PAPER REF: 7214

HOW BUILD ORIENTATION AND THICKNESS OF ALLOWANCE MAY AFFECT THE FATIGUE RESPONSE OF DMLS PRODUCED 15-5 PH STAINLESS STEEL

Dario Croccolo[1], Massimiliano De Agostinis[1], Stefano Fini[1], Giorgio Olmi[1(*)], Nebojsa Bogojevic[2], Snezana Ciric-Kostic[2]

[1]Department of Industrial Engineering (DIN), University of Bologna, Bologna, Italy
[2]Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia
[(*)]*Email:* giorgio.olmi@unibo.it

ABSTRACT

The present study is focused on the fatigue strength of 15-5 PH Stainless Steel, built by Direct Metal Laser Sintering. Six-specimen sets were manufactured, mechanically and thermally treated and tested under rotating bending fatigue. The study investigates the effects of the build orientation (parallel, perpendicular, or 45° inclined with respect to the vertical stacking direction) and of allowance for machining (1mm or 3mm at gage). The results, processed by an ANOVA methodology, indicate that allowance for machining has a beneficial effect on the fatigue response. Removing the surface irregularities, averagely leads to a 19% enhancement of the fatigue limit. The build orientation also becomes beneficial, when the slanted samples are included in the experiment. In this case, a fatigue strength increase up to 20% can be achieved. Further developments will include the investigation of the effects of heat and surface treatments, involving also further materials in the study.

Keywords: rotational bending, fatigue strength, stainless steel, direct metal laser sintering, build orientation, allowance for machining.

INTRODUCTION

Nowadays, there is an increasing interest towards Additive Manufacturing (AM) techniques, as this technological process is potentially capable of producing even complexly shaped parts in a relatively short time (Scott-Emuakpor, 2015; Abe, 2001). In addition, the parts can be easily built, with a high level of flexibility, starting from a CAD model (Rafi, 2013; Santos, 2006; Herderick, 2011). AM offers further advantages arising from a faster time-to market, a high efficiency in material utilization with a particularly reduced powder waste (Razavi, *in press*). A possible drawback of AM techniques consists in the residual stresses that may be generated during part building. Therefore, suitably shaped supports are usually applied to safely attach the built part to a rigid base-plate, thus preventing its movements through the powder bed or distortions induced by the residual stress field (Rafi, 2013). Moreover, AM produced parts are likely to be affected by defects, being often due unmolten particles, entrapped gas bubbles, or missing fusion (Razavi, In Press; Vilaro, 2011). Direct Metal Laser Sintering (DMLS) by EOS and Selective Laser Melting (SLM) by MTT Technologies Group can be mentioned among the most important AM processes for metals (Herderick, 2011). Nowadays they can be regarded as basically the same technique, being grouped under the powder bed fusion technologies. They both have wide applications to metals, as pointed out in recent review studies (Herderick, 2011; Lewandowski, 2016).

The aforementioned base-plate is usually placed on a horizontal plane, and the parts are generated along a vertical stacking direction. A number of studies, involving different materials and AM processes have been focused on the possible effect of the build direction on the mechanical static and fatigue responses of the manufactured parts. Some researchers investigated a possible influence of the angle between the main axis of inertia (namely, the longitudinal axis of the specimen) and the stacking direction on the part strength (Edwards, 2014; Edwards, 2015). The possible effect of the build direction on the fatigue response, considering both the fatigue limit and the fatigue strength in the finite life domain, was also the topic of a previous study by the same authors. This research involved MS1 Maraging steel parts, built, considering three different orientations, with post-manufacture mechanical and heat treatments. An experimental campaign led to the result that the fatigue response is not significantly affected by the build direction, since, for Maraging steels, post-manufacture treatments have a great role at removing sources of anisotropy (Croccolo, 2016).

Further research in the literature was focused on the mechanical behaviour of 15-5 PH stainless steel parts. This type of steel is commonly used in applications such as aircraft components, or for parts under high pressure or working in harsh corrosive environments, including valves, shafts, fasteners, fittings and gears (Rafi, 2013; Abdelshehid, 2007). A lack of studies on the effect of the build direction on the fatigue properties of this steel can be pointed out. In particular, the research (Rafi, 2013) was focused on the build orientation effect on the static response only. Additional studies (Ozbaysal, 1994; Palanisamy, 2016; Wu, 2002) deal with the static properties of 17-4 PH stainless steel, focusing on the effects of build direction and microstructure, whereas very few deal with the fatigue response of this steel. Moreover, just two build orientations are considered in the aforementioned studies, except for one, mainly dealing with low cycle fatigue (Brandl, 2012).

