FATIGUE PROPERTIES OF ADDITIVELY MANUFACTURED COPPER ALLOY

KRATOCHVÍLOVÁ Vendula, VLAŠIC František, MAZAL Pavel, KOUTNÝ Daniel

Brno University of Technology, Faculty of Mechanical Engineering, Brno, Czech Republic, EU
xkrato04@vutbr.cz, vlasic@fme.vutbr.cz, mazal@fme.vutbr.cz, koutny@fme.vutbr.cz

Abstract

This study evaluates fatigue properties of copper (Cu) alloy Cu7.2Ni21.8Si1Cr produced by selective laser melting technology (SLM). This technology belongs to additive manufacturing or 3D printing technologies and allows produce metal parts with complicated shapes in short production time and without the need to use expensive molds or large material waste. As the SLM technology is still under intensive research, the production process is not optimized for wide range of materials (most of studies were focused on titanium or aluminum alloys). Low quality of SLM materials is mainly connected with production defects caused by big temperature gradients during production. The SLM material is subjected to fatigue bending tests, which are supplemented by acoustic emission (AE) measurement and fractography analysis. By AE is possible to analyze fatigue behavior in detail and determine different fatigue stages and mechanism of crack propagation. After verification experiments, it is also possible to predict the remaining fatigue life. All results are compared with fatigue properties of conventionally produced Cu alloy AMPCOLOY® 944 (Cu7Ni2Si1Cr) using standard S-N curves. The fatigue life of SLM material is slightly worse than we can observe in conventionally produced materials and AE results suggest that there is different mechanism of crack propagation. As expected, the fractography study shows there is big amount of production defects (mainly pores) in SLM material and the crack origins are located near them.

Keywords: Fatigue, Cu alloy, selective laser melting, acoustic emission

1. INTRODUCTION

Additive manufacturing (AM) or 3D printing technologies became common in wide range of industrial fields in last years. The main benefit is possibility to produce complicated shaped parts in comparatively short time, which could be used for production of prototypes or special piece production. Selective laser melting (SLM), one of the AM technologies, adds a benefits of metal parts production. The technology principle is shown on the **Figure 1**; the part is built in layers which are connected by melting by focused laser beam [1].

However, the quality of SLM produced materials is low in comparison with common production. The main problems, including low fatigue resistance, are connected with internal production defects such as pores, shrinkages or un-melted material [2, 3] and cracks caused by residual stress [4]. Any new SLM material needs a lot of intensive studies to find the optimal production parameters and achieve as the best properties as is possible. The most important production parameters are laser power [5], laser power density [6], scanning speed, hatch distance and laser beam diameter [7]. Also the metal powder quality must be considered [8], the main indicators are particle size distribution, amount of small particles, flowability, humidity and amount of oxides.

Testing of SLM copper (Cu) alloys has been described in several works. Zhang et al. [7] described an influence of laser energy density on relative density of K220 Cu alloy samples. It was found that increasing of laser density also increase samples relative density, until reaching 200 J/mm^3. With optimal parameters it was achieved 99.9 % of relative density and the samples microstructure was consisted of cellular dendrites.

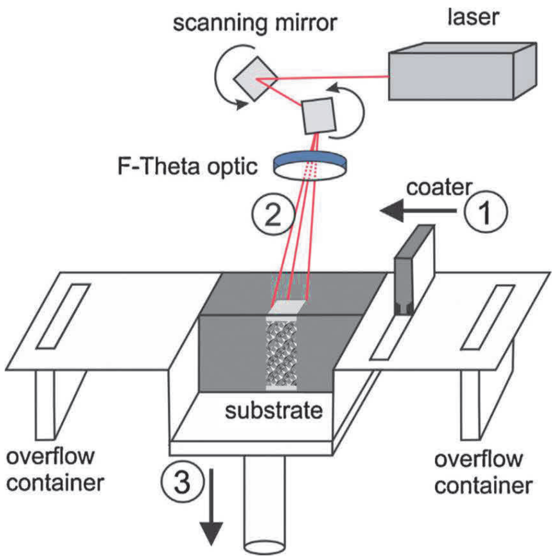


Figure 1 Selective laser melting principle [1]

Scundio et al. [9] produced samples from Cu10Sn alloy. Fast solidification caused that SLM material had fine-grained microstructure and the best achieved relative density was 99.7 %. The SLM material had significantly better yield and tensile strength (220 and 420 MPa) than compared cast material (120 and 180 MPa).

