Influence of the orientation of steel parts produced by DMLS on the fatigue behaviour

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Abstract.

The goal of this paper is to present studies of the influence of orientation of steel samples during additive manufacturing to their fatigue behaviour. The samples were produced from maraging steel EOS MS1 and stainless steel EOS PH1 using direct laser metal sintering technology. Three sets of samples were manufactured for each of the materials, with slopes of longitudinal axis of the samples being 0° (horizontal), 45° (slanted) and 90° (vertical) with respect to the horizontal building plane. All the samples were post-processed by heat treatment, shot-peening and machining, and tested according to the ISO 1143 standard. The curves for finite life domain were calculated using ISO 12107, and an estimation of the fatigue limit was made by Dixon-Mood method. The obtained results show that the building orientation has no significant influence on fatigue strength of maraging steel samples, while the stainless steel samples with slanted orientation of the axis have fatigue strength of up to 20% higher than the samples with horizontal or vertical orientation of the axis.

Keywords: fatigue behaviour, fatigue limit, S-N curve, additive manufacturing, DMLS, build orientation

1 Introduction

The paper is focused on studying of dependence of the fatigue strength on the orientation of steel samples during the process of direct metal laser sintering (DMLS). The study is a part of a research program, carried out within the framework of the Horizon 2020 project A_MADAM, that aims to improve knowledge about the dynamic behavior of additive manufacturing products [1].

Additive Manufacturing (AM) technologies represent a family of manufacturing technologies that, unlike more conventional subtractive and forming technologies, build a part by addition of raw material. The most important advantages of AM are their ability to be used for manufacturing of products with complex shape and the short lead-in times due to the independence of the manufacturing equipment on product. These advantages make AM technologies the optimal choice for production of prototypes ("rapid prototyping" applications) and small series of products ("rapid manufacturing" applications), but also leaves them as the only choice in numerous shape-integrated applications (lightweight products based on cellular design, tools with conformal cooling channels, highly efficient turbine blades and heat exchangers, etc.) [2].

All the current AM technologies have layerwise production principle, which means that a product is made by addition of successive parallel thin layers of material. Each layer represents a cross-section of the product, which is calculated by software for preparation of production on the basis of the CAD model. Regarding that the whole manufacturing process is controlled by the computer software, the AM technologies became available after "IT revolution" and massive production of low-cost computers by the end of XX century.

As the mechanical strength is an important characteristics of components of mechanical systems, the choice of AM technologies that are used for manufacturing of mechanical parts is limited to a narrow set of technologies that may process metals, alloys, high-performance polymers and composite materials. Such AM technologies are based on the principle of joining of the powder of material by high-energy beam, and they are called powder-bed-fusion technologies. The most common powder bed technologies are Direct Metal Laser Sintering, Selective Laser Melting and Electron Beam Melting that are used for processing of metals and alloys and the Selective Laser Sintering for processing of polymers and polymer-based composites [3]-[5].

Direct Metal Laser Sintering (DMLS) technology uses laser beam as the high-energy beam for melting of powders of iron, copper, nickel, aluminium and titanium alloys. The materials and their densities used in AM are comparable to metal alloys obtained by traditional technologies, which makes DMLS technology the most popular technology for AM production in automotive and aerospace industry, but also a preferable choice for production of advanced tools and cooling components. The key breakthrough in improving the DMLS technology was development of appropriate "scanning strategies", i.e. time order of the exposition of different parts of a layer to the laser-beam [6].

As all the other AM technologies, DMLS is still new, and the knowledge of the mechanical properties of the metal parts produced with AM technologies is still scarce. In the literature are mostly presented the results which describing the static characteristics and very few papers presents the fatigue testing of the parts produced with AM of the steel, titanium, aluminium and nickel alloys [7]-[19]. It is still not known if the calculation principles developed for traditional technologies may be applied to the parts manufactured by the DMLS technology, and not even if the parts manufactured by DMLS technology have deterministic behaviour regarding the fatigue strength. The questions of influence of the production process parameters and post-processing procedures to the dynamic behaviour of DMLS products are still open. On the other hand, the dynamic behaviour of products is critical in all automotive and aerospace applications, and this discrepancy between the existing and knowledge and needs was inspiration for the research and results presented in this paper.

