IS SURFACE FINISH REALLY DECISIVE FOR THE FATIGUE OF ADDITIVELY MANUFACTURED Ti ALLOY?

Michaela FOUSOVÁ [1], Dalibor VOJTĚCH [1], Jan DŽUGAN [2]

[1]*University of Chemistry and Technology, Prague, Czech Republic, EU*
fousovam@vscht.cz, vojtechd@vscht.cz

[2]*COMTES FHT a.s., Dobrany, Czech Republic, EU,* jan.dzugan@comtesfht.cz

Abstract

Powder bed techniques of additive manufacture, where the built product is surrounded by a loose powder, yield low-quality surfaces. The powder particles that are in a close contact with the product adhere to its surface, either by thermal diffusion effects or by partial melting by contour scan tracks. The surface of additively manufactured metals has been shown to negatively affect mechanical properties, with the most negative impact on fatigue. Besides, these particles can loosen and cause problems during part operation. With respect to the above-mentioned problems, different ways of surface finish have been applied. In this study, we tested the samples of the Ti6Al4V alloy prepared by selective laser melting with three different surface finishes (as-built, machined and machined + tumble polished), and subjected them to high-cycle fatigue tests. Although many authors have reported on the positive effect of a surface finish on fatigue, in this study, we show that it might not always be true.

Keywords: Additive manufacture, SLM, fatigue, Ti6Al4V

1. INTRODUCTION

In the last decade, additive manufacturing (AM) has generated much interest because it offers specific features that conventional manufacturing cannot. The most outstanding benefit is the ability to prepare complex designs, e.g. with internal porous structures, in one step. As AM products are formed by the gradual addition of input materials, their final form is directly based on 3D computer models [1]. The most commonly-used AM techniques are the so-called powder bed techniques, such as selective laser melting (SLM) or electron beam melting (EBM), which offer the highest resolution. In powder bed techniques, thin layers of powders are deposited onto a build plate and subsequently melted by a focused energy source in coordinates given by the 3D model [2]. Although high-quality products reaching up the theoretical density can be currently manufactured, there are still some limitations.

The most significant limitation of powder bed AM techniques is the low surface quality of the products. Because a built product is surrounded by loose powder throughout the AM process, the powder particles in a close contact with the product surface adhere to it, either via thermal diffusion effects or via partial melting by contour scanning. Such particles become a firm part of the product at the cost of its dimensional accuracy. The larger the powder size, the more pronounced the deviations are [3]. Apart from deviations from precise shapes and dimensions, the surface of additively manufactured metals has been shown to negatively affect their mechanical properties, with the most negative impact on fatigue [4]. Moreover, loosely bound particles can also yield in operational risks (wear abrasion, inflammation in the body etc.) in case they become detached [5].

To address the above-mentioned problems, various processes of surface finishing have been tested. Although conventional machining and polishing have been applied widely [6-10], such mechanical surface treatment is only applicable for simple-shaped products. For more complex shapes, sand blasting [11], shot-peening [12], laser surface treatment (ablation [13], remelting [14]) and ultrasonic abrasive finishing [15] have been tried.

However, all these techniques are inadequate for the surface treatment of porous structures [16], for which different approaches have been sought. Several researchers have investigated chemical treatment in specific mixtures of acids [17,18] or electrochemical polishing [19]. Unfortunately, there is not a perfect solution so far. Thus far, well-defined, reliable and repeatable method for the uniform removal of the rough surface of AM metals has not been reported in the literature.

One of the most studied materials prepared by powder bed AM techniques is the Ti6Al4V alloy due to its great combination of material properties and wide range of potential applications, even in very demanding conditions (e.g. aircraft parts, safety car parts, orthopaedic or dental implants, chemical plants). Although the AM process is already optimized and high-density, high-strength products can be obtained, material fatigue strongly limited by the rough surface is of central interest. In our previous research [20], the fatigue strength values of the Ti6Al4V alloy prepared by SLM and EBM fell well below the given limit for the conventionally-prepared material. The comparison between the two AM technologies revealed that the surface had the major influence on the fatigue behaviour. Similarly, other studies showed that this material did not meet the desired value of fatigue strength when tested in the as-built condition [21,22], stating that the surface finish is the decisive factor in the fatigue performance [23]. Many researchers thus implemented a post-fabrication machining in an attempt to increase the fatigue strength. While some were successful [16,23-25], others were not [26,27]. This raises a question: Is the surface finish really the key factor in the fatigue of AM metals?

