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New Developments of Laser Processing Aluminium Alloys via Additive Manufacturing Technique

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Abstract

The significance of this research lies in its potential to create an Additive Manufacturing technology of novel lightweight materials for industrial applications. The work reported here focuses on studies performed with low power fiber laser and investigates the feasibility of introducing high strength aluminium alloys and custom developed Al powder systems to the Selective Laser Melting (SLM) process. Al-Si powder alloys were used as a reference point. The understanding of the behaviour the investigated alloys is essential if the SLM process to be fully controlled for a manufacturing environment.

Keywords: Additive Manufacturing (AM); Selective Laser Melting (SLM); Aluminium alloys structures; Layer manufacturing

1. Motivation / State of the Art

Selective Laser Melting (SLM) is an additive manufacturing technology, which is capable of producing functional prototypes with complex geometries and thin structural walls. In SLM technology metallic powders are molten in layers by laser energy in order to produce dense metal parts. Aluminium as a lightweight construction material is very attractive for manufacturing parts characterized by good mechanical properties and a good weight ratio. The significant increase in the usage of aluminium alloys in manufacturing can also be explained by their relatively low cost to specific strength ratio. However up to now there is no breakthrough in processing high strength Al alloys by SLM method. This work presents new powder system developments and a process qualification in order to get parts with high strength and super-high-strength aluminium alloys and functionally gradient material properties (FGMs). Powder systems with different particle size and distribution of elementary components were used to produce alloys during laser melting with different microstructural conditions. The next challenge for SLM is using metal powders characterized by different size of particles in one and the same plane. This can be realized due to our custom developed Al-Cu / Al-Zn compositions.

Current state-of-the-art of the SLM process has the main focus on Al-Si powders [1-3]. These metal powders, for example AlSi12 and AlSi10Mg, are relatively easy to process due to the small difference between liquidus and solidus temperature (melting and solidification point) compared to high strength aluminium alloys (Al-wrought alloys). Some work has been done on Al 6061 by SLM to fabricate heat sinks [4]. However this powder was proven

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unstable to processing [5]. The next research on Al 6061 in comparison with AlSi12 via SLM was recently conducted [6]. In this case the difficulties in processing aluminium were caused by thin oxides formations (thin oxide films) which lead to porosities. Another challenge is the high reflectivity of Al powder.

The aim of this work is to investigate the opportunities of introducing novel ready blended high strength and custom developed Al powder systems to the SLM technique based on low average power Ytterbium fiber laser.

2. Experimental

The initial SLM process investigations were performed on Al-Si metal powders as a reference point for further research. It should be mentioned that air atomising spray technology was used to produce these blend powders for the additive manufacturing of SLM parts. The experiments were carried out with AlSi12 metal powders, Figure 1 shows an example of this powder. The powder particles have a median particle size between 25 μm and 45 μm.

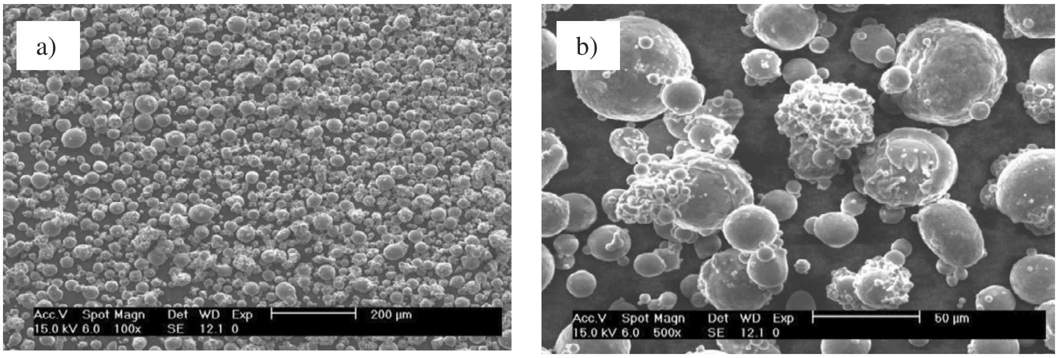

Figure 1: SEM micrographs of aluminium alloy powder Al Si12; (a) sample of powder; (b) close-up of grain size/shape particles

The other aluminium powder that was selected for initial work was AlSi10Mg. Figure 2 shows an example of this powder. The powder has the same median particle size as the AlSi12 powder. Both used aluminium powders are near cast eutectic casting alloys and have spherical particle shapes.

