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Mechanical properties and microstructure of AlSi10Mg alloy obtained by casting and SLM technique

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ABSTRACT

Selective laser melting (SLM) techniques are gaining popularity recently. Due to increasing requirements of the manufacturing industry regarding cost production reduction, methods based on additive manufacturing (AM) are more and more attractive. SLM method allows fabricating parts with minimum post-processing machining requirements. Considering the above, this technique is applied mainly in aviation, automotive industry and medicine. Manufacturing parts by SLM method demands strictly defined parameters in particular when using aluminium alloys, due to high risk of porosity. The aim of research was to evaluate the possibility of replacing traditional casting of small-lot details by novel SLM method in specified manufacturing conditions. This study contains comparison of chosen physical and mechanical properties of AlSi10Mg alloy obtained by SLM method and by casting. As-received as well as heat treated (T6 heat treatment) materials were examined. Both types of the billets were subjected to hardness, tensile and Charpy impact tests, before and after T6 heat treatment. For SLM material relative density was also specified. Microstructure of cast and SLM samples was analyzed using light microscopy. The results of the research lead to conclusion, that the key aspect is the appropriate selection of parameters of manufacturing of the parts by SLM method.

Keywords: SLM - selective laser melting, aluminium alloy, AlSi10Mg, microstructure, mechanical properties, heat treatment

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1. INTRODUCTION

AlSi10Mg alloy belongs to hypoeutectic aluminium alloys group. Due to good mechanical properties combined with low density, corrosion resistance and excellent castability it is widely used in automotive industry, aircraft and military applications [1, 2]. Eutectic Al + Si phase present in this alloy may significantly affect its ductility and strength, but also makes this material difficult to machine. Low shrinkage and relatively low melting temperature is characteristic for AlSi10Mg alloy. For those reasons this alloy is mainly used for casting [3-5]. Taking above into consideration, properties of AlSi10Mg alloy give opportunities to apply it in manufacturing process based on Additive Manufacturing (AM). Current publications and research are focused on investigations of mechanical and physical properties of AlSi10Mg alloy obtained by AM methods. The nature of the microstructure is widely analyzed. Optimal process parameters are also studied for improving relative density and properties [6-8].

Nowadays, the aim is to fully automate industrial processes and minimize manufacturing costs with reducing production time. Considering the above, the techniques based on AM may be suitable for rapid prototyping complex-shape parts. Selective laser melting (SLM), also known as direct metal laser sintering (DMLS) is technique using laser beam to selectively melt powder metal layer by layer to achieve final component based on 3D computer aided design (CAD) data [1,9]. Due to growing industry filed requirements regarding producing lightweight, complex-shape parts, AM techniques such as SLM become attractive for automotive and aerospace industry, especially in manufacturing components from Al alloys, Ti alloys and Ni superalloys [7]. This technology is also useful in producing artificial cellular metals, where controlled structure, high impact energy absorption and high gas permeability is required [10]. Application of AM technology is also beneficial from economical and ecological point of view. SLM allows producing complex structures continuously what leads to weight reduction of finish product. Additionally serial production results in waste reduction which gives benefits in energy and time savings [8].

Designing of SLM process requires selection of suitable parameters. To achieve high mechanical properties and low porosity of product, laser, scan, material and temperature related parameters should be taken into consideration. It has been proven, that combination of parameters such as hatch spacing and scan speed affects density of finished product significantly [8, 11].

2. EXPERIMENTAL RESEARCH

2. 1. Aim and scope of study

The aim of the research was to compare chosen mechanical properties as well as character of microstructure of AlSi10Mg alloy obtained by novel SLM method and by casting. The investigations involved microstructure observations in as-delivered conditions and after T6 heat treatment for both types of billets. Hardness measurements were conducted on samples in initial state and after quenching and aging. Tensile and Charpy impact tests were performed for those materials before and after heat treatment. For samples obtained by SLM method, relative density was also determined.

2. 2. Material for research

Billets obtained by casting were delivered by Thoni-Alutec Sp. z o.o. Spectrometric analysis of chemical composition (Table 1) was also included. The initial material used in tests was delivered as set of cylindrical billets 120 mm long and 20.5 mm in diameter (Figure 1a).

Table 1. Chemical composition of AlSi10Mg powder and AlSi10Mg cast alloy.

