Abstract

The main aim of the study is to compare fatigue processes and its acoustic emission (AE) signal of conventional produced material and material produced by selective laser melting (SLM) technology. The SLM offers the same benefits as the rest of the rapid prototyping technologies, the most important is big range of produced shapes, but without expensive moulds, cores or huge material waste. However the mechanical properties of these materials are currently worse than those of conventionally produced materials.

AE method was used to get new information about fatigue damage of SLM materials. This study summarizes results from bending fatigue tests of reference Al alloy AW-2618A (AlCu2Mg1.5Ni) and SLM material with comparable chemical composition. Acquired AE and fatigue data from both materials were compared. The fractographic and metallographic analysis were also conducted as complement.

Internal defects and inhomogeneities in SLM materials cause different fracture behaviour than we can see at conventional materials. Differences in fatigue behaviour of SLM materials are strongly reflected in AE signal. The results may be used to improve the production of SLM materials in order to get better material characteristics. AE data helps to understand the fatigue behaviour of SLM materials in order to predict crack initiation.

Keywords: selective laser melting, acoustic emission method, fatigue, crack, Al alloy

1. Introduction

Rapid prototyping (RP) technologies, especially those that enable to produce metal parts are nowadays under intensive studies. Selective laser melting (SLM) technology produces parts by adding thin material layers, which are connected by melting by focused laser beam (Fig. 1a) [1]. This allows producing parts with complicated shapes without huge material waste or expensive moulds and cores.

As the SLM technology is still under research, achieved mechanical characteristics, especially fatigue, are not as good as in case of conventional produced materials. Current studies were aimed mainly on titanium alloy and steel, aluminium alloys have been overlooked. For titanium alloy Ti-6Al-4V was possible to get better fatigue life than is usual in cast material and equivalent to the cast material with heat treatment [2]. For stainless steel SS 316L and 15-5PH was possible to get only 20-25% lesser fatigue life than has conventionally produced materials and fatigue life was strongly effected by surface quality [3]. This is mainly connected with internal defects, which could be more or less similar as casting or welding defects – porosity, lack of material, but we can also see typical SLM defects for example unmelted powder in cavities [2, 4].

Those defects could be eliminate by optimizing of process parameter, which are scanning speed [5], laser power [6], powder grain size and quality [7], building strategy [8], hatch spacing [9] and layer thickness [10].

Acoustic emission (AE) is one of the standard non-destructive (NDT) methods. It allows to detect, localize and evaluate defects during their formation, so it is suitable for fatigue process
monitoring [11]. There is possible not only to detect and characterization fatigue damage growth [12], but also to distinguish various stages of fatigue phases, to predict the rate of crack propagation [13] and to identify sources of AE in metals fatigue specimens and relate them to damage mechanisms [14, 15].

2. Material and methods

Testing material is aluminium alloy. The results from fatigue testing and AE data of SLM material were compared with results of reference conventionally produced (extruded) material from Al alloy AlCu2Mg1,5Ni (2618A) with T6 heat treatment, chemical composition of SLM material is similar. Chemical composition of both materials is shown in Table 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mg</th>
<th>Ni</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference material</td>
<td>0,24</td>
<td>1,1</td>
<td>2,5</td>
<td>1,5</td>
<td>1,2</td>
<td>0,04</td>
</tr>
<tr>
<td>SLM powder</td>
<td>0,15</td>
<td>1,0</td>
<td>2,66</td>
<td>1,39</td>
<td>1,22</td>
<td>0,2</td>
</tr>
</tbody>
</table>

SLM samples were produced by SLM 180 HL machine. At the beginning there were tried different process parameters. Quality of produced samples were evaluated on the basis of relative density, the best result was 0,35 %. The final optimal parameters were: laser power 200 W, laser speed 100 mm/s, hatch distance 110 µm and beam diameter 82 µm. Scanning strategy were meander and it is shown in the Fig. 1b) [17].

A set of 26 specimens was made from reference material, 13 pieces of this set were subjected to heat treatment (T6). 3 sets of 4 pieces were made from SLM material. Two sets were made from new powder; the difference was in the distribution of samples on the plate. Samples from 1st set (identified as 2015) were made one by one, but pieces from 2nd set (identified as 2016) were produced together. 3rd set was made from recycled powder.

On the metallographic samples (Fig. 2) we can clearly see layer borders and a lot of defects near them (red arrows in the Fig. 2). This kind of internal structure has bad influence on fatigue life.

