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TECHNOLOGICAL FEATURES IN FABRICATION OF Co-Cr DENTAL ALLOY BY SELECTIVE LASER MELTING

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ABSTRACT

The process of selective laser melting (SLM) is an alternative to the conventional technologies and can be used to solve many of their problems. During SLM process, an object is produced directly from a virtual 3D model by melting a metal powder layer by layer using a laser. Incorrectly selected process parameters can lead to defects decreasing the details quality.

The purpose of the present paper is to analyze the peculiarities of the production of dental Co-Cr alloy by SLM method and to propose technological regimes for manufacturing of fixed partial dentures with high density. Four-component dental bridges are used as samples, which are made of Co212-f ASTM F75 alloy using SLM 125 machine. The accuracy and structure of the specimens are investigated by OM and SEM. The influence of technological parameters of the SLM process on the quality of the details is analyzed.

It is found that in order to ensure high accuracy of the constructions, it is necessary to make changes in the dimensions at the stage of the virtual model, as the corrections are the same on all axes. Optimal technological parameters - laser power and scanning speed are calculated and proposed, which provide a dense structure and high mechanical properties of the details, manufactured of Co-Cr dental alloy by SLM method with the equipment used. The results of this study will be useful for successful implementation of the SLM equipment in dentistry for production of high quality Co-Cr constructions.

1. INTRODUCTION

Co-Cr dental alloys are one of the most commonly used for production of various constructions in prosthetic dentistry due to their biocompatibility, high mechanical properties and relatively low cost. The manufacture of dental constructions from Co-Cr-based alloys is usually carried out by casting process [1-4], which is characterized by many manual operations. They not only increase the production time and costs, but also are a prerequisite for generating of errors, leading to a further decrease in quality [1]. The process of selective laser melting (SLM) is an alternative to the traditional manufacturing technologies and allows solving a number of their problems. The use of SLM technology minimizes the quantity of manual labor, shortens the production time and improves the quality. In addition, this process allows individual prosthetic constructions and implants with special anatomical features and complex geometry to be designed and manufactured [1,5].

The first SLM-based equipment is developed in Germany in 1999 by *Fockele&Schwarze (F&S)*, and the first mass-produced machine *MCP Realizer 250* is launched in 2004 [6]. Despite the facts, SLM is still considered a new technology and is constantly being improved in terms of the methods used and process parameters, the materials being processed and the mechanical properties of the details.

During the SLM process, a virtual three-dimensional (3D) model of the part to be manufactured is first created. Then, using special software, this model is divided into layers of a certain thickness. The manufacturing of the detail itself is carried out directly from a virtual 3D model by melting a metal powder layer by layer using a laser [1-6].

The main operation in the SLM process is scanning with laser beam of a thin layer of powdered material, previously applied to the base of the working table [5-7]. Modern SLM machines provide a minimum layer thickness of 20 μm [6]. The manufacturing process of the object is carried out along the scanning direction of the laser beam and the individual traces of the molten metal can be observed in the cross section of one layer. Thus, the quality of the details, produced by SLM, depends on the quality of each trace and each individual layer [7-9].

Depending on the materials, equipment and production strategy used, the parameters of the SLM process are divided into three main groups [7,8,10]:

1) Powder material: composition, size distribution, shape, optical properties, thermal conductivity, layer thickness for each production cycle;

2) Laser: type, power, laser spot diameter, energy distribution over the laser beam, scanning speed and the use of protective gas;

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3) Production strategy: determining the orientation and distance between the individual traces for the manufacture of each plane, determining the relative position of the object in two mutually perpendicular plains.

Incorrectly selected process parameters, production strategy, object orientation and insufficient quality of metal powder can lead to defects associated with the technology: unmelted particles on the surface and in the bulk of the workpiece [3]; lack of soldering; presence of pores, cracks and non-metallic inclusions; residual stresses and high surface roughness [8-10].

In order to achieve high mechanical properties, it is important that the details, made by SLM, have high density and optimum surface quality. Therefore, it is necessary to determine the optimal values of the technological parameters (laser power, scanning speed, layer thickness and distance between individual traces), which most strongly affect the properties of the manufactured objects - porosity, roughness, accuracy, hardness and mechanical properties [6-9,11,12]

The purpose of the present paper is to analyze the features of the production of Co-Cr dental alloy by the method of selective laser melting and to propose technological regimes for manufacturing of fixed partial dentures (FPDs) with high density.

