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INFLUENCE OF SLM PARAMETERS ON COCR ALLOY

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Abstract: Among the most advanced technologies recently developed, selective laser melting (SLM) is one of the most innovative. The present SLM work aimed to determine the effect of laser power on hard metals such as cobalt chrome (CoCr) alloy. The following physical-mechanical proprieties were determined: ultimate tensile strength, Young modulus, surface hardness, and porosity level. Using industrial computer tomography (CT), the micro-porosity of SLM specimens was analyzed. It was observed that the laser power affects both the mechanical properties and microstructure of CoCr parts. Decreasing the porosity level will increase the mechanical resistance. The lowest porosity level was recorded on samples manufactured with 120 W. On the other hand, lower laser power (70 W) can improve the elasticity of SLM parts down to 19 GPa. The highest ultimate tensile strength was obtained at 120 W, maintaining constant the other SLM parameters. The highest surface hardness was 239 HB. Depending on implant requires, the SLM process can customize even the physical-mechanical properties of CoCr alloy. Future SLM research is needed to evaluate the fatigue limit of CoCr implants using the present technological parameters. From our point of view, the SLM technology will change the medical manufacturing industry, making it much flexible and customized.

Key words: *CoCr alloy, tensile strength, CT investigation, porosity, hardness.*

1. INTRODUCTION

Selective laser melting (SLM) process is one of the most interesting 3D Printing technologies which is used for rapid prototyping and small-scale manufacturing [1-4]. Metal alloys come in a powder form with a wide range of shapes and sizes [5]. Products can be manufactured directly from virtual models using selective laser melting process, bypassing typical manufacturing procedures such as cutting technologies [6]. New designs not achievable using traditional subtractive technology can be developed now [7-10]. Because the components are constructed layer by layer, organic shapes, interior features, and difficult passageways that could not be cast or machined are achievable [11-13].

The choice of material is critical in design step. From engineering point of view, the physical-mechanical properties of SLM products are required to elaborate new features or optimized topology [2], [14], [15]. For this reason, the influence of SLM parameters is important to be known.

Previous studies were focused on micro-porosity of SLM parts analyzed using industrial computer tomography (CT). In general, these works were focused on aluminum and titanium alloy [16], [17].

On the other hand, cobalt chrome (CoCr) alloy possesses a high durability and corrosion resistance. This alloy is used in clinical practice for the hard tissue reconstruction because of favorable biocompatibility and mechanical properties. The most frequent CoCr applications developed are medical implants like knee prosthesis, dental bridges or dental prosthesis, and cardiovascular stents [18].

The present work aimed to determine the impact of laser power on physical-mechanical proprieties of hard metals such as CoCr. Moreover, the micro-porosity of SLM specimens was CT analyzed.

2. MATERIAL AND METHODS

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The CoCr powder was purchased from Scheftner company (Germany) and it has the granulation between 10 µm to 45 µm (Starbond CoS Powder 30). The chemical composition satisfies ISO 22674 for medical materials, free of beryllium, nickel, and cadmium (Figure 1).

To analyze the influence of laser power on SLM parts, a Sisma Dual Laser machine was used, and standard samples were manufactured (Figure 2). The standard tensile samples were designed according to ISO 6892 (Metallic materials tensile testing). The laser power was varied between 70 W to 120 W and the other parameters were maintain constant as following: 500 mm/s scanning speed, 50 µm layer thickness, and 0,10 mm hatch distance. Previous research demonstrates the limits of laser power [18], [19]. The scanning strategy adopted was “x/y”. Using this SLM parameters, more than 20 specimens were printed, being orientated horizontally on machine platform.

Tensile stress–strain behavior was measured using a universal testing system (Instron 8801, Figure 3). The surface hardness was measured using WPM Leipzig tester (type HPO 250) and Brinell hardness was determined.