This paper follow ups previous studies of the fatigue behaviour of aluminum alloys using acoustic emission (AE) [10, 11]. AE is on of the non-destructive methods that allow a continuous monitoring of fatigue process. In this study the result from SLM production of Cu alloy Cu7.2Ni1.8Si1Cr are presented. Its chemical composition is similar to commercial Cu alloy AMPCOLOY® 944. This material is mainly used for tools (moulds) used for manufacture of plastic parts. Possibility of production these tools by SLM technology could bring such benefits as are described above. The main aim of presented study is to determine fatigue behaviour of this SLM material as the first step before next investigation of practical use.

2. EXPERIMENTAL PROCEDURE

2.1. Material

Testing SLM material is Cu alloy Cu7.2Ni1.8Si1Cr, metal powder is from company Sandvik Osprey. The reference material is conventionally produced (extruded) AMPCOLOY® 944 (Cu7Ni2Si1Cr). Chemical composition of both materials is shown in **Table 1**.

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

Element	**Ni**	**Si**	**Cr**	**Others**
AMPCOLOY® 944	7	2	1	0.5
SLM powder	7.5	1.8	0.94	0.114

SLM samples were produced by SLM 280HL machine from company SLM Solution GmbH. Production parameters were: laser power 400 W, scanning speed 1100 mm/s and hatch distance 90 µm. Achieve relative density is 99.5 % (measured on special samples by computer tomography), tensile yield strength 380 MPa, tensile strength 545 MPa and hardness 171 HV.

The microstructure of SLM material is characterize by clearly visible border of layers and a few defects, mainly pores and shrinkages, located near of them (**Figure 2**).

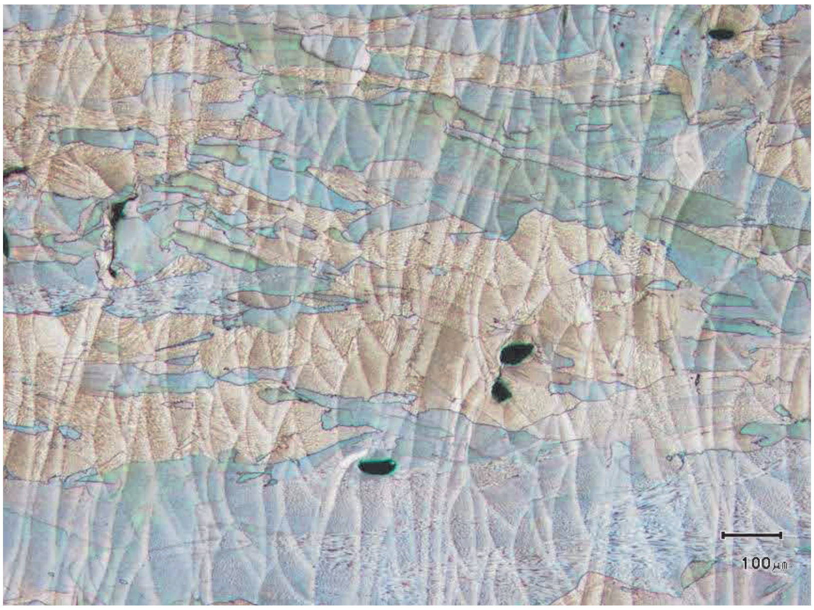
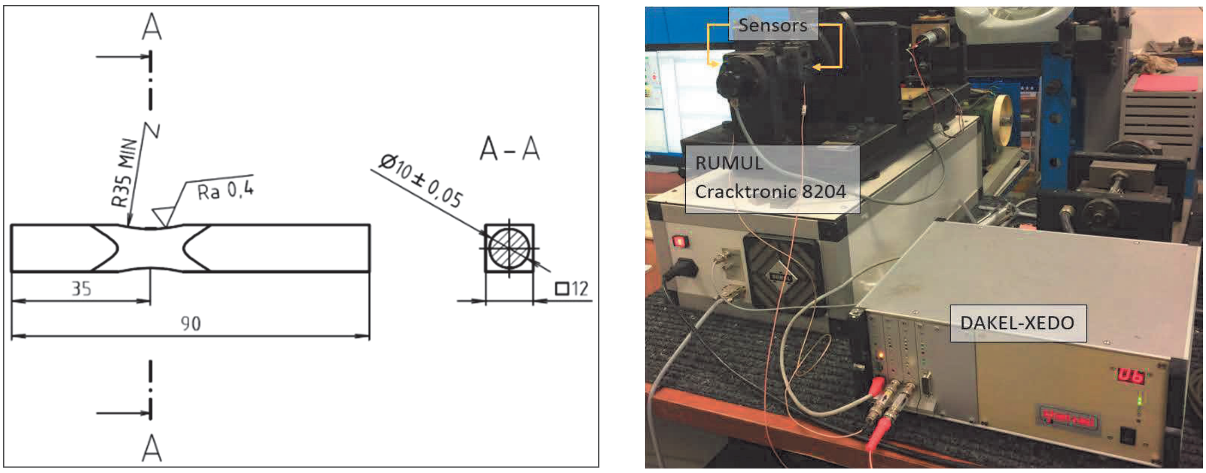


