Acoustic Emission Response to Fatigue Damage of Additively Produced and Cast Materials

Vendula Kratochvilova[1a], Frantisek Vlasic[1b], Pavel Mazal[1c] and David Palousek[1d]
1 Brno University of Technology, Faculty of Mechanical Engineering, Czech Republic,
[a] xkrato04@vutbr.cz, [b] vlasic@fme.vutbr.cz, [c] mazal@fme.vutbr.cz,
[d] palousek@fme.vutbr.cz

Abstract

Additive manufacturing (AM) or 3D printing technologies allow to produce parts with complicated shapes in a relatively short time and without large amounts of material waste. These parts are more and more used in different types of engineering applications. The latest studies are mainly aimed at improving the quality of the material produced by AM in order to achieve the same or better quality as conventional materials, resulting in the need for testing these materials.
The study presented evaluation and comparison the fatigue processes of additively produced and cast materials using acoustic emission method. The used additive technology is selective laser melting (SLM), which is used to produce metal parts. Tested material is aluminium alloys AlSi9Cu3, which is commonly used in aluminium castings production. The material is tested in as-cast or as-built condition without any heat treatment. All samples were subjected to fatigue bending tests in high-cycle regime and the results were evaluated by acoustic emission measurement. This allows a deep analysis of the fatigue process and comparison of the characteristics of both materials. The main goal is to analyse the acoustic emission response to fatigue damage and the correlation between this response and fracture mechanism.
Results shows that fatigue life of SLM material is better than casting material with same chemical composition. Acoustic emission detects stages of fatigue process and crack initiation and localization.

1. Introduction

Additive manufacturing (AM) or rapid prototyping (RP) become more and more common in last years. The main advantages are obvious, fast production of complicated or customized parts in relatively short time and also favourable price, thanks to recent boom and intensive research. Selective laser melting (SLM) is one of AM technologies, which is used to produce metal parts.

SLM principle is shown on the figure 1 (1). Thin layers of metal powder are connected by focused laser beam. It allows to produce parts with complicated shapes, but final material quality could be relatively low. It is mainly connected with internal defects, such as lack of material with unmelted powder particles (2) or cracks caused by a large temperature gradient. These defects can be eliminated by optimizing of production parameters (3,4) or post-processing heat treatment (5,6). Brandl et al. processes the

AlSi10Mg alloy in his work (5). It was showed that with optimal process parameters it is possible it is possible to achieve better fatigue resistance than standard.

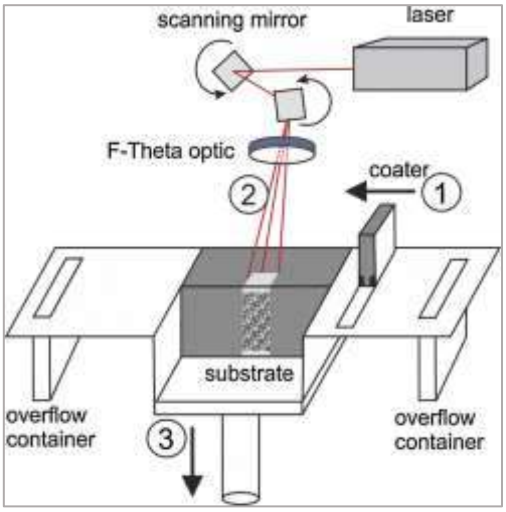

Figure 1. SLM principle. (1)

However our last work (6) showed that it is not possible to process all aluminum alloys by SLM technology. Fatigue resistance of SLM material AlCuMg1.5Ni was significantly lower, then extruded material. The quality of production series and also individual samples was unstable. Comparison of results with same tests of alloy AlSi10Mg showed that SLM technology is more suitable for alloys with a chemical composition closer to the eutectic.

Acoustic emission (AE) method can be used for on-line monitoring of fatigue loading and crack propagation (7,8). It was showed that is possible to determine 3 fatigue stages – pre-initiation, initiation, post-initiation, which describes the fatigue process and predict the rate of crack propagation. Comparison of AE signal during fatigue loading of SLM and extruded material showed that the fatigue behaviour of SLM material is totally different (6). The main differences can be observed in the ratio of fatigue stages. While in case of SLM material, the post-initiation stage is the longest, and the pre-initiation is relatively short, in case of extruded material the pre-initiation stage takes most of the fatigue lifetime, see figure 2 (6).