In this study, we apply conventional machining to remove the original rough surface of the Ti6Al4V alloy prepared by SLM and thereby increase its fatigue resistance. We show that the machining does not result in any significant improvement, what we link, based on the fractographic analysis, to the inherent structure of the AM material.

2. MATERIALS AND METHODS

In this study, the effect of surface finish on fatigue was demonstrated using the Ti6Al4V alloy (Ti grade ELI 23) prepared by Selective Laser Melting (SLM). Samples were designed in a CAD software based on the requirements set by the ASTM E606 standard.

For SLM, an M2 Cusing machine (ConceptLaser, Germany), equipped with one 200W Yb:YAG fiber laser, was used. The input material was supplied in the form of a gas-atomized powder with average particle size of 30 μm (rematitan® CL, Dentaurum, 15-45 μm). Processing parameters, which were set according to the recommendation of the SLM supplier, are summarized in **Table 1**. An island scanning strategy (with islands of 5 x 5 mm^2 area) was selected. All samples were built in the vertical Z-direction. Three series of 12 samples were produced.

The first series was kept in the as-built condition. Two other series were subjected to surface finishing. The second series was machined by turning to a roughness of Ra = 0.4 μm. The third series was machined by turning + tumble polished using a disk finishing machine OTEC CF 1x18T supplied with ceramic abrasive particles.

Table 1 Processing parameters applied for the SLM of the Ti6Al4V fatigue samples

Laser power	Laser scanning speed	Laser spot size	Hatching distance	Layer thickness
200 W	1250 $mm \cdot s^{-1}$	200 μm	80 μm	30 μm

Fatigue test were performed using a 10 kN servohydraulic testing system in accordance with ASTM E466-7 standard. Testing was done at room temperature under force-controlled amplitudes (160-600 MPa) at an asymmetry ratio $R = -1$ and frequencies of up to 50 Hz. The fatigue limit was evaluated after 10^7 cycles.

The surface of the prepared samples was documented by a scanning electron microscope TESCAN VEGA 3 (SEM). To assess the influence of a particular surface finish, selected samples were subjected to a fractographic analysis using SEM after the fatigue tests. The samples loaded at an amplitude of 300 MPa were selected for a comparison of fracture surfaces.

3. RESULTS AND DISCUSSION

3.1. Surface finish

Figure 1 shows surfaces of the tested sample series. The as-built surface shows a significant roughness, which is associated with adhered particles of the unmelted powder and 'melt pools' overlapping in successive layers (**Figure 1a**). The mean roughness depth *Rz* of 31±12 µm [20] thus corresponds to the average size of powder particles. Turning removes the original surface and results in regular grooves (**Figure 1b**). When tumble polishing is applied, this directionality is removed and pits formed by abrasive particles are homogeneously distributed over the entire surface (**Figure 1c**).

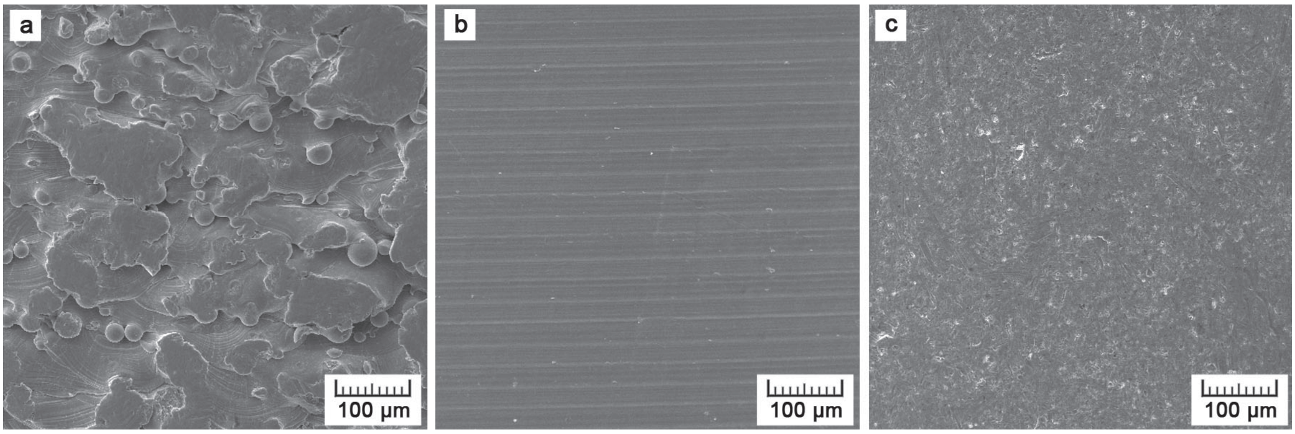

Figure 1 Surfaces of three tested sample series: (a) as-built, (b) machined, (c) machined + tumble polished

