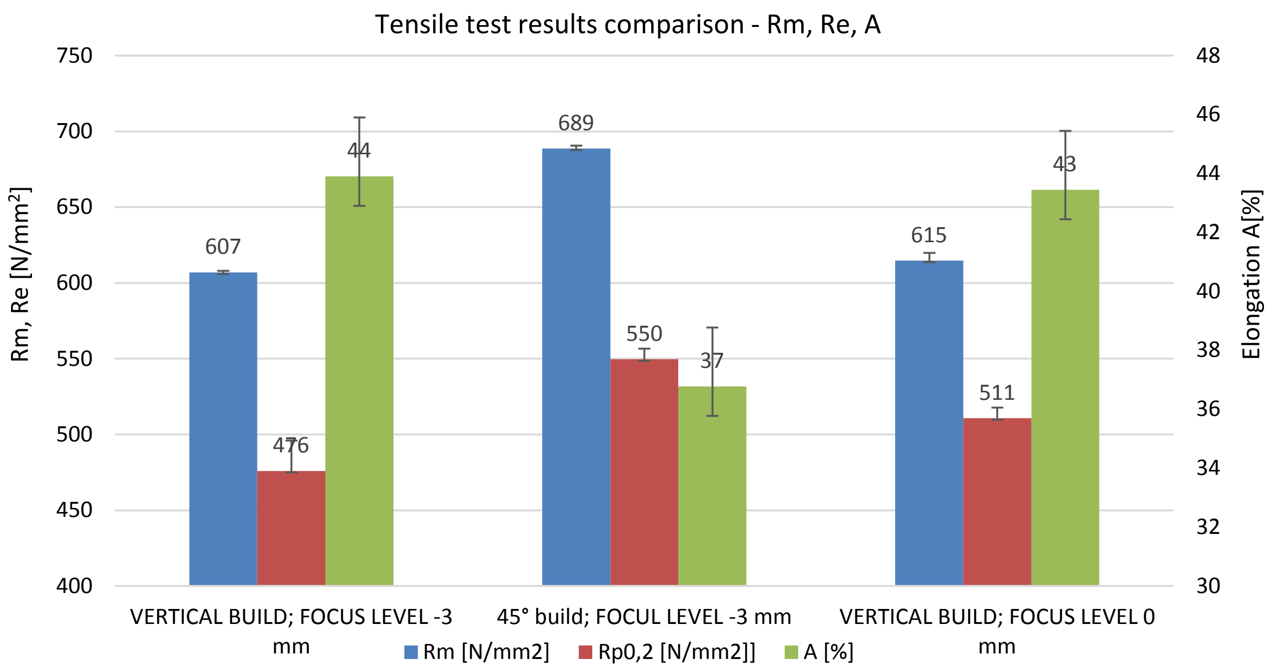

Fig. 4. *Tensile test results for vertical and tilted bars, effect of focus move*

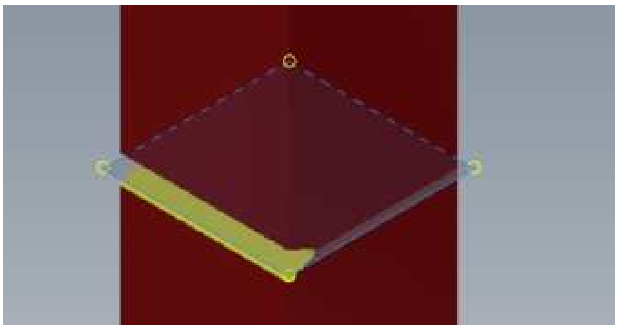

Fig. 5. *Notch orientation on vertical samples.*

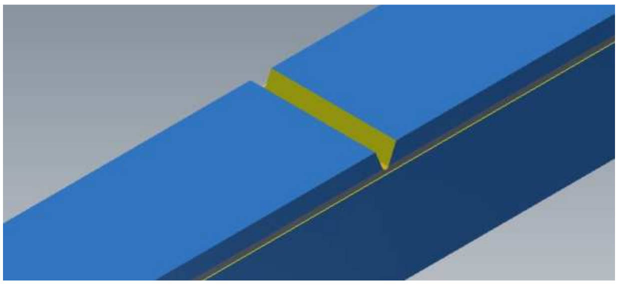

Fig. 6. *Notch orientation on horizontal samples in particular level of melting.*