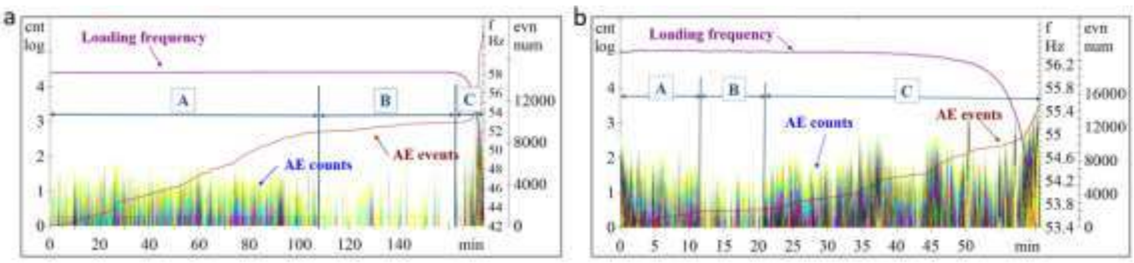

Figure 2. AE record of extruded (a) and SLM material (b), alloy AlCu2Mg1.5Ni. A – pre-initiation stage, B – initiation stage, C – post-initiation stage (6)

2. Material and methods

2.1 Material

Based on the previous study (6) the used alloy is AlSi9Cu3. This alloy is commonly used for casting and its chemical composition is close to the eutectic. The reference material is standard gravity cast. Tensile strength of SLM material was 485 MPa and 177 MPa in case of cast material.
Comparison of microstructure of both materials is shown on the figure 3. The microstructure of cast material contains a significant amount of material phases with sharp geometry. On the contrary, these phases were not presented in the microstructure of SLM material, only small rounded pores and boundaries of the building layers can be observed.

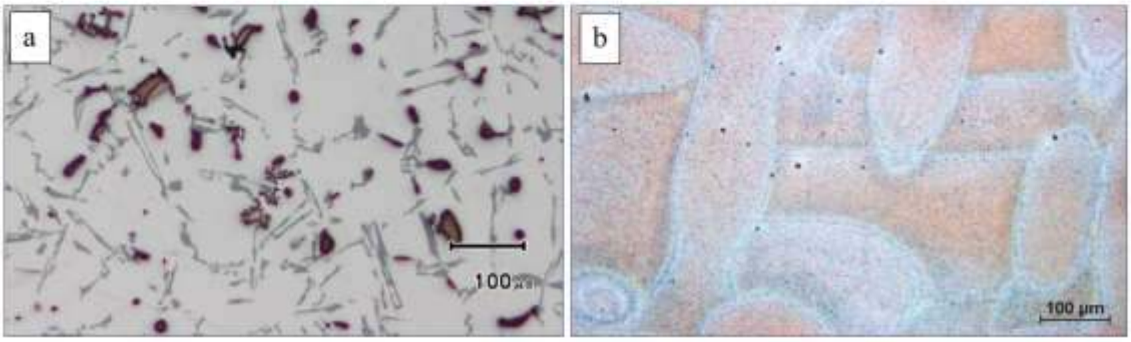

Figure 3. Microstructure of cast (a) and SLM (b) material.

SLM parameters were: laser power 400 W, laser speed 1300 mm/s, hatch distance 150 μm and beam diameter 82 μm. The process of determination of optimal production parameters is not described in this work, as it is part of another study.

2.2 Fatigue testing and AE measurement

Both materials were tested in as-cast resp. as-built condition without any heat treatment. In total, 11 specimens of SLM material and 12 specimens of cast material were tested. All specimens were machined to the shape according the figure 4a and fatigue tested. Tests were carried out by electro-resonance machine RUMUL Cracktronic 8204 at room temperature. Fatigue cycle was sinusoidal with stress ration was R = -1.

Acoustic emission (AE) signal was detected by DAKEL-XEDO monitoring systems using two piezoelectric DAKEL MIDI sensors with 35 dB preamfilters. XEDO system allows 12-bit synchronous sampling with sampling frequency 2MHz and continuous saving data to a computer. The sensor were clamped on each end of the specimens by Loctide glue. The measuring station is shown on the figure 4b.