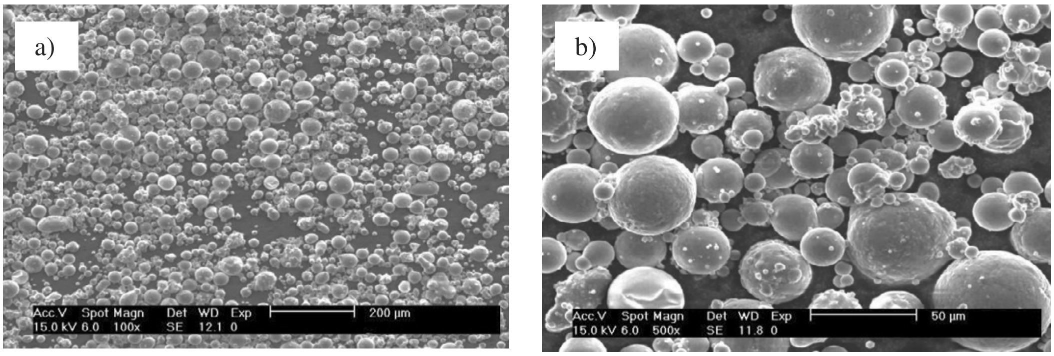

Figure 2: SEM micrographs of aluminium alloy powder AlSiMg10 (a) sample of powder; (b) close-up of grain size/shape particles

In a next step the feasibility of introducing high strength Al powder alloys (e.g.: 2xxx/7xxx series aluminium) to the SLM process was investigated. Up to now these powders have not been commercially used for a SLM application. Figure 3 shows an Al-Cu blend powder composition (2xxx). The average particle diameter (d50) is 45 μm. This powder shows spherical shape particles and high quality regarding particle scale.

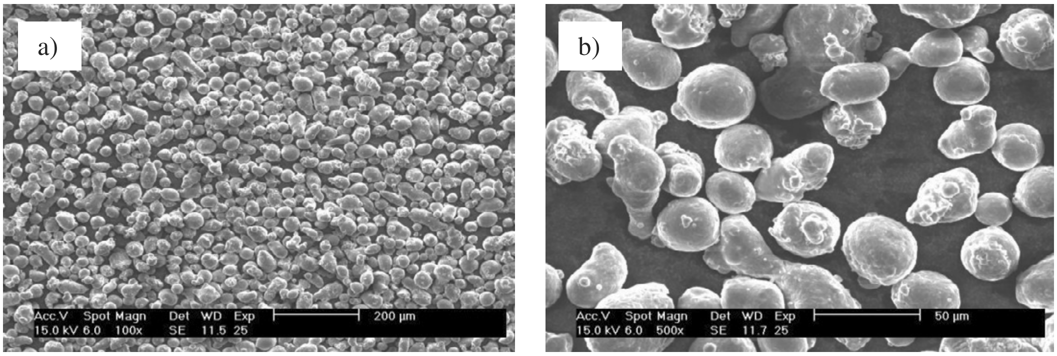

Figure 3: SEM micrographs of aluminium alloy powder 2xxx (a) sample of powder; (b) close-up of grain size/shape particles

Figure 4 shows the Al-Zn blend powder composition (7xxx). This powder shows the same average particle diameter (d_{50}) of 45 µm as the 2xxx blend. However in comparison with the Al-Cu powder more longitudinal shaped particles were observed.

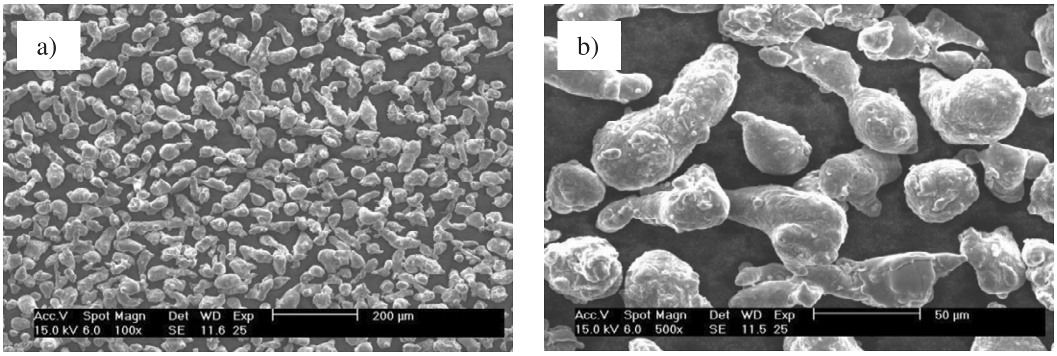

Figure 4: SEM micrographs of aluminium alloy powder 7xxx (a) sample of powder; (b) close-up of grain size/shape particles