The subject of this paper consists in an experimental study on the fatigue response of 15-5 PH stainless steel parts fabricated by the DMLS process. Two factors were considered: the build direction and the post-processing procedure. In particular, three different build orientations were considered, with different inclinations of the main axis of inertia of the parts with respect to the base plate. Regarding the post-processing procedure, the effect of allowance and subsequent machining, with different thicknesses of material to be removed was studied. This experimental plan derives its motivations from the previous study dealing with Maraging steel (Croccolo, 2016), which was focused on the effect of the build orientation, and from some recent studies, e.g. (Edwards, 2015; Zhang, 2017; Zhang, 2016; Van Hooreweder, 2012), which are starting to investigate the effects of the amount of material to be removed after sintering on mechanical properties. However, in these papers, the size effect of the block, from which the part is machined, is studied from the point of view of fracture mechanics. In particular the properties related to crack growth seem to be improved, when machining components from oversized blocks. Similar investigations dealing with high cycle fatigue properties are still missing. Issues of novelty also arise from considering three orientations with respect to the vertical stacking direction: horizontal, vertical and slanted.

EXPERIMENTAL

The experimental campaign was performed under rotating bending, following the ISO 1143 (ISO 1143, 2010) Standard. Specimens were designed accordingly, with reference to the cylindrical smooth geometry (with uniform cross section at gage). A drawing of the specimen is shown in Figure 1, with indication of all its dimensions and tolerances. The chemical composition of 15-5 PH stainless steel (PH1 stainless steel by EOSGmbH-Electro Optical Systems, Krailling/Munich, Germany) is provided in Table 1 (http://www.eos.info/material-m).
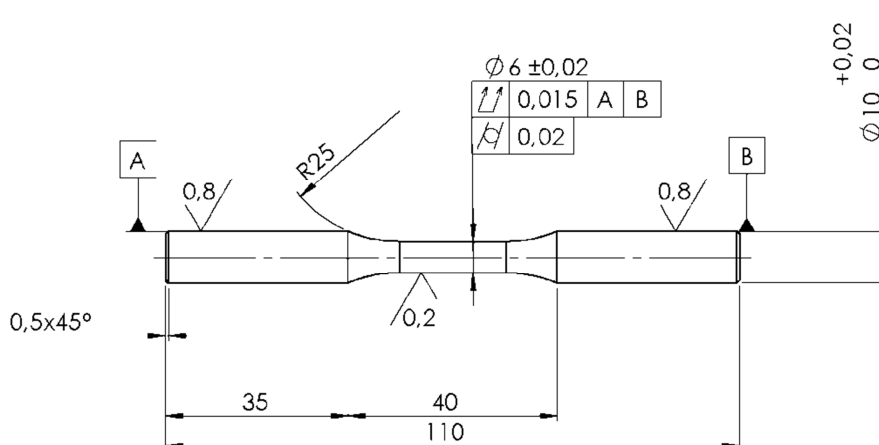
Fig. 1 - Technical drawing of the sample for fatigue tests under rotating bending (all dimensions in mm)

Table 1 - Chemical composition of 15-5 PH1 Stainless Steel by EOS

Cr [%]	Ni [%]	Cu [%]	Mn [%]	Si [%]	Mo [%]	Nb [%]	C [%]	Fe [%]
14-15.5	3.5-5.5	2.5-4.5	≤ 1	≤ 1	≤ 0.5	0.15-0.45	≤ 0.07	Balance

The specimens were manufactured by EOSINT M280 system (EOS GmbH - Electro Optical Systems, Krailling/Munich, Germany), equipped with Ytterbium fibre laser with 200W power and emitting 0.2032mm thickness and 1064nm wavelength infrared light beam. The process takes place in an inert environment and the scanning speed may range up to 7000 mm/s. The machine features a working space with 250×250 mm dimensions on the horizontal plane and a maximum height of 325 mm. The applied process parameters were defined according to the EOS Part Property Profile named "Surface". In particular, the layer thickness was set to 20 µm and a parallel scan strategy with alternating scan direction was adopted. For the subsequent layers the scanning direction was rotated by approximately 70°, in order to prevent or reduce in-plane property variations.