Figure 2 Microstructure of SLM material

2.2. Fatigue testing and acoustic emission measurement

8 specimens were produced from SLM material and 7 specimens from AMPCOLOY® 644, according the drawing on the **Figure 3a**. The fatigue bending test were conducted by at room temperature, with sinusoidal fatigue cycle in stress ratio R = -1. Approximate loading frequency was 52 Hz.

Acoustic emission (AE) signal was detected by DAKEL-XEDO monitoring systems using two piezoelectric DAKEL MIDI sensors with 35 dB preamfilters, see **Figure 3b**. XEDO system allows 12-bit synchronous sampling with sampling frequency 2 MHz and continuous saving data to a computer. The sensors were clamped on each end of the specimens by Loctide glue in order to get a two channel linear location system.



a) b)

Figure 3 a) Geometry of fatigue testing specimen (in mm); b) measurement system

3. RESULTS

The results from fatigue bending test and AE analysis of both materials were compared. The S-N curves of both materials are shown on the **Figure 4**.

Fatigue limit is around 235 MPa for SLM material and 285 MPa for AMPCOLOY® 644 reference material. The difference is less significant in lower amplitude (resp. fewer cycles).

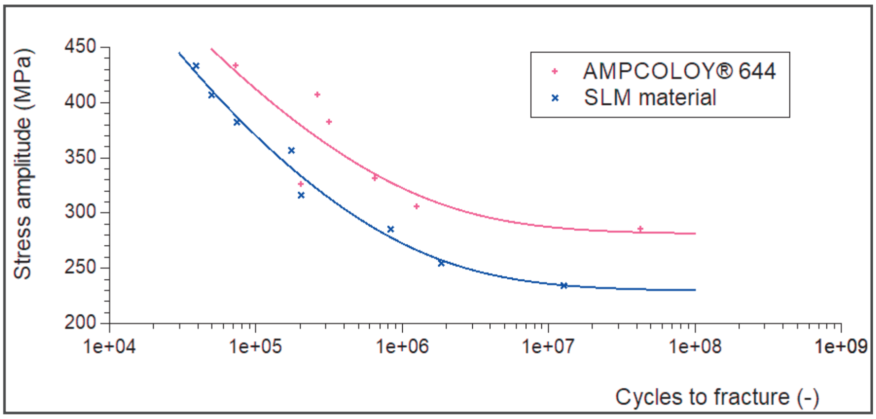
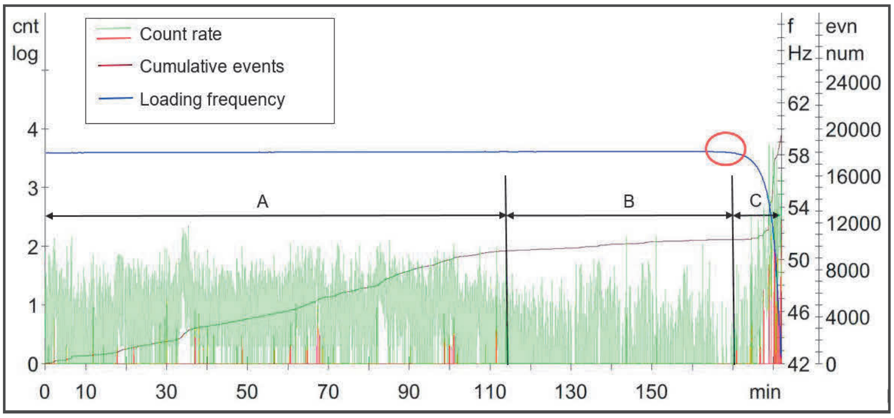
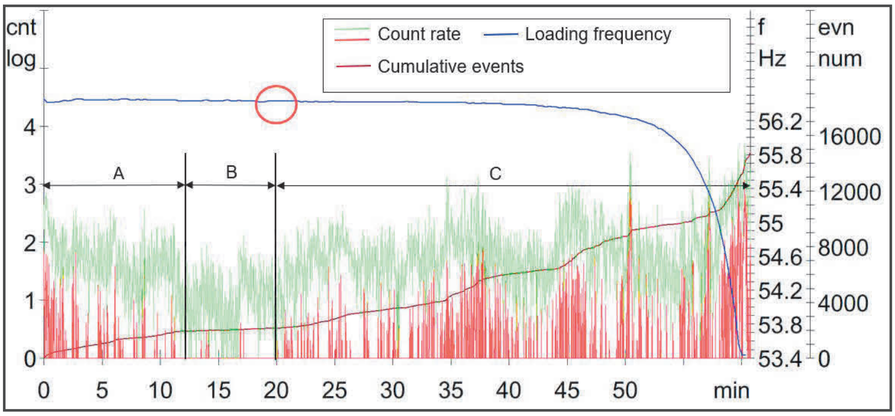