The work reported here also shows results performed with custom developed Al-Cu / Al-Zn powder systems and investigates the feasibility of applying them to the Selective Laser Melting process. In Figure 5 a custom developed Al-Cu powder system is depicted. In this case the average particle size of Al was selected as d_{50} = 35 µm and for Cu d_{50} = 3 µm was chosen. Backscattered electron mode of scanning electron microscope (BSE-SEM) was used for the chemical characterization of a powder composition, a result of this characterization method is presented in Figure 5b.

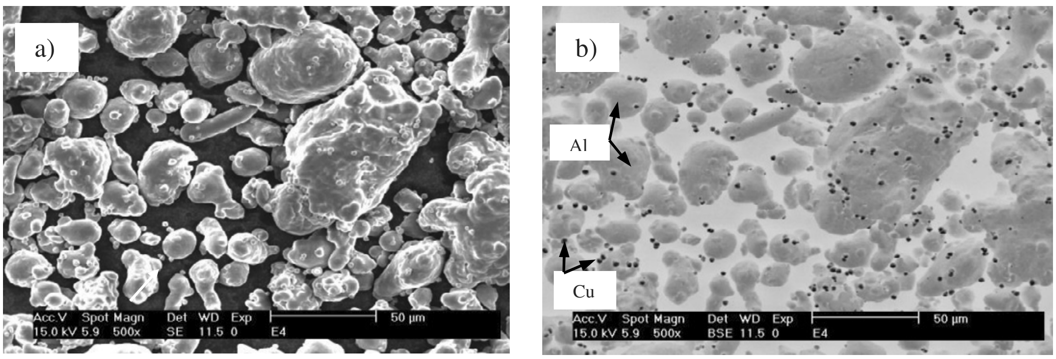

Figure 5: SEM micrographs of custom developed Al-Cu powder system (a) sample of powder in SEM; (b) sample of powder in BSE-SEM

BSE is useful for the powder characterization since it can perform qualitative and semi-quantitative compositional microanalysis. When a SEM is used in BSE mode, the brightness of an image correlates with the atomic number. This effect was very helpful to identify small Cu particles, which can be observed as black dots in Figure 5b. The results show that a homogeneous powder system with stable interconnections between Al and Cu particles can be produced via tumbling mixing. The shape of the Al and Cu particles does not change during the mixing process.

The aim of this work was also to produce a custom powder system with a different particle size and distribution of elementary components. For this research an Al-Zn system with Al (d_{50} = 35 µm) and Zn (d_{50} = 5 µm) particles was chosen. The custom developed powder systems are used in order to create aluminium alloy compositions during laser melting with different microstructural compositions. Regarding system technology the SLM study was carried out using a 200W single mode fiber laser (IPG, YLR-200 SM). The laser source has a central wavelength of 1070 nm and a minimum laser spot size d = 10 µm. The laser beam is fibre guided to a 4 axis laser workstation, which is illustrated in Figure 6.