	Al	Si	Mg	Cu	Mn	Fe	Ni	Zn	Pb	Sn	Ti
Powder*	Balnc.	9.0-11.0	0.2-0.45	≤0.05	≤0.45	≤0.55	≤0.05	≤0.1	≤0.05	≤0.05	≤0.15
Cast alloy**		9.51	0.349	0.008	0.126	0.294	0.0043	0.0095	0.0019	-	0.13

*Based on EOS GmbH material data sheet.

**Based on spectrometric analysis of chemical composition delivered by Thoni-Alutec Sp. z o.o.

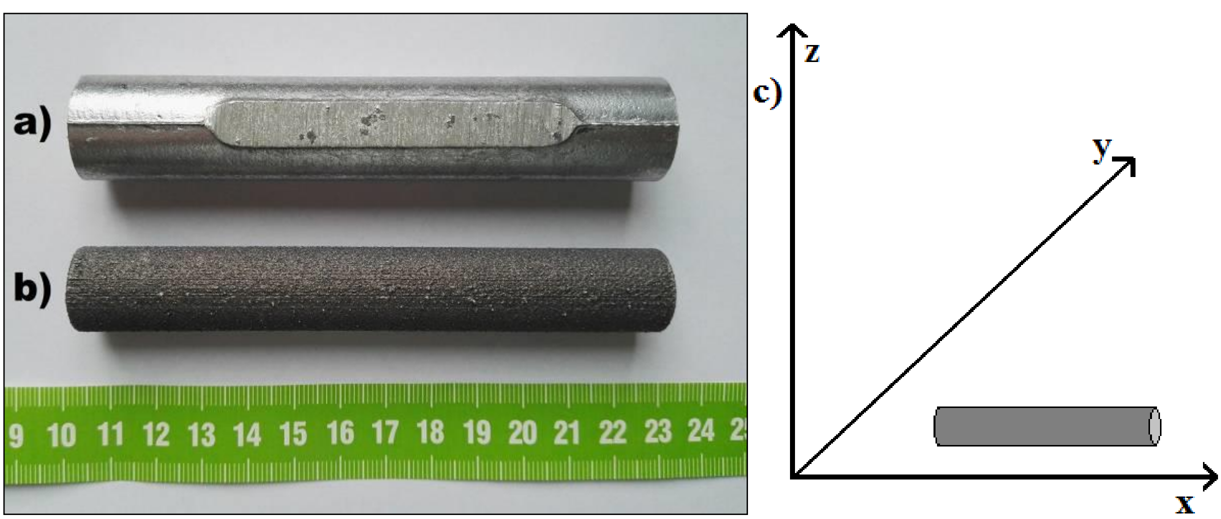


Figure 1. As-delivered AlSi10Mg billets: **a)** casting, **b)** sintered; **c)** schematic representation of building directions.

AlSi10Mg powder supplied by EOS GmbH was used in SLM process. Chemical composition of this material is presented in Table 1. Sintered billets were made by The Institute of Advanced Manufacturing Technology in Cracow using a Renishaw AM 250 SLM machine equipped with 400 W fibre laser and focal laser beam diameter of 75 μm. Maximum dimensions of the part being built with this equipment is 250 × 250 × 300 mm (X, Y, Z). SLM process was optimized as follows: maximum laser power (400 W), laser scan speed was 2000 mm/s, powder layer thickness was 50 μm, point distance was 75 μm and hatch spacing was 165 μm. Meander scan strategy was used in this work. This strategy assumes sintering layer rotated from the previous one by an angle of 67° every second [12]. Billets were build horizontally, along X axis. Schematic representation of building directions is shown on Figure 1c. Delivered material for test had a cylindrical shape with dimensions 120 mm long and 16.5 mm in diameter (Fig. 1b).

2. 3. Heat treatment

Samples for tests were cut off from both AlSi10Mg billets before and after T6 heat treatment process. Cast and sintered billets were solution heat treated in the temperature of 535 °C for 10h and then water quenching. Next materials were artificial aged in the temperature of 155 °C for 6h, then slow cooled at room temperature.