Figure 4 S-N curves of SLM and AMPCOLOY® 644 materials



a)



b)

Figure 5 AE signal and loading frequency: a) AMPCOLOY® 644, stress amplitude - 331 MPa, b) SLM material stress amplitude - 316 MPa

The results from AE measurement of both materials are shown on the **Figure 5**. Both materials have three fatigue stages - pre-initiation (A), initiation (B) and post-initiation (C), red rings marked the main crack initiation. The pre-initiation stage (A) at the load beginning is typical with significant AE activity caused by changes in material microstructure, glide and interaction of dislocations and persistent slip band formation. While the pre-initiation stage of reference material is the longest and takes almost 2/3 from total fatigue lifetime, the same stage of SLM material takes only 1/4 from total lifetime. The initiation stage (B) is characterized by low and stabile AE activity, the microcracks propagation starts here. The initiation stage of reference material is relatively longer than the same stage of SLM material, where this stage is the shortest. In the last stage (post-initiation - C) the AE again significantly increase and the long cracks propagate here. The stage takes most of the SLM material fatigue lifetime, so the crack propagation is much slower then we can observe in reference material. These results indicate different mechanism of crack initiation and propagation. The crack in AMPCOLOY® 644 material is propagate mainly by changes in the microstructure - interaction of dislocations or persistent slip band formation, the crack in SLM material is propagate by connection between production defects or production layers boundaries.

The fractography study supplemented the fatigue and AE measurement, see **Figure 6**. The study shows that crack origin is located in the defect near the specimen surface (red ring on the **Figure 6**). Rough surface of the cavity indicate that it is a shrinkage and as there are some unmelted metal powder grains in the cavity, this defect was probably created during the production. Similar defects are observed on the whole fracture surface, which confirms the theory of crack propagation by linking defects.