2. MATERIALS AND METHODS

• Materials and technologies for samples manufacturing

Co-Cr dental alloy Co212-f ASTM F75 with chemical composition: 65.20 Co; 28.30 Cr; 5.48 Mo; 0.754 Si; 0.164 Fe; 0.036 V [wt.%] was used in the study. It was especially developed for operation of the SLM equipment. For that purpose, it was in the form of powder with an average particle size of 15-45 µm, with 92% of the fraction being 15-30 µm and 7-8% between 30-45 µm.

Table 1 *Technological parameters of SLM process during manufacturing of dental bridges*

Parameter	N, W	V, mm/s	l_c, mm	t_c, mm	E, J/mm^2
Regime 1 of manufacturing of dental bridges					
Volume border	100	500	0,13	0,03	51,3
Volume area	100	340	0,13	0,03	75,4
Volume offset hatch	95	400	0,13	0,03	60,9

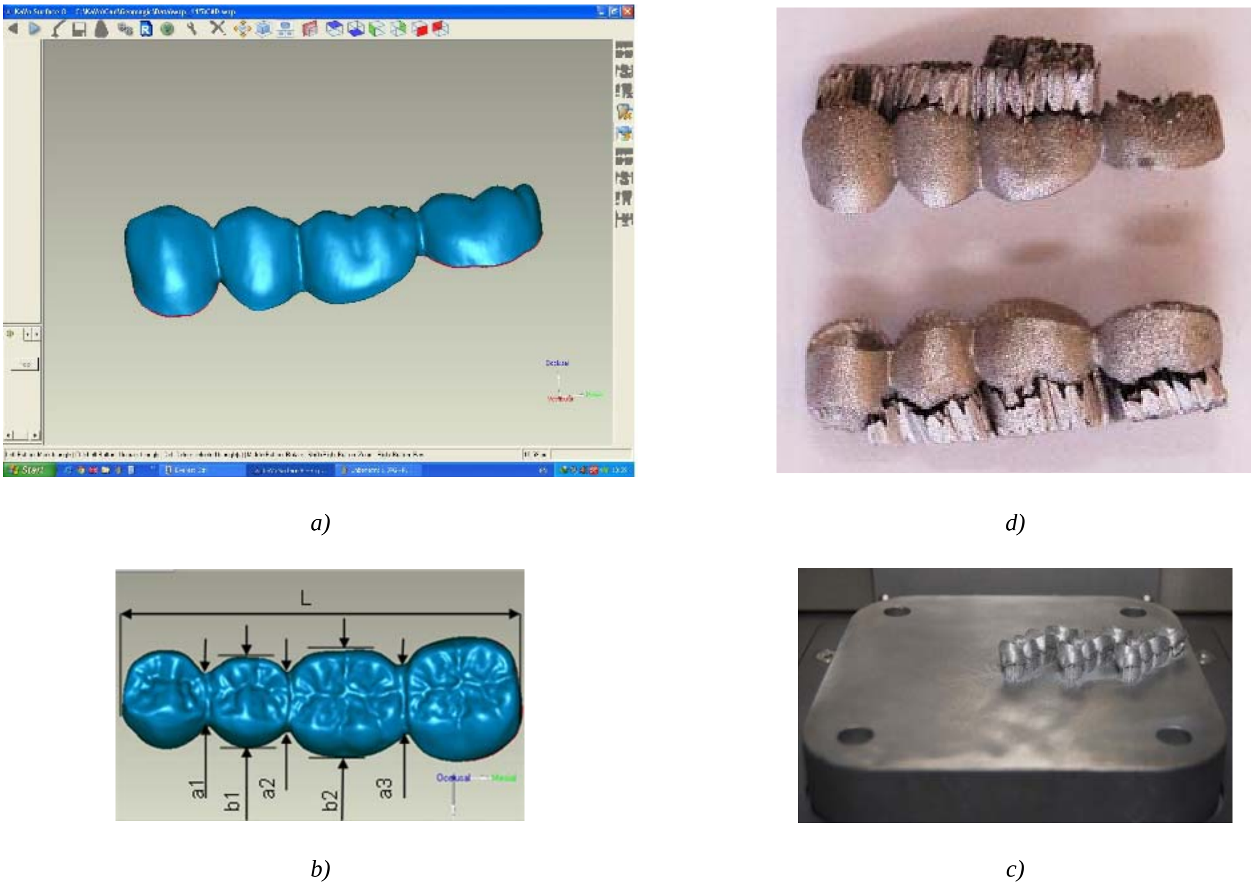


Fig. 1. Manufacturing of dental bridges by selective laser melting (SLM): virtual model – a) and b), position of the bridges on the machine table – c) and as-produced bridges – d)