The micro-porosity was CT analyzed using a Phoenix V tome system illustrated in Figure 4. CT system is outfitted with a 3D measurement package that generates accurate, dependable data while using streamlined software and completely automated scan operations. Using 5-axes manipulation, the CT can examine materials up to 10 kg and 500 mm diameter. For better precision, the 180 kV nano focus X-ray tube and 240 kV microfocus tube are combined. Voxel sizes for the 240kV microfocus tube are down to 2µm, and for the 180kV nano focus tube, they are down to less than 1µm.

On each sample, an area of 150 mm^2 was measured at 30 mm from the base was marked (Figure 5). Wax was glued to the ends of the marked area so that the area to be scanned on the computer screen could be determined. The samples were placed in the middle of laser, considering the foam and the CT investigation was performed (Figure 5).

Co	Cr	W	Mo	Si	Other constituents
59.0 %	25.0 %	9.5%	3.5%	1%	max. 1.0 %

Fig. 1. Nominal values of alloy composition in mass percent of CoCr powder

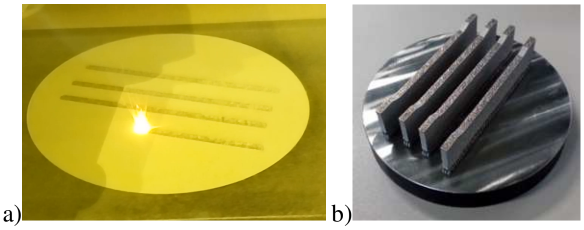

Fig. 2. a) Samples SLM manufacturing,
b) Specimens printed and their build-up orientation

Fig. 3. Mechanical tests using Instron 8801

Fig. 4. Industrial CT type Phoenix V tome x S

Fig. 5. Sample placed into CT scanner before scanning

3. RESULTS

3.1 Tensile strength and Young modulus

Figure 6 shows the samples after tensile trials. The mechanical results are resumed graphically as can be seen in Figure 7. Tensile properties such as ultimate tensile strength (UTS) and Young modulus were determined. The tensile tests showed the anisotropic behavior of SLM samples due to the generative production principle also observed in other works [18], [20].

From 70 W to 85 W, it shows a sudden growth in values, but after that, the values are rising continuously (Figure 7). It was observed that if the laser power is lower than 85 W, it will conduct to the lowest mechanical resistance. At 120 W laser power was obtained the highest values of ultimate tensile strength (UTS) and Young modulus (Figure 7). The mechanical response is addicted to laser power.

3.2 Surface hardness

Because of the high porosity level, the optimal solution was to determine the Brinell hardness. The indentation was performed using a 2.5 mm diameter ball with an applied load of 187.5 kgf for 30 seconds on each specimen. The hardness result can be seen in Figure 8a. Analyzing the data, the hardness increased from 82.5 HB for the 70 W sample, to 131 HB for the 85 W sample, and for the laser power of 100 W the hardness has 239 HB. It was observed that for the laser power of 120 W the hardness has decreased to 229 HB. These results are similar with other works [21].

Another characteristic of hardness is represented in Figure 8b, and it shows the dimension of impression diameter on the sample surface. The indentation represented by the impression diameter is inversely proportional to hardness and reaches the lowest diameter of 0.98mm for the laser power of 100 W. The impression has a continuous decrease from 1.6mm for the 70 W sample to 0.98 mm in diameter for the 100 W sample (Figure 8b). For the 120W sample, it is recorded that impression slightly increase to 1 mm.

