Article

The influence of exposure energy density on porosity and microhardness of the SLM additive manufactured elements

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Abstract: Selective Laser Melting (SLM) is an additive manufacturing technique. It allows to produce elements with very complex geometry using metallic powders. A geometry of manufacturing elements bases only on 3D CAD data. The metal powder is melt selectively layer by layer using ytterbium laser. The paper contains results of porosity and microhardness analysis made on specimens which were manufactured during specially prepared process. Final analysis helped to discover connections between changing hatching distance, exposure speed and porosity. There was no significant differences in microhardness and porosity measurement results in the planes: perpendicular and parallel to the machine building platform surface.

Keywords: Additive Manufacturing, SLM Technology, porosity research, microhardness research

1. Introduction

In recent years an intensive development of Additive Manufacturing technology (AM) has been observed. This innovative technology is often called "3D printing". It became one of the leading automated production technologies and it seems to be as important as subtractive manufacturing, plastic forming or casting [1]. Selective laser melting (SLM) is one of the most perspective additive manufacturing techniques. It base on selective fusion of metallic powders using ytterbium laser, where the manufacturing process is based on "powder bed". During the last 10 years it became one of the most developed AM technologies [2,16].Regarding to other additive manufacturing techniques

- selective laser melting is characterized by:

- high dimensional accuracy of the manufactured elements,
- relatively low anisotropy of mechanical properties,
- a significant number of available materials,
- low porosity of the manufactured elements.

The SLM process is based on the low granulation powder (15 - 45μm). The building job can be modified by changing different parameters which indirectly and / or directly affect the quality of the melted area. Mentioned possibilities of modifying the manufacturing process in the SLM technique created the possibility to conduct scientific research by many scientific and industry facilities [3-8]. One of the most common topics are the analysis of the process parameters which influence on the mechanical properties of manufactured elements [3, 5, 6]. In this paper, the influence of manufacturing process parameters on the porosity and microhardness of the additive manufactured elements was determined.

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The modified parameters were:

- laser power,
- exposure velocity,
- hatching distance.

Basing of the conducted research, final conclusions were formulated and further research directions were defined.

2. Experimental

Porosity and microhardness tests were carried out on specimens with the same geometry. Specimens had the form of cubes with a side length of 10mm. These test parts were designed in such a way to assure analysis of the distribution of mechanical properties in two different planes. The first was a plane parallel to the building platform surface, the second one was a plane perpendicular to the platform surface.

The mentioned planes are showed in Fig. 1. As "xy" was named the plane parallel to the building platform surface, which is also normal to the direction of element growth (Z axis). The plane perpendicular to the building platform surface, which is also tangent to the direction of element growth (Z axis) is marked with as "yz".

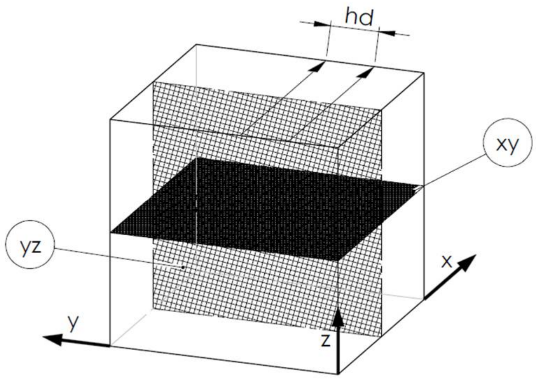

Figure 1. 3D model of a cubic sample, where: xy - plane parallel to the building platform surface, xy - plane perpendicular to the building platform surface, hd- (hatching distance) - distance between the exposure vectors, Z - direction of growth (element building).

For each sample, different sets of process parameters were used, which are summarized in Table 1. Modified parameters were components of the equation (1) which affects the additive manufacturing energy density.

$$\rho_E\left[\frac{J}{mm^3}\right] = \frac{L_P[W]}{e_v\left[\frac{mm}{s}\right]\cdot h_d[mm]\cdot l_t[mm]} \quad (1)$$

Where:

- L_P - laser power [W],
- e_v - exposure velocity [mm/s],
- h_d - hatching distance [mm],
- l_t - layer thickness [mm].