The samples - four-part dental bridges were made directly from the virtual model (Fig. 1-a,b) using a machine *SLM 125 (SLM Solutions, Germany)*, equipped with a continuous Nd:YAG laser. For the samples production, the operating mode, recommended by the company manufacturer of the equipment, was used (Table 1) - 100 W laser power, 0.2 mm diameter of the laser beam spot, 30 µm layer thickness and 0.13 mm distance between the individual traces in the layer [13]. In the manufacturing process, the laser first scanned the outer contour of the layer of the first part of the sample and then filled the areas inside the contour with traces at an angle of 45°. It then passed to the same layer of the next part of the sample, thus forming the entire layer. To ensure production in the above conditions, the length of the bridge constructions was at an angle of 45° relative to the X and Y axes of the machine table, while the vertical axes of the teeth were parallel to the building direction - Z axis(Fig. 1-c). The supports, necessary for the SLM process, were designed on the occlusal surface of the teeth (Fig. 1-d).

• Accuracy measurement

The accuracy of the samples was investigated by measuring (Fig. 1-b):

1) The width of the connectors between the bridge bodies and the crowns, fixing the bridges - a1, a2 and a3;

2) The width of the bridge bodies - b1 and b2 and

3) The length of the bridges - L.

The absolute difference (mm) of the samples' dimensions and the relative error (%) compared to the cast bridge-base model were calculated. Detailed information about the specimens' measurements is given in the work of Dzhendov D. et al [14].

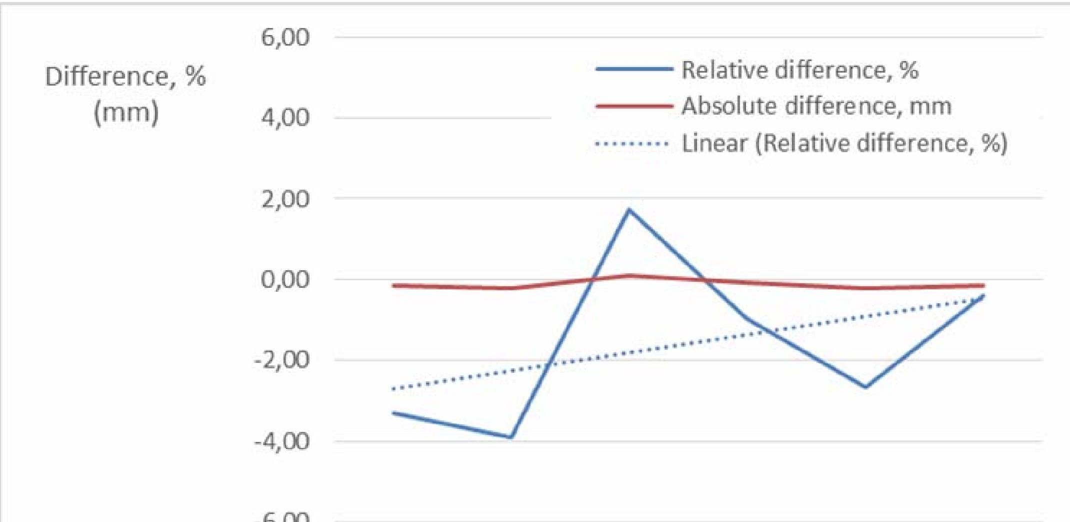
• Structure investigation

The structure of Co-Cr dental alloy, manufactured by SLM, was observed on preliminary prepared cross-sections of dental bridges by optical microscopy *XJL-17A* and dual beam scanning electron/focused ion beam system *(SEM/FIB LYRA I XMU, TESCAN)*.