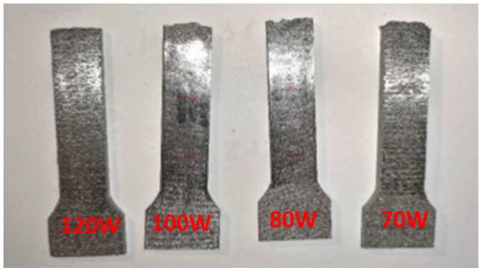

Fig. 6. SLM samples after tensile tests

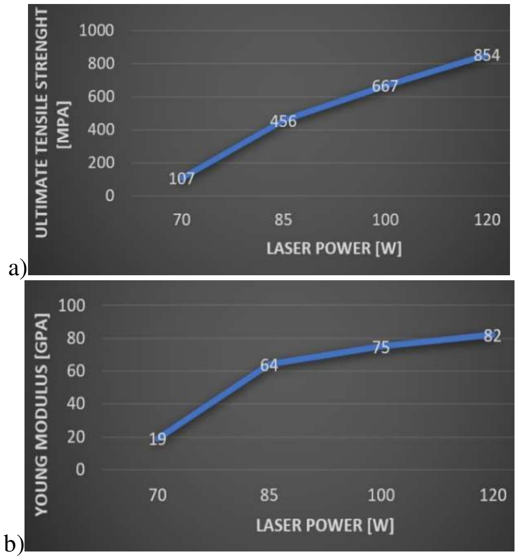

Fig. 7. Influence of laser power on CoCr parts SLM-manufactured: a) Ultimate tensile strength (UTS), b) Young modulus

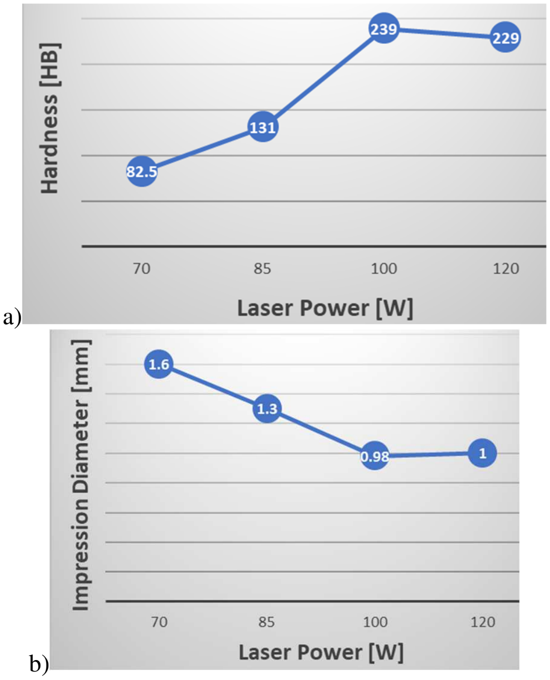

Fig. 8. Influence of laser power on:
a) Brinell hardness,
b) Impression diameter of the ball, indented on surface

3.3 CT investigation

Due to the ability of X-rays to penetrate different materials, CT scanning is used in non-destructive evaluations and testing applications.

Typical industrial CT can be used to investigate flaws, such as voids or cracks, in particle analysis of materials, and to determine methodological aspects (nominal deviations or surface quality) [19], [22]. Based on preliminary investigations, the authors found that the CT settings offer the possibility to penetrate dense metals such as CoCr with a maximum 5 mm thickness [19]. To corelate the mechanical results with porosity, X-ray CT scanning was performed on CoCr specimens. The CT results can be seen in Table 1, where the following aspects are summarized: number of porosities detected, largest diameter of pores, volume of largest pore, voids volume, and porosity level. Using these CT data, the influence of laser power is showed in graphics drawn below (Figure 9 and Figure 10).

According to CT scanning, two main types of defects were recorded in material such as porosities and voids. Porosities represent the amount of material that has not been fully melted and continues to have the characteristics of powder form. Voids are empty spaces or gas accumulation in the final product which are not filled with material. These defects influence the mechanical properties of SLM implants.

As can be observed in Figure 9a, the total number of pores tends to decrease with increasing laser power. The sample made with the power laser of 70 W recorded the highest number of porosities, being around 3460.

From the 70 W sample to the sample made with 85 W laser power, the number of porous significantly decrease to 1842 (Figure 9a). The lowest number of porous has been recorded for the sample made with 120 W (421 porosities). The largest defect detected have a diameter of 2.1 mm and it was recorded on sample fabricated with 70 W laser power and it have 0.1 mm^3 volume (see Table 1). Not only the number of porous decreases with increasing the laser power, but also the porosity level (Figure 9b). The lowest porosity level was determined at 120W at it was approx. 1.7% and the highest was 5.2% for samples fabricated with 70 W.