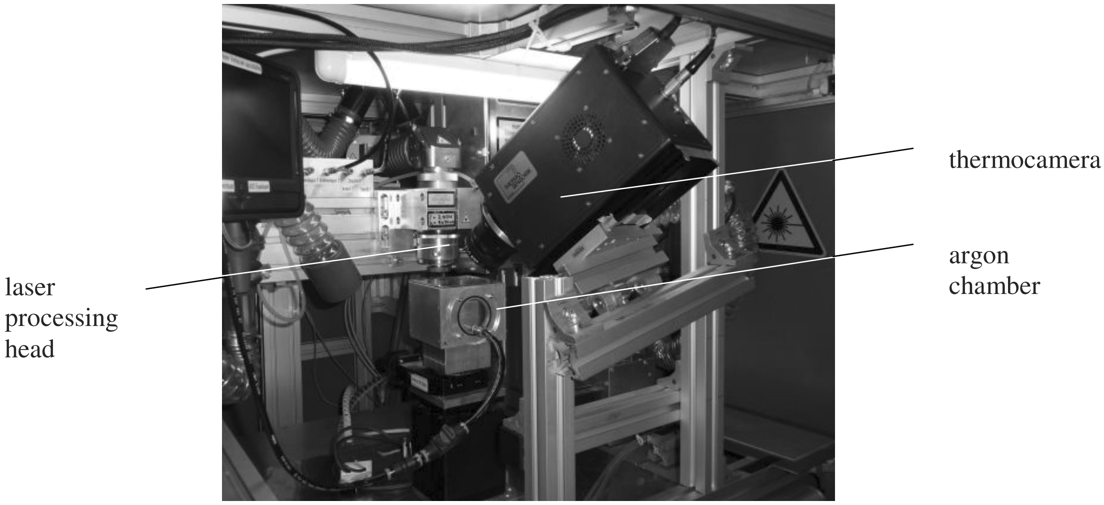

Figure 6: Laser workstation

The various metal powder systems were distributed manually inside the argon chamber, which is visible in Figure 6. The melting experiments were carried out on Al 6082 coupons as a substrate for fabricated aluminium surface layer. Single melting lines were fabricated and analysed.

3. Results and Discussion

The initial Selective Laser Melting (SLM) process investigations were performed on AlSi12 and AlSi10Mg powder, which is a mainly designed for new SLM applications. As an example deposited single tracks of AlSi10Mg on an Al 6082 substrate after laser processing is illustrated (Figure 7). The melted AlSi10Mg metal powder shows a dense and crack-free structure, which can also be seen in higher magnification (Figure 7b). Figure 8 shows SEM micrographs, which illustrate the upper surface layer of an AlSi10Mg deposited layer. No brittle or hard oxidation upper layer was noticed, which is very promising for a further development of a multi layer manufacturing process of reactive materials. The supersaturated solution of melted powder line was generated as a result of refinement structure within very fine Si precipitations. However dissolving of Si precipitations is very limited, much below 1 wt. %. The identical microstructure was observed in the middle zone of the deposited line. Also the bottom zone of deposited line is very homogeneous within a smooth transition zone between base material and deposited metal powder (Figure 8b).

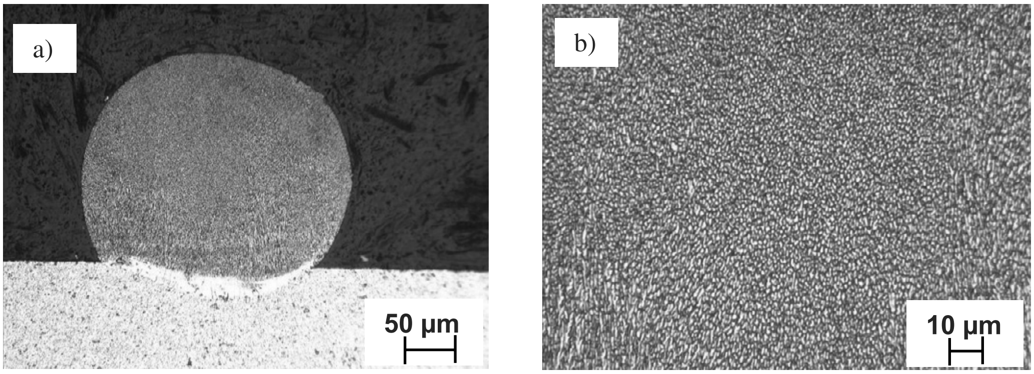

Figure 7: Optical micrographs of aluminium alloy Al Si10Mg on Al 6082 substrate after SLM processing (a) formation of single track; (b) microstructure of melted middle zone

The Mg2Si intermetallic phases of Al 6082 base material were dissolved into the metal matrix. Metallographic analysis show that there are no separated intermetallic phases in the metal matrix. This micrographs also show an orientated grain structure according to the direction of the heat escape from the heat affected zone (HAZ).