3. RESULTS OBTAINED

Our study has confirmed the high repeatability of the dimensions of SLM dental bridges [14]. The results also show that the dimensions of the bridge constructions, produced by SLM, are smaller by 0.41% to 3.92% compared to the base bridge model, manufactured by casting (Fig. 2). These differences are most likely due to the shrinkage of the alloy in the SLM process. There is a dependence of the relative difference on the size value - it decreases with its increase. A comparison of the values of the absolute difference shows that they are very close for all dimensions and range from 0.07 mm to 0.20 mm. Therefore, in order to fabricate accurate FPDs or infrastructures for them from Co-Cr alloys by SLM, it is necessary to increase all dimensions of the virtual model by an average of 0.15 mm.

The structure of the Co-Cr dental alloy, produced with the regime recommended by the company producer of the SLM equipment, is porous with the presence of unmelted and partially melted powder particles in the volume of the detail and unwelded layers near the surface (Fig. 3). The pores have an elongated shape and large variations in sizes from 50 µm to 300 µm. It can be seen that the pores are in the areas with no good welding between the particular molten traces or layers. The pores themselves are characterized with irregular shape and sharp corners at the junction between two layers (shown by arrows in Fig. 3). In addition, many of them contain partially molten alloy particles.



	a1	a2	a3	b1	b2	L
Relative difference, %	-3,30	-3,92	1,72	-0,96	-2,67	-0,41
Absolute difference, mm	-0,15	-0,20	0,10	-0,07	-0,23	-0,14

Fig. 2. Difference between dimensions of SLM produced dental bridges and base bridge model