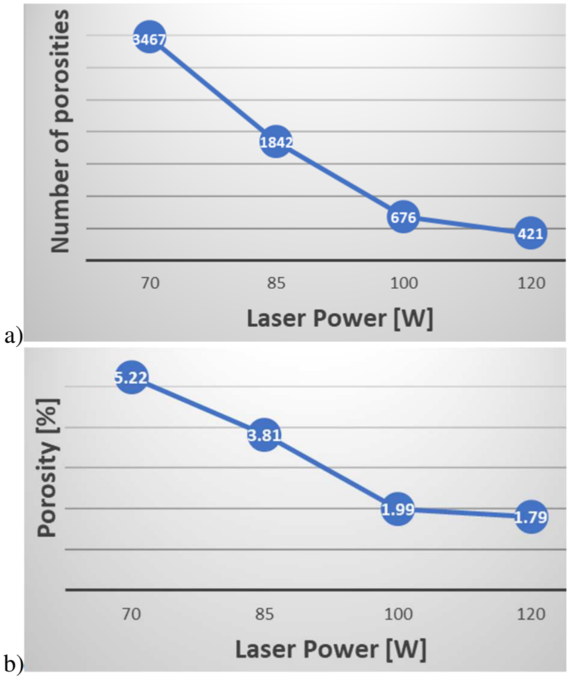

Fig. 9. Influence of laser power on:
a) Number of porosities detected using CT,
b) Porosity level

In Figure 10 is represented the volume of voids found in a certain measured volume of samples. According to these results, the voids are also influenced by the laser power. The

Table 1. Data obtained from CT investigation.

Laser power used for printing [W]	CT results					
	Number of porosities detected	Largest diameter of pores [mm]	Volume of largest pore [mm^3]	Measured volume [mm^3]	Voids volume [mm^3]	Porosity level [%]
70	3467	2.15	0.11	441.02	24.29	5.22
85	1842	1.97	0.10	357.19	14.15	3.81
100	676	1.92	0.12	350.86	7.13	1.99
120	421	1.68	0.11	351.44	6.39	1.79

measured volume for the 70 W sample was 441mm^3 and recorded a voids volume of 24.2mm^3 (Figure 10). The measured volume was constant at around 350 mm^3 for samples manufactured with 85, 100, and 120 W. In this case, the voids volume decreases from 14.1mm^3 to 6.3 mm^3 (Figure 10). Comparing samples made of 100 W and 120 W, it was observed that the voids volume it's not so sudden anymore and it has a difference of only 0.7 mm^3.

Furthermore, the CT data was used to 3D reconstruct the samples. Figure 11 illustrates the randomly position of the detected porosities. As can be observed in Figure 9a and Figure 10, the porosity level tends to decrease with increasing laser power. The sample made with the power laser of 70 W recorded the highest porosity level of 5.2%. From the 70 W to 100 W, the porosity recorded a significant decrease, from 5.2% to 1.9%. Between 100 W and 120W sample, there is not as big a difference and the porosity level decreased from 1.9% to 1.7%.

The inspection of complex surfaces involves challenges in terms of the measurement strategy [23], [24]. The actual study was limited on samples, but future studies should inspect complex CoCr surfaces. In addition, customized implants have gained importance due to better performance over their generic counterparts due to the precise adaptation to the region of implantation, reduced surgical times and better cosmetics [25-28]. Future research is required to evaluate the fatigue limit of SLM parts made of CoCr using the present parameters.