The modified parameters were the laser power, the exposure velocity and the hatching distance. These specific components had been determined by the optical system and the energy source.

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It was caused by the possibility of analyzing the impact of modified parameters in a small range of its changes. Analysis of the influence of layer thickness on porosity and microhardness would be difficult to verify in this case due to the many reasons:

- proper calibration of the powder reservoir (recouter),
- inert gas flow speed,
- clearance in the worm gear in the building platform leveling mechanism.

Table 1 Sets of analyzed production parameters

Parameters set	L_P [W]	e_v [mm/s]	h_d [mm]	ρ_E [J/mm3]
1	190	900	0,12	58,64
2	190	990	0,12	53,31
3	190	810	0,12	65,16
4	200	900	0,12	61,73
5	200	990	0,12	56,12
6	200	810	0,12	68,59
7	180	900	0,12	55,56
8	180	990	0,12	50,51
9	180	810	0,12	61,73
10	190	900	0,13	54,13
11	190	990	0,13	49,21
12	190	810	0,13	60,15
13	200	900	0,13	56,98
14	200	990	0,13	51,80
15	200	810	0,13	63,31
16	180	900	0,13	51,28
17	180	990	0,13	46,62
18	180	810	0,13	56,98
19	190	900	0,11	63,97
20	190	990	0,11	58,16
21	190	810	0,11	71,08
22	200	900	0,11	67,34
23	200	990	0,11	61,22
24	200	810	0,11	74,82
25	180	900	0,11	60,61
26	180	990	0,11	55,10
27	180	810	0,11	67,34
28	150	400	0,08	156,25
29	150	700	0,06	119,05
30	120	300	0,08	166,67

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The manufacturing process parameters were changed within +/- 10% of the recommended value (item 1 in Table 1). In addition, the parameters 28-30 (Table 1) significantly differ from the SLM System manufacturer's data. The reason to test these parameters was a good mechanical properties of specimens tested and described in the study [3]. The specimens (Figure 2) were created during single process. The manufacturing file for the machine was prepared using the SLM Metal Build Processor module in the Magics software. All specimens were manufactured using 316L austenitic steel powder.

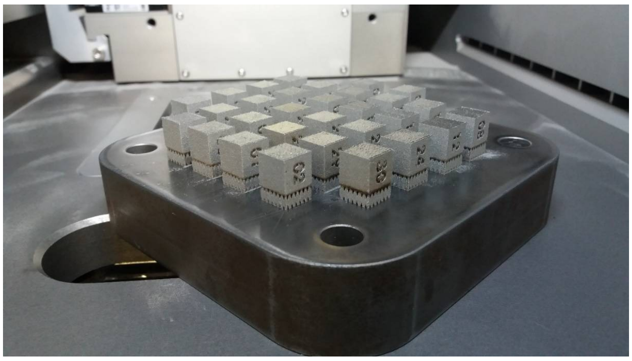

Figure 2. SLM 125 HL building platform with manufactured specimens

3. Porosity analysis results and discussion

For each specimen the porosity was analyzed in the central part of the metallographic section. All visible pores were marked in both analyzed planes. The porosity was determined by images analyze using a scanning electron microscope (Figure 3).