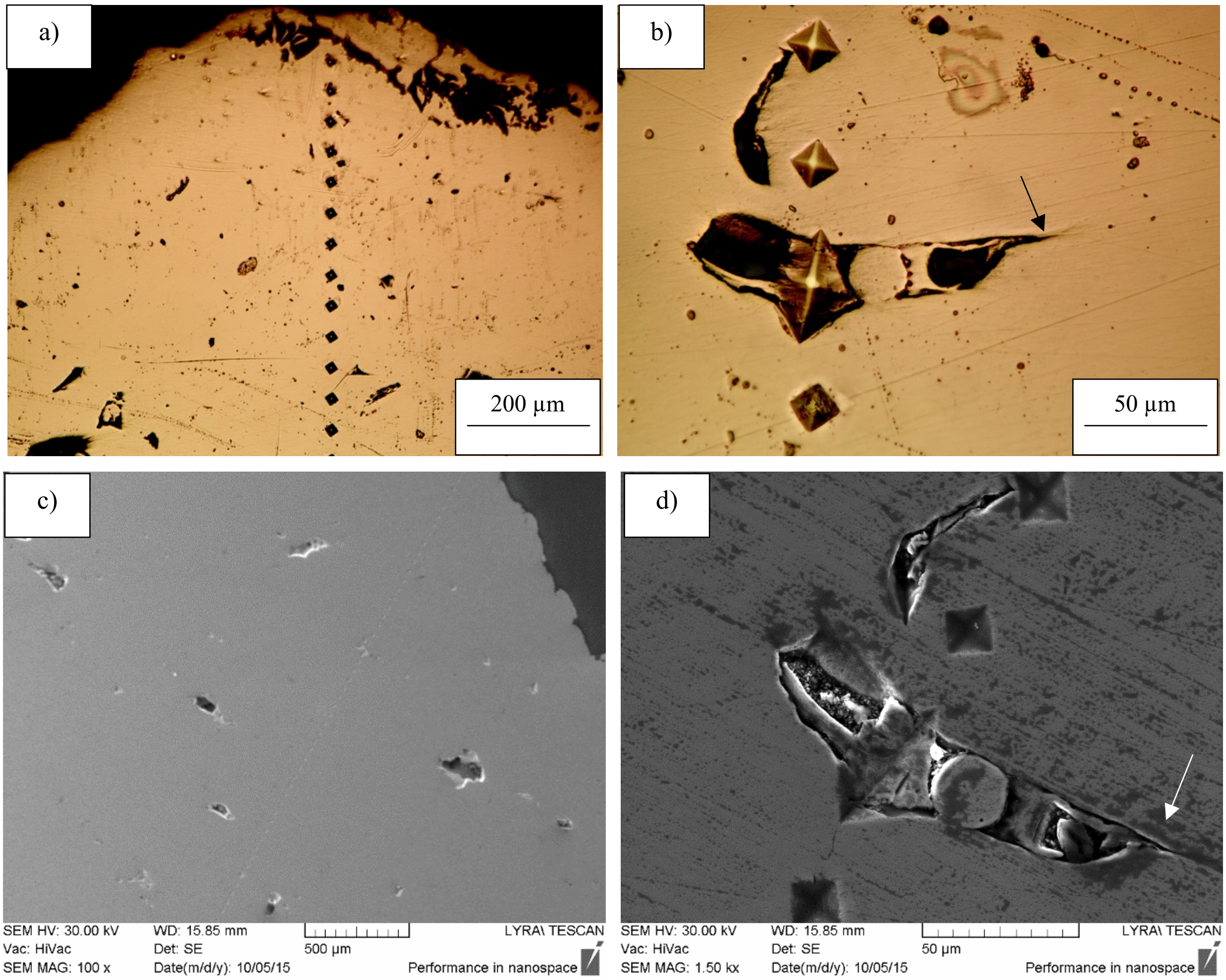


Fig. 3. Structure of Co-Cr dental bridges, produced by SLM: OM images – a), b) and SEM images - c) and d)

4. DISCUSSION

In the SLM process, the power density N_s [W/cm^2] of the laser is the main parameter for obtaining a high quality detail [2,8,15]. It directly affects the volume energy density E_v [kJ], required for melting a local volume of metal powder in the zone of laser impact [15,16]:

$$E_v = \frac{N_s}{V} \quad (1)$$

where: E_v - volume energy density [J/cm^3], N_s – power density [W/cm^2]; V – scanning speed [cm/s].

Since the power density Ns is calculated by formula (2) [16]:

$$N_s = \frac{4N}{\pi d^2} \quad (2)$$

where: N – laser power [W], d – laser spot diameter [cm].

Therefore, the volume energy density E_v depends directly in proportion to the laser power and inversely proportional to the scanning speed and the diameter of the laser spot (3) [15].

$$E_v = \frac{4N}{V\pi d^2} \quad (3)$$

However, formula (3) reflects the energy density for melting a volume of metal in a single trace, considering only the parameters of the laser, without taking into account other factors related to the metal powder and the production strategy.

In order to calculate the energy density E, required for melting the volume of metal in a whole layer of the detail, formula (4) has been proposed [10]. In addition to the laser power and the scanning speed, the distance between the individual traces and the thickness of the building layer are taken into account.

$$E = \frac{N}{V l_c t_c}, \quad (4)$$

where: E is the energy density [J/mm^2], N is the laser power [W], V is the scanning speed [mm/s], $l_{\tilde{n}}$ – distance between the individual molten traces in one layer [mm], $t_{\tilde{n}}$ - thickness of the building layer during SLM [mm].

Insufficient energy density E during the SLM process results in incomplete melting of the surface layer, poor welding between the individual layers and traces, presence of pores and cracks [10]. Below a critical value of E, the porosity increases very rapidly [11]. Exceeding the value of the required energy can cause evaporation of material, leading to defects and decrease in density [10]. Therefore, obtaining a dense structure in the volume of the workpiece, without changing the thickness of the building layer and the distance between the individual traces, can be achieved by varying the laser power and the scanning speed (formula 4).

In optimization, it should be taken into account that different power/speed combinations produce defects of different shapes and sizes [10]. Operation with low energy density and high scanning speed leads to large defects (>100 μm) with an uneven shape due to partial melting of the powder particles. At high energy densities and low scanning speeds, the pores are small in sizes (<100 μm) and spherical in shape due to the inclusion of gases in the molten pool. The defects in the structure of the SLM Co-Cr alloy, observed in our studies, are rather from the first group and lead to low density with a dense structure/pores ratio of 87.47%/12.53% [17]. Since the energy density depends in direct proportion to the laser power and inversely proportional to the scanning speed (formula 4), it is advisable for obtaining a dense structure the laser power to be increased. It is not desirable to reduce the speed, because this leads to agglomeration of metal powder, spheroidization phenomena, irregularities on the surface of the molten pool and defects such as pores, which will prevent the even application of the next layer of powder [18]. Increasing the laser power, respectively the energy density, leads to an increase in the hardness and strength characteristics of Co-Cr alloys [18,19].

