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EFFECTS OF MACHINING ON THE FATIGUE STRENGTH OF STEEL COMPONENTS PRODUCED BY DMLS

Abstract: *Direct metal laser sintering (DMLS) is the additive manufacturing (AM) technology that allows production of metal machine components with complex geometry. Due to the layer-wise production principle, its products usually require post-processing, predominantly machining, to achieve uniform or requested surface quality. Given the increasing application of DMLS technology in industry and insufficient published data about the effects of machining on the fatigue properties of steel, the focus of this research is put to investigation of the influence of thickness of allowance for machining to fatigue strength of DMLS products.*

Previous studies revealed significant differences in the mechanical behaviour of samples made of different kinds of steels, both during production and testing. Unlike the samples made from maraging steel, the samples made from stainless steel often deformed during cooling due to the strong residual stresses, and revealed dependence of mechanical properties on orientation during production process.

To improve the understanding of the differences, fatigue testing according to ISO 1143 was performed on samples manufactured from two kinds of steel, maraging steel 1.2709 and stainless steel 15-5. Twelve sets of samples were tested with the aim to investigate the effects of machining allowance and build orientation according to an extensive DoE experimental plan.

Key words: *Additive manufacturing, fatigue strength, machining allowance, build orientation*

1. INTRODUCTION

The paper presents a part of research related to the Horizon 2020 project "Advanced design rules for optimal dynamic properties of additive manufacturing products - A_MADAM", which represents a systematic study of fatigue behaviour of steel parts produced by Direct Metal Laser Sintering (DMLS) technology.

DMLS belongs to family of powder bed fusion (PBF) additive manufacturing (AM) technologies, where a product consist of subsequent layers, which are obtained by melting of powder particles. During the fast process of melting and cooling, the new layer is joined to the previous layer of the product. The melting is performed by focused laser beam, and the produced heat causes high temperature gradients in material during the manufacturing (also called "building") of the product. It is clear that the bonds within a layer and between the layers are not of the same strength, and the anisotropy of the produced material is reduced by heat treatment of the products.

The aim of the A_MADAM project is to establish design rules for the best fatigue performances of DMLS parts. The interest for fatigue behaviour is driven by increasing production of lightweight, shape-integrated and optimized components in automotive and aerospace applications, which are known to subject the machine parts to dynamic loads. For these reasons, the previous research of the fatigue behaviour were focused to light metals and their alloys, in particular aluminium, magnesium and titanium. However, DMLS is also used in tooling applications, and the advanced tools are made from DMLS steels. Finally, DMLS is used also for production of advanced medical tools from stainless steel, and that were the reasons who motivated the research in the A_MADAM project.

2. EXPERIMENT

2.1. Material and specimen

Specimens were designed according to the experimental plan for testing campaign that comprised rotating bending following the ISO1143 [1] standard. The smallest dimension allowed by the standard, with diameter at gauge 6 mm, was chosen to reduce production costs. A drawing of the specimen with indication of all its dimensions and tolerances is shown in Fig. 1.

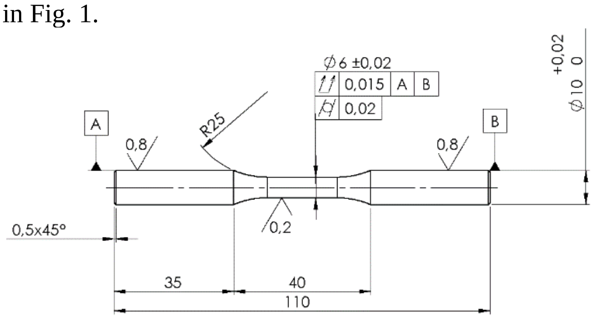

Fig. 1. Specimen with 6 mm diameter at gage in agreement with ISO 1143 standard [1]

The experimental campaign involved two steels with chemical compositions given in Table 1: the maraging steel EOS MS1, equivalent to DIN 1.2709 [2], and the stainless steel EOS PH1 equivalent to DIN 1.4540 [2].
The experiments for each of the two materials were arranged using a 3-by-2 scheme, with three levels for the building orientation (horizontal (H), vertical (V) and slanted (S) (with an angle of 45 degrees to the base plate), and two levels for thickness of allowance (0.5 mm and 3mm for PH1 and 1mm and 3mm for MS1), with a total of 2x(3x2) specimen sets and 109

specimens. The complete experimental plan is summarized in Table 1. Each of the sets consisted of 7 to 13 specimens. The number of specimens in each of the sets is also reported in Table 1.