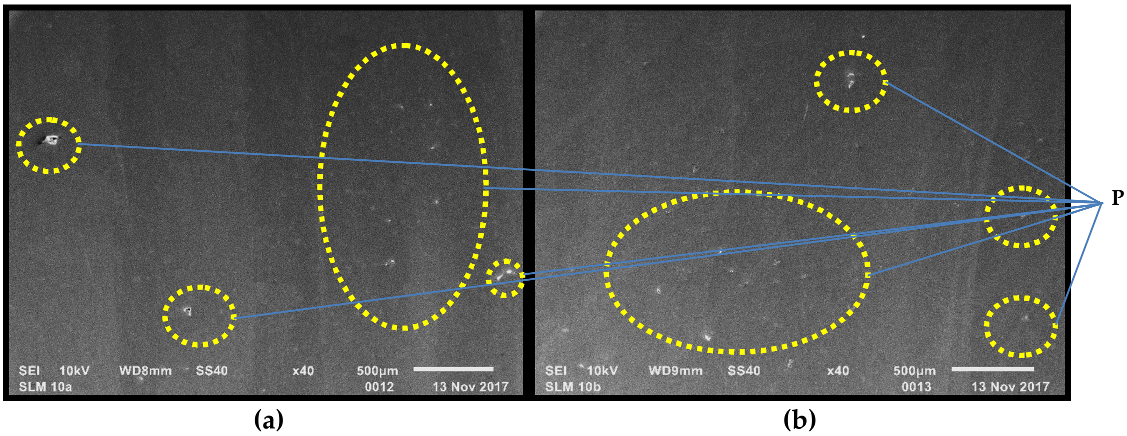

Figure 3. Image of visible pores in the plane parallel (a) and perpendicular (b) to building platform surface, (areas of pores marked with the letter "P")

Porosity quantitative analysis were based on the microstructure images. It was carried out using a histogram check in GIMP 2 software. The determination of porosity was based on the calculation of the quotient (2):

$$\rho[\%] = \frac{L_p}{L_c} \cdot 100\% \qquad (2)$$

Where:
L_p-number of pixels in the contoured pores,
L_c-number of pixels of the image entire area.

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The porosity analysis allowed to determine the influence of used laser power, hatching distance and exposure velocity (Fig. 4). The analysis includes the groups of parameters in which only one was different from the parameters tested.

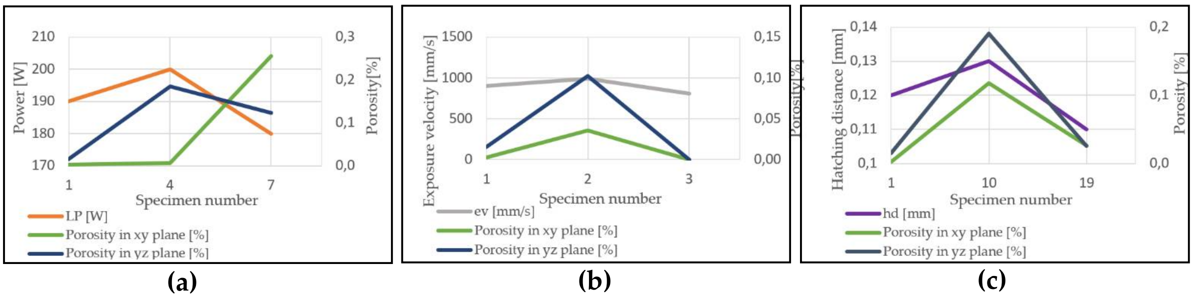

Figure 4. The influence of power (a), exposure velocity (b) and hatching distance (c) on porosity in the parallel (xy) and perpendicular plane (yz) to the building platform surface

Based on the conducted analysis of the laser power influence graphs, the exposure velocity and the hatching distance (Fig. 4), it can be noticed that the power modification has no direct effect on the porosity changes. However, the influence of the other two parameters is noticeable. During changing the exposure velocity in the range of +/- 10% the porosity changes slightly - 0.02%. A significant impact on the porosity can be seen when the hatching distance changes.

To emphasize the representation of the porosity changes, depending on the exposure velocity and hatching distance, proper diagrams were plotted (Figures 5, 6). It allows to notice changes in the porosity in all specimens and also note the highest porosity peaks in the specimens. It was also observed that the exposure velocity and the hatching distance raise enhance the porosity growth (specimens 16 and 17 in the Fig. 9).