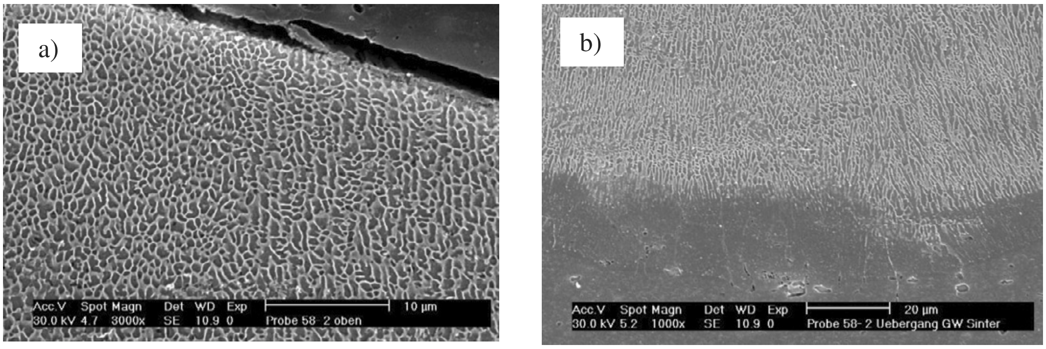

Figure 8: SEM micrographs of aluminium alloy Al Si10Mg on Al 6082 substrate after SLM processing (a) microstructure of upper surface formation of single track; (b) microstructure of bottom area formation of single track fused into Al 6082 substrate

To examine the effects of the SLM process on the melted surface layers (laser single track formations) hardness measurements were made (HV 0.002), which are presented in the microhardness distribution in Figure 9.

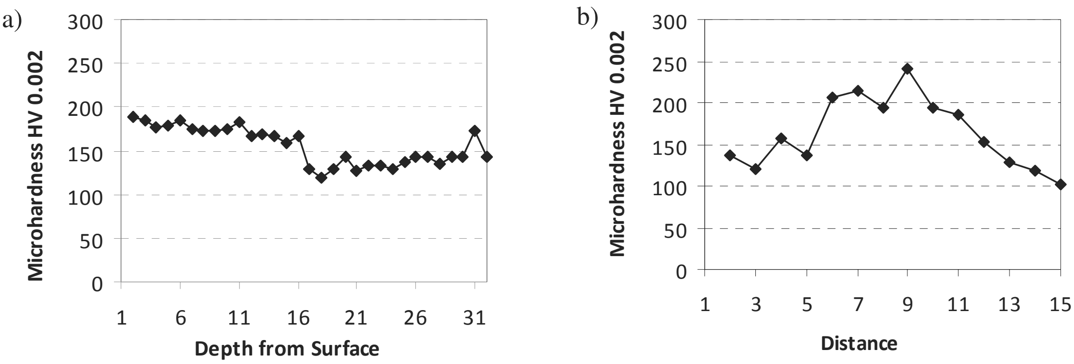

Figure 9: Variation of microhardness of aluminium alloy Al Si10Mg on Al 6082 substrate after SLM processing (a) SLM zone with depth; (b) SLM zone with width

In Figure 9a the microhardness distribution of depth from the bottom surface layer is depicted. In Figure 9b the microhardness distribution along the path under the deposited and fused metal powder (width) into the substrate is presented. The microhardness of the AlSi10Mg deposited line is about 70 HV 0.002 higher than the base material (substrate). This is a reason refinement structure within very fine Si precipitations due to fast crystallization (high cooling rate).

The feasibility of introducing high strength Al powder alloys to the SLM process was analysed. SLM processing effects on Al-wrought alloys were investigated. The studies include laser processing parameters development (single track laser irradiation strategy) and material processing results under argon-based environment. The metallographic analysis of the manufactured single track formations, microhardness tests, and geometrical measurements (high and width of SLM tracks) are shown. In Figure 10a a laser deposited single track of an Al-Cu alloy composition (2xxx) is illustrated. It was observed that the melted track is characterized by a high density and a crack-free structure. The micrograph illustrated in Figure 10 shows the middle surface layer of Al 2xxx after SLM. No brittle hard oxidation upper layer was noticed, which is very promising for further development of multi additive layer manufacturing process of reactive materials.

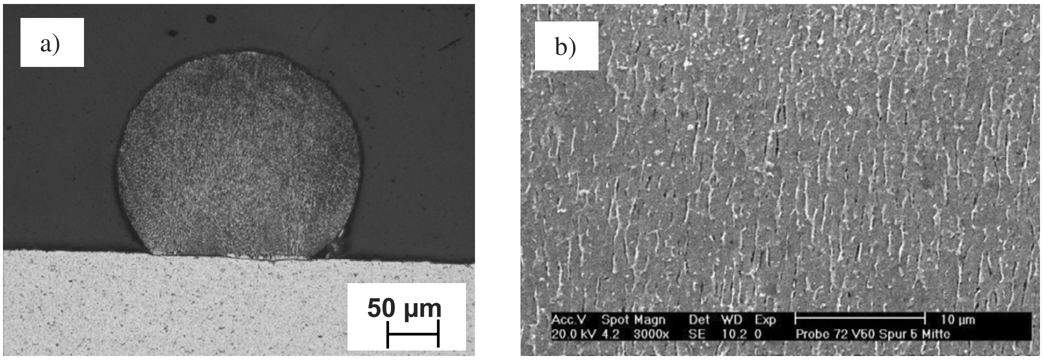

Figure 10: Micrographs of aluminium alloy 2xxx on Al 6082 substrate after SLM processing (a) Optical micrograph of formation of single track; (b) SEM micrograph of microstructure of melted middle zone