2. 4. Metallographic investigations

Microstructure observations of cast and SLM AlSi10Mg alloy in as-delivered and after T6 heat treatment conditions were conducted on optical microscope LEICA DM4000M. Chosen microstructures are shown in Figure 2 and 3. Figure 2a demonstrates microstructure of AlSi10Mg alloy obtained by SLM method in as-built condition. It revealed three different types of grain structure. In the middle section of melt pool fine grain structure was obtained. In sides of melt pool grains are coarser and elongated towards the heat source. Region between two melt pools overlapping is called heat affected zone (HAZ). This type of structure has been previously described in the literature [8,9]. Pores in the mounted cross-section were observed (Fig. 2b). Key-hole pores length ranged from 250 μm to 700 μm. Smaller, spherical pores were identified as metallurgical pores.

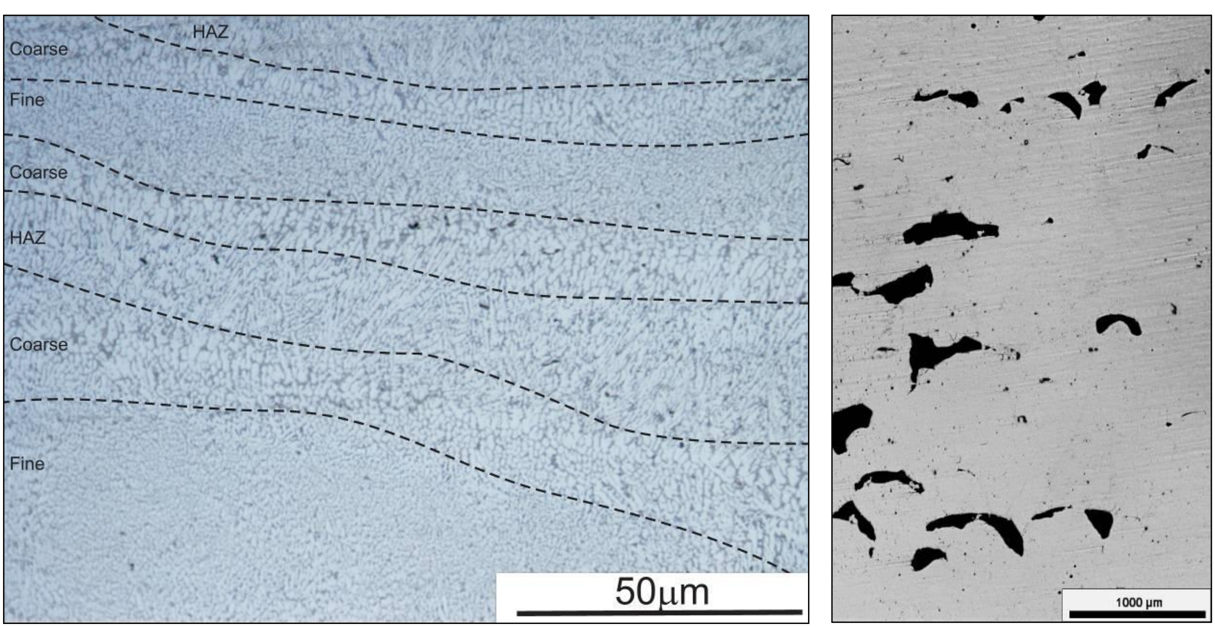
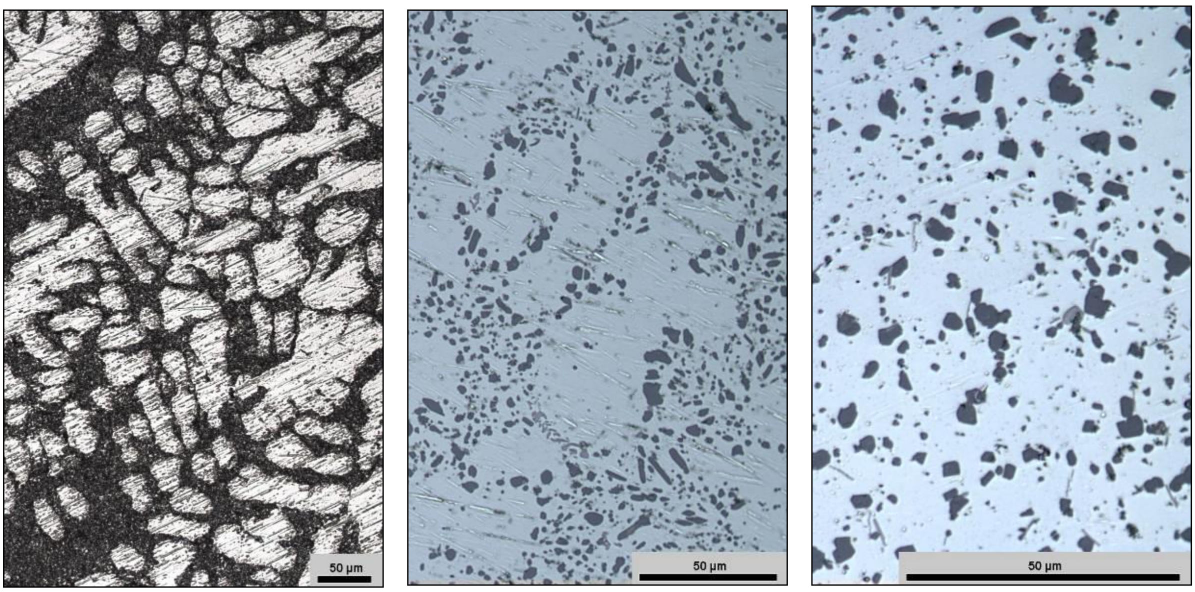


