FATIGUE PROPERTIES OF EN AW-2618A ALUMINUM ALLOY PRODUCED BY SELECTIVE LASER MELTING TECHNOLOGY

ZEMANOVÁ Lucie, KRATOCHVÍLOVÁ Vendula, VLAŠIC František, MAZAL Pavel

Brno University of Technology, Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno, Czech Republic, EU

Abstract

The aim of this study is an investigation of fatigue properties and degradation development caused by cyclic loading in EN AW-2618A aluminum alloy fabricated by selective laser melting (SLM). Recently, the growing significance of aluminum as a constructional material is evident, and due to possibility of manufacturing parts with complicated geometry, it would be beneficial to be able to produce high-strength aluminum alloys using SLM. Sets of SLM specimens using different process parameters and specimens from extruded material with the same chemical composition were produced. Bending fatigue tests using symmetric cycle at different stress amplitudes were performed. During the tests acoustic emission (AE) was recorded in order to observe processes occurring in the material. Obtained AE signal was correlated with fractographic analysis. Fatigue tests showed that extruded material had significantly better fatigue performance compared to SLM. Moreover, fatigue resistance of SLM material is strongly dependent on process parameters settings and production conditions. AE signal analysis and fractography revealed that development of damage in SLM alloy was completely different from extruded material.

Keywords: Fatigue, EN AW-2618A, selective laser melting, acoustic emission

1. INTRODUCTION

Selective laser melting (SLM) is an additive manufacturing (AM) technology, which uses laser beam for melting layers of metal powder. Parts are created only by adding material, which enables creating components with complex shape that cannot be fabricated using any other known technology. A thin layer of powder is recoated on a building platform, a laser beam traces part's cross-section shape, then the platform moves down by the layer thickness and the process is repeated until the part is finished [1].

AM is associated mainly with rapid prototyping (RP), as part is fabricated using 3D CAD model and no other tools or molds are needed. Recently, AM is intended to be used not only for prototypes manufacturing, but also for production of functional models, tooling components or patterns for casting. For that reasons increased demands on quality, accuracy and type of material arise. Nowadays about 20 materials, e.g. stainless steels, titanium alloys, nickel-based superalloys, or cobalt-chrome alloys, are commonly processed by SLM [2]. Among aluminum alloys, 4xxx series is often used for SLM, on the contrary possibility of processing high-strength alloys such as 7xxx or 2xxx series were not researched yet.

For every new SLM material it is necessary to carry out a study to find optimal process parameters, in order to achieve homogeneous material and thus good mechanical properties of produced parts. Many papers describes influence of process parameters, e.g. laser power, scanning speed [3], hatch spacing [4], layer thickness [5], powder particle size [6], preheating of building chamber [7] or scanning strategy [8] on relative density and mechanical properties.

Achieving the highest possible relative density is critical for fatigue performance. Imperfections, e.g. pores, cracks, unmelted particles, cause stress concentration and initiation of fatigue cracks [1]. Another problem of SLM is residual stress in fabricated parts, which leads again to formation of cracks [9].

All above mentioned effects contributes to the fact that SLM material has 20-25% less resistance to cyclic loading then material produced by standard technologies [10]. Due to the main use of high-strength aluminum alloys in aerospace, where cyclic loading plays the most important role, intensive research of fatigue properties is crucial and it is a subject of many studies.

Acoustic emission (AE) is non-destructive testing method, which is based on detecting transient elastic waves generated in material during its deformation. Due to the possibility of continuously monitor dynamic process related to structural degradation, AE is advantageously used during fatigue testing [11]. By analyzing of AE signal, it is possible to detect initiation of fatigue crack, to predict the rate of crack propagation or to distinguish various stages of fatigue degradation and specify the processes, that occur during the cyclic loading [12, 13].

2. MATERIAL AND EXPERIMANTAL PROCEDURE

The subject of investigation was aluminum alloy EN AW-2618A produced by SLM and by traditional technology (extruded). Fatigue performance was evaluated and compared. This study is a part of GACR project "Design of advanced materials using selective laser melting" and builds on outcomes of optimization of SLM process parameters described in study [14].

2.1. Material

Material EN AW-2618A belongs to the 2xxx group of aluminum alloys, in which the main alloy element is copper. Chemical composition of reference material and powder for SLM was analyzed. Both materials meet requirements given by ČSN-EN 573-1 standard, details of chemical composition are mentioned in **Table 1**.