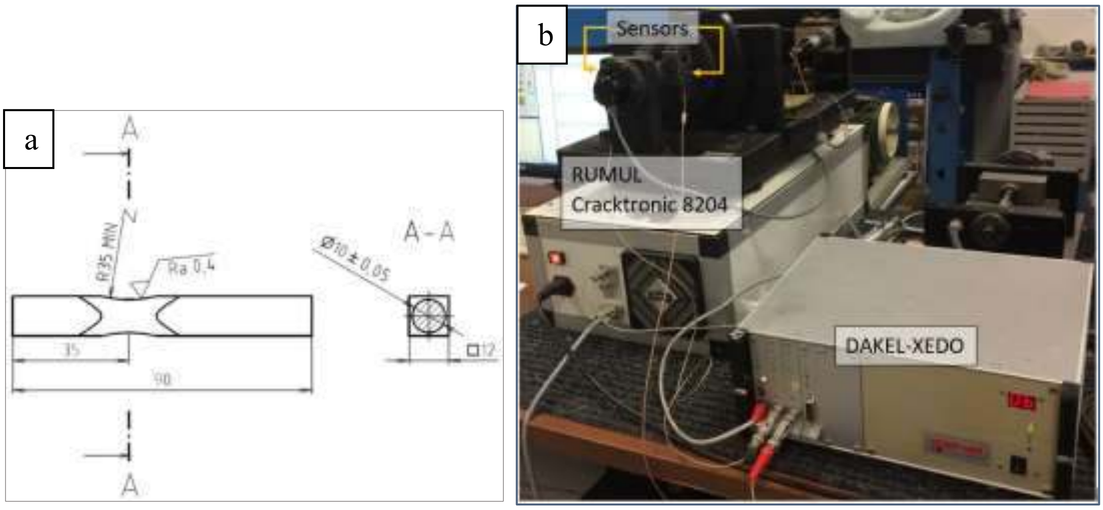

Figure 4. Geometry of machined sample (a) and measuring station (b).

3. Results and discussion

Results of fatigue testing of both matetrials were compared using S-N curves in log-log coordinates, see figure 5. The fatigue resistance of SLM material is slightly better. It is probably caused by material phases with sharp geometry, which are present only in the cast microstructure.

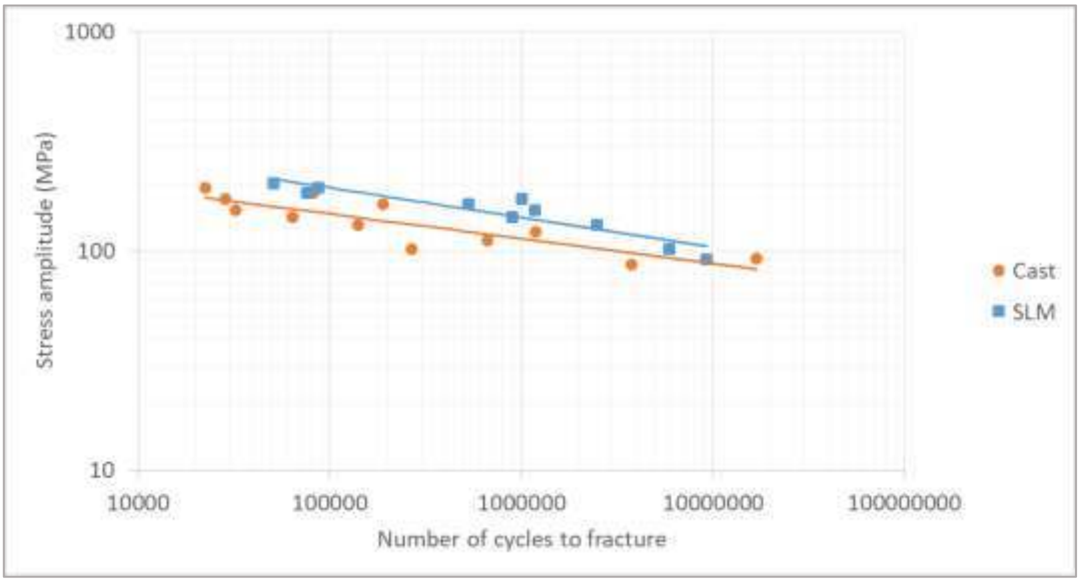

Figure 5. S-N curves of SLM and cast material.