Vertical samples printed with standard FL -3 mm strategy exhibited lowest impact toughness 127 J/cm^2. Slight increase was observed in case of horizontal samples regardless of the position of the notch. An improvement of 48% was achieved by introduction of FL 0 mm strategy on vertical samples (

4.4. Brinell hardness

With respect to anisotropy observed in previous analyses Brinell hardness was measured. Using load force 187,5 kp (1839 N) quenched ball of 2,5 mm in diameter was indented to the material (designated HBS 2,5/187,5 acc. to CSN EN ISO 6506-1).

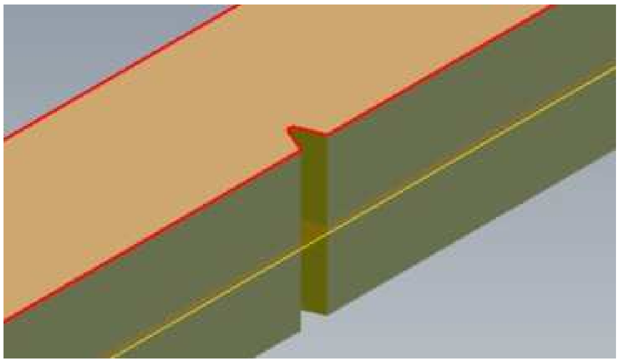

Fig. 7. *Notch orientation on horizontal samples perpendicular to melting levels.*

Again FL 0 mm strategy brought more positive results and hardness rise to 244 HBS 2,5/187,5 (vs. 217 in case of FL 0 mm), see Fig. 9.

Based on ASTM E140-97 hardness can converted to Rockwell HRC hardness to be compared with Concept Laser materials data sheet. FL -3 mm strategy closely didn't meet catalogue value (217 HBS ~ 19 HRC), whereas FL 0 mm did (244 HBS ~ 23 HRC).

4.5 Metallography

DMLS technology is sensitive to higher level of porosity. Test samples where cut in multiple directions and several metallographic samples were prepared both in polished and etched state. Etching was performed electrolytically by 10% oxalic acid.

Porosity is unmeasurable in case of all kinds of samples and in all directions (Fig. 10). Any other metallurgical defects such as cracks, bubbles, unmelted powder, lack of fusion inclusions were not revealed. In order to reduce internal stresses and distortion during cooling down "chessboard pattern" is often used. This pattern was made clearly visible after etching (Fig. 11). Microstructure differs a lot from conventional austenitic material with annealing twins.