All the specimens underwent surface cleaning by micro-shot-peening, in order to close the pores that may be induced by laser sintering. Afterwards, the H900 heat treatment was performed (Rafi, 2013; http://www.eos.info/material-m), thus following the recommendations by EOS. For this purpose, the samples were kept at the temperature of 482°C for 2 hours after a ramp increase (from the room temperature) in 1 hour time. Finally, the specimens underwent machining and refining by grinding with the aim of accomplishing the roughness and dimensional specifications and of improving the fatigue performance.

Six specimen sets were manufactured: those of types #1 and #4 were built while lying horizontally on the base plate, therefore the angle between their longitudinal axis and the vertical stacking direction was 90°. Whereas, those of types #2 and #5 were built while standing vertically: in this case, the angle between their main axis of inertia and the stacking direction was 0°. Finally, the samples of sets #3 and #6 were built along a 45° inclined direction with respect to the base plate, so that the angle between their longitudinal axis and the vertical stacking direction was 45°. The difference between the samples of sets #1 and #4 is that the first ones were produced with the same shape as shown in Figure 1, with a 1mm uniform allowance both at the gage (diameter increased from 6 to 8 mm) and at the heads (diameter increased from 10 to 12 mm). The samples were then machined to meet the drawing specifications, regarding both dimensions and roughness. Conversely, the samples of set #4 were built with a cylindrical shape with 12 mm diameter over their entire length. It implies

that the allowance was 1mm at the heads and 3mm at the specimen gage. These samples also went through machining to meet the same specifications as in Figure 1: therefore, a higher thickness of material was removed at the gage with respect to the samples of type #1. The same difference applies also to sets #2-#3 (built with uniform allowance and reduced section at gage) and #5-#6 (built with cylindrical layout).

The described experimental plan can be regarded as a 2-factor experiment: the first factor, build orientation, was investigated over three levels (horizontal, vertical and slanted), whereas the second one, allowance (material thickness to be removed by machining) was considered at two levels (1 mm and 3mm at gage). This experimental plan is summarized in Table 2, with indication of sample set numbers and of short names to be used in the following. Each set was composed by 7 to 10 samples (the number of samples for each set is also reported in Table 2), considering that some samples were unfortunately damaged during manufacturing.

Table 2 - Experimental plan involving 2 factors (at 3 and 2 levels) and 6 treatment combinations

		Thickness of allowance for machining	
		1 mm	3 mm
Orientation of the longitudinal axis of the sample (during the building process)	Horizontal	Set #1 (H,1): 7 samples	Set #4 (H,3): 9 samples
	Vertical	Set #2 (V,1): 10 samples	Set #5 (V,3): 10 samples
	Slanted	Set #3 (S,1): 10 samples	Set #6 (S,3): 9 samples

The fatigue campaign made it possible to obtain the S-N curves and the fatigue limits (FLs). A staircase method was applied to determine the FL: for this purpose, the series of failure and not-failure events was processed by the Dixon method (Olmi, 2013; Dixon, 1983; Olmi, 2010; Van Hooreweder, 2012). A life duration of 10^7 cycles was set as run-out, based on the few available data on the fatigue response of sintered 15-5 PH stainless steel (Rafi, 2013). The Dixon method is an abbreviated staircase method that makes it possible to estimate FL even from a short series of nominal trials at staircase (four to six in this work). A confidence analysis (90% confidence level) was also performed based on the standard deviation of FL (scattering of the experimental results) and on the size of the sequence that led to its computation. The data in the finite life domain were processed according to the Standard ISO 12107 (ISO 12107, 2012): the stress and life were linearly interpolated in logarithmic coordinates. The lower and upper limits of the S-N curve have been determined, based on the standard deviation of the logarithm of the fatigue life. Respective failure probabilities of 10% and 90% were considered together with a 90% confidence level.