Table 1 Chemical composition of reference and SLM material (wt.%)

	Si	Fe	Cu	Mg	Ni	Ti
Reference material	0.24	1.1	2.5	1.5	1.2	0.04
Powder for SLM	0.15	1	2.66	1.39	1.22	0.2

Microstructure of reference material was observed without heat treatment and in T6 state (solution annealing at 530 °C for 8 hours, cooling in water and artificial aging for 20 hours at 200 °C). Material has a microstructure typical for wrought aluminum alloys. Preferential grain orientation in the direction of extrusion was apparent. Intermediate phase particles constitute spacing also in a direction concordant with extrusion direction, as shown in **Figure 1**. No material inhomogeneities, pores or shrinkages were visible.

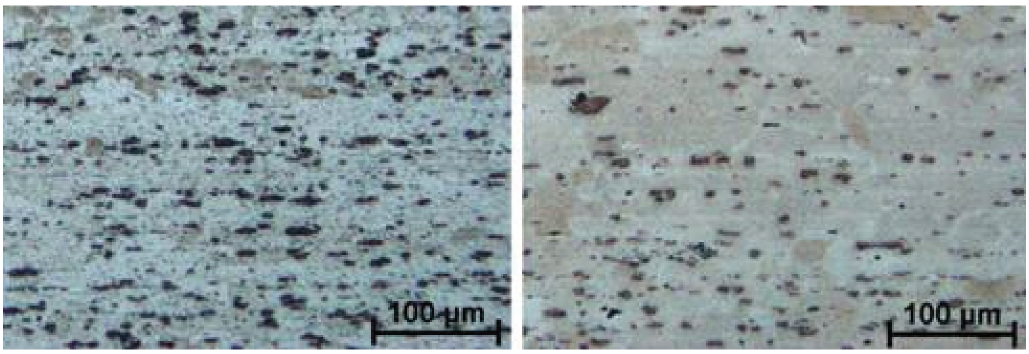

Figure 1 Microstructure of reference material without heat treatment (left) and after T6 heat treatment (right)

Microstructure of SLM material is characterized by anisotropy with respect to the building direction, as is shown in **Figure 2**. It is possible to observe a number of inhomogeneities in the volume (pores, cracks). Furthermore, there are visible traces of laser sintering and solidifying the grain boundaries, these places are the most often cracked. Intermediate phase particles are very fine (finer than for the reference material) and occur along the tracks of the laser.

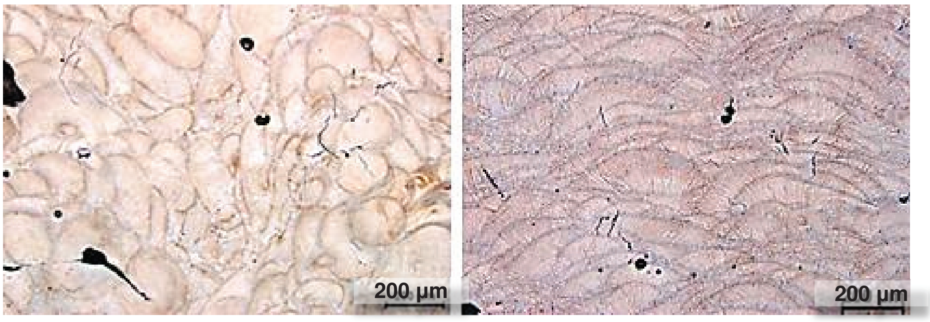

Figure 2 Microstructure of SLM material in the transverse (left) and longitudinal (right) direction

Although high relative density (99.65 %) was achieved, SLM material has worse mechanical properties then material fabricated classical. Results from tensile testing are summarized in **Table 2**.

Table 2 Averaged mechanical properties of reference and SLM material

	$R_{p0.2}$ (MPa)	R_m (MPa)	E (GPa)	A (%)	Z (%)
Reference material	272.5	391.8	74.3	13.7	28.8
Reference material (T6)	372.3	435.5	73	9.2	25
SLM material	192.5	211	61	0.6	1.4

Specimens for fatigue testing made from reference material were machined out of the extruded rod in a way that the direction of the rod axis was coincident with the axis of the sample. The shape and dimensions of the samples are shown in the **Figure 3**. SLM samples with the same geometry were machined from blocks produced by SLM, while the built layers were perpendicular to the axis of the sample.