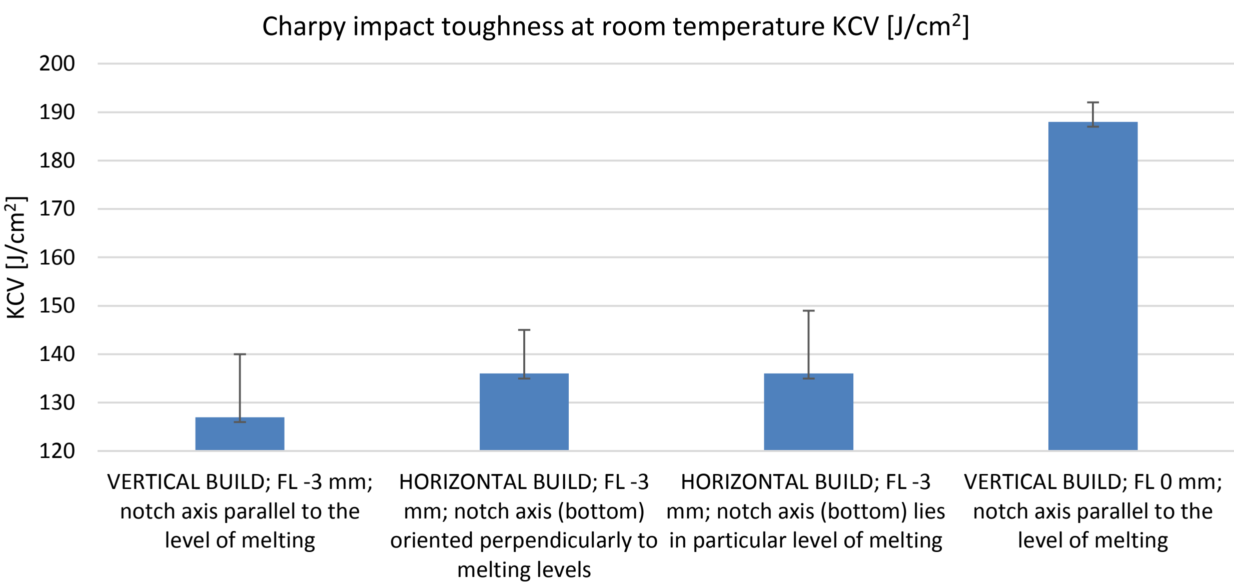

Fig. 8. *Notch orientation on horizontal samples perpendicular to melting levels.*

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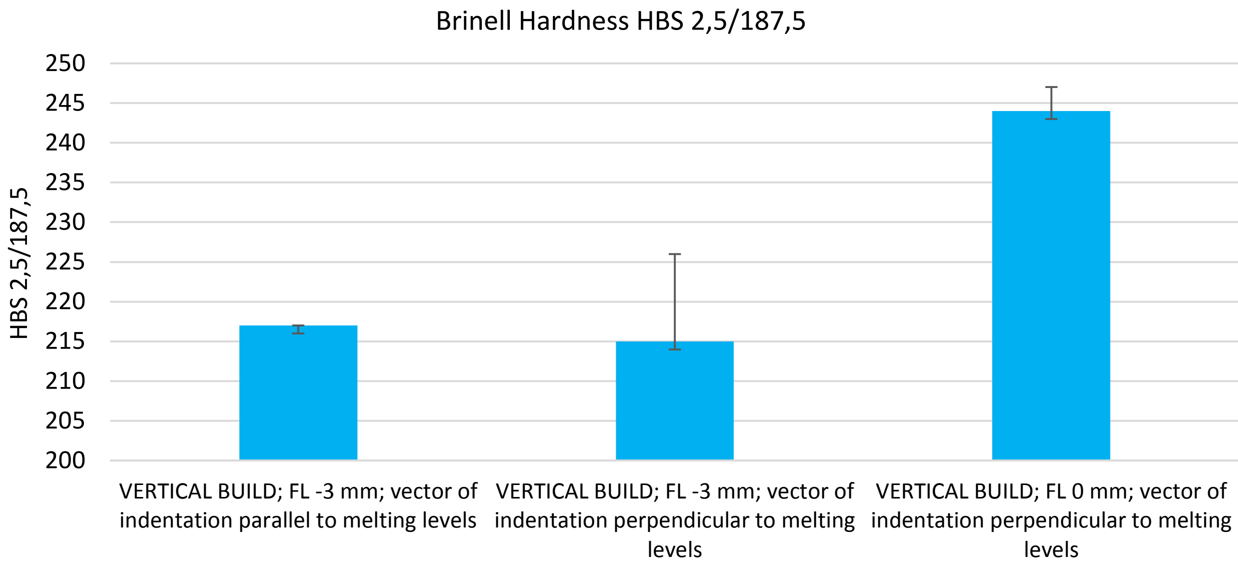