Figure 2. a) Microstructure of as-build SLM AlSi10Mg alloy; **b)** porosity in mounted cross-section of SLM sample.

Microstructures of cast AlSi10Mg alloy are presented in Figure 3a,b. In as-delivered condition (Fig. 3a) structure was characterized by large α-Al grains and irregular eutectic phase. Due to heat treatment the morphology of microstructure has been changed (Fig. 3b). Eutectic converted into Si spherical particles located around primary α-Al grains. Figure 3c demonstrates microstructure of T6 heat treated SLM AlSi10Mg alloy. In the result of solution treatment and aging Si particles have been grown and uniformly dispersed in Al matrix.



a) **b)** **c)**

Figure 3. a) Microstructure of cast AlSi10Mg alloy in as-delivered condition – etched; **b)** T6 heat treated cast AlSi10Mg alloy; **c)** T6 heat treated SLM AlSi10Mg alloy.

2. 5. Density measurements

Relative density measurements were performed by comparing the weight of sample in distilled water and air according to Archimedes method. Relative density was calculated by taking into account theoretical bulk density as 2.68 g/cm^3 [13]. Material in as-delivered condition has relative density of 92.54 %. Due to T6 heat treatment, relative density increased to 97.5 %. It could be the effect of diffusing of chemical elements to the low-concentration areas by volume diffusion mechanism. High level of porosity is connected with chosen parameters of SLM process. High scan speed results in low relative density [8]. The optical micrographs (Fig. 2b) show that the greater part of pores are keyhole pores rather than metallurgical pores. Those pores were formed due to rapid solidification without filling spaces between each layer of material. Described type of structure could have an impact on low mechanical properties in particular on tensile test results.

2. 6. Mechanical properties

Hardness measurements were conducted on cast samples as well as on sintered samples, before and after T6 heat treatment. Hardness was measured on cross and longitudinal section, in the centre region of sample. Distance between measurements was 0.5 mm. In Table 2 average results of HV_1 with standard deviation are presented. In Figure 7 comparison of average hardness of tested materials was presented. Additionally, for sample obtained by SLM method, hardness distribution depending on building direction was prepared. Results are shown in Figure 4.

Table 2. Chosen mechanical properties of AlSi10Mg alloy obtained by casting and SLM technology.

	E, GPa	**0,2 % Yield Stress, MPa**	**UTS, MPa**	**Elongation, %**	**HV_1**	**Impact energy, J/cm^2**
SLM	32	159	160	1.59	107 ± 2	3.4
cast	114	99	193	6.52	67 ± 3	3.8
SLM T6	64	171	192	1.77	109 ± 3	2.6
cast T6	104	242	309	6.89	108 ± 6	3.6