The achievable hardness values for Al 2xxx are 159 ± 6.6 HV0.002, which is an increase of 16 % compared to conventionally processed material (Al 2xxx-T4: 137 HV). In Figure 11a a laser deposited single tracks of Al-Zn alloy composition (Al 7xxx) is presented. In this case it was also noticed that the melted track is characterized by a high density and crack-free structure. The very fine microstructure was observed in the laser additive single track formation of Al 7xxx alloys as well (Figure 11b).

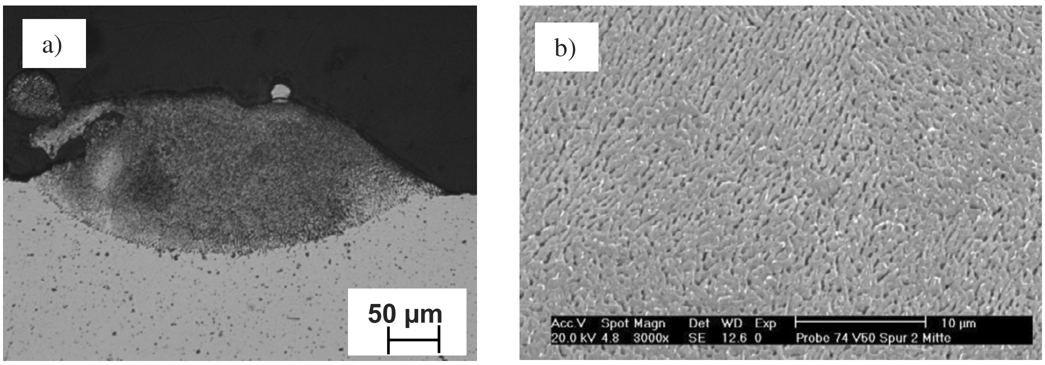

Figure 11: Micrographs of aluminium alloy 7xxx on Al 6082 substrate after SLM processing (a) Optical micrograph of formation of single track; (b) SEM micrograph of microstructure of melted middle zone

The feasibility of introducing custom developed Al powder systems to the SLM process was investigated. In Figure 12 Al-Cu alloy of single track formations after SLM are depicted. The copper content is different in the presented optical micrographs. The structure on the left side shows custom developed Al alloy within 2% wt. Cu (Figure 11a) and on the right side shows structures of Al alloy within 5% wt. Cu (Figure 11b). It was noticed, that the microstructure of single track formations are free of cracks and a high density.

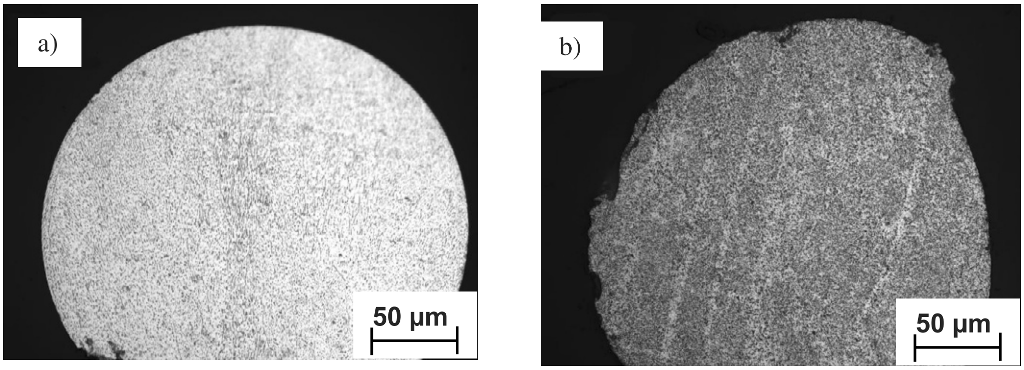

Figure 12: Optical micrographs of custom developed Al-Cu alloy on Al 6082 substrate after SLM processing (a) formation of single track of Al-2 wt. % Cu; (b) formation of single track of Al-5 wt. % Cu

The very high cooling rates during SLM of the powder based on the bulk aluminium base material cause a very fine microstructure. The supersaturated crystal shows finest precipitations smaller than 2.5 µm. The directional solidification follows the highest thermal gradient. In Figure 13 custom developed Al-Cu alloy with high 11.8 wt. % Cu content after SLM is shown. This single track formation also displays refinement microstructures without cracks, which can be seen in higher magnification (Figure 13b).