Fig. 9. *Average Brinell hardness overview.*

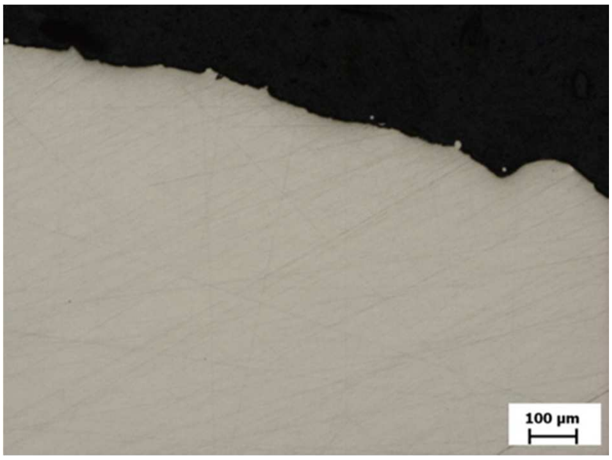

Fig. 10. *Radial cross-section of tensile test bar – free of porosity*

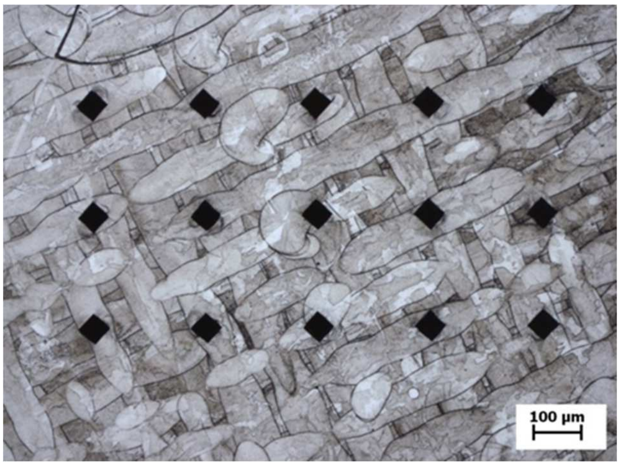

Fig. 11. *Etched condition with part of hardness matrix*

Material doesn't have polyhedral grain structure with obvious grain boundaries, but micrograph is created by very smooth "weld-like" individual traces of laser beam.

Microhardness mapping was performed on FUTURE-TECH FM-100 auto-loading and auto-reading device. Measurement was done in line with ČSN EN ISO 6507-1 specification using 500g loads (HV0,5). Matrix 5x10 indents was defined and outstanding measurement stability was achieved: 228±6 HV0,5.

5. Conclusion

DMLS technology is revolutionary and undoubtedly belongs to the fastest growing industries. In the development phase it is necessary to take into account real mechanical properties and their anisotropy. The situation is even more serious because there is a tendency to use additive manufacturing to topological optimization work and the creation of lightweight structures.

This article was aimed at initial verification of mechanical properties in different directions and determining the effect of laser focusing level shift towards the level of melting.

Tensile properties are not uniform in all directions. More than 10% increase of yield strength and ultimate strength was observed on 45°tilted round tensile test bars. This increase is at the expense of elongation decrease in almost the same percentage. Vertical direction enables to achieve slightly better geometrical product specifications and lower surface roughness in all respects. In case of hardness and impact toughness such a significant anisotropy was observed.

Focusing of the laser into the level of melting (FL = 0 mm) has unexpected impact on mechanical properties. In comparison with standard printing (FL = -3 mm) following differences were found:

- higher Ultimate Tensile Strength by 1,2%
- higher Yield Tensile Strength by 7,3%
- lower Elongation by 1,25%
- higher Charpy Impact Toughness by 48%
- higher Brinell Hardness by 12 %

Metallographical analysis confirmed possibility of manufacturing porosity-free products. Microstructural differences of DMLS and conventionally manufactured material were described. Stable results of microhardness

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mapping goes in line with uniform appearance on optical microscopy.

DMLS technology obviously provides the ability to modify material properties by alternation of various process parameters as well as conventional thermo-mechanical processes. The knowledge in the field of spatial anisotropy and ability to affect mechanical properties via change of process parameters represents the future step in topology optimization.

Acknowledgement

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List of symbols

A	elongation [%]
E	Young Modulus [N/mm^2]
FL	Focus Level [mm]
HBS	Hardness Brinell [-]
HRC	Hardness Rockwell [-]
HV	Hardness Vickers [-]
KCV	Charpy impact toughness [J/cm^2]
Re	Yield point [N/mm^2]
Rm	Tensile Strength Rm [N/mm^2]
λ	Thermal conductivity [W/mK]

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