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Investigation of the Best Manufacturing Orientation of Co-Cr-W-Si Dental Prosthetic Elements in the Selective Laser Melting Process

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Abstract: It is well known that Selective Laser Melting (SLM) does not provide the same mechanical properties in all directions of the part. This is due to the microstructural grain orientation and pore shape in SLM products. Therefore, depending on the direction of the pressure applied to the SLM product, a different manufacturing orientation is required to achieve the best mechanical properties. Changing the microstructural grain orientation is difficult through SLM, but a process to reduce the size and number of the pores can be discovered through different combinations of manufacturing parameters. In prosthodontics, pressure is usually applied in the vertical direction, which leads to compression and bending of crowns with bridges. The compressive load can be easily absorbed in the crowns, but the bending force has a significant effect here. Therefore, a product with high tensile strength and high ductility is needed to survive longer. Considering these requirements, this study determined the best parameters for laser processing by SLM method to reduce porosity and improve mechanical strength and ductility of Co-Cr-W-Si alloy products. The result is a relative product density of 100% for cubic specimens and a yield strength, ultimate tensile strength, and elongation at break of the tensile specimens of 900 MPa, 1200 MPa, and 15%, respectively, obtained in specimen build-up in the Z direction with a laser power of 60 W and a scanning speed of 450 mm/s. Eventually, the best orientation for the production of dental prosthetic elements using the SLM process was determined.

Keywords: Cobalt-chromium alloy; dental implant; density; tensile strength; ductility; selective laser melting

1. Introduction

The production of dental prosthetic elements with high ductility at high bending strength is the prime challenge for the manufacturer [1,2]. These mechanical properties ensure a longer service life for these products [3]. Since the Selective Laser Melting (SLM) process offers high flexibility in manufacturing considering product design and customized product requirements with short production times, it is considered the most suitable manufacturing process [4]. In addition, the SLM process can provide higher mechanical properties compared to conventional manufacturing processes [5].

In the production of metallic biomedical products, especially in the production of cobalt-chromium denture elements, the SLM process is chosen as the best option in the industry [2]. On the other hand, cobalt-chromium alloys are the most attractive alloy system for dental applications due to their high ductility combined with high mechanical strength and biocompatibility (no deliberation of cell-toxic agents) [6].

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Additionally, tungsten (W) and silicon (Si) provide higher strength in the cobalt-chromium alloy system [7]. The modulus of elasticity of Co-Cr-W-Si is greater than 230 GPa. It was found that Co-Cr is easier to fabricate by SLM comparing other metals, and the melting point of Co-Cr-W-Si (1320-1420°C) is suitable for SLM process [8]. Due to its high density (8.6 g/cm^3), less spattering and low powder fly occur during manufacturing, which is reflected in dense part production [9]. Co-Cr-W-Si shows high corrosion resistance (ion release 3.5 μg/cm^{2}x7d) for dental applications [6]. Therefore, Co-Cr-W-Si is considered one of the best alloys for the production of dental prosthetic elements [10].

Therefore, this research work is concerned with discovering the best laser manufacturing parameters and manufacturing orientation to achieve the above-mentioned characteristics of the dental prosthetic elements. Different laser powers and scanning speeds were selected to find out the best combinations. Three different orientations in X, Y and Z directions were considered in the fabrication of the tensile specimens. Therefore, this paper will be helpful for prospective manufacturers and researchers to determine the best laser parameters and orientations for fabricating Co-Cr-W-Si parts using SLM.

2. Experimental

2.1. Materials

Co-Cr-W-Si powder with a diameter between 10 and 40 μm, provided by Dentaurum, Germany, was used to prepare the samples in this study. The elemental composition of the alloy is 60.5 wt% Co, 28 wt% Cr, 9 wt% W and 1.5 wt% Si, while the other elements are Mn, N, Nb and Fe with a total of < 1 wt% and it is free of nickel, beryllium and gallium.

2.2. Methods

Two types of specimens were produced using the Arrow Metal Printing - LMP200 SLM machine provided by Dentas, Maribor, Slovenia, namely cubic and tensile specimens. The dimensions of the cubic specimens were 8 mm × 8 mm × 8 mm. The gauge length, total length, gauge width, and gauge thickness of the tensile specimens were

15.34 mm, 33 mm, 2 mm, and 1 mm, respectively, and the radius of the gauge fillet was 3 mm. The cubic specimen was built up after 2 mm support height, and the tensile specimens were made above 2 mm support height in X, Y and Z directions, as shown in Fig. 1.