The bending fatigue tests were carried out by electro-resonance RUMUL Craetronic 8204 testing machine. The fatigue cycle was sinusoidal in stress ratio R = -1, test were conducted in high-cycle region in room temperature. Approximate loading frequency was about 52 Hz.
AE signal was detected by a DAKEL-XEDO and also by IPL system using two piezoelectric DAKEL IDK-09 sensors with 35 dB preamplifiers. The sensors were clamped on each end of the specimen by Loctite glue in order to create a two channel linear location system. Advanced IPL continuous data storage system was used to record all the incoming signals sampled by 2MHz. This system covers the frequency bandwidth of approximately 20 – 800 kHz with a total system gain of 80 dB. The threshold detection of the AE hits was frequently applied in post processing.

3. Results

All specimens were machined to the shape in the Fig. 3 and fatigue tested in same conditions at different stress level. The results were compared using standard S-N curves (Fig. 4). SLM material has significantly worse fatigue resistance than reference extruded material. Extruded material with T6 treatment has slightly better results than material without treatment. The results of SLM material fatigue show that the quality of produced material is strongly depend not only on process parameters, but also on the quality of the used metal powder. Specimens made from recycled powder have significantly worse fatigue resistance than specimens from new powder.

The AE measurements were carried only at several stress levels. In order to get an overview of the AE activity, the number of counts and cumulative number of events was observed, at the beginning in the reference material (Fig. 5). The beginning of loading (pre-initiation stage) is characterized by high AE activity caused by changes in material microstructure, interaction and glide of dislocations and persistent slip band formation. This stage is followed by low and
constant AE activity, which takes about 1/3 of the lifetime; micro-cracks start to propagate here (initiation stage). AE activity significantly increases in the last stage, where the long crack is growing (post-initiation stage).

The same three stages were observed in the SLM material, but the AE activity is significantly different (see Fig. 5b). The main differences are in count rate, ratio and duration of the stages. First two stages, pre-initiation and initiation stages, takes about half of the total fatigue lifetime, especially the initiation stage is much shorter than in reference material. This behaviour is probably cause by large amount of production defects (pores and shrinkages).

Significant differences were also observed in the AE amplitude values and duration in different phases of fatigue process (comparing the initial phase is given in Fig. 6). In the pre-initiation stage of the reference material was observed a lot of events with big scatter of amplitude value and its duration, most events from the 1st stage of SLM material have amplitude between 45 and 48 dB$_{AE}$ with low duration. Reference material initiation stage is characterized by signal with low amplitude and duration, which are coming from the micro-crack initiation, the same stage of SLM material is characterized by higher amplitude with low duration.
Figure 6. Linear regression of AE events in the initiation stage of AlCu2Mg1.5Ni (a) and same stage of SLM material (b)

Figure 7. Distribution of signal energy in different stages of fatigue
(a) AlCu2Mg1.5Ni, (b) SLM

Percentage of the overall signal energy in the different stages of fatigue process for reference material and SLM material is given in Fig. 7. The crack initiation phase (“ini” in the graph) normally spans the minority of the considered life-cycle in reference material while the pre-initiation phase (“pre-“ in the graph) usually covers almost the entire life-cycle. Unfortunately, this study did not confirm the relationship between phase duration and bending amplitude. More convincing and consistent results come from SLM material. Here is clear, despite the inhomogeneous structure of SLM, the crack propagation phase (“post-“ in Fig. 7b) spans more than 2/3 life-cycle in all cases of amplitude level. This is caused by manufacturing defects cause early crack initiation and growth due to cyclic loading. Therefore the initiation phase as well as pre-initiation phase is very short here. This is also seen in Fig. 5b where the loading frequency is going down very soon and AE hits change its parameters.

The fatigue and AE measurements were supplemented by fractographic study, see Fig. 8 and Fig. 9. There is clearly visible a production defects in the Fig. 8 (red ring), the unmelted powder particles (yellow arrows) shows, that the defect was created during production.
The red rings in the Fig. 9 and 10 mark the crack origins, which are located in the production defects. There are the unmelted powder particles in the cavities, so those defects were also created during the manufacturing process.
4. Conclusion

The results from fatigue testing of aluminium alloy AlCu2Mg1,5Ni and SLM material with similar chemical composition supplemented by AE measurement and fractographic were presented in the paper. The results from both material were compared and many differences, but also some similar behaviour were observed.

All 3 batches of SLM material have significantly worse fatigue life than conventionally produced (extruded) material. The AE signal showed the same three stages in both materials, pre-initiation, initiation and post-initiation stage. The ratio of the stages, AE amplitude and duration is significantly different in SLM and reference material.

The fractographic study of SLM samples showed that the crack origins are located in the surface defects, which were created during the production. The production parameters for production of cyclical loaded parts from material AlCu2Mg1,5Ni is not optimized yet and further research is needed.

5. Acknowledgements

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References