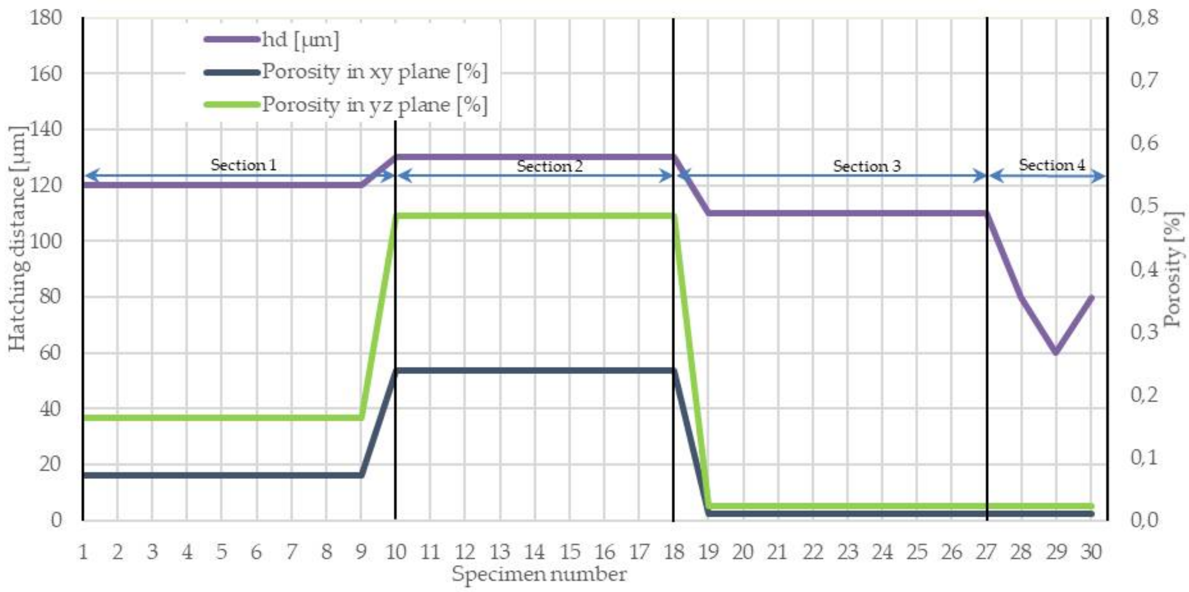

Figure 5. Variations of the average porosity in four ranges referenced to modified hatching distance in particular parameters group

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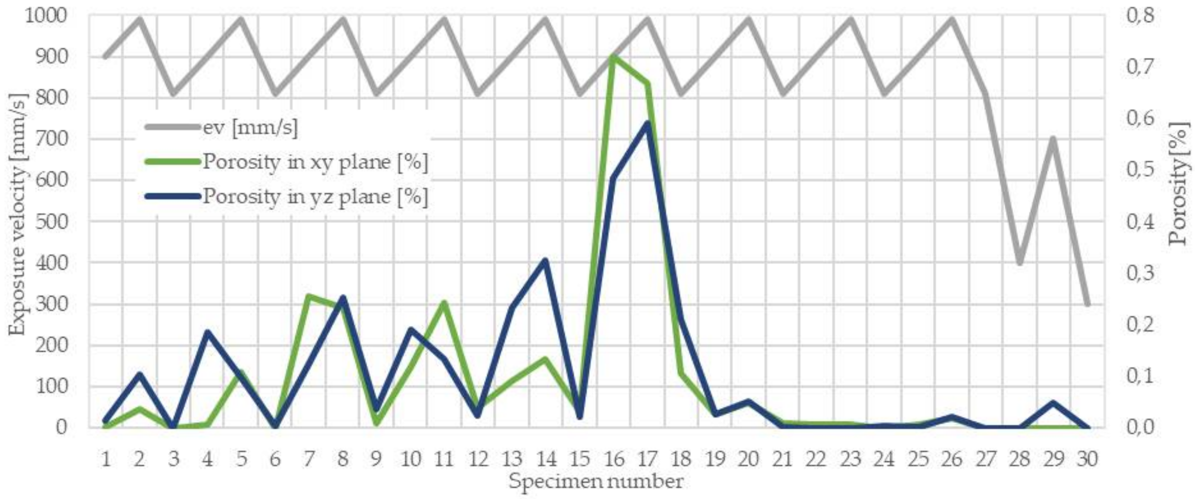

Figure. 6. Porosity changes related to modified exposure velocity in particular parameters group

The hatching distance directly affects the porosity of the elements produced using SLM. The parameter increasing by 10% results in a nearly twice increasing the proportion of pores. This phenomenon is caused by increasing the distance between subsequent melt paths. It determines a reduction of the number of molten metallic powder particles. It could be observed in the parallel (xy) and perpendicular (yz) plane to the building platform surface.