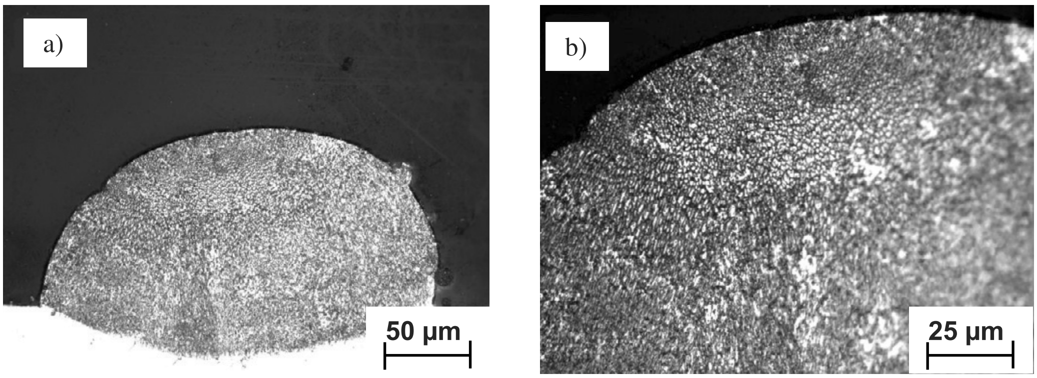

Figure 13: Optical micrographs of custom developed Al-11.8 wt. % Cu alloy on Al 6082 substrate after SLM processing (a) formation of single track; (b) microstructure of upper melted zone

The adequate selected SLM parameters can produce various structures of Al-Cu alloys. For example in Figure 14 two different microstructures of the same custom developed Al-11.8 wt. % Cu alloy are demonstrated. In this case slower scan speed, v = 10 mm/s, generated structures characterized by longitudinal grains in direction to heat escape flow (Figure 14a). The same powder system, processed with a higher scan speed v = 30 mm/s, produced very homogeneous and fine microstructures (Figure 14b). All in all the microstructure can be characterized by an observable grain refinement in conjunction with finely dispersed intermetallic phases. This means the coarse and microstructure can selectively be adjusted with an adapted process, e.g. with different irradiations with slower heating and cooling rates.

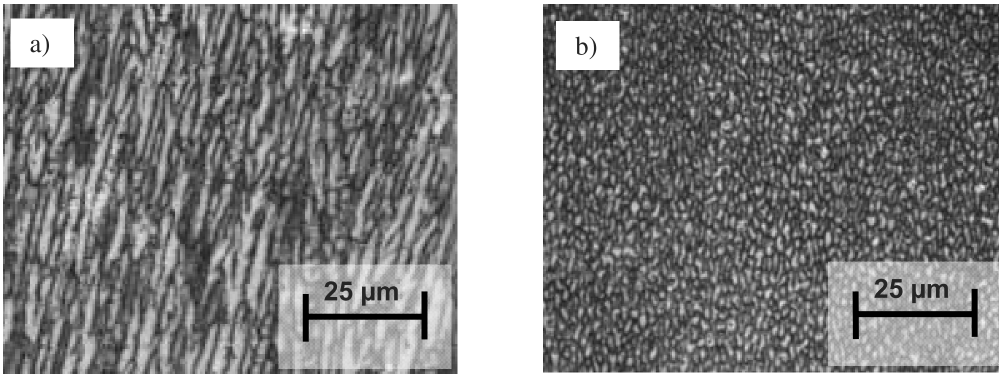

Figure 14: Optical micrographs of custom developed Al-11.8 wt% Cu alloy on Al 6082 substrate after SLM processing (a) microstructure of middle melted zone within scan speed v = 10 mm/s; (b) microstructure of middle melted zone within scan speed v = 30 mm/s

In Figure 15 Al-Zn alloy of single track formations after SLM are depicted. Structures on the left side show the custom developed Al alloy within 2 % wt. Zn (Figure 15a) and on the right side shows an upper surface layer in higher magnification (Figure 15b). Al-Zn alloy compositions were not so trivial to process due to high Zn reactive nature. However the obtained results of single track formations demonstrated homogeneous microstructures characterized by a high density and no cracks.