The specimens were tested under rotating bending fatigue by a rotary bending testing machine, where the specimen is loaded in the four-point bending configuration, so that bending moment Mb keeps constant over the entire sample length, and in particular at its gage (Olmi, 2013). The sample was clamped at its ends by a pressure of approximately 70 MPa (Croccolo, 2013; Croccolo, 2014). All the tests were conducted under fully reversed bending load (stress ratio R =- 1) at the frequency f of 60 Hz.

Fractographic and micrographic analyses were then performed with the aim of investigating the possible presence of porosities, inclusions, spots of oxides and micro-cracks. For this

purpose, a Stemi 305 stereo-microscope (by ZEISS, Oberkochen, Gernany) has been utilized for fractographies, whereas an Optiphot-100 optical microscope (by Nikon, Melville, NY, United States) has been applied for both micrographic and (more zoomed) fractographic analyses. In the case of micrographies, chemical etchings were performed by the following solution for a duration of 30s after heating in oven up to 90°C. 20 ml of Glycerol ($C_3H_8O_3$) were mixed with 10 cc of Nitric Acid (HNO_3), then 20 cc of Chloridric Acid (HCl) were mixed with 10 cc of Hydrogen peroxide (H_2O_2).
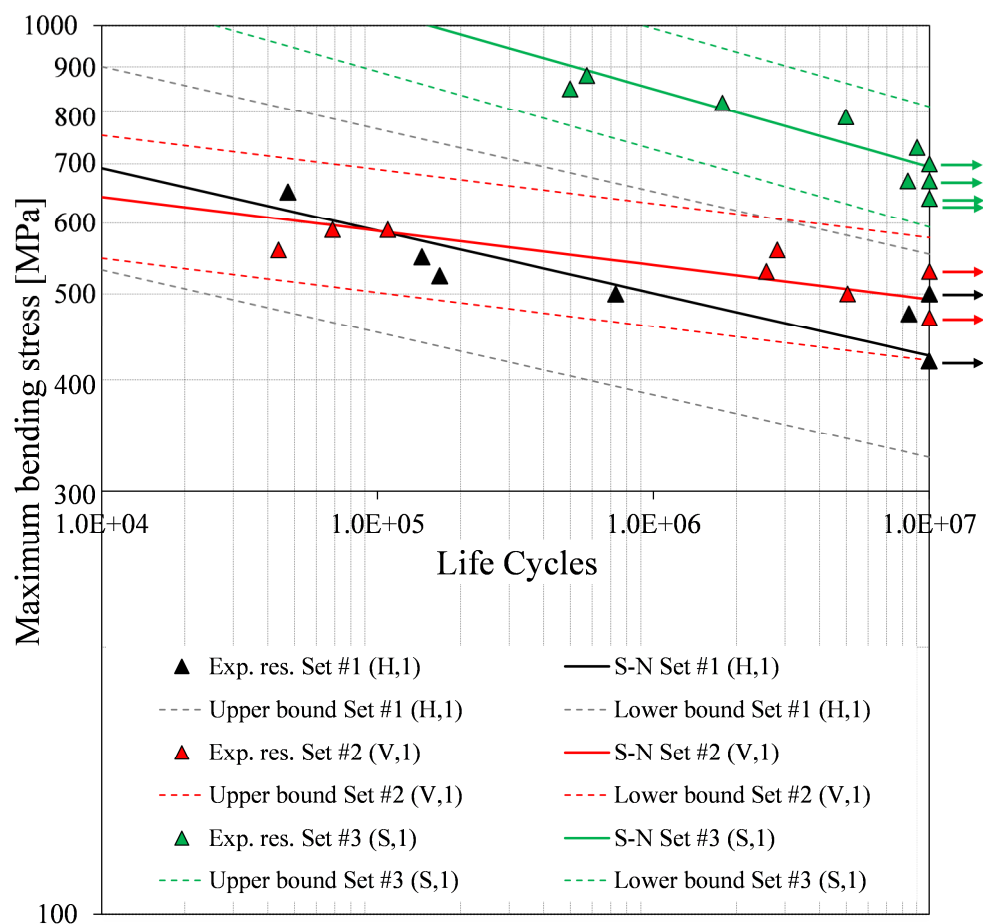

Fig. 2 - S-N curves for sample Sets #1 (H,1), #2 (V,1) and #3 (S,1) (arrows indicate run-outs): effect of the build orientation compared for reduced (1 mm) allowance for machining

RESUME OF THE RESULTS AND CONCLUSIONS

The following points are worth mentioning, concerning the performed experimentation and the achieved results.