The optimal parameters of the SLM process, which provide a dense structure and high mechanical properties, established in the work of Wang JH et al [18] are: laser power 160 W, scanning speed 1100 mm/s and a distance between the individual traces 0.05 mm. The energy density, calculated with these data, is $E = 97\ J/mm^2$. Studies of other scientists [19] also confirm that at energy densities within these limits, the strength characteristics of Co-Cr dental alloys are the highest; therefore in our work we accept this value as optimal.

Based on the analysis done and comparison with the technological parameters, used for manufacturing of the bridge constructions (Table 1), the reason for the obtained porous structure, unmelted and partially melted powder particles as well as non-welding of the last surface layers is clear. At all stages of the layer formation in the process of SLM, the energy density is lower than $97\ J/mm^2$, i.e. insufficient to obtain a high-density structure.

Table 2 *Proposed technological parameters of SLM process for manufacturing of dense Co-Cr dental bridges*

Parameter	N, W	V, mm/s	l_c, mm	t_c, mm	E, J/mm^2
Regime 2					
Volume border	190	500	0,13	0,03	97,4
Volume area	130	340	0,13	0,03	98,0
Volume offset hatch	150	400	0,13	0,03	96,2
Regime 3					
Volume border	190	500	0,13	0,03	97,4
Volume area	190	500	0,13	0,03	97,4
Volume offset hatch	190	500	0,13	0,03	97,4

Table 3 *Technological features for manufacturing of Co-Cr dental alloy by SLM*

Technological feature	Fixed partial denture (crown, bridge)
3D printing process	
Equipment	*SLM 125*
Alloy	Co212-f ASTM F75
Layer thickness	30 μm
Design of the virtual model	
Position	Vertical axes of the teeth must be parallel to the printing direction Z-axes.
Corrections of the dimensions	Increase with 0.15 mm along the three axes.
Proposed technological regimes of the SLM process	
Technological parameters	They have to ensure dense structure and high mechanical properties (Table 2): Regime 2 Regime 3

The technological parameters - laser power and scanning speed, providing a dense structure and high mechanical properties of details made of Co-Cr dental alloy, are calculated using formula (4). Therefore, in order to achieve the optimal value of the energy density, while maintaining all other parameters, it is necessary to increase the laser power. In this case, the energy density differs at different stages of the manufacture of the layer (Regime 2, Table 2). If this creates difficulties, it is possible to proceed to a simultaneous increase in the laser power and the scanning speed of the volume until they align with those of the boundary layer (Regime 3, Table 2). In this case, the same technological parameters are used at all stages, which guarantee the required energy density, facilitated process control and fast manufacturing of the construction.

Table 3 summarizes the technological features for manufacture of dental constructions of Co-Cr alloy by SLM, providing a dense structure, high accuracy and mechanical properties. It is evident that, in using the same equipment and alloy, it is needed the dimensions to be corrected still at the virtual model generating stage and to work with regimes, ensuring enough energy density in order to have possibility the whole thickness of the powder layer to be melt. This will guarantee high dimensional accuracy, dense structure and high mechanical properties of the SLM produced constructions of Co-Cr dental alloy.

5. CONCLUSION

The features of production of fixed partial dentures from Co-Cr dental alloy by selective laser melting are analyzed in this article. It is found that for ensuring high accuracy of the details, it is necessary to make changes in the dimensions at the stage of the virtual model design, as the corrections values are same in the all three axes. The optimal technological parameters - laser power and scanning speed are calculated and proposed, which can provide a dense structure and high mechanical properties of the details, manufactured of Co-Cr dental alloy by the SLM method with the equipment used. The results of the present work will be useful in the successful implementation of the SLM equipment in dentistry for production of high-quality constructions from Co-Cralloy.