3.2. Fatigue

Figure 2 shows the Wöhler's curves of the tested samples with three different surface conditions. The curves are more or less overlapping, what suggests that there is not such a strong influence of the surface. The fatigue endurance limits, which reached comparable values, are summarized in **Table 2**. To explain the surface finishing was not beneficial, fracture surfaces of samples loaded at the amplitude of 300 MPa (**Figure 3**) were subjected to the fractographic analysis and compared. The number of cycles that these samples endured was in the order of 10^4 (see **Table 2**).

In all cases, a crack initiated from a superficial defect. In the as-built sample, even two initiation sites were observed (**Figure 3a**). Crack initiation occurred at the original surface, where overlaps of layers and powder particles exhibit a notch effect. The major crack and fragile morphology of the fatigue fracture can be seen in **Figure 3d**. In the machined sample, only one main initiation site was detected. Although machining removed surface irregularities acting as stress concentrators, it brought internal defects into the proximity of the sample surface. **Figure 3e** shows that the crack initiated at a lack-of-fusion (LOF) defect. LOF defects results from inappropriate interconnection between adjacent scan tracks/layers. If thermal conditions are altered and melt pools size is consequently reduced, melt pools do not overlap perfectly. Even completely unmelted particles can thus be trapped in the solidified material [28]. LOF defects are usually slit-shaped, so act as significant stress concentrators. In the tumble polished sample, a similar LOF defect initiated the fatigue crack (**Figure 3d**). As this discontinuity spread out to the depth of about 0.5 mm, it significantly promoted the crack propagation. As a result, the fatigue life of this sample was slightly lower than in the machined one despite its lower surface roughness.

Table 2 Fatigue endurance limits and number of cycles endured by the samples loaded at 300 MPa

	as-built	**machined**	**machined + tumble polished**
σ_c (MPa)	212±10	165±5	200±5
N (-) at σ_a = 300 MPa	29.976	87.628	28.481

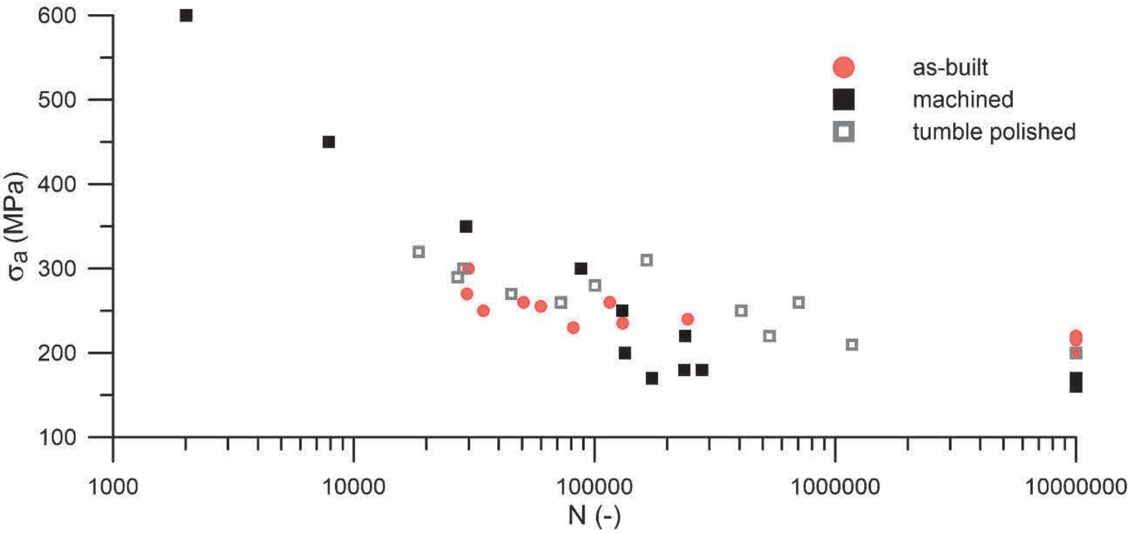

Figure 2 Wöhler's curves for the SLM Ti6Al4V samples with three surface conditions

