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Combined Effect of Build Orientation and Energy Density on Density and Mechanical Properties of Selectively Laser Melted Co-Cr-W-Si

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Abstract: The selective laser melting (SLM) process for manufacturing metals continues to be challenging in terms of achieving the maximum metallurgical properties that the process can provide. There are a variety of manufacturing parameters in the process that have individual characteristics, and when combined with other variables, the characteristics can be varied. However, in this study, the two most important manufacturing parameters, namely build direction and laser power, were considered to investigate their effects on density and tensile properties. Previously, the best scanning speed, hatch spacing, and layer thickness were determined, which directly affect the volumetric energy density in the SLM process. In this study, three different orientations and three different laser powers were selected, namely the X, Y, and Z directions and 55 W, 75 W, and 95 W laser power, respectively. Significant differences in product density were observed for the samples fabricated in the different orientations and with the different laser powers. The specimens fabricated in the Z direction always exhibit higher strength and ductility, which are significantly different from the specimens fabricated in the X and Y directions, while the laser power was 75 W and 95 W, respectively.

Keywords: cobalt-chromium alloy; orientation; density; tensile strength; ductility; selective laser melting

1. Introduction

Selective laser melting (SLM) is the most attractive process for metal additive manufacturing because once the powder is formed, the material does not need to be exposed to air before the part is manufactured [1]. From the time the metal powder is formed until the part is manufactured in the SLM chamber, the material can be kept in a protective environment. As a result, SLM processes are commonly used in aerospace, automotive and biomedical applications [2,3]. The layer-by-layer laser fashion process of metals in the SLM process offers great manufacturing flexibility, from in-situ alloys to complex products [4,5]. In addition, it is ideal for manufacturing customized metallic products of interest to biomedical implant manufacturers [6,7]. However, due to the layer-by-layer formation and different laser parameters, the metallurgical properties of the products vary greatly [8]. For example, the orientation of the product during manufacturing and the laser parameters, especially laser power, scanning speed and hatch distance, have a major impact on the metallurgical properties, while numerous other process parameters also have some influence [9].

While there are several literatures on build orientation in SLM process considering the other metals, there are few research articles on Co-Cr alloys, especially Co-Cr-W-Si alloys. However, the authors of the article found large differences in the density and tensile properties of Co-Cr-W-Si products due to the combined effects of orientation and laser

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power (energy density was considered here). Since Co-Cr-W-Si is considered one of the most suitable materials for dental prostheses and multiple loads are encountered during application, maximum possible mechanical properties are desired [10]. The remarkable strength, hardness, corrosion, and wear resistance of cobalt-chromium-molybdenum alloys make them suitable materials for wind turbine and engine parts as well [5]. Therefore, in this work, the effects of different orientations, namely the X, Y, and Z directions, and three different energy densities for each direction on the tensile properties and product densities of Co-Cr-W-Si produced by SLM were investigated. The energy densities were determined using the changing laser power, while the other best parameters such as scanning speed and hatch spacing had already been determined in previous experiments.

2. Experimental

2.1. Materials

The specimens for this investigation were created using Co-Cr-W-Si powder that had a diameter of between 10 and 40 m and was supplied by Dentaurum, a German company. The alloy has an elemental composition of 60.5 wt% Co, 28 wt% Cr, 9 wt% W, and 1.5 wt% Si, with less than 1 wt% amounts of Mn, N, Nb, and Fe, and no nickel, beryllium, or gallium.

2.2. Methods

The tensile specimens have been fabricated using the Arrow Metal Printing - LMP200 SLM machine provided by Dentas, Maribor, Slovenia. The orientations of the specimens have been shown in Fig. 1. They are oriented in X, Y and Z directions considering the major axis of the specimens. The gauge length, total length, gauge width, gauge thickness and radius of the gauge fillet of the specimens were 15.34 mm, 33 mm, 2 mm, 1 mm and 3 mm, respectively. The specimens were set up on a base at least 2 mm high. The width of the specimens was kept upright for the specimens oriented in the X and Y directions, while the specimens oriented in the Z direction were kept upright in the longitudinal direction (major axis).