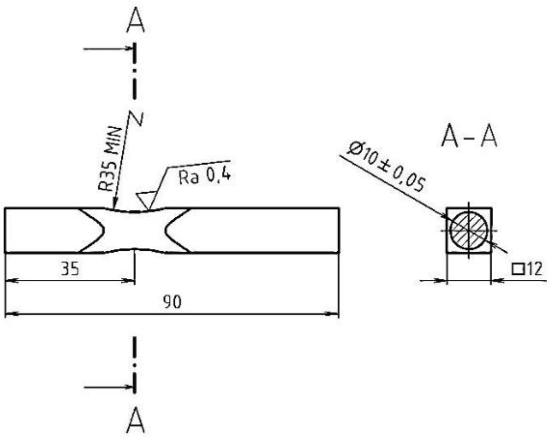

Figure 3 Specimen for the fatigue testing

2.2. Fatigue testing

Fatigue tests were performed using electro-resonance RUMUL Cracktronic machine. The sample is clamped in the jaws of the machine, which one is fixed and the other is moving. Details can be seen in **Figure 4**.

Symmetric sinusoidal loading cycle with frequency about 50 Hz was used. Tests were carried out at room temperature up to fracture.

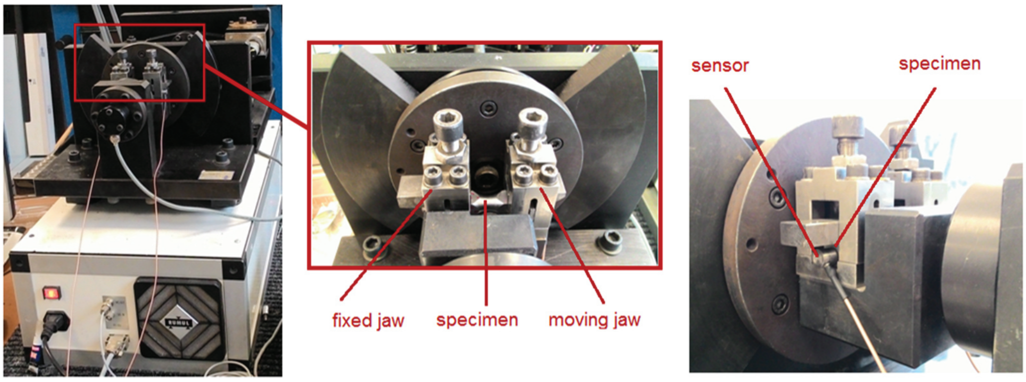

Figure 4 RUMUL Cracktronic testing machine

2.3. AE recording

AE was detected by two DAKEL IDK-09 sensors with 35 dB preamplifiers, which were attached to specimen's ends by glue as shows **Figure 4**. AE signal was recorded by system XEDO, which enables 12-bit synchronous sampling with sampling frequency 2MHz and continuous saving data to a computer.

2.4. Results

S-N diagram of reference material is shown in **Figure 5** left. It can be seen, that the material has slightly better fatigue resistance with T6 heat treatment. Fatigue performance of SLM material is significantly worse compared to the reference material. When loading stress amplitude of 183 MPa was used, reference material failed after 412 800 cycles while SLM failed after 13 300 cycles (more than 30 times less). More than that, it was found out, that fatigue properties of SLM material are strongly dependent on a precious compliance of manufacturing process. Although the same process setting was used, very different results were obtained in case of specimens from recycled metal powder. These samples had even worse fatigue resistance as shows **Figure 5** right. To complete the S-N curves and determine the endurance limit, more specimens would be needed. The research is still on the beginning and more detailed results will be published in the next paper.

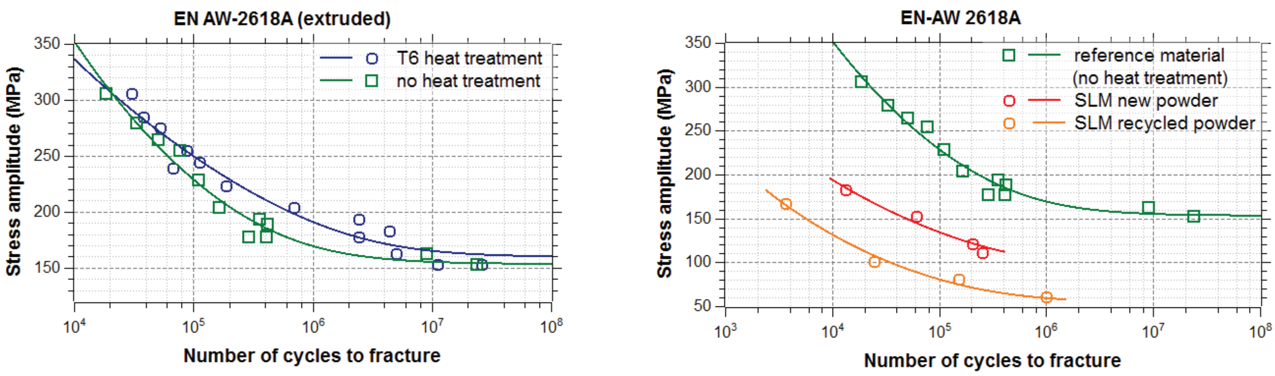

Figure 5 Obtained S-N diagrams of extruded and SLM material

Comparison of typical fracture surfaces of reference material and SLM specimens can be seen in **Figure 6**. The reference material has typical appearance of fatigue fracture with well recognizable point of initiation on the surface of the sample. At higher magnification some inclusions of Cu and Mg can be observed.