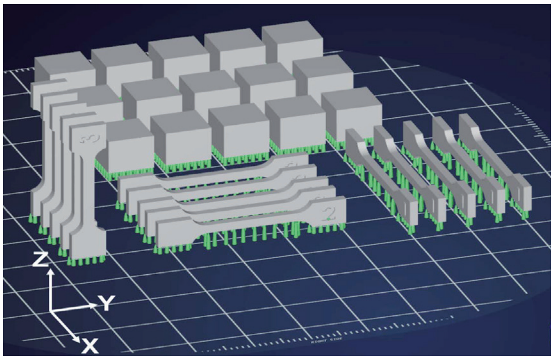

Figure 1: STL files of cubic and tensile specimens and their orientation for fabrication

To obtain the best combinations of laser power and scanning speed, two steps were followed considering higher power to lower power (95 W and 60 W, respectively). The scanning speed was increased from 300 mm/s to 470 mm/s in the first step of the study, as listed in Table 1. The first step showed that increasing the speed improves the product density, which also means that decreasing the energy density (ED) results in a higher product density. Therefore, in the second step, the ED was decreased by reducing the laser power to 60 W and the scan speed was increased from 220 mm/s to 450 mm/s (see Table 2). The scanning speed was started at a lower speed in the second step of the study to obtain sufficient ED and to determine the best combination of parameters. The laser beam diameter was 50 μm and the hatch spacing was

35 μm throughout the experiment.

The densities of the cube-shaped specimens were measured according to Archimedes' principle with an accuracy of ±0.1 milligram using an electronic weight and density calculation machine. Six measurements on each cube were considered to determine the density. Tensile tests were performed in an INSTRON-1255 computerised data acquisition system at room temperature at a rate of 0.01 mm/s. For each set of specimens, three cubes were used to measure density, while five tensile specimens were used for each test condition. After the test specimens by SLM, they were ground and the surface polished. This removed the support rods that were connected to the surface of the gauge, and the surface was also freed from notches.

Table 1: Manufacturing parameters in the first step of the study

Sample number	*Laser power (W)*	*Scanning speed (mm/s)*	*Energy Density (J/mm2)*	*Product density (g/cm3)*
I-1	95	300	4.11	8.26
I-2	95	330	3.74	8.36
I-3	95	370	3.33	8.52
I-4	95	420	2.94	8.44
I-5	95	470	2.63	8.39

Table 2: Manufacturing parameters in the second step of the study

Sample number	*Laser power (W)*	*Scanning speed (mm/s)*	*Energy Density (J/mm2)*	*Product density (g/cm3)*
II-1	60	220	3.54	8.59
II-2	60	260	3.00	8.55
II-3	60	300	2.60	8.58
II-4	60	350	2.23	8.57
II-5	60	450	1.73	8.65

3. Results and Discussion

3.1. Density

The product densities of the sample are shown in Table 1 and Table 2 from the first and second steps of the study, respectively. However, in Fig. 2, the effect of laser power and scanning speed on the densities of the samples can be easily seen. Fig. 2 clearly shows that increasing the scanning speed leads to an increase in density, which is due to the minimization of porosity. The porosity is mainly due to the spatter and keyhole effects [9,11]. A higher ED resulted in more spattering of the molten materials. On the other hand, the probability of keyhole continuation being destroyed is higher at low and high scanning speed than at medium scanning speed. The interruption of a keyhole causes the pore formation at the interruption points. Therefore, it can be seen that the medium speed leads to better density of the samples. It can also be seen that a decrease in ED results in a higher density as the material spatter decreases compared to the higher ED at the beginning of the samples.

After reviewing the results from the first step of the study, the laser power was reduced in the second step of the study to obtain the effective lower ED. However, at this lower laser power (60 W), it was necessary to study the effects of the pore formation mechanisms at an even lower speed. Therefore, the study was conducted at a scanning speed of 220 mm/s to 450 mm/s. The density results in the second step of the study are shown in Fig. 2. Eventually, a relative density of 100% is achieved, and the best density is obtained with a laser power of 60 W and a scanning speed of 450 mm/s.

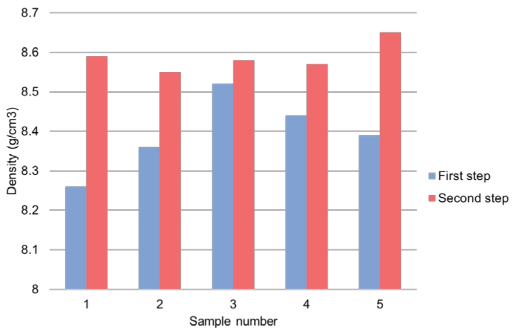

Figure 2: Density of samples prepared in the (a) first and (b) second steps of the study

The results in the second step showed that not only the ED has an influence, but also the laser power plays an important role in the production. Although the ED was higher at the beginning of the second step, the fabrication succeeded well due to the low laser power, which is much better than the high power of 95 W. Similar results were also observed by

Pal et al [12] for the Ti-6Al-4V alloy samples, where the density was significantly improved with lower laser power. This is due to the fact that the keyhole is less likely to be destroyed. Moreover, lower laser power resulted in lower ED at a place at a time rather than higher laser power, which significantly reduced the tendency of molten metal spattering.