Records of AE signal are shown on the figure 6 and 7. Three fatigue stages are clearly visible. Pre-initiation stage (A) is characterized by significant AE activity caused by changes in microstructure. Then the AE activity decreases, the initiation stage (B) begins and micro-cracks are formed. The AE activity increases again in post-initiation stage (C), the main crack is propagate.

Main differences we can observe in the ration of stages. While the stages of the cast material are more or less evenly distributed throughout fatigue life time, the length of the SLM stages is different. The shortest stage of SLM material is pre-initiation (A). and the post-initiation stages (C) takes almost half of total fatigue life time. This suggest different mechanism of crack initiation and propagation. The main crack in cast material is primarily initiated by changes in the microstructure, but in the case of SLM material, the pores are connected by micro-cracks.

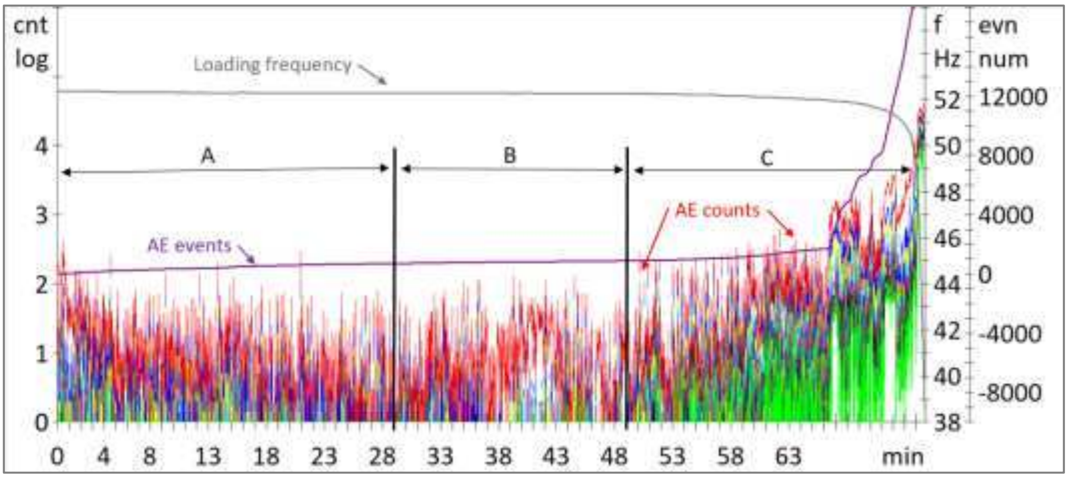

Figure 6. AE records of cast material. Stress amplitude 132 MPa.

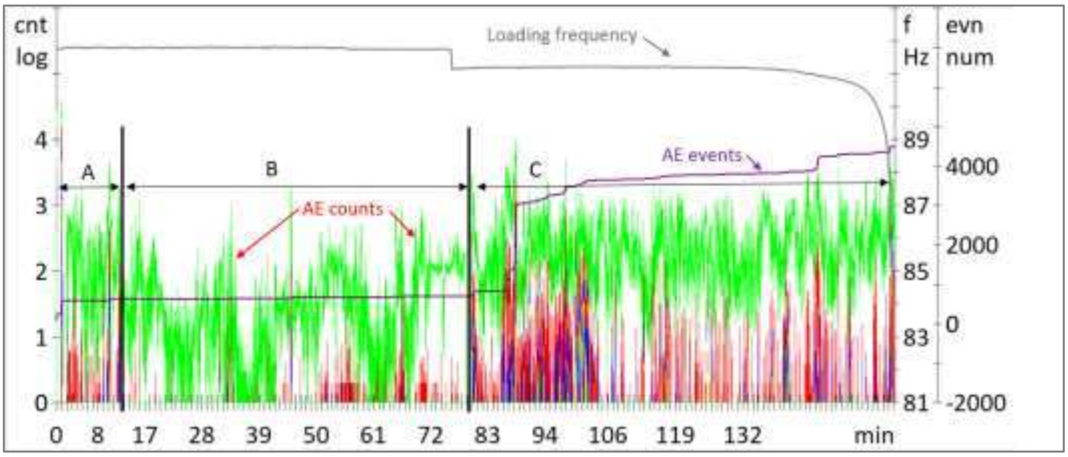

Figure 7. AE records of SLM material. Stress amplitude 142.6 MPa.