The fracture surface of SLM specimens is irregular and rough. Higher magnification is not necessary to see, that material contains a large number of inhomogenities of various shapes. Cracks are formed by connecting of the porosity already at low stress amplitudes. Cracks occur also on the surface, where is the highest bending stress. Both crack types can spread across the cross section as the main fatigue crack.

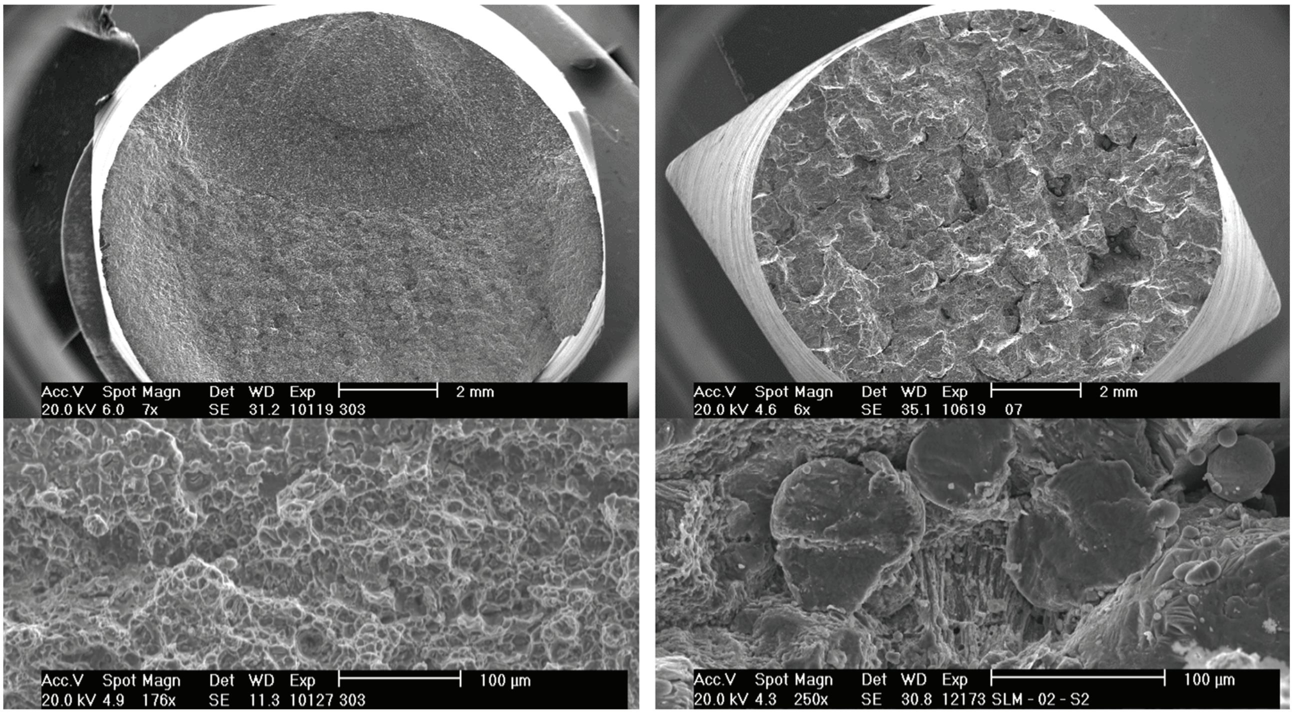

Figure 6 Fracture surfaces of reference (left) and SLM material (right)

From the analysis of obtained AE signal (**Figure 7**) is obvious that damage development in SLM material is different from extruded samples. In case of reference material, 70 % of fatigue life, changes at microstructure level and cumulative damage take place. Nucleation of main crack and its propagation can be clearly distinguished by rapid decrease in loading frequency and increase of counts.