The specimens were manufactured by DMLS machine EOSINT M280 equipped with Ytterbium fibre laser with 200 W power and emitting 0.2032 mm thickness and 1064 nm wavelength infrared light beam. The process takes place in an inert environment and the scanning speed may range up to 7000 mm/s. The production chamber machine has a horizontal baseplate with dimensions 250×250 mm, and a production height of 325 mm.

Knowing that the materials and DMLS technology are relatively new, and wishing that the results of this research be used by majority of users of DMLS technology, the applied process parameters were selected according to the standard recommendations of manufacturer of the material. In particular, the layer thickness was set to 20 μm for the stainless steel (EOS "Surface" set of the parameters) and 40 μm for maraging steel (EOS "Performance" set of the parameters). A parallel scan strategy with alternating scan direction was adopted. Between the subsequent layers, the scanning direction was rotated by approximately 70°, in order to prevent or reduce in-plane property variations.

		Material Thickness of allowance for machining			
		PH1		**MS1**	
		1 mm	3 mm	0.5 mm	3 mm
Orienta- tion	Hori- zontal	PH_{H1} 7 sp.	PH_{H3} 9 sp.	$MS_{H0.5}$ 7 sp.	MS_{V3} 10 sp.
of the of the	Verti- cal	PH_{V1} 10 sp.	PH_{V3} 10 sp.	$MS_{V0.5}$ 7 sp.	MS_{H3} 13 sp.
longitu- dinal axis	Slan- ted	PH_{S1} 10 sp.	PH_{S3} 9 sp.	$MS_{S0.5}$ 7 sp.	MS_{S3} 10 sp.

Table 1. Design of the experimental campaign (DoE)

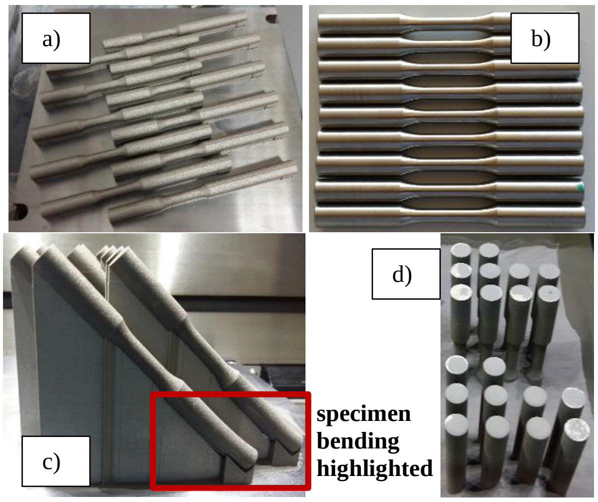

Fig. 2. Chosen stages of PH1 specimens' production: a) Set PH_{H1} after DMLS process, b) Set PH_{H3} after machining and finishing, c) Set PH_{S1} before detachment, d) Sets PH_{V1} and PH_{V3} during residual powder removal

During the building process, the samples were connected to the base plate with the support structures. These structures have double role: to transfer the heat from the laser scanning area to base plate, and to keep the parts at fixed positions during the manufacturing process.

After the manufacturing by DMLS process, the samples were treated by micro-shot-peening by steel spheres with diameter of approximately 0.7 mm, under 5-bar flow pressure, for the purposes of cleaning of residual powder, closing the pores and improvement of the surface quality. After that, they were heat-treated according to the EOS materials data sheet recommendations [2]. MS1 specimens were exposed to temperature of 490°C for 6 hours, while the PH1 specimens were exposed to temperature of 482°C for 3 hours. After cooling process in fresh air, the specimens were removed from the building plate using wire electro discharge machine, and then, underwent machining and refining by grinding with the aim of achieving the roughness, dimensional specifications and improving of the fatigue performance. Figure 2 shows chosen stages of the manufacturing process.

The production of PH1 specimens required considerably more efforts and resources than production of MS1 specimens because of the large tensile residual stresses, caused by higher temperature gradients during production of PH1 and higher thermal expansion coefficients of PH1. The temperature gradients in DMLS production of PH1 are higher because the thicknesses of layers are twice smaller. As a result, some PH1 specimens bent and even detached from the supports, remaining permanently deformed (Fig.2c).

2.2. Test procedures

The aim of fatigue testing was to determine the S-N curves and the fatigue limits (FL) for each of the sets of specimens. The 4-point rotary bending tests with load ratio R=-1 and frequency of 60 Hz were performed. The initial stages of testing of each of the sets was aimed at determining fatigue behaviour in finite life domain by S-N curve. A life duration of 10^7 cycles was set as run-out. The results in the finite life domain were analysed according to the Standard ISO 12107 standard [4]. The staircase method was then used to determine the fatigue limit (FL). For this purpose, the series of failure and not-failure events was processed by the Dixon method [3].