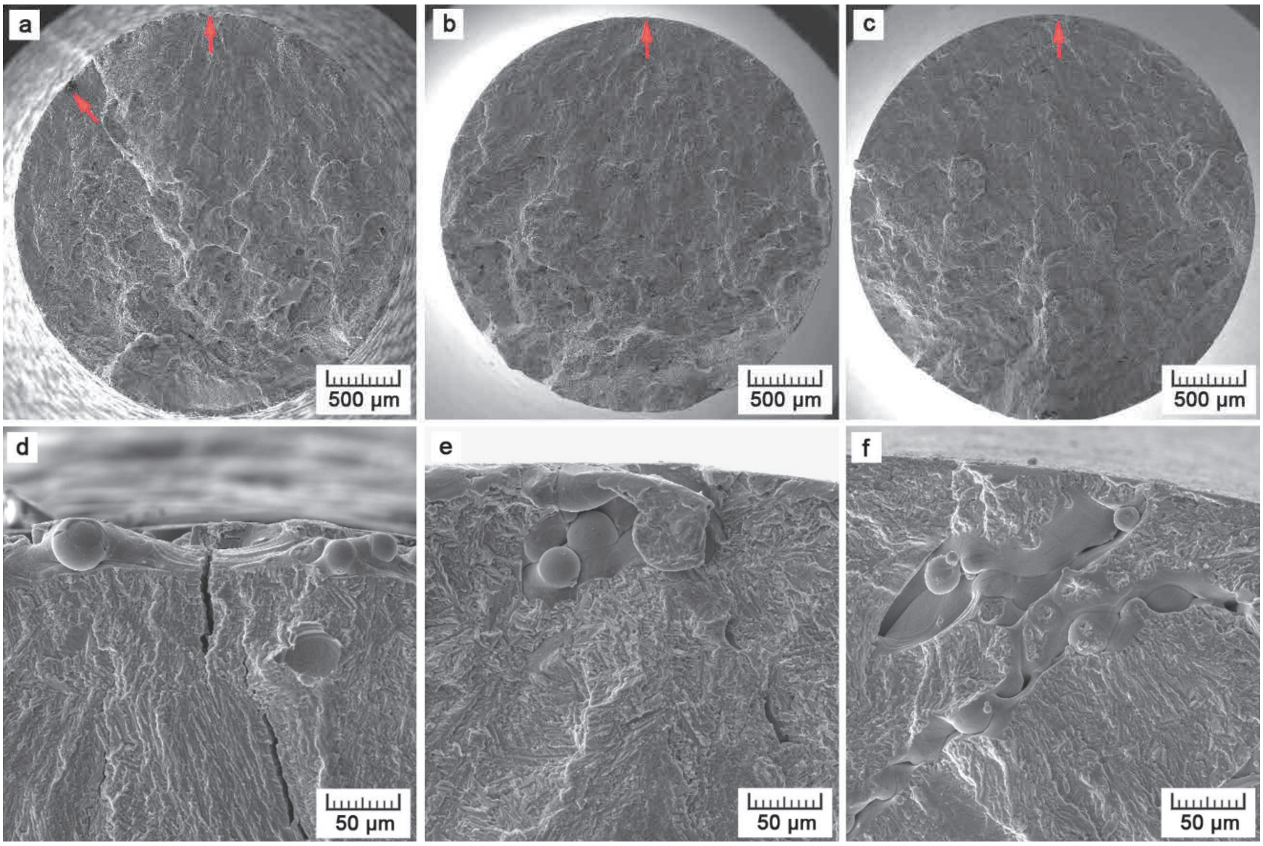

Figure 3 Fracture surfaces of (a, d) as-built, (b, e) machined and (c, f) machined + tumble polished samples loaded at an amplitude of 300 MPa. *Red arrows show initiation sites which are displayed in detail in (d-f)*

No general trend can be deduced from our observations. Machining slightly decreased the fatigue endurance limit because sub-surface defects became exposed and even more critical to the fatigue than the roughness of the original surface. Tumble polishing that followed might seem to slightly improve the fatigue strength, but it is not provable as the LOF defects were distributed within the samples randomly.