2 Experiment

The conducted experimental study is based on ISO 1143 standard for fatigue testing by rotating bending [20]. This standard defines the testing procedure, the load scheme, and the sample geometry. The four-point bending load was selected as one of the possible loads defined by the standard, and the sample geometry for this type of testing is presented at the Fig. 1. The hourglass shape of the samples with 6 mm diameter at the gauge and 10 mm diameter at the head was chosen as the smallest shape recommended by the standard. With the selected testing strategy, the bending moment has constant value over the whole gauge length and stress is equally distributed within the gauge, as it is presented in Fig.2.

The samples were tested at the Alma Mater Labs of University of Bologna /Italy/, on the machine for four-point bending load shown in Fig. 2. All the tests were performed under reverse bending load (stress ratio R=-1) at the frequency of 60 Hz. Before testing, all the samples were measured to check their diameters at the gauge and at the head. Roughness measurement and throughout were also checked against nominal values provided by ISO 1143 standard. The initial stages of testing of each sample set were aimed at determining fatigue behaviour in finite life domain (-N relation) and rough estimation of fatigue limit. The modified Dixon staircase method was used to obtain more accurate estimation of fatigue limit with related maximum likelihood band [21]. The processing of data in finite life domain has been performed according the ISO 12107 standard [22]. Stress and life cycles were linearly interpolated in logarithmic coordinates. The lower and upper limits of the -N curves were determined based on standard deviation with probabilities of failure of 10% and 90% respectively for 90% confidence level. The series of failure and non-failure tests outcomes have then been processed by Dixon method for a life duration of 10 million cycles, which was set as the run-out limit.

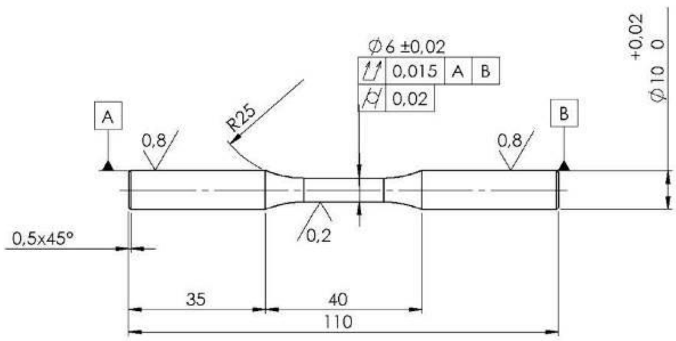


Fig. 1. Sample geometry 20.

Samples were produced by DMLS machine EOSINT M280 (EOS GmbH – Electro Optical Systems, Krailling-Munich /Germany/) in the "3D Impulse" laboratory of Faculty of Mechanical and Civil Engineering in Kraljevo /Serbia/. The EOSINT M280 machine is equipped with Ytterbium 200W laser.

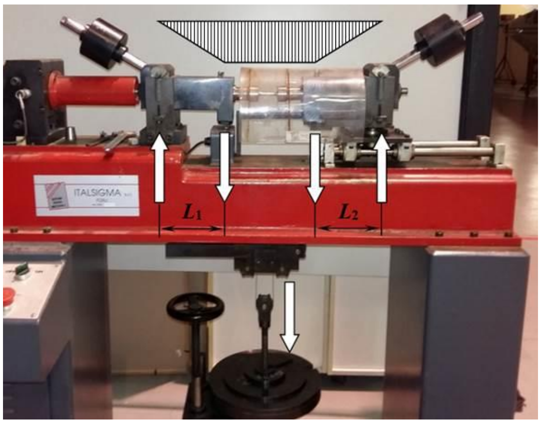


Fig. 2. Rotating bending machine with load distribution shematics.

Materials used for sample manufacturing are maraging steel EOS MS1 equivalent to DIN 1.2709 [23] and the stainless steel EOS PH1 equivalent to DIN 1.4540 [23].

For the selection of the production process parameters were used recommendations of the manufacturer of the machine for the presented materials. For MS1 maraging steel were applied process parameters defined according as EOS "Performance" set of the parameters, with the layer thickness set to 40 μm. For PH1 stainless steel was used the EOS "Surface" set of the parameters, with the layer thickness set to 20 μm.

During the manufacturing process, the samples were connected to the base plate with the support structures. These structures have double role, first to remove the heat from the manufacturing area, and second to keep the parts at fixed positions during the manufacturing process.