Six sample sets have been manufactured: horizontally, vertically and 45° inclined with respect to the base plate, built with uniform 1mm allowance and with an incremented one, 3mm, at specimen gage (manufactured as cylindrical parts). This experiment can therefore be regarded as a 3-by-2 plan, involving two factors, build orientation and material thickness to be removed, respectively with three and two levels. The fatigue tests led to the determination of both the sloping parts of S-N curves and of the fatigue limits. The fatigue curves in the finite life domain for the three sample sets with 1 mm allowance are shown in Figure 2, whereas the

S-N curves for those with incremented thickness to be removed by machining are plotted in Figure 3. The fatigue limits, considering the aforementioned run-out of 10^7 cycles, are finally collected in the bar graph in Figure 4.
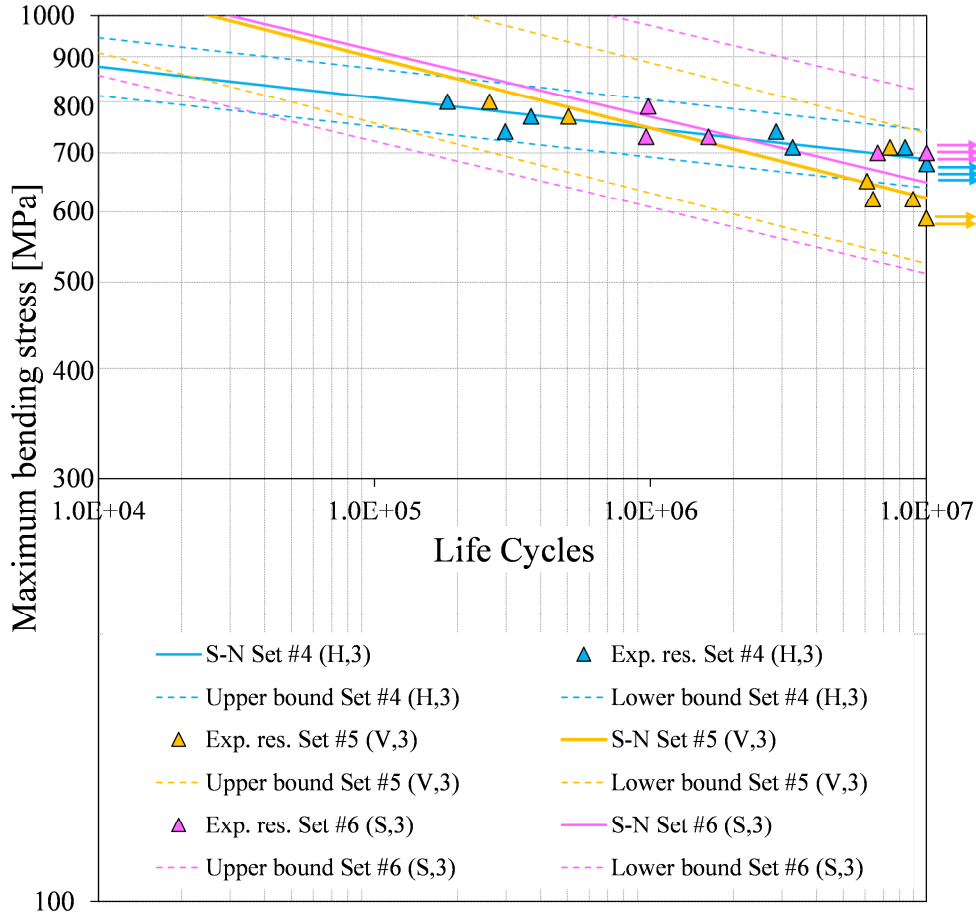
Fig. 3 - S-N curves for sample Sets #4 (H,3), #5 (V,3) and #6 (S,3) (arrows indicate run-outs): effect of the build orientation compared for incremented (3 mm) allowance for machining
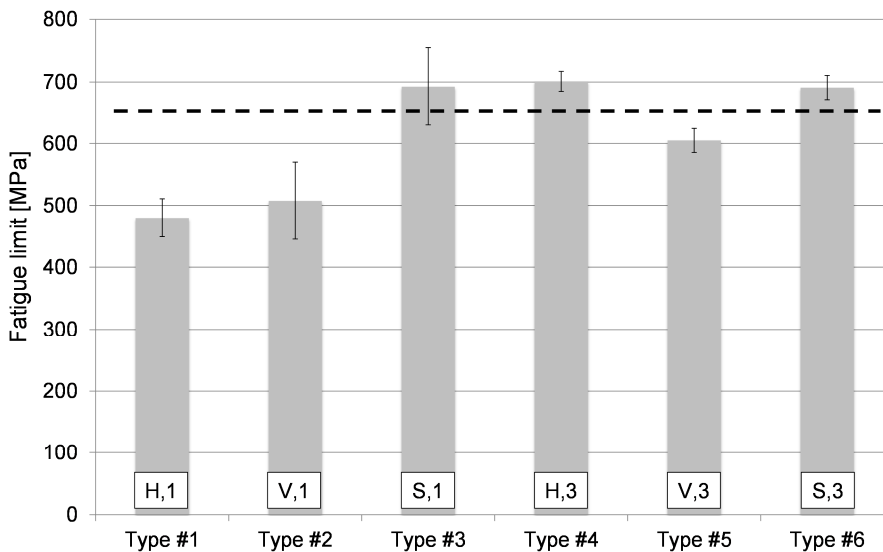
Fig. 4 - Fatigue limits for 10^7 cycles run-out plotted together with their confidence bands (95% confidence level)