Before the fatigue testing, according to the standard 1143, hardness, dimensions and roughness of the samples were measured. At the end of the experimental campaigns, fractographic and micrographic analyses were performed with two aims: 1) to identify of the crack nucleation point and of the zones of stable and unstable crack propagation, and 2) investigation of the possible presence of porosities, inclusions, spots of oxides and micro-cracks [5, 6].

3. SUMMARY OF RESULTS AND DISCUSSION

The obtained results have been statistically processed by the ANOVA method to assess the influence of the two observed factors and their interaction. The effects of the building orientation are presented in other research papers [5, 6] and in this paper we shortly discuss the influence of the thickness of allowance for machining.

Figures 3 and 4 show the graphs with fatigue curves in the finite life domain for all tested sets, presented by material type and levels of the DoE plan. The fatigue limits are presented by material type in bar graphs in Figure 5.

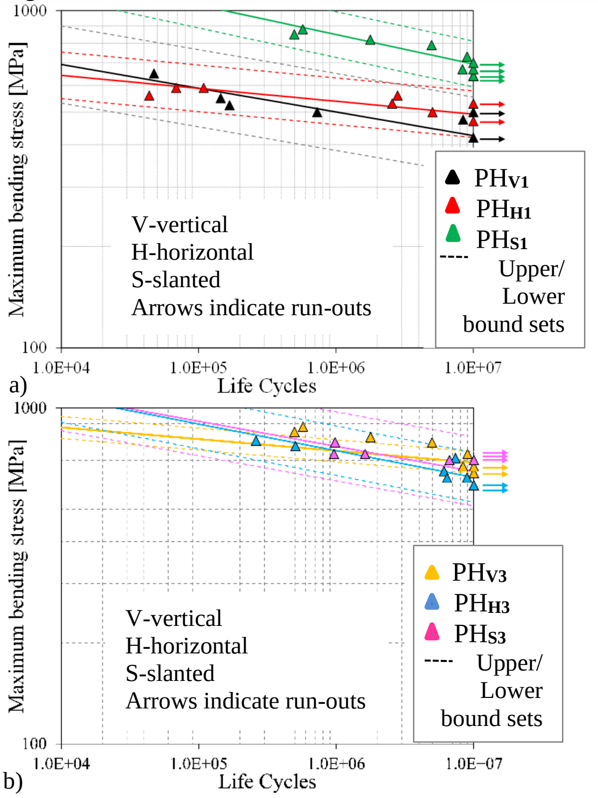

Fig. 3. S-N curves in the finite life domain for 3+3 sets of specimens manufactured from PH1 (two-factor design for one allowance level): a) allowance is 1 mm, and b) allowance is 3 mm

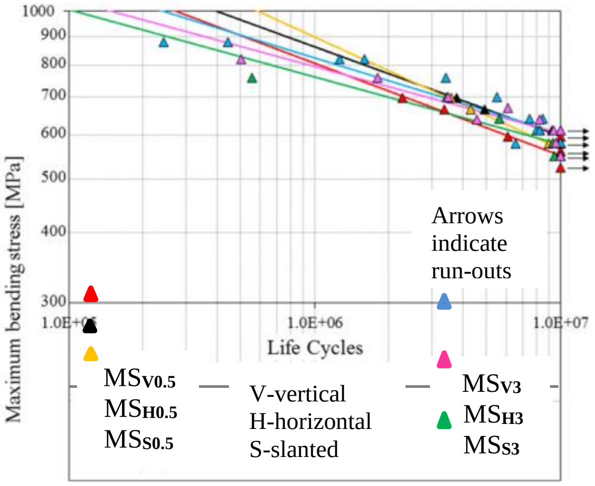

Fig. 4. S-N curves in the finite life domain for six specimens sets from MS1 (two-factor design for two allowance levels, 0.5 and 3 mm)

The results of the ANOVA analyses have shown that all the differences between the data describing different sets of maraging steel MS1 are negligible (3% significance level), meaning that the two factors do not have significant influences and that no interaction occurs. The ANOVA table for two factor design regarding maraging steel MS1 is given in top part of Table 2, and high levels of p (>>0,005) indicate the insignificance of the studied factors. The result means that the heat treated maraging steel MS1 has an isotropic fatigue behaviour and that its fatigue response does not exhibit any significant variation for different thicknesses of machining. The average value of the fatigue limit, involving all six sets, is 590 MPa, corresponding to 29% of the ultimate tensile stress (UTS) of the studied material following the heat treatment.