After the DMLS manufacturing process, the samples were first shot-peened by steel spheres with approximate diameter of 0.7 mm for the purposes of cleaning of residual powder and improvement of the surface quality. After the shot-peening, heat treatment was performed according to the EOS materials data sheet recommendations 23, which means that the MS1 samples were expoed to temperature of 490°C for 6 hours, while the PH1 samples were expoed to temperature of 482°C for 3 hours. Heat treatment considerably lowers the amount of residual stress accumulated in samples due to the temperature gradients that arise during the manufacturing process. Finally, after the heat treatment, the samples were removed from the building plate using wire electro discharge machine (EBM).

In order to study the influence of the samples orientation during the production process, six sample sets were manufactured, a three sets for each of the two materials. During the production, the samples of each of the three sample sets had different orientations of the longitudinal axis with respect to the building plane. The longitudinal axis of the samples of the first set were normal to the horizontal building plane (vertical axis-denoted by "V"), the longitudinal axis of the samples of the second set were parallel to the horizontal building plane (horizontal axis-denoted by "H"), while the longitudinal axis of the samples of the third set were inclined to the horizontal building plane by the angle of 45^0 (slanted axis-denoted by “S”), as it is shown in the **Error! Reference source not found.**. In this way, the samples with vertical axis had layers normal to the longitudinal axis, and the samples with horizontal axis had the layers parallel to the longitudinal axis.

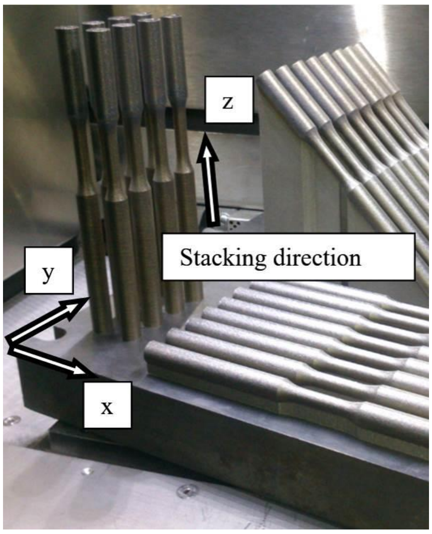


Fig. 3. Samples orientation on the base plate

All the produced samples have the diameters increased by 1 mm for MS1 and 2 mm for PH1 samples. The increased diameters enable to achieve the surface quality required by the ISO 1143 standard by additional machining.

The complete list of the manufactured samples is presented in the Table1.

Table 1 Produced number of the samples for testing

Orientation of the longitudinal axis	Material (thickness of the allowance for machining)	
	Maraging steel MS1 0.5mm	Stainless steel PH1 1mm
Vertical	MS1-V: 8 samples	PH1-V: 10 samples
Horizontal	MS1-H: 8 samples	PH1-H: 10 samples
Slanted	MS1-S: 8 samples	PH1-S: 10 samples

3 Results

The results of the fatigue testing are presented in **Error! Reference source not found.**2 (MS1 and PH1 samples). In the table is given the information about the longitudinal axis orientation of the sample.

Table 2. Results of testing of samples made from MS1 and PH1

Vertical							
Sample	Stress [MPa]	Life [cycles]	Failure	Sample	Stress [MPa]	Life [cycles]	Failure
MS1-V1	699	2277295	Y	PH1-V1	651	4834809	Y
MS1-V2	665	3374203	Y	PH1-V2	711	1871476	Y
MS1-V3	596	6090458	Y	PH1-V3	590	108926	Y
MS1-V4	524	-	N	PH1-V4	590	68686	Y
MS1-V5	560	-	N	PH1-V5	470	-	N
MS1-V6	560	-	N	PH1-V6	560	43729	Y
MS1-V7	596	-	N	PH1-V7	530	-	N
				PH1-V8	560	2807208	Y
				PH1-V9	530	2564861	Y
				PH1-V10	500	5047111	Y
Horizontal							
Sample	Stress [MPa]	Life [cycles]	Failure	Sample	Stress [MPa]	Life [cycles]	Failure
MS1-H1	699	3780607	Y	PH1-H1	420	-	N
MS1-H2	665	4926903	Y	PH1-H2	550	144726	Y
MS1-H3	579	-	N	PH1-H3	524	167829	Y
MS1-H4	610	8225283	Y	PH1-H4	500	-	N
MS1-H5	579	1642162	NV	PH1-H5	500	728708	Y
MS1-H6	579	-	N	PH1-H6	475	8423284	Y
MS1-H7	610	9262114	Y	PH1-H7	651	47315	Y
Slanted							
Sample	Stress [MPa]	Life [cycles]	Failure	Sample	Stress [MPa]	Life [cycles]	Failure
MS1-S1	699	1368541	NV	PH1-S1	640	-	N
MS1-S2	665	1042346	NV	PH1-S2	670	8344160	Y
MS1-S3	550	-	N	PH1-S3	640	-	N
MS1-S4	579	8997765	Y	PH1-S4	670	-	N
MS1-S5	699	3582162	Y	PH1-S5	700	-	N
MS1-S6	665	4309539	Y	PH1-S6	880	573080	Y
MS1-S7	550	-	N	PH1-S7	730	9012402	Y
MS1-S8	579	-	N	PH1-S8	790	4974052	Y
				PH1-S9	820	1776278	Y
				PH1-S10	850	497854	Y