The results have been processed by statistical methods (Olmi, 2012): the outcomes of the conducted analyses indicate that allowance has a significant effect at enhancing the fatigue response. Conversely, the build orientation does not have an effect, when just horizontal and vertical orientations are considered. However, this factor turns to be significant, as slanted samples are included in the experiment: this orientation proved to be able to improve the fatigue strength.

These results have been carefully discussed, to get a better awareness of the impact of the studied factors and of the stacking process on the fatigue properties. The retrieved outcomes indicate that machining makes it possible to remove the irregularities and residual stresses induced by the additive process, which are mainly concentrated at the surface layers (between the external contour lines and the inner solid portion). Moreover, the slanted orientation has the effect of reducing the notch effect due to defects arising from unmelted spots, powder residuals or scan errors due to lack of perpendicularity between the surface and the laser path. The overall amount of defects per layer is reduced and the resistance against crack propagation is also improved due to the layered structure. This issue has a noticeable impact on the mechanical response, considering that, taking advantage of build orientation, or removing the surface irregularities may lead to increments of the fatigue strength in the order of 20%. Moreover, it is worth noticing that the optimization of these factors leads to a fatigue performance that is well comparable to that of wrought material (ratio between the fatigue limit and the ultimate tensile strength around 50%). This is a very important point, especially with regard to the applications that combine the great advantages of additively produced parts (in particular, the remarkable drop of the time to market) and the need for a satisfactory structural strength.

Finally, fractography and micrography have shown that, despite heat treatments, the layered structure induced by the process is still well visible, which can explain the observed moderate effect of build orientation on fatigue. Micrographies depicting the microstructures on the build plane and along the stacking direction are shown in Figure 5.
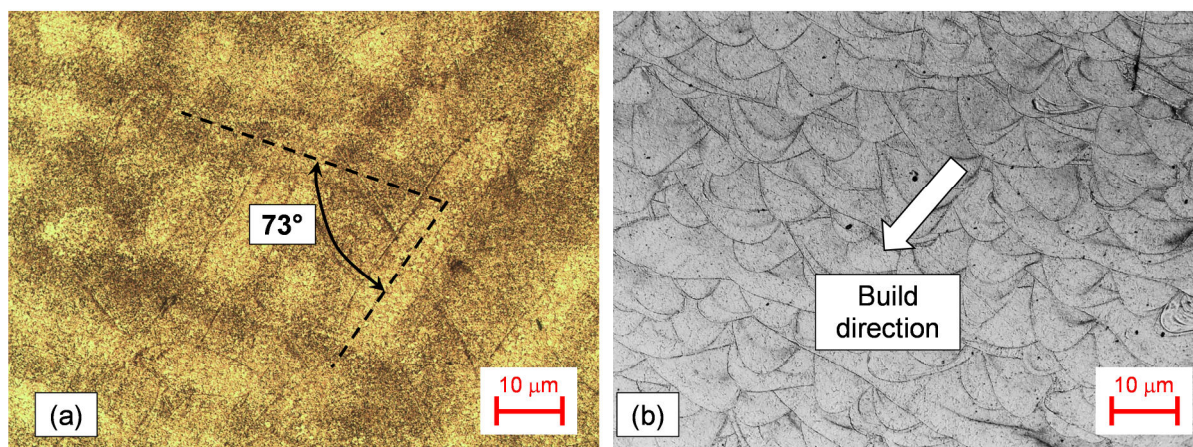