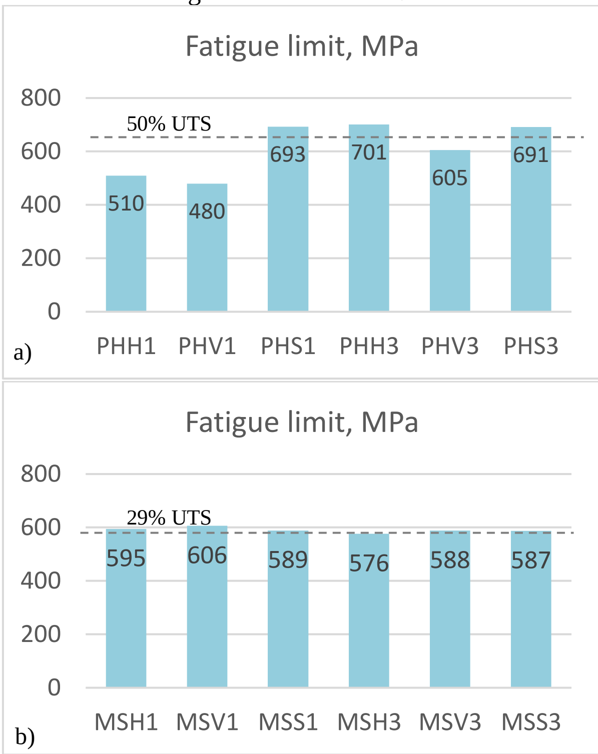

Fig. 5. Bar graph summarizing the fatigue limits for the six specimen types: a) stainless steel PH1, b) maraging steel MS1

	Factor	***p***
MS1	Orientation – 3 levels vertical-horizontal-slanted	0,65
	Thickness of allowance	0,04
	Interaction	0,28
PH1	Orientation – 3 levels vertical-horizontal-slanted	$4.0{\cdot}10^{-5}$
	Thickness of allowance	$3.1{\cdot}10^{-4}$
	Interaction	$3.4{\cdot}10^{-4}$
PH1	Orientation – 2 levels vertical-horizontal	0.45
	Thickness of allowance	$1.9{\cdot}10^{-5}$
	Interaction	0.22

Table 2. Two-factor ANOVA analysis

Conversely, the analyses of the results for samples sets made of stainless steel PH1 indicate that both of studied factors have influence on fatigue response. The results of two-factor ANOVA analysis with 3 orientation levels and 2 levels of allowance for the PH1 stainless steel is summarized in Table 1-middle, where low values of p in the last column indicate that both of the factors and their interaction are highly significant. If ANOVA analysis is applied to the 2x2 scheme that excludes the slanted specimens (Table 2-down), then significance of the building orientation ceases (and so does the interaction of factors), while the thickness of allowance retains its high significance. This result confirms the influence of the thickness of the allowance for machining, and indicates the differences due to building orientation appear only when slanted specimens are taken into account. It should noticed that increase of thickness of allowance for machining generally has the effect of increasing the fatigue limit (Fig.6 -right).

A probable reason for improvement of fatigue resistance of PH1 made by DMLS with increase of the thickness of allowance for machining could be removal of the surface layers with high residual stresses (Fig.2). The detrimental effects of residual stresses to fatigue behaviour are well known and documented [7].

Finally, it should be pointed out that the optimization of the considered factors leads to a fatigue strength that is compares favourably to that of wrought material, with ratio between the fatigue limit and the ultimate tensile strength being over 50%.

4. CONCLUSIONS

The paper discusses the influence of the machining to fatigue strength of steels manufactured by DMLS. The study is based on fatigues testing of specimens of two different kinds of steels, stainless steel PH1 and maraging steel MS1 which were manufactured with different levels of thicknesses for allowance for machining: 1 and 3 mm for PH1 and 0.5 and 3 mm for MS1. Since the DMLS production is essentially an anisotropic process, the testing sets had also to consider variation of the building direction of the samples. Specimens belonging to individual sets were manufactured simultaneously, and all the specimens underwent micro-shot-peening and heat treatment recommended by manufacturer of the material.

The obtained results were analysed using ANOVA methodology, and the results have shown that machining has different influences to different types of steel. While the thickness of allowance increases fatigue strength of the stainless steel PH1 in finite life domain and FL, at least in the range of thicknesses 1-3 mm, the influence of thickness of allowance in the range 0.5-3 mm to fatigue behaviour of maraging steel MS1 could not be established.

Since the fatigue behaviour of steels is driven by surface quality, presence of the defects in microstructure and residual stresses, the obtained results suggest that the positive influence of thickness for machining is related to removal of the surface layers with internal stresses. Furthermore, the difference of influences of thickness of allowance for machining to different types of steels suggests that the factors that influence residual stresses, such as thermal expansion coefficients and thickness of the layers, should be carefully considered when fatigue behaviour of materials manufactured by DMLS is of interest.

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