REFERENCES

[1] Dikova T., Dzhendov D., Simov M., Katreva-Bozukova I., Angelova S., Pavlova D., Abadzhiev M., Tonchev T. Modern trends in the development of the technologies for production of dental constructions. J of IMAB. 2015 Oct-Dec 21(4) 974-981

[2] Jevremovic, D., Puskar T., Kosec B., Vukelic D., Budak I., Aleksandrovic S., Egebeer D., Williams R. The analysis of the mechanical properties of F75 Co-Cr alloy for use in selective laser melting (SLM) manufacturing of removable partial dentures (RPD), Metalurgija 2012 51(2) 171-174

[3] Lu Y, Wu S, Gan Y, Li J, Zhao C, Zhuo D, Lin J. Investigation on the microstructure, mechanical property and corrosion behavior of the selective laser melted CoCrW alloy for dental application. Materials Science and Engineering 2015;49:517-525

[4] Takaichi A., Suyalatu, Nakamoto T. et al., Microstructures and mechanical properties of Co–29Cr–6Mo alloy fabricated by selective laser melting process for dental applications, Journal of the Mechanical Behaviour of Biomedical Materials 2013;21:67–76

[5] Dzhendov D, Dikova T,Application of selective laser melting in manufacturing of fixed dental prosteses. J of IMAB 2016 Oct-Dec;22(4):1414-1417

[6] Thomas D. The Development of Design Rules for Selective Laser Melting, PhD thesis, University of Wales Institute, Cardiff, Oct. 2009, 318p.

[7] Yadroitsev I., Bertrand Ph., Smurov I. Parametric analysis of the selective laser melting process, Applied Surface Science 253 (19):8064-8069

[8] Yadroitsev I., Krakhmalev P., Yadroitseva I., Johansson S., Smurov I. Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder, Journal of Materials Processing Technology 2013;213:606–613

[9] Yadroitsev I., Smurov I. Surface Morphology in Selective Laser Melting of Metal Powders, Physics Procedia 2011;12:264–270

[10] Introduction to additive manufacturing technology. A guide for designers and engineers. Eds. Aumund-Kopp C. and Riou A. European Powder Metallurgy Association 2015, 1st Edition: 41 p. www.epma.com

[11] Lu L-X, Sridhar N., Zhang Y-W. Phase field simulation of powder bed-based additive manufacturing. Acta Materialia 2018 Feb;144:801-809

[12] Vandenbroucke B., Kruth J-P. Selective laser melting of biocpmpatabile metals for rapid manufacturing of medical parts, Rapid Prototyping Journal 2007;13(4):196-203

[13] Dolgov N.A., Dikova T., Dzhendov D., Pavlova D., Simov M. Mechanical Properties of Dental Co-Cr Alloys Fabricated via Casting and Selective Laser Melting, International Journal “Materials Science. Non-Equilibrium Phase Transformations”, 2016;2(3):3-7

[14] Dzhendov D, Pavlova D, Simov M, Marinov N, Sofronov Y,Dikova T,Todorov G, Kalachev Y,[Geometrical accuracy of fixed dental prostheses manufactured by additive technologies][in Bulgarian],Proceedings of the 8-th Int. Sci. Conference for young researchers“Technical Science and Industrial Management”, 15-16.09.2014, Varna, Bulgaria, STUME, 2014;1:13-17

[15] Dikova T., Dzhendov D., Simov M. Microstructure and Hardness of Fixed Dental Prostheses Manufactured by Additive Technologies, Journal of Achievements in Mechanical and Materials Engineering, 2015 Aug;71(2):60-69

[16] Stavrev D., Dikova Ts., Shtarbakov Vl., Milkov M. Laser Surface Melting of Austenitic Cr-Ni Stainless Steel, Advanced Materials Research 2011;264-265:1287-1292

[17] Dikova T. [Density Investigation of Dental Bridges, Produced by selective Laser Melting] [in Bulgarian], Proceedings of the Int. Sci. Conference “Industry 4,0”, 13-16 Dec 2017, Borovets, Bulgaria, STUME. 2017 Dec 1(1):149-152

[18] Wang J.H., Ren J., Liu W., Wu X.Y., Gao M.X., Bai PK. Effect of Selective Laser Melting Process Parameters on Microstructure and Properties of Co-Cr Alloy. Materials 2018 Sep;11(9):1546

[19] Grzesiak D., Krawczyk M. Effects of the Selective Laser Melting Process Parameters on the Functional Properties of the Co-Cr Alloy. International Journal of Recent Contributions from Engineering, Science& IT (iJES) 2015 Mar 10 3(1):39-42