For each of the sample orientations, the results of testing of each of the samples from the sample set are described by the sample identifier (column “Sample”), the nominal stress value at the gauge (column “Stress”), the observed number of cycles (“Life”) and by the final outcome of the test (column “Failure”). In the last column, the failure outcome is indicated by “Y”, the run-out outcome is indicated by “N”, while the “NV” indicates that the test is not valid because the break occurred at the head, instead at the gauge, of the sample (**Error! Reference source not found.**). The samples without indication of the testing outcome were not tested because they were broken during machining process (two samples from MS1 and three samples of PH1).

Since DMLS manufacturing process is expensive, at the initial experiment plan consisted of eight samples per set, as this was considered as the minimum number size of a set to obtain finite life domain curve and fatigue limit value. At the time of planning, there was no indication of potential problems that could arise during machining or testing process. After the problems appeared with the MS1 samples that were tested first, the number of the samples in the PH1 sets was increased to ten.

Fig. 4. Failure on sample head

The number of the samples that passed the planned test is given in Table 3.

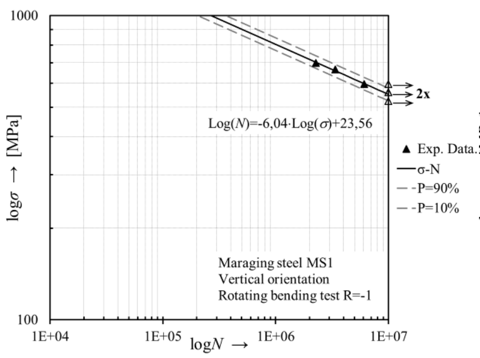
Table 3. Final number of tested samples

Orientation of the longitudinal axis	Material and thickness allowance for machining	
	Maraging steel MS1 1mm	Stainless steel PH1 2mm
Vertical	MS1-V: 7 samples	PH1-V: 10 samples
Horizontal	MS1-H: 7 samples	PH1-H: 7 samples
Slanted	MS1-S: 8 samples	PH1-S: 10 samples

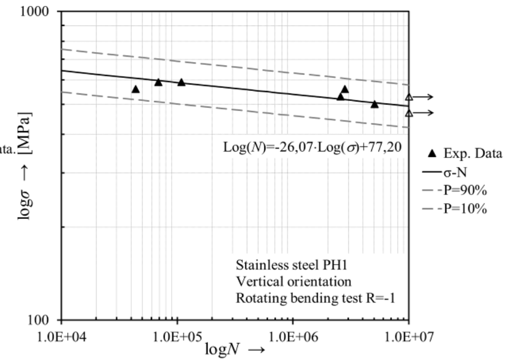
4 Discussion

4.1 σ-N curves

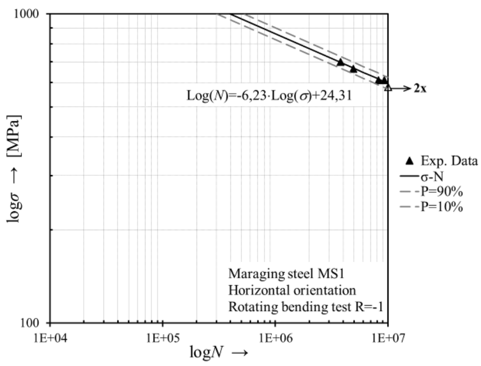
The results were processed according to the ISO 12107 standard to determine curves in finite life domain. The bending stresses and the corresponding number of cycles to failure were presented in log-log diagram, and the σ-N curves were retrieved using linear regression. Run-outs are indicated by arrows.