Fig. 5 - Micrographic analyses on horizontally built samples: (a) laser scans on the build plane (contiguous planes are visible, relative angle highlighted), (b) layers along the stacking direction

Further developments will include the investigation of the effects of heat and surface treatments, including also further materials in the study. Possible effects, in terms of the generation of oxidation spots and of voids, arising from the actual position of the parts in the build chamber will also be investigated.

Further details on the applied methodology, on the results and on the novel approach to data analysis are available in (Croccolo, 2018).

ACKNOWLEDGMENTS

REFERENCES

[1] Scott-Emuakpor O, Schwartz J, George T, Holycross C, Cross C, Slater J. Bending fatigue life characterisation of direct metal laser sintering nickel alloy 718. Fatigue Fract. Eng. Mater. Struct., 2015, 38, pp. 1105-1117.

[2] Abe F, Osakada K, Shiomi M, Uematsu K, Matsumoto M. The manufacturing of hard tools from metallic powders by selective laser melting. J. Mater. Process. Tech., 2001, 111, pp. 210-213.

[3] Rafi HK, Starr TL, Stucker BE. A comparison of the tensile, fatigue, and fracture behaviour of Ti-6Al-4V and 15-5 PH stainless steel parts made by selective laser melting. Int. J. Adv. Manuf. Tech., 2013, 69, pp. 1299-1309.

[4] Santos E, Masanari S, Osakada K, Laoui T. Rapid manufacturing of metal components by laser forming. Int. J. Mach. Tool Manu., 2006, 46, pp. 1459-1468.

[5] Herderick E. Additive Manufacturing of Metals: A Review. In Proc. of Materials Science and Technology (MS&T), October 16-20, 2011, Columbus, Ohio.

[6] Razavi SMJ, Ferro P, Berto F, Torgersen J. Fatigue strength of blunt V-notched specimens produced by selective laser melting of Ti-6Al-4V. Theor. Appl. Fract. Mec., In Press, DOI: 10.1016/j.tafmec.2017.06.021.

[7] Vilaro T, Colin C, Bartout JD. As-fabricated and heat-treated microstructures of the Ti-6Al-4V alloy processed by selective laser melting, Metall. Mater. Trans. A, 2011, 42A (10), pp. 3190-3199.

[8] Lewandowski JJ, Seifi M. Metal Additive Manufacturing: A Review of Mechanical Properties. Annu. Rev. Mater. Res., 2016, 46, pp. 151-186.

[9] Edwards P, Ramulu M. Fatigue performance evaluation of selective laser melted Ti-6Al-4V. Mat. Sci. Eng. A-Struct., 2014, 598, pp. 327-337.

[10] Edwards P, Ramulu M. Effect of build direction on the fracture toughness and fatigue crack growth in selective laser melted Ti-6Al-4V. Fatigue Fract. Eng. Mater. Struct., 2015, 38, pp. 1228-1236.

[11] Croccolo D, De Agostinis M, Fini S, Olmi G, Vranic A, Ciric-Kostic S. Influence of the build orientation on the fatigue strength of EOS maraging steel produced by additive metal machine. Fatigue Fract. Eng. Mater. Struct., 2016, 39, pp. 637-647.

[12] Abdelshehid M, Mahmodieh K, Mori K, Chen L, Stoyanov P, Davlantes D, Foyos J, Ogren J, Clark R Jr., Es-Said OS. On the correlation between fracture toughness and precipitation hardening heat treatments in 15-5PH Stainless Steel. Eng. Fail. Anal., 2007, 14, pp. 626-631.