Detailed analysis of AE events is given on the figure 8. Clear difference between SLM and cast material could be observed. In the pre-initiation stage of SLM material, the amplitude of the most events is between 2800 and 3200 mV, but in case of cast material it is between 800 and 1800 mV. In the initiation stage the significant difference can be observed in rise time of events. Rise time of the most AE events in initiation stage of SLM material is between 200 and 700 µs, but in case of cast material it is between 200 and 1700 µs. This confirm the hypothesis about different mechanism of crack initiation.

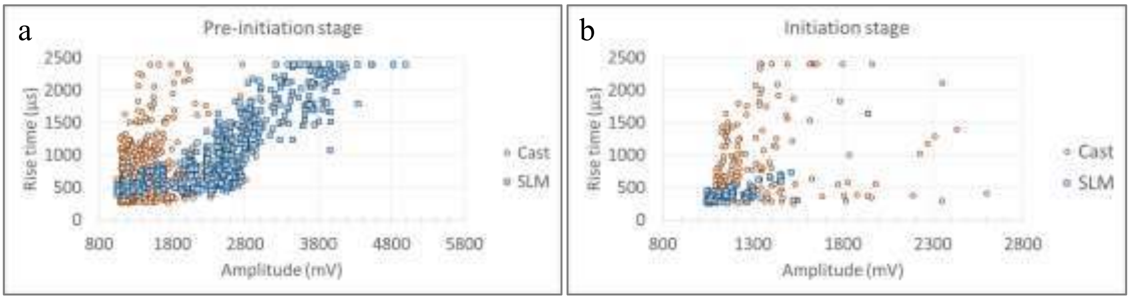

Figure 8. Rise time (µs) and amplitude (mV) of AE events. (a) pre-initiation, (b) initiation stage

Fatigue testing and AE measurement were supplemented by fractography. The scanning electron microscopy image of SLM material fracture surface is shown in the figure 9. The crack initiation is located in the subsurface defect (red ring in the figure 9). Significant amount of pores can be observed on the fracture surface, some of them are connected by micro-cracks.

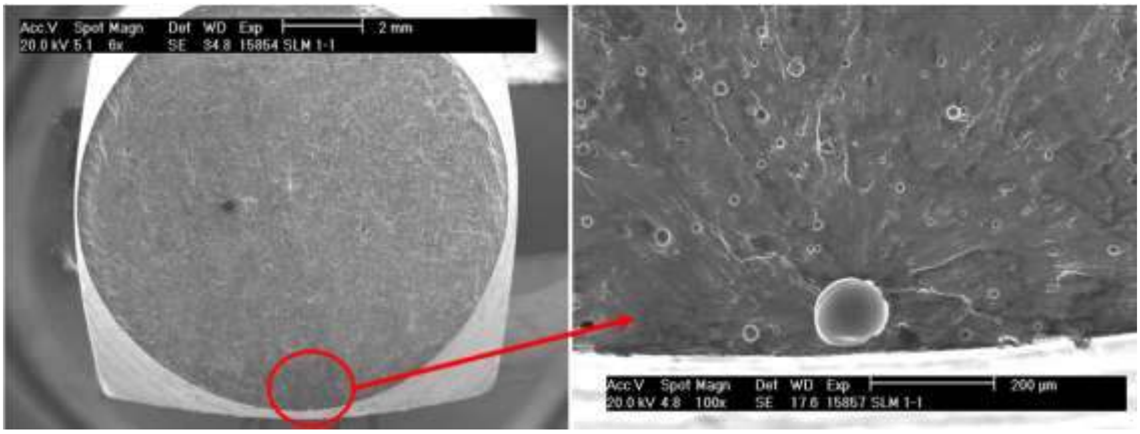

Figure 9. Fracture surface of SLM material.

4. Conclusion

The results of fatigue tests with AE measurement of material produced by SLM technology and cast alloy AlSi9Cu3 were presented. The SLM material has slight better fatigue resistance than cast material with similar chemical composition.

Significant difference were observed in AE signal. Both materials have three typical fatigue stages – pre-initiation, initiation and post-initiation stage, but the ration of them is different. While the phase of the cast material is evenly distributed throughout fatigue life time, the length of the SLM phase is different. This observation together with detailed analysis of amplitude and rise time of AE events and fractography of fracture surface suggests different mechanism of crack formation and propagation. The main crack in cast material is primarily initiated by changes in the microstructure, but in the case of SLM material, the pores are connected by microcracks.

Acknowledgements

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