Processing of Magnesium Alloy by Selective Laser Melting

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Abstract. This paper presents results on processing AZ31 magnesium alloy with Selective Laser Melting technology. The process optimization was performed according to the Design of Experiments methods. The porosity analysis shown that fully dense specimens were achieved. Thanks to the Analysis of Variance (ANOVA), the impact of changed parameters on the porosity was characterized. The paper also presents results of material characterisation. Microstructure evaluation shown fine, equiaxial grains, which could be responsible for uniform mechanical properties and good elongation. Carried out mechanical tests proves, that the properties of AZ31 material obtained in additive process are correspond for conventional cast alloy.

Keywords: Selective laser melting · Magnesium alloy · Design of experiments · Additive manufacturing · Mechanical properties

1 Introduction

Because of very low density and high specific strength [2], Magnesium have been drawing attention since century as a prospective engineering material.

It is commonly known, that the rapid oxidation is the biggest disadvantage for magnesium based materials for industrial applications. But this feature thanks to fast resorption of oxidation products and a non-invasive excretion from organisms make magnesium as an attractive biomaterial. Hitherto resorption rate of magnesium was too rapid compared to the growth of bone tissue and impossible to control. Because of that, magnesium alloys was not adopted into common use in medicine [3, 5, 10, 14, 15].

SLM process seems to be very interesting for processing magnesium based materials, because of the protective atmosphere and additionally high temperature gradient between the melted pool, the surrounding non-melted powder and solidified material, may bring promising results as a new properties of processed materials, because of microstructure refinement.

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2 Materials and Methods

In this research an AZ31 alloy was used, provided by TLS Technik GmbH. Powder granules have good spherical shape, what was confirmed during conducted powder characterization including chemical composition, which complies the ASTM standard [16]. The Selective Laser Melting process of investigated magnesium alloy were performed using ReaLizer SLM50 device, equipped with 100 W laser power, focused on process platform to 100 µm. All specimens investigated in this research were made with 50 µm layer thickness, Argon was used as a shielding gas.

Laser micrometalurgy process was optimized in order to minimize material porosity, according to experiments plans based on Design of Experiments (DoE) methodology. The range of used energy densities needed to melt analysed material, were analytically calculated, using heat transfer model for laser beam metal welding [6, 11],

$$(\Delta T) = \frac{A_\lambda P}{2\pi\lambda V}\exp\left(\frac{r^2}{4at}\right), \tag{1}$$

Taking into account an absorptivity of analysed powder material for laser wavelength used in SLM50 device, and bulk density which influences on material conductivity, an initial process parameters values range were defined. This process parameters values were then used during planned full factorial design at 3 levels and central rotatable composite experiment [10]. In performed experiments an impact of change the basic process parameters on resulting material porosity was evaluated. During designed experiments, the laser power (P), distance between each scanning point (pt_{dist}), and exposure time in single point (t_{expo}), were analysed, which are with other unchanged parameters, the components of linear energy density (Line $energy_{density}$),

$$Line\ energy_{density} = \frac{P}{V_{scan} * spotsize}, [\mathrm{J} * \mathrm{mm}^{-2}] \tag{2}$$

$$V_{scan} = \frac{pt_{dist}}{t_{expo}}, [\mathrm{mm} * \mathrm{s}^{-1}] \tag{3}$$

Process parameter sets used during experiments are presented in Tables 1 and 2.

Table 1. Defined values used during 3 level full factorial design for three factors.

Factors	Values			
Laser beam power – P (W)	×1	60	75	90
Point distance – pt_{dist} (µm)	×2	10	15	20
Time exposure in single point – t_{expo} (µs)	×3	40	80	120

Table 2. Defined values used during central rotatable composite design.