4. CONCLUSION

In this paper, we show that the surface finish may not always be beneficial to the fatigue of AM metals. It becomes decisive only under specific conditions that the material must meet. On the example of Ti6Al4V alloy prepared by SLM, we manifest that the material fatigue strength remained low despite removing the high surface roughness of the as-built samples having a strongly negative influence. Although the samples were prepared according to the recommendation of the SLM machine supplier, they exerted a certain amount of lack-of-fusion defects. By surface machining, these defects reached the surface and, instead of surface notches, became the main initiation sites of fatigue cracks. Therefore, if such defects are present, the contribution of surface finish is questionable.

ACKNOWLEDGEMENTS

The authors wish to thanks the Czech Science Foundation (project no. P108/12/G043) for the financial support of this research and to the Prospon company for providing the testing material.

REFERENCES

[1] TOFAIL, S.A.M., KOUMOULOS, E.P., BANDYOPADHYAY, A., BOSE, S., O'DONOGHUE, L. and CHARITIDIS, C. Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Materials Today*. 2018. vol. 21, no. 1, pp. 22-37.

[2] SING, S.L., AN, J., YEONG, W.Y. and WIRIA, F.E. Laser and electron-beam powder-bed additive manufacturing of metallic implants: A review on processes, materials and designs. *Journal of Orthopaedic Research*. 2016. vol. 34, no. 3, pp. 369-385.

[3] FOX, J.C., MOYLAN, S.P. and LANE, B.M. Effect of Process Parameters on the Surface Roughness of Overhanging Structures in Laser Powder Bed Fusion Additive Manufacturing. *Procedia CIRP*. 2016. vol. 45, pp. 131-134.

[4] GREITEMEIER, D., DALLE DONNE, C., SYASSEN, F., EUFINGER, J. and MELZ, T. Effect of surface roughness on fatigue performance of additive manufactured Ti-6Al-4V. *Materials Science and Technology*. 2016. vol. 32, no. 7, pp. 629-634.

[5] SALLICA-LEVA, E., JARDINI, A.L. and FOGAGNOLO, J.B. Microstructure and mechanical behavior of porous Ti-6Al-4V parts obtained by selective laser melting. *Journal of the Mechanical Behavior of Biomedical Materials*. 2013. vol. 26, pp. 98-108.

[6] BRANDÃO, A.D., GUMPINGER, J., GSCHWEITL, M., SEYFERT, C., HOFBAUER, P. and GHIDINI, T. Fatigue Properties Of Additively Manufactured AlSi10Mg - Surface Treatment Effect. *Procedia Structural Integrity*. 2017. vol. 7, pp. 58-66.

[7] FORTUNATO, A., LULAJ, A., MELKOTE, S., LIVERANI, E., ASCARI, A. and UMBRELLO, D. Milling of maraging steel components produced by selective laser melting. *The International Journal of Advanced Manufacturing Technology*. 2018. vol. 94, no. 5, pp. 1895-1902.

[8] CHAN, K.S., KOIKE, M., MASON, R.L. and OKABE, T. Fatigue life of titanium alloys fabricated by additive layer manufacturing techniques for dental implants. *Metallurgical and Materials Transactions A*. 2013. vol. 44, no. 2, pp. 1010-1022.

[9] ABOULKHAIR, N.T., MASKERY, I., TUCK, C., ASHCROFT, I. and EVERITT, N.M. Improving the fatigue behaviour of a selectively laser melted aluminium alloy: Influence of heat treatment and surface quality. *Materials & Design*. 2016. vol. 104, pp. 174-182.

[10] SANTOS, L.M.S., FERREIRA, J.A.M., JESUS, J.S., COSTA, J.M. and CAPELA, C. Fatigue behaviour of selective laser melting steel components. *Theoretical and Applied Fracture Mechanics*. 2016. vol. 85, pp. 9-15.

[11] BAGHERIFARD, S., BERETTA, N., MONTI, S., RICCIO, M., BANDINI, M. and GUAGLIANO, M. On the fatigue strength enhancement of additive manufactured AlSi10Mg parts by mechanical and thermal post-processing. *Materials & Design.* 2018. vol. 145, pp. 28-41.

[12] ALMANGOUR, B. and YANG, J.-M. Improving the surface quality and mechanical properties by shot-peening of 17-4 stainless steel fabricated by additive manufacturing. *Materials & Design.* 2016. vol. 110, pp. 914-924.

[13] MOHAMMAD, A., MOHAMMED, M.K. and ALAHMARI, A.M. Effect of laser ablation parameters on surface improvement of electron beam melted parts. *The International Journal of Advanced Manufacturing Technology*. 2016. vol. 87, no. 1, pp. 1033-1044.