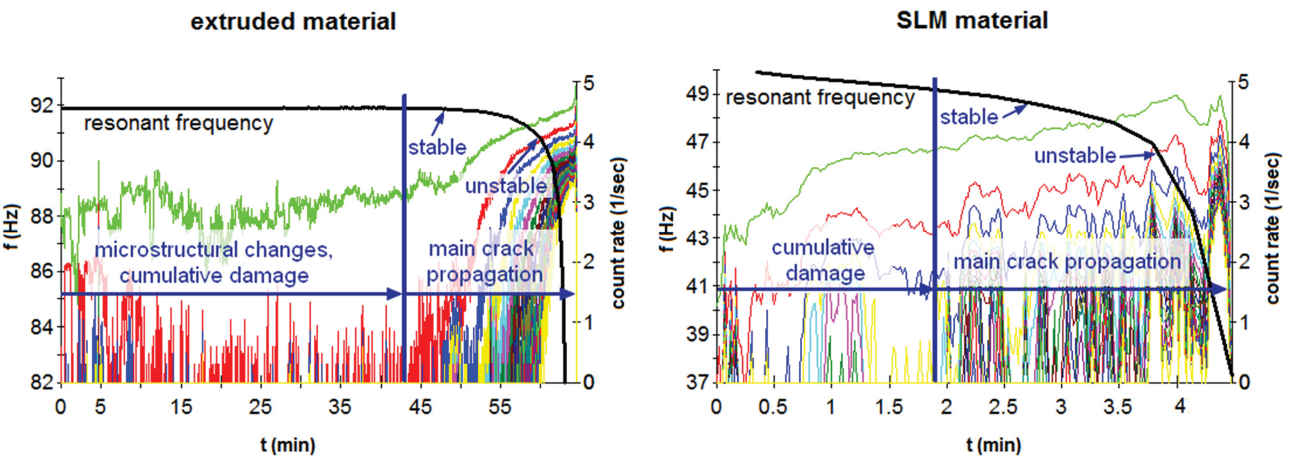

Figure 7 AE signal and resonant frequency of reference and SLM material, stress amplitude 183 MPa

In SLM samples resonant frequency decreases from the beginning of loading. SLM samples are more acoustic active in general, so the start of the main crack's growth is not so clearly visible. But in contrast to reference material, stage of crack propagation occupies a major proportion of lifetime. Detailed analysis of detected AE signal shows more differences in the development of fatigue damage between extruded and SLM material. Typical waveforms are different for all stages of fatigue, which indicates that fracture mechanisms of reference and SLM material are not the same.

2.5. Discussion

Fatigue life of SLM EN AW-2618A is significantly shorter than the extruded material. In [10] it was reported, that SLM material could have up to 25 % worse fatigue performance compared to conventionally produced, here it can be seen even worse fatigue properties. The lower the loading amplitude, the larger is the difference between fatigue life of SLM and extruded material, which is the same conclusion as was described in [10]. Fatigue cracks start from the surface or subsurface, from the places with pores, non-melted spots or other inhomogenities, which correlates with the findings of the paper [1]. From this point of view it is crucial to obtain material with high relative density, which is connected with using suitable process parameters, as was reported in [5].

3. CONCLUSION

The aim of this paper was description of fatigue behavior of aluminum alloy EN AW-2618A fabricated by SLM technology and comparing obtained results with extruded material of the same chemical composition. As expected, fatigue performance of SLM material is significantly worse compared to the extruded material. This is the result of incomplete homogenity, which is one of the main issues of SLM technology in general. Nucleation of fatigue cracks starts at the places with inhomogenities on surface or subsurface. Majority of the fatigue life of SLM material consists of fatigue cracks propagation. In case of extruded material, fatigue cracks nucleation begins on the surface as well, but it is not connected with any inhomogenities. Phase of crack propagation occupies comparatively shorter time of fatigue life compared to the SLM material. Resonant frequency trends are also not the same and AE signals suggests completely different damage mechanisms. Fatigue properties of SLM EN AW-2618A alloy are not comparable with conventionally produced material yet. More than that, fatigue performance is strongly dependent on a precious compliance of manufacturing process and consequently obtaining material with high relative density. To reach similar mechanical properties as extruded alloy, it is necessary to continue with SLM optimization process.

ACKNOWLEDGEMENTS

The authors would like to thank the Czech Science Foundation (GACR) for the funding of the project GA15-23274S, Design of advanced materials using selective laser melting. The project is also supported by NETME Centre (New Technologies for Mechanical Engineering), Reg. No. CZ.1.05/2.1.00/01.0002 and, in the follow-up sustainability stage, supported through NETME CENTRE PLUS (LO1202) by financial means from the Ministry of Education, Youth and Sports under the „National Sustainability Programme I“ and by the project No. FSI-S-14-2329 “Vibro-isolation system of cosmic carrier payload” of the Faculty of Mechanical Engineering.

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