Factors	Values				
	$-\sqrt{2}$	-1	0	1	$\sqrt{2}$
V_{scan} ($mm{*}s^{-1}$)	90	100	125	150	160
Laser beam power – P (W)	60	65	75	85	90

For the SLM process optimization, cuboid specimens (3 × 4 × 5 mm) were made. The porosity of manufactured specimens was examined on 3 perpendicular cross-sections. Prepared specimens were grinded and polished, and then monochromatic microscopic picture were evaluated, where porosity was the ratio of dark pixels (pores), in entire specimen picture pixel amount.

Prepared cross-sections were used during micro-hardness tests using Zwick/Roell ZHV JS-2000 device. Specimens with minimal porosity were etched with acetic-picral and analysed in order to reveal material microstructure using Zeiss EVO MA25. An chemical composition of processed material was also measured.

Optimized process parameters set, which allows to obtain minimal porosity, were used to manufacture specimens for mechanical testing (static tensile and compression tests). Mechanical tests were performed on Instron 3384 and MTS 370 Bionix. Specimens for tensile testing were designed with comply to dimensional ratio according to polish standard [12]. During tensile tests specimens built in two orientations were analysed in order to evaluate mechanical properties anisotropy (horizontal and inclined to process platform) – Fig. 1. Because of pro-cessing volume limitation, vertical specimens could not be manufactured. Specimens for compression tests were designed according to standard [13], and were manufactured in 3 orientations (horizontal, vertical and inclined).

Fig. 1. Tensile test specimens, made from AZ31 with SLM technology.

3 Results

Performed optimization procedure and manufactured specimens allows to set processing window, and obtain satisfactory porosity in melted material less than 0.5%. With all analysed process parameters set during experiment based on central rotatable plan, material porosity was below 1%, and the minimum porosity in the material was

0.3% with the deviation of 0.17% (determined according to assumptions for repetition of experiments in central point of experiment). An example of specimen cross-sections is presented Fig. 2a.

Process parameters values set have no influence on hardness of obtained material in analysed range of volume energy density (Volume $Energy_{density}$),

$$Volume\ energy_{density} = \frac{P}{V_{scan} * layer_{thickness} * line_{dist}}, [\mathrm{J} * \mathrm{mm}^{-3}] \quad (4)$$

The measured hardness of processed material was from 64 to 71 HV0.1, and for specimens with minimal porosity reached 69 ± 1 HV0.1.

Microstructural analysis revealed very uniform microstructure on all analysed specimens surfaces, consisting of equiaxed grains – Fig. 2b. The grain size in the comparison to cast alloy is much finer, which is common for all materials after SLM process – Fig. 3 [8].

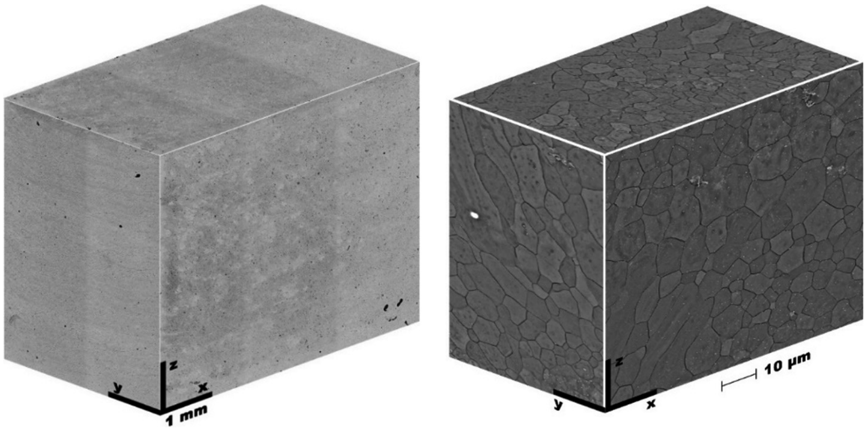

Fig. 2. Example of specimen with one of the lowest porosity in the material, made from AZ31 with SLM. (a) microscopic picture, (b) microstructure obtained with SEM (Specimen no. 9 – laser power: 75 W, scan velocity: 125 mm*s^{-1}, Line energy density: 6.00 J*mm^{-2})

Analysis of microstructure depending on specimen planes, shows that some longitudal grains oriented in z-axis could be observed, but they are not so big as like for other materials processed by SLM, especially titanium or nickel based alloys [4].