A similar case can be observed during analyzing influence of the exposure velocity, where porosity increasing with this parameter growth. It had been noticed in both analyzed planes. This parameter does not affects the porosity as much as the change of the hatching distance, but with 10% change in the exposure velocity it is noticeable. Fig. 8 and 9 shows changes in porosity related to the modification of the hatching distance and the exposure velocity for all specimens. Noteworthy are the porosity peaks for specimen 16 and 17, where both the exposure velocity and the hatching distance have been increased.

Specimens manufactured using the unusual parameters proposed in [3] did not assured better porosity and microhardness. These settings (marked in the section 4 in Fig. 6) gave very similar properties to the rest of the manufactured elements. The main feature of the settings from the study [3] was the significantly smaller hatching. Lowering this value negatively affects the process's efficiency.

4. Microhardness analysis results and discussion

The microhardness analysis were carried out on the same specimens which were used in porosity research. For each of the planes, a different configuration of the distribution of measurement points was adopted:

- In the plane parallel to the building platform (xy in Fig. 1), the influence of the linear exposure method on microhardness changes in five parallel rows was checked (fig. 7),

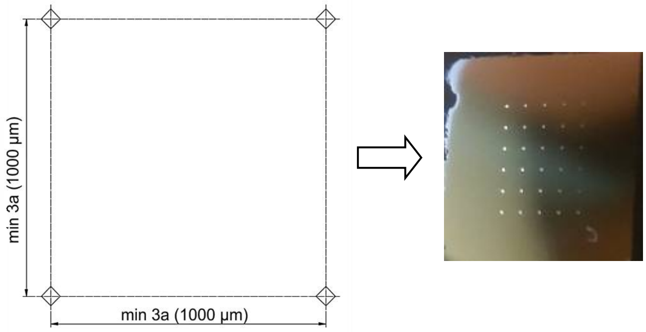

Figure 7. Distribution of the measurement points on a plane parallel to the building platform surface

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• In the plane perpendicular to the building platform surface, the effect of joining successive layers on microhardness changes in three parallel rows was checked (Fig. 8).

Similarly to the porosity research, the influence of the laser power, the exposure velocity and the hatching distance (Fig. 9) on the microhardness distribution in the specimens was determined. Also in case of microhardness analysis, the groups of parameters in which only one of the tested parameters changed were

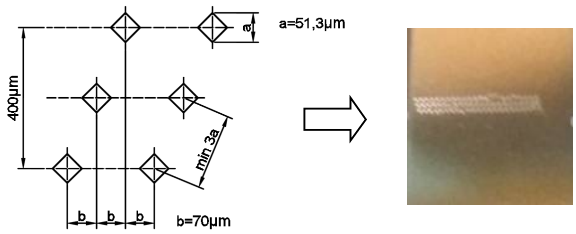

Figure 8. Distribution of the measurement points on a plane perpendicular to the building platform surface

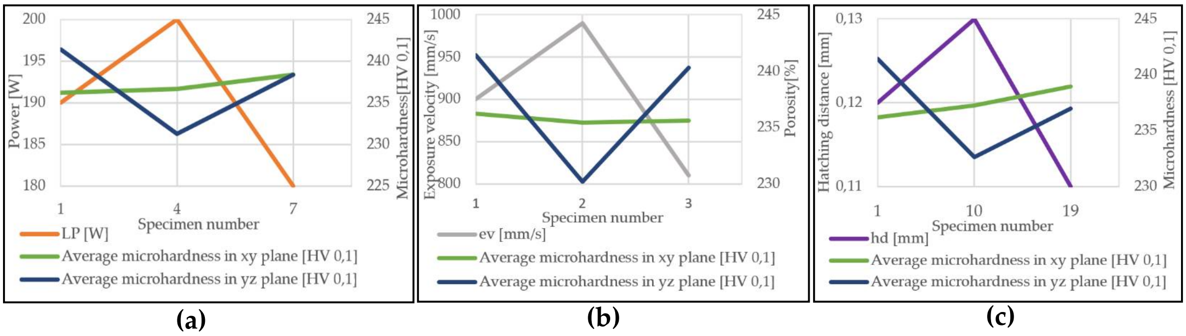

Figure 9. The influence of power (a), exposure velocity (b) and hatching distance (c) on microhardness in the parallel (xy) and perpendicular plane (yz) to the building platform surface.