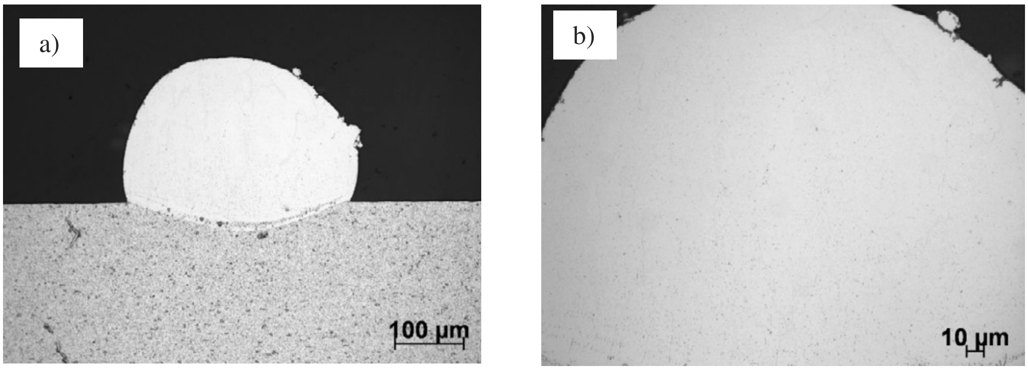

Figure 15: Optical micrographs of custom developed Al-2 wt. % Zn alloy on Al 6082 substrate after SLM processing (a) formation of single track; (b) microstructure of upper melted zone

In Figure 16 Al-Cu alloy of layer formation after SLM is presented. This sample demonstrates our current work towards multi-layers approach of the SLM process.

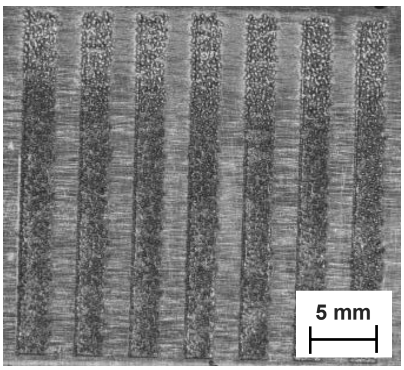

Figure 16: Picture of Al-Cu alloy layer on Al 6082 substrate after SLM processing

4. Conclusion

This shows possibilities for a development of new light weight material powder systems, which are based on Al components. The following conclusions can be drawn based on this work:

- One of the main aims of our work is to produce custom powder systems with different particle sizes and distributions of elementary components. The example of Al-Cu and Al-Zn shows that this was possible.
- Homogeneous powder systems with stable interconnections between Al and Cu / Zn particles were successfully achieved. Several powder system compositions based on Al were developed, e.g.: Al-2 wt.% Cu, Al-5 wt.% Cu, Al-6.8 wt.% Cu, Al-11.8 wt.% Cu, Al-2 wt.% Zn, Al-5 wt.% Zn and Al-10 wt.% Zn. The shape of the Al and Cu / Zn particles does not change during the mixing process
- The big SLM challenge with using metal powders characterized by different sizes of particles in one and the same layer can be realized due to our custom developed Al-Cu / Al-Zn compositions
- Our custom developed Al-Cu / Al-Zn powder systems were able to create very promising aluminium alloys compositions during laser melting with different microstructural conditions
- Feasibility of introducing ready blend high strength Al powder alloys (e.g.: 2xxx/7xxx series aluminium) to the SLM process shows great potential. No brittle hard oxidation upper layer was noticed on melted lines, which is very promising for further development of multi additive layer manufacturing process of reactive materials
- The manufactured additive layers, characterized by a fine microstructure with homogeneously dissolved intermetallic phases in the metal matrix, has a big potential for usability properties of the final manufactured product
- Future investigations will continue the development of novel Al-Cu / Al-Zn custom powder systems. This work proved the feasibility of introducing custom and ready blended high strength Al powder alloys to SLM process applications. Multi-layer investigations will continue and expand to 2D details to reach final destinations of complex 3D SLM parts.

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