3.2. Tensile properties

As shown in Fig. 1, the tensile specimens were fabricated in three directions parallel to the X, Y, and Z axes, respectively, and their mean stress-strain diagrams are shown in Fig. 3. It can be clearly seen that the specimens fabricated in the Z direction have both higher strength and ductility compared to those fabricated in the X and Y directions. In the first step of the study, the yield strength (YS) is almost equal in all directionally fabricated specimens, being about 850 MPa. However, the ultimate tensile strength (UTS) is different for them which are 1009 MPa, 1066 MPa and 1145 MPa respectively. A significant difference in elongation at break was found between the specimens, and high elongation is desirable in dentures to sustain longer. The elongation occurred in the specimens is 8%, 7.3% and 12.8%, respectively.

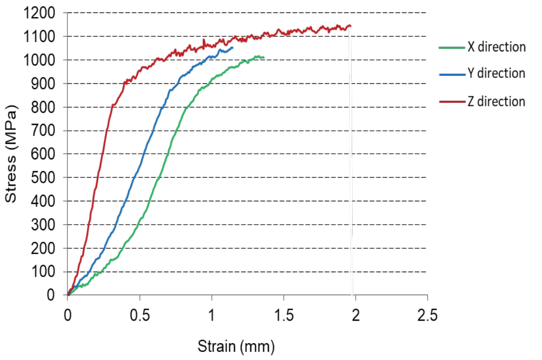

Figure 3: Stress-strain graph of the tensile samples manufacture in the first step of the study.

As the specimens were fabricated in the second step of the study with a lower ED as well as a lower laser power, the mechanical properties of the specimens fabricated in the Z direction improved, as shown in Fig. 4. The values YS, UTS and the elongation at break of this specimen are 900 MPa, 1200 MPa and 15%, respectively. On the other hand, for the specimens fabricated in the X and Y directions, these values are 750 MPa, 970-1010 MPa, and 6.5%, respectively. Therefore, the mechanical properties of the specimens fabricated in the X and Y directions deteriorate slightly in the second step of the study. Eventually, the mechanical properties in the Z direction are significantly higher than in the X and Y directions.

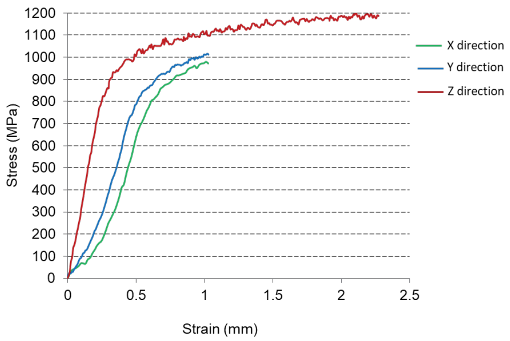

Figure 4: Stress-strain graph of the tensile samples manufacture in the second step of the study.

3.3. Dental prosthetic fabrication

Since the pressures in the crowns act in the Z direction, as shown in Fig. 5, the bending of the bridges occurs in the Z direction. Therefore, the bridges require higher strength in the Z-direction than in the X- and Y-directions to sustain. Since SLM manufacturing has higher mechanical properties in the Z-direction, it is important to manufacture the dental prosthetic elements keeping in the horizontal direction, as shown in Fig. 5. The results can usually be generalized to other production machines if they have the same laser beam diameter.

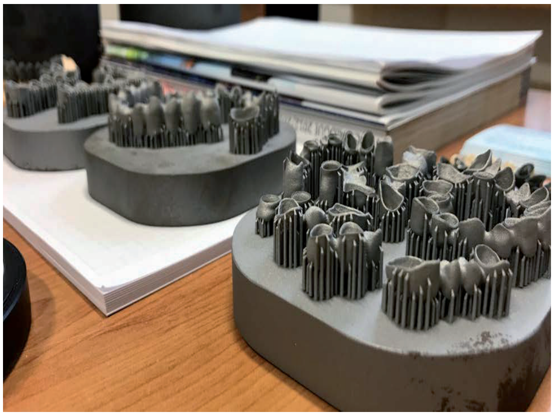

Figure 5. An example of manufacturing of crowns with bridges for dental application.

4. Conclusions

This study deals with the improvement of density and observation of mechanical properties in three different directions (X, Y and Z) of Co-Cr-W-Si alloy prepared by selective laser melting. Some insights were obtained on the increase of strength as well as on the required orientation to obtain a sustainable product by means of mechanical loading. Eventually, the required orientation for the fabrication of dental prosthetic elements was understood.

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