[14] KRUTH, J.P., BADROSSAMAY, M., YASA, E., DECKERS, J., THIJS, L. and HUMBEECK, J. Part and material properties in selective laser melting of metals. *Proceedings of the 16th international symposium on electromachining.* 2010.

[15] TAN, K.L. and YEO, S.H. Surface modification of additive manufactured components by ultrasonic cavitation abrasive finishing. *Wear*. 2017. vol. 378-379, pp. 90-95.

[16] VAYSSETTE, B., SAINTIER, N., BRUGGER, C., ELMAY, M. and PESSARD, E. Surface roughness of Ti-6Al-4V parts obtained by SLM and EBM: Effect on the High Cycle Fatigue life. *Procedia Engineering*. 2018. vol. 213, pp. 89-97.

[17] WYSOCKI, B., IDASZEK, J., BUHAGIAR, J., SZLĄZAK, K., BRYNK, T., KURZYDŁOWSKI, K.J. and ŚWIĘSZKOWSKI, W. The influence of chemical polishing of titanium scaffolds on their mechanical strength and in-vitro cell response. *Materials Science and Engineering: C*. 2018. [In press].

[18] HOOREWEDER, B.V., LIETAERT, K., NEIRINCK, B., LIPPIATT, N. and WEVERS, M. CoCr F75 scaffolds produced by additive manufacturing: Influence of chemical etching on powder removal and mechanical performance. *Journal of the Mechanical Behavior of Biomedical Materials*. 2017. vol. 70, pp. 60-67.

[19] BAICHENG, Z., XIAOHUA, L., JIAMING, B., JUNFENG, G., PAN, W., CHEN-NAN, S., MUILING, N., GUOJUN, Q. and JUN, W. Study of selective laser melting (SLM) Inconel 718 part surface improvement by electrochemical polishing. *Materials & Design*. 2017. vol. 116, pp. 531-537.

[20] FOUSOVÁ, M., VOJTĚCH, D., DOUBRAVA, K., DANIEL, M. and LIN, C.-F. Influence of Inherent Surface and Internal Defects on Mechanical Properties of Additively Manufactured Ti6Al4V Alloy: Comparison between Selective Laser Melting and Electron Beam Melting. *Materials*, 2018. vol. 11, no. 4, pp. 537.

[21] KAHLIN, M., ANSELL, H. and MOVERARE, J.J. Fatigue behaviour of notched additive manufactured Ti6Al4V with as-built surfaces. *International Journal of Fatigue.* 2017. vol. 101, Part 1, pp. 51-60.

[22] BERETTA, S. and ROMANO, S. A comparison of fatigue strength sensitivity to defects for materials manufactured by AM or traditional processes. *International Journal of Fatigue*. 2017. vol. 94, pp. 178-191.

[23] CHASTAND, V., QUAEGEBEUR, P., MAIA, W. and CHARKALUK, E. Comparative study of fatigue properties of Ti-6Al-4V specimens built by electron beam melting (EBM) and selective laser melting (SLM). *Materials Characterization*. 2018. [In press].

[24] WYCISK, E., EMMELMANN, C., SIDDIQUE, S. and WALTHER, F. High cycle fatigue (HCF) performance of Ti-6Al-4V alloy processed by selective laser melting. *Advanced Materials Research*. 2013. vol. 816-817, pp. 134-139.

[25] BAGEHORN, S., WEHR, J. and MAIER, H.J. Application of mechanical surface finishing processes for roughness reduction and fatigue improvement of additively manufactured Ti-6Al-4V parts. *International Journal of Fatigue*. 2017. vol. 102, pp. 135-142.

[26] EDWARDS, P. and RAMULU, M. Fatigue performance evaluation of selective laser melted Ti-6Al-4V. *Materials Science and Engineering: A.* 2014. vol. 598, pp. 327-337.

[27] FATEMI, A., MOLAEI, R., SHARIFIMEHR, S., PHAN, N. and SHAMSAEI, N. Multiaxial fatigue behavior of wrought and additive manufactured Ti-6Al-4V including surface finish effect. *International Journal of Fatigue*. 2017. vol. 100, pp. 347-366.

[28] MUKHERJEE, T., WEI, H.L., DE, A. and DEBROY, T. Heat and fluid flow in additive manufacturing - Part II: Powder bed fusion of stainless steel, and titanium, nickel and aluminum base alloys. *Computational Materials Science*. 2018. vol. 150, pp. 369-380.