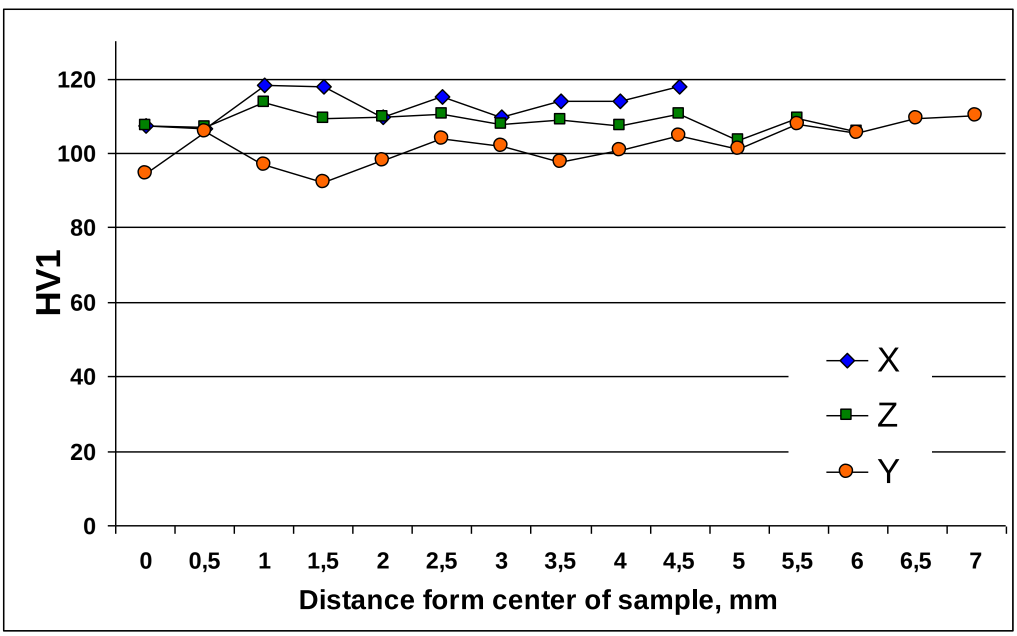


Figure 4. Hardness distribution for AlSi10Mg alloy obtained by SLM method depending on building direction.

Hardness measurements results shown difference between cast alloy and material obtained by SLM method in as-delivered condition. Sample cut off from sintered billet have about 60% higher hardness than cast material. This is caused by fine grain microstructure formed during laser melting process and rapid solidification of powder particles. Major differences in hardness distribution regardless to building direction were not observed. Considering metallographic observations, such low-range deviation is the result of the uniform microstructure. On cross section in Y direction lower hardness value were observed in the centre of sample (Fig. 4). Due to T6 heat treatment hardness of sample made by casting increased about 60 %. This effect is correlated with microstructure of heat treated AlSi10Mg alloy. Due to quenching and aging fine spherical Si particles were formed, what improves mechanical properties. For sample obtained by SLM technique strengthening effect was not significant.

Tensile tests were conducted on Zwick-Roell Z250 at room temperature. Test speed was 3 mm/min and initial force was 200 N. Both types of billets were tested before and after heat treatment. Samples for tests were made according to EN ISO 6892-1:2009 standard. For sintered material, tests were performed on samples cut out from billets built along X axis (Fig. 6a). Average test results are presented in Table 2. Figure 5 illustrates true stress- true strain curves for tested materials.

The as-delivered SLM samples exhibits tensile strength of 160 MPa and elongation of 1.59 %. T6 heat treatment has an influence on the mechanical properties of SLM material. Both factors, tensile strength and elongation increase (192 MPa and 1.77 % respectively). No significant necking was observed in any of the tested samples. Regarding the results of tensile test, cast sample was significantly different. In as-delivered condition, the tensile and yield strength are 99 MPa and 193 MPa respectively and elongation of 6.52 % . Due to T6 heat treatment tensile and yield strength increase to 242 MPa and 309 MPa respectively. Improvement of elongation was not significant.