[13] Ozbaysal K, Inal OT. Age-hardening kinetics and microstructure of PH 15-5 stainless steel after laser melting and solution treating. J. Mater. Sci., 1994, 29, pp. 1471-1480.

[14] Palanisamy D, Senthil P, Senthilkumar V. The effect of aging on machinability of 15Cr-5Ni precipitation hardened stainless steel. Arch. Civ. Mech. Eng., 2016, 16, pp. 53-63.

[15] Wu J, Lin C. Tensile and fatigue properties of 17-4 PH stainless steel at high temperatures. Metall. Mater. Trans. A, 2002, 33, pp. 1715-1724.

[16] Brandl E, Heckenberger U, Holzinger V, Buchbinder D. Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behaviour. Mater. Des., 2012, 34, pp. 159-169.

[17] Zhang X, Martina F, Ding J, Wang X, Williams S. Fracture Toughness and Fatigue Crack Growth Rate Properties in Wire + Arc Additive Manufactured Ti-6Al-4V. Fatigue Fract. Eng. Mater. Struct., 2017, 40 (5), pp. 790-803.

[18] Zhang J, Wang X, Paddea S, Zhang X. Fatigue crack propagation behaviour in wire+arc additive manufactured Ti-6Al-4V: effects of microstructure and residual stress. Mater. Des., 2016, 90, pp. 551-561.

[19] Van Hooreweder B, Moens D, Boonen R, Kruth J-P, Sas P. Analysis of fracture toughness and crack propagation of Ti-6Al-4V produced by selective laser melting. Adv. Eng. Mater., 2012, 14, pp. 92-97.

[20] International Organization for Standardization ISO 1143:2010. Standard - Metallic materials - Rotating bar bending fatigue testing. International Organization for Standardization (ISO), 2010, Geneva, Switzerland.

[21] http://www.eos.info/material-m.

[22] Olmi G, Freddi A. A new method for modelling the support effect under rotating bending fatigue: Application to Ti-6Al-4V alloy, with and without shot peening. Fatigue Fract. Eng. Mater. Struct., 2013, 36 (10), pp. 981-993.

[23] Dixon WJ, Massey F Jr.. Introduction to Statistical Analysis. McGraw-Hill, New York, United States, 1983.

[24] Olmi G, Comandini M, Freddi A. Fatigue on shot-peened gears: Experimentation, simulation and sensitivity analyses. Strain, 2010, 46 (4), pp. 382-395.

[25] Van Hooreweder B, Moens D, Boonen R, Sas P. The critical distance theory for fatigue analysis of notched aluminium specimens subjected to repeated bending. Fatigue Fract. Eng. Mater. Struct., 2012, 35, pp. 878-884.

[26] International Organization for Standardization ISO 12107:2012. Metallic Materials - Fatigue Testing - Statistical Planning and Analysis of Data. International Organization for Standardization (ISO), 2012, Geneva, Switzerland.

[27] Croccolo D, De Agostinis M, Olmi G. Fatigue Life Characterisation of Interference Fitted Joints. In: Volume 2B: Advanced Manufacturing, pp. 106-116, In Proc. ASME - American Society of Mechanical Engineers, ISBN: 9780791856192, San Diego (CA, United States), November 15-21, 2013, DOI: 10.1115/IMECE2013-63515.

[28] Croccolo D, De Agostinis M, Fini S, Morri A, Olmi G. Analysis of the Influence of Fretting on the Fatigue Life of Interference Fitted Joints. In: Volume 2B: Advanced Manufacturing. pp. 1-10, ASME - American Society of Mechanical Engineers, ISBN: 9780791846445, Montreal, Canada, 14-20 November, 2014, DOI: 10.1115/IMECE2014-38128.

[29] Olmi G. Low Cycle Fatigue Experiments on Turbogenerator Steels and a New Method for Defining Confidence Bands. J. Test. Eval., 2012, 40 (4), Paper ID JTE104548.

[30] Croccolo D, De Agostinis M, Fini S, Olmi G, Bogojevic N, Ciric-Kostic S. Effects of build orientation and thickness of allowance on the fatigue behaviour of 15-5 PH stainless steel manufactured by DMLS. Fatigue Fract. Eng. Mater. Struct., 2018, 41, pp. 900-916.