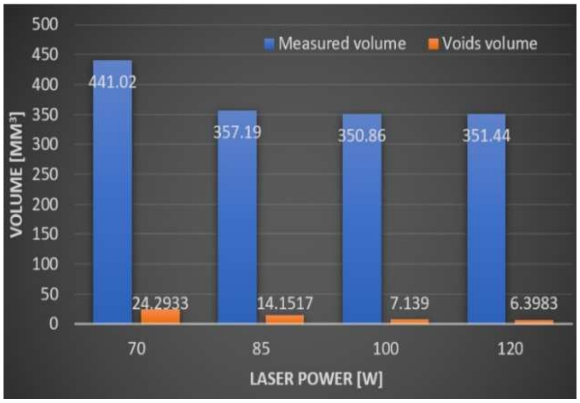

Fig. 10. CT result focused on voids volume

4. CONCLUSIONS

It can be concluded that laser power affects both the mechanical properties and microstructure of CoCr parts SLM manufactured.

Decreasing the porosity level will increase the mechanical resistance. The lowest porosity level was recorded on samples manufactured with 120 W.

On the other hand, lower laser power (70 W) can improve the elasticity of SLM parts down to 19 GPa. The highest ultimate tensile strength was obtained at 120 W and maintain constant the other SLM parameters.

To obtain the highest surface hardness, 100 W laser power should be used because it will build component with 239 HB surface hardness.

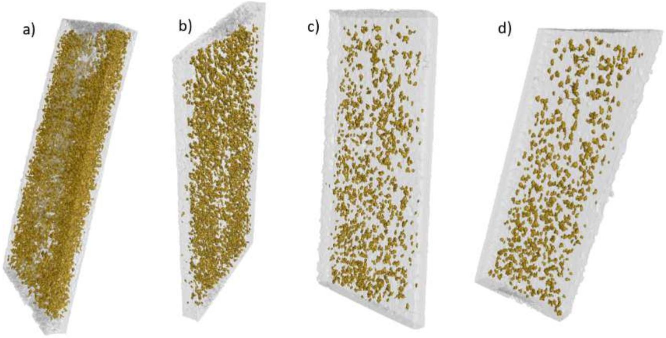

Fig. 11. Virtual reconstruction of samples using CT data. Samples are arranged in ascending order of laser power: a) 70 W, b) 85 W, c) 100 W, and d) 120 W

Depending on part demands, SLM process can customize even the physical-mechanical properties.

From our point of view, the SLM technology will change the medical manufacturing industry, making it much flexible and customized.

5. ACKNOWLEDGEMENT

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Influenta parametrilor SLM asupra aliajului CoCr

Rezumat: Dintre cele mai avansate tehnologii dezvoltate recent, topirea selectivă cu laser (SLM) este una din cele mai inovative. Lucrare are ca scop prezentarea efectului puterii laserului asupra metalelor dure, cum ar fi aliajul de crom cobalt (CoCr), in timpul procesului SLM. Au fost determinate următoarele proprietăți fizico-mecanice: rezistența la tracțiune, modulul Young, duritatea suprafeței şi nivelul de porozitate. Utilizând tomografia computerizată (CT), a fost analizată micro-porozitatea epruvetelor fabricate prin tehnologia SLM. S-a observat că puterea laserului afectează atât proprietățile mecanice, cât și microstructura pieselor din CoCr. Scăderea nivelului de porozitate va creşte rezistența mecanică. Cel mai scăzut nivel de porozitate a fost înregistrat pe eprivetele fabricate cu o putere a leserului de 120 W. Pe de altă parte, o putere laser mai mică (70 W) poate îmbunătăți elasticitatea pieselor SLM până la 19 GPa. Cea mai mare rezistență maximă la tracțiune a fost obținută la 120 W, menținând constant ceilalți parametri ai procesului. Cea mai mare duritate a suprafeței a fost de 239 HB. În funcție de cerințele implantului, procesul SLM poate personaliza chiar și proprietățile fizico-mecanice ale aliajului CoCr. Sunt necesare cercetări viitoare pentru a evalua limita de oboseală a implanturilor de CoCr folosind parametrii tehnologici actuali. Din punctul nostru de vedere, tehnologia SLM va schimba industria de producție medicală, făcând-o mult flexibilă și personalizată.

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