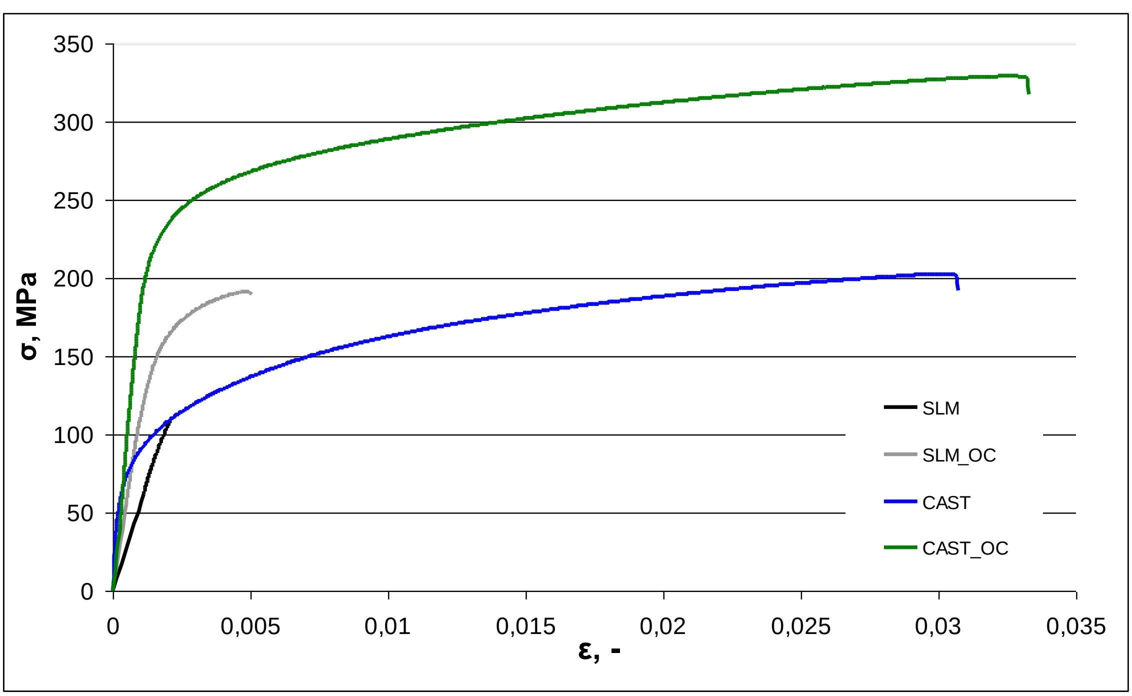


Fig. 5. Stress-strain curves for SLM and cast AlSi10Mg alloy in as-delivered condition and after T6 heat treatment.

High porosity of samples obtained by SLM technique affect the poor tensile test results. Refinement of microstructure during heat treatment improves mechanical properties only to a certain extent. Significant increase of tensile strength for AlSi10Mg samples obtained by casting is the result of precipitation of Mg_2Si phase [14].

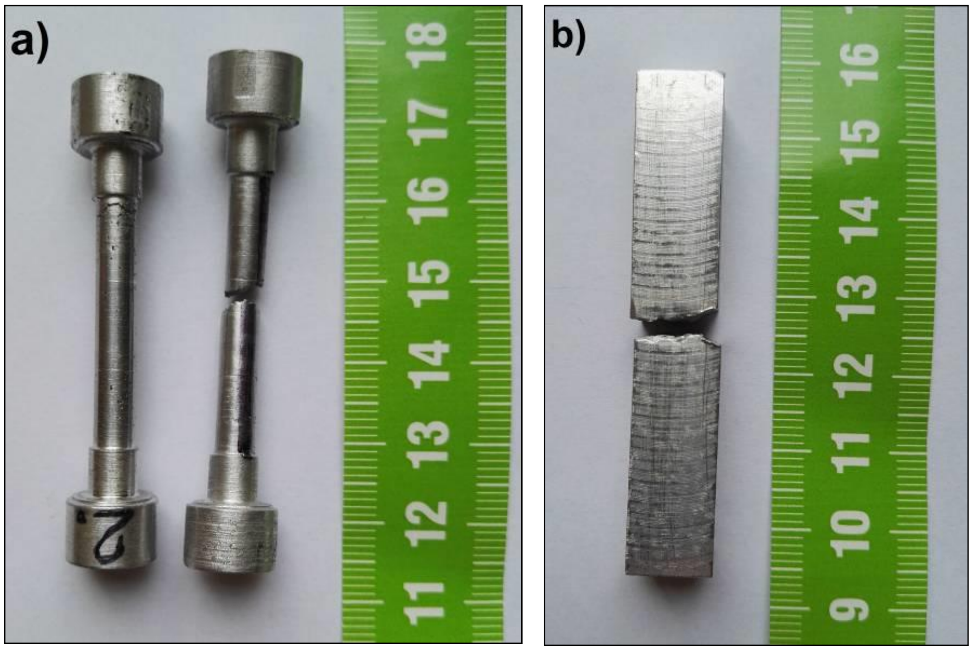


Fig. 6. Samples prepared for mechanical properties tests: **a)** tensile test; **b)** Charpy impact test.