The chemical composition of powder material used in research corresponds to ASTM Standard, but during the SLM process the composition of processed material slightly differs – Fig. 4. Performed measurements, revealed higher content of Al and Zn.

Mechanical properties of AZ31 alloy processed in SLM technology are presented in Table 3. Yield strength values reached 187 ± 11 MPa, and Ultimate Tensile Strength

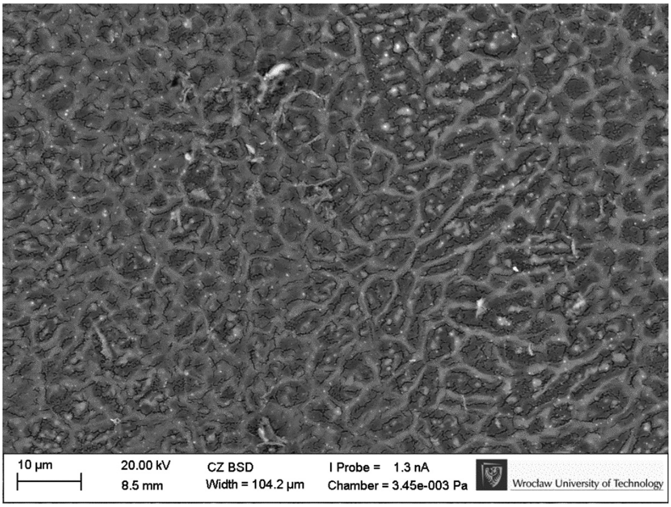

Fig. 3. Microstructure of referenced cast AZ31 alloy.

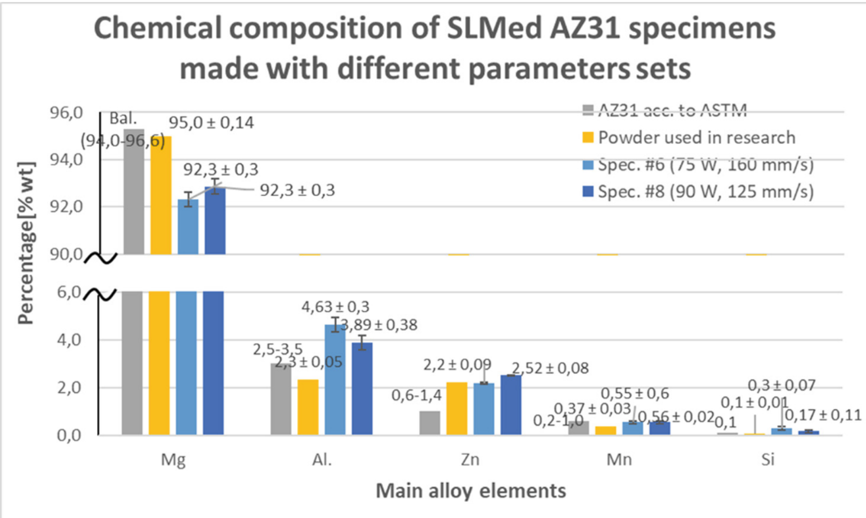

Fig. 4. Microstructure of referenced cast AZ31 alloy.

was 212 ± 34 MPa. Compressive strength and elongation during compression is dependent on specimens orientation during the build, and maximal measured values reached 387 ± 29 MPa of Rs and 19.8 ± 0.7% of elongation for specimens manufactured in vertical orientation.

Table 3. Mechanical properties of AZ31 alloy made with SLM, obtained during tests.