Proper preparation of the microhardness research allowed to observe the lack of direct impact of parameters changes. The only observed dependence is the effect of the exposure velocity on microhardness, where microhardness decreases with the increase of the exposure velocity. However, it is insignificant and fits within the limits of measurement error. The lack of direct dependence between microhardness and one of the modified parameters was the reason for further analyzes. The diagram of exposure energy density affect on microhardness was prepared. In sets where the parameters are changing in the range of +/- 10% from the recommended value, there is a noticeable relationship between the exposure energy density and the microhardness change (Fig. 10).

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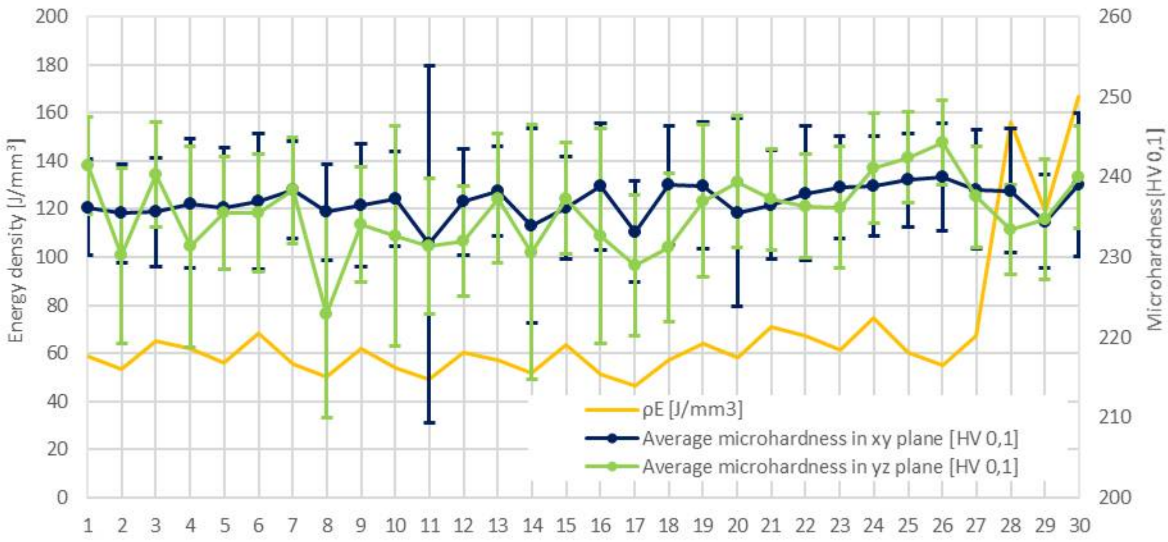

Figure 10. The influence of exposure energy density on microhardness in particular groups of parameters.

Microhardness distribution on both of the measured planes, helped to discover that in a range of modification of parameters by +/- 10% of the nominal value, microhardness slightly increases with the growth of the exposure energy density. Those changes could be connected only with exposure velocity. Recorded on Fig. 10 microhardness changes are related only to the change in the exposure speed – which affects the exposure energy density. This statement is valid for the range of parameter changes within +/- 10% of the nominal value of the parameters only. It can be concluded that the influence of modifying manufacturing parameters on microhardness is not as important as in the case of porosity.

5. Final conclusions

Analysis of changes the laser power, exposure velocity and hatching distance allowed to identify the influence of these parameters on porosity and microhardness of specimens additive manufactured using the SLM technique. The research allowed to define the following conclusions:

• there is no significant differences in microhardness and porosity measurement results in the planes: perpendicular and parallel to the machine building platform surface,

• the hatching distance has a significant influence on the porosity of the manufactured elements. As the hatching distance increases, the microstructure porosity of this element increases,

• exposure velocity changes affects the porosity
- the lower the exposure velocity, the lower the microstructure porosity,

• the relationship between exposure energy density changes and microhardness was identified. In the range of +/- 10% of the nominal value of the parameters, the increase of microhardness with an increase of the exposure energy density has been observed,

• conducted analyzes of porosity and microhardness allowed for the selection of 5 groups of parameters which will be used to produce specimens for further research.

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