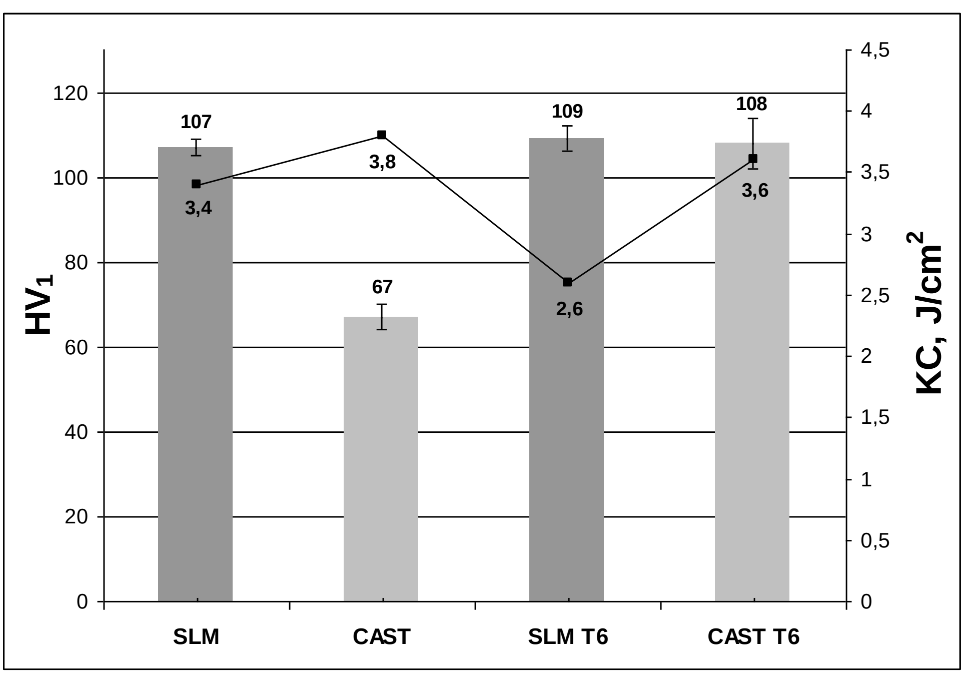


Fig. 7. Comparison of hardness and impact energy of AlSi10Mg alloy obtained by casting and SLM method.

Samples for Charpy impact test had dimensions of 10 mm x 10 mm x 55 mm, with notch depth 2 ± 0.75 mm (Fig. 6b). Both types of materials were tested before and after T6 heat treatment. As well as for tensile test, samples from sintered material were cut out from billets build along X axis. Test was conducted on impact test machine with maximum torque 5 kpm. Results are presented in Table 2. Comparison of impact test results and average hardness was presented in Figure 7.

Test results shown, that Charpy impact energy of as-built SLM samples was insignificantly lower than for conventionally cast AlSi10Mg material. Due to T6 heat treatment for both types of materials impact energy decreases. It is caused by microstructure modification during heat treatment and formation of spherical Si phase.

3. CONCLUSIONS

Based on the results of the performed research and observations conducted on cast and SLM AlSi10Mg alloy, the following conclusions can be drawn:

- Taking into consideration production parameters of SLM material, metallographic observation as well as references knowledge, optimization of conditions of sintering through decrease of scan speed and hatch spacing will have an impact on favourable microstructure and on decrease of number of key-hole pores.
- Microstructure of cast AlSi10Mg alloy in as-delivered conditions characterized by large α-Al dendrites. As expected, due to T6 heat treatment, spherical Si particles are located on primary α-Al grain boundaries.
- Relative density measurements confirmed metallographic observations. SLM material has low relative density in relation to solid material. Effect of T6 heat treatment was reduction of porosity.
- Strength tests showed significant differences between AlSi10Mg alloy obtained by casting and SLM technology. Due to fine microstructure SLM material has higher hardness value than cast material. However, tensile tests demonstrate, that material sintered under given conditions has significantly lower properties than material conventionally cast.
- T6 heat treatment had an impact on tested materials. For cast alloy it caused increase of hardness and tensile strength and expected decrease of impact strength, related to the formation of spherical Si-phase. For SLM material, increase of hardness and tensile strength was not significant. Whereas, decrease of impact strength was noticeable.

Summarizing all the results of the research and observations, it should be noted that the SLM technology gives wide range of possibilities to manufacture complex-shape structures and components. However, to achieve high mechanical properties and favourable microstructure, the parameters should be selected properly, to avoid high porosity, which is mainly responsible for the poor properties of tested material.

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