	Tensile strength test			Compressive strength test	
Specimen	YS (MPa)	UTS (MPa)	Strain at damage - Δl (%)	Compressive strength – Rs (MPa)	Strain at damage - Δl (%)
SLM horizontal	183 ± 8	212 ± 34	7.9 ± 2.9	377 ± 29	17.3 ± 1.2
Inclined	187 ± 11	207 ± 54	7.7 ± 6.0	355 ± 46	16.2 ± 2.5
SLM vertical	–	–	–	387 ± 29	19.8 ± 0.7
Ref.	153 ± 48 [1, 12, 16]	248 ± 28 [1, 12, 16]	8.0 ± 4.0 [16]; 14.0 ± 2.0 [1, 12]	145 ± 35 [12]; 486 ± 4 [7]	19.7 ± 7.2 [7]

4 Discussion

During the SLM process of magnesium alloy, significant soot emission was observed. It is common problem, described also by [13]. The evaporation products deposits on the whole process chamber surfaces (Fig. 5). Analysis of the evaporation products, shows that no contamination in the material appears.

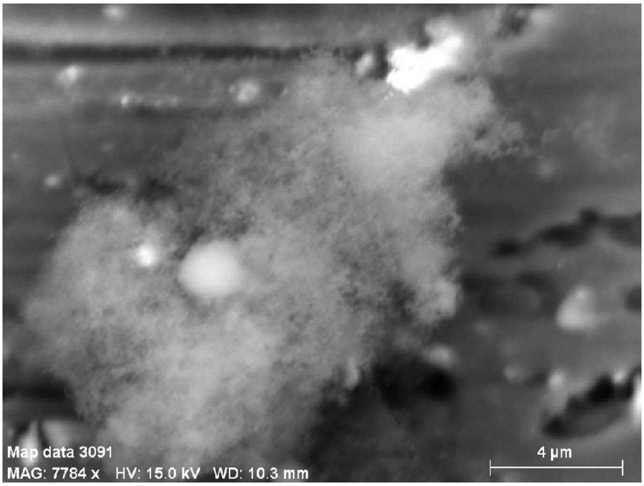

Fig. 5. Cauliflower like products of magnesium evaporation.

Performed analysis of variance (ANOVA) for the described experiment, based on p-value (0.303) shown that for the assumed level of confidence α = 0.05, the impact of factors on the results was not significant. P-value was lower (0.055) for hardness but it was not low enough to indicate that the factors change had significant influence on the results (>0.05). Among all factors under analysis, the greatest impact on the material porosity was exerted by scan velocity, but still it did not reach the level that would be significant as regards impact on changes (p-value = 0.084). In the case of hardness, the laser power had significant impact on the results (p-value = 0.005) [9].

The reason of an increase in Aluminum and Zinc content in processed material is magnesium evaporation. Chemical composition of the as-built material became more near AZ61 than AZ31. This fact could lead to higher strength and hardness of the processed material, due to higher Al and Zn content.

Both, the Yield Strength and Ultimate Tensile Strength are satisfactory for obtained material by SLM. Obtained tensile properties values, slightly differs from values for reference cast material, but the yield strength exceeds values for cast alloy by 20%. Values of compression strength are lower than for ref cast alloy. Especially for biomedical applications as a metallic implants, compression strength is important property, and special attention should be paid to improve this characteristics.

There is no significant anisotropy of mechanical properties dependent on build orientation, which is surprisingly result for SLM processed material, but could be explained by equiaxial and uniform microstructure without columnar grains.

Surprisingly the elongation values for material obtained in SLM technology, both during tensile like compression tests are comparable to cast alloy, which is not common for materials processed in SLM. After SLM process, most materials are brittle, and their values increase after additional HT.

5 Summary and Conclusions

The studies presented in this paper show that magnesium based alloy powders can be processed by SLM technology. The obtained results of material porosity and micro-hardness are satisfactory. Therefore, further research is needed to explore application areas for Selectively Laser Melted magnesium alloy powders. The obtained good values of the mechanical properties indicate the wide spectrum of applications of SLM technology for processing magnesium based alloys.

In the nearest future the authors are planning to conduct a research on other magnesium alloys and some investigations on influence of used process parameters values on microstructure, mechanical properties and corrosion resistance.

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