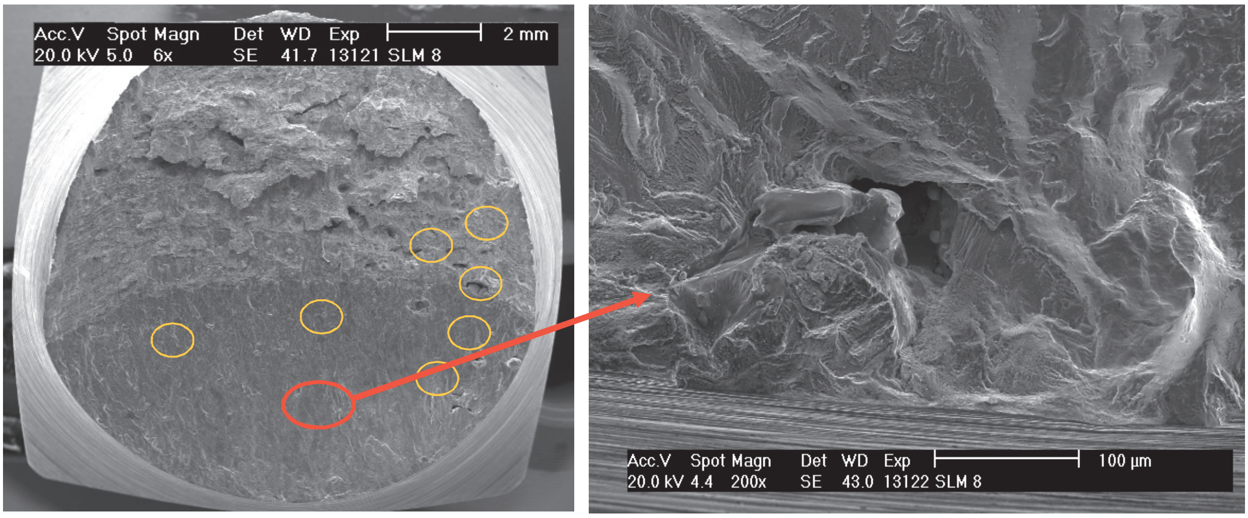


Figure 6 Fractography of SLM material

4. CONCLUSION

Study of fatigue behavior of SLM Cu alloy Cu7.2Ni1.8Si1Cr was presented. The results from fatigue test and AE measurement were compared with same measurement of conventionally produced (extruded) material AMPCOLOY® 644, these measurements were supplemented by fractography study of SLM material. The comparison of fatigue test results shows that SLM material has worse fatigue resistance than reference material, but the difference is less significant in lower amplitude (resp. fewer cycles).

The AE measurement analysis showed three fatigue stages in both materials - pre-initiation, initiation and post-initiation, but the ratio of stages was different. While the longest stage of SLM material was post-initiation, for the reference material it was the pre-initiation stage. This observation together with fractographic study indicated different mechanism of fatigue crack propagation.

Future investigation should be focused on deeper analysis of AE signal and the results should by complemented by same measurement of SLM Cu alloy after heat treatment.

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REFERENCES

[1] LÖBER, L., SCHIMANSKY, F. P., KÜHN, U., PYCZAK, F., ECKERT, J. Selective laser melting of a beta-solidifying TNM-B1 titanium aluminide alloy. *Journal of Materials Processing Technology*, 2014, vol. 214, pp. 1852-1860.

[2] RAFI, H. K., STARR, T. L., STUCKER, B. E. A comparison of the tensile, fatigue, and fracture behavior of Ti-6Al-4V and 15-5 PH stainless steel parts made by selective laser melting. *International Journal of Advanced Manufacturing Technology*, 2013, vol. 69, no. 5-8, pp. 1299-1309.

[3] LIU, Q., ELAMBASSERIL, J., SUN, S., LEARY, M., BRANDT, M., SHARP, P. K. The effect of manufacturing defects on the fatigue behaviour of Ti-6Al-4V specimens fabricated using Selective laser melting. In: *11th International Fatigue Congress*. Melbourne, Australia: 2014, pp. 1519-1524.

[4] MERCELIS, P., KRUTH, J-P. Residual stresses in Selective laser sintering and Selective laser melting. *Rapid Prototyping Journal*, 2006, vol. 12, no. 5, pp. 254-265.

[5] SONG, B., DONG, S., DENG, S., LIAO H., CODDET, C. Microstructure and tensile properties of iron parts fabricated by selective laser melting. *Optics and Laser Technology*, 2014, vol. 56, no. 3, pp. 451-460.

[6] ZHANG, D. Q., LIU, Z. H., LI, S., MUZZAMMIL, M., WONG, C. H., CHUA, C. K. Selective Laser Melting: On the Study of Microstructure of K220. In: *1st International Conference on Progress in Additive Manufacturing*. Singapore: 2014, pp. 176-184.

[7] SANTOS, E. C., SHIOMI, M., OSAKADA, K., LAOUI, T. Rapid manufacturing of metal components by laser forming. *International Journal of Machine Tools & Manufacture*, 2005, no. 46, pp. 1459-1468.

[8] FORET, P., BAUER D. Effect of process gas and powder quality on AlSiMg and Ti64 powder bed fusion processed parts for the aerospace industry. In *World PM 2016*. Hamburg, Germany: 2016, pp. xx.

[9] SCUDINO, S., UNTERDÖRFER, C., PRASHANTH, K. G., ATTAR, H., ELLENDT, N., UHLENWINKEL, V., ECKERT, J. Additive manufacturing of Cu-10Sn bronze. *Materials Letters*, 2015, no. 156, pp. 202-204.

[10] ZEMANOVÁ, L., KRATOCHVÍLOVÁ, V., VLAŠIC, F., MAZAL, P. Fatigue properties of EN AW-2618A aluminum alloy produced by Selective laser melting technology. In: *METAL 2016: 25th Anniversary International Conference on Metallurgy and Materials*. Brno: TANGER, 2016, pp. 1583-1589.

[11] KRATOCHVÍLOVÁ, V., VLAŠIC, F., MAZAL, P., PALOUŠEK, D., KOUTNÝ, D. Fatigue damage of aluminum alloy EN AW 2618A produced by SLM technology. In *World PM2016.* Hamburg, Germany: 2016, pp. 1-6.