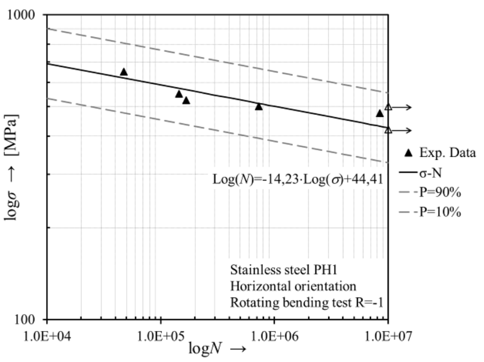
(a) MS1 vertical



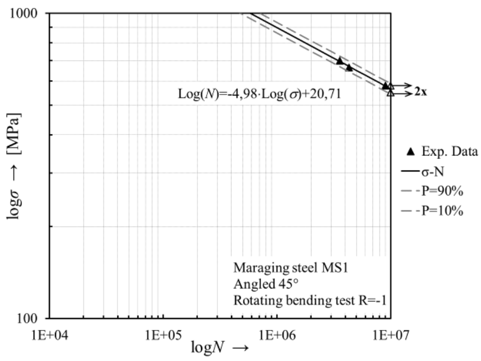
(d) PH1 vertical



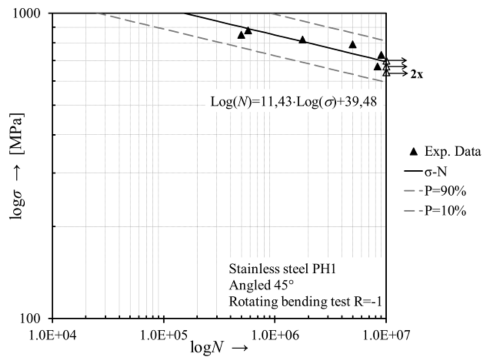
(b) MS1 horizontal



(e) PH1 horizontal



(c) MS1 slanted



(f) PH1 slanted

Fig. 5. σ-N curves for maraging steel MS1 and stainless steel PH1

If more than one run-out occurred at the same stress level, the number of run-outs is written at the end of the arrow (for example “2x” indicates 2 run-outs). Details about material type, sample orientations and type of load are also included in diagrams. Six plots are presented at **Error! Reference source not found.** 5. The three vertical plots on the left side present the trends of the σ-N curves derived from testing of the MS1 samples for with vertical, horizontal and slanted axis ((a), (b) and (c) respectively). The three vertical plots on the right side are trends of the σ-N curves derived from testing the PH1 samples with vertical, horizontal and slanted axis ((d), (e) and (f) respectively). This three by two array of plots makes easy to compare the influence of the building orientation (by columns) and the results of different materials (by rows).

By comparison of the graphs (a), (b) and (c) at the **Error! Reference source not found.**, it can be notices that the slopes of the garphs are very similar for all three MS1 sample orientations. It can also be noticed that their run-outs are at similar stress levels and that the probability bands are narrow (close to σ-N curve).

The results of the PH1 samples tests are strikingly different. The most important difference is that the slope of the σ-N curve for samples with slanted axis is not similar to the slopes of the σ-N curves of the samples with vertical and horizontal samples. The obtained results suggest that the PH1 samples with horizontal and vertical axis seem to be more sensitive to dynamic loads than PH1 samples with slanted axis. Further difference in comparison with MS1 samples is that the run-outs of PH1 samples with slanted axis occured at higher stress values than run-outs of the PH1 samples with horizontal or vertical direction (and MS1 samples for that matter). The third difference in comparison with MS1 samples is that the probability bands for all three PH1 sample orientations are wider than for the MS1 samples. Finally, the results of the PH1 sample tests in finite life domain show larger data scatering than the results of the MS1 samples.

4.2 Fatigue limit (FL)

Without of the post-processing procidure(in the “as-built” state) the ultimate tensile strenght (UTS) was 1100 MPa for MS1 samples and 1050 MPa for PH1 samples 23. After the post-processing by age hardening the UTS os MS1 and PH1 become 1930 MPa and 1310 MPa, respectively 23. It may be noticed that, while the UTS of the materials differ by about only 5% in the as-built state, the age hardening causes substantial difference between the UTS of the materials, raising it to 47% in favour of MS1 [23].

The fatigue limit values were calculated with 95.5% confidence level using the modified Dixon staircase method for all six sample sets. Comparative diagram of FL for MS1 samples with the three axis orientations is given at Fig. 6. The FL ispresented with the bar graphs with appropriate confidence bands considering twice standard deviation. It can be noticed that all three sample sets have close values of FL.

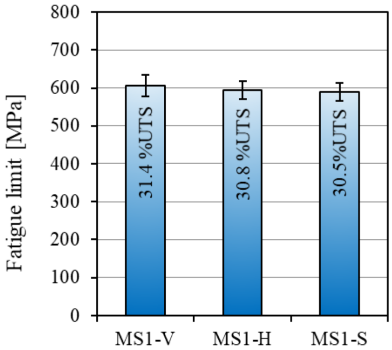


Fig. 6. Fatigue limits for MS1

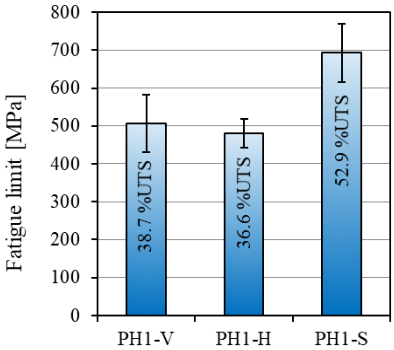


Fig. 7. Fatigue limits for PH1

While MS1 samples show consistent FL around 30% of UTS regardless the orientation of the longitudinal axis during production, the PH1 samples show different behavior. The samples with vertical and horizontal axis have similar estimated FLs of 507.4 MPa (38.7% of UTS) for vertical orientation and 479.85 MPa (36.6% of UTS) for horizontal orientation. The PH1 samples with slanted axis, on the other hand, have estimated FL of 692.5 MPa, which is 52.9% of UTS. It is unexpected that even if UTS of PH1 is lower than for MS1, the PH1 samples with slanted axis have higher FL value than MS1 sample sets. The fatigue limits of PH1 samples with all three orientations of the axis are compared in the bar graph on Fig. 7, with their confidence intervals considering the twice standard deviation. One may notice that for all the samples except the PH1 samples with slanted orientation have FL/UTS ratios much lower than the commonly accepted 50% value for metallic materials 23, 25.

5 Conclusion

The paper presents results of analysis of influence of build orientation to the fatigue strength of parts manufactured by direct metal laser sintering (DMLS). Six sample sets, three per material type, were manufactured on EOSINT M280 DMLS machine and all were machined to final dimension according ISO 1143 standard for rotary bending testing. The obtained results of testing were sufficient to construct and process σ–N curves with their confidence bands (for 10% and 90% failure probability and 90% confidence level) in finite life domains and fatigue limits for all six sample sets involving 49 samples. The fatigue behaviour of the DMLS produced samples shows deterministic nature which leads that the standard methodologies for calculation of the fatigue strength may be applied.

The statistically processed results for maraging steel MS1 have indicated that part orientation has no significant influence on fatigue strength in finite or infinite life domain. FL were estimated to be close to 30% of UTS for this material. Regarding the stainless steel PH1, the processed results show higher FL/UTS ratio close to 40% for the samples with horizontal and vertical axis. These FL are considerably lower than FL of MS1 samples with corresponding orientations, which is in accordance to lower values of UTS for PH1 samples than for MS1 samples. These results suggest that, in general, the DMLS production process leads to products with lower fatigue resistance than traditional technologies. The most probable reason for this is presence of increased amount of material defects, porosities and irregularities in microstructure of the DMLS material [18],[19]. The most intriguing results, however, were obtained for PH1 samples with slanted axis. With fatigue limit of 692.5 MPa, which is around 53% of UTS, these samples showed the highest fatigue strength of all studied sample sets. The obtained result suggests that the proper selection of the building orientation of the parts can improve their fatigue resistance even if the basic material has lower UTS. Therefore, the DMLS may have even some positive effects to fatigue strength of the products. The most probable explanation of the observed effect is that boundaries between layers prevent or extend crack propagation [17]-[19].

Further research is needed to better understand the effects of DMLS microstructure, residual stresses, the optimal post-processing methodologies and studies of other materials.

Acknowledgments

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