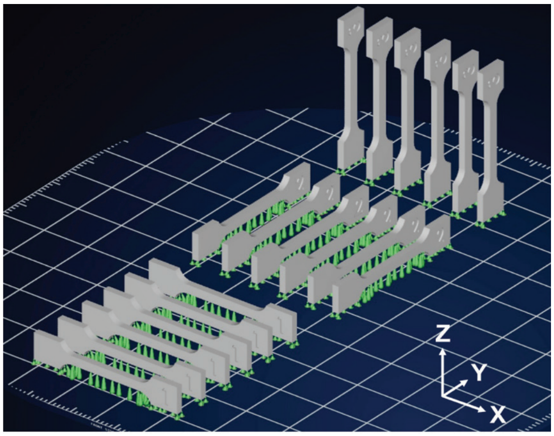

Figure 1. SLM manufacturing orientation of tensile specimens.

The selected energy densities for each orientation have been listed in Table 1. The energy density (ED) has been changed by changing the laser power. The best range of other parameters providing the best EDs was determined from previous studies by the authors. Therefore, the laser powers have been set to 55 W, 75 W, and 95 W, while the EDs were determined to be 1.1 J/mm^2, 1.5 J/mm^2, and 1.9 J/mm^2, respectively.

Table 1. Build orientations and energy densities of the specimens.

Sample category	Build orientation	Laser power (W)	Scanning speed (mm/s)	Hatch space (mm)	Energy density (J/mm^2)
X55	X direction	55	650	0.035	1.1
X75		75	650	0.035	1.5
X95		95	650	0.035	1.9
Y55	Y direction	55	650	0.035	1.1
Y75		75	650	0.035	1.5
Y95		95	650	0.035	1.9
Z55	Z direction	55	650	0.035	1.1
Z75		75	650	0.035	1.5
Z95		95	650	0.035	1.9

3. Results and Discussion

3.1. Density

The densities of the samples fabricated in different ED resulted in differences in product density, as shown in Fig. 2. The differences in density are due to the difference in the total volume of porosity. A low ED caused insufficient melting, which caused the unmelted zones in the lower parts of the melt pools. These unmelted zones melted while ED increased. On the other hand, the intensity of the laser at low laser power (55 W) was not sufficient to keep continuation of the keyhole during melting. The disruption of the keyhole therefore caused small pores in the samples. In addition, when the ED was increased significantly (1.9 J/mm^2), spattering of materials from the melt pool occurred due to the lower viscosity, causing the action zone to lose some materials. Therefore, the material spattering was responsible for the decrease in density in the sample fabricated with high ED (1.9 J/mm^2).

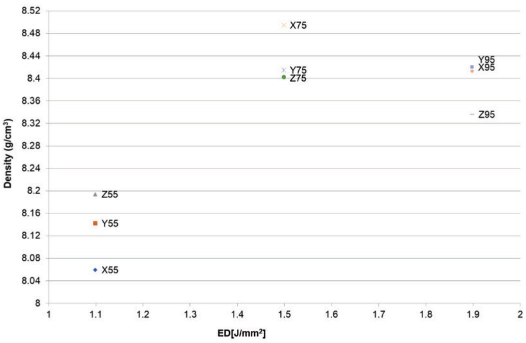

Figure 2. Densities of the specimens.

It was found that the densities were lower for the tensile specimens compared to the cubic specimens prepared in other experiments. The cubes were scanned with an area of 8 mm × 8 mm, while the tensile specimens were scanned with 1 mm × 2 mm or 1 mm × 6 mm or 1 mm × 33 mm. Therefore, the thin dimensioned products or the smaller scanned area caused higher porosity. Although the cubes had a product density of 100%, the tensile specimens achieved a significantly lower density using the same combination of laser parameters.

3.2. Tensile properties

The results of the tensile tests are shown in the stress-displacement diagrams in Figs. 3, 4, and 5 for the specimens fabricated at 55 W, 75 W, and 95 W, respectively. The displacements are the elongations that occurred while the gauge length was 15.34 mm. From the figures, it can be seen that the specimens had built up in Z direction have significantly higher strength and ductility compared to the specimens fabricated in the X and Y directions. Comparing the X and Y orientations, the specimens built in the Y direction have slightly higher strength, although their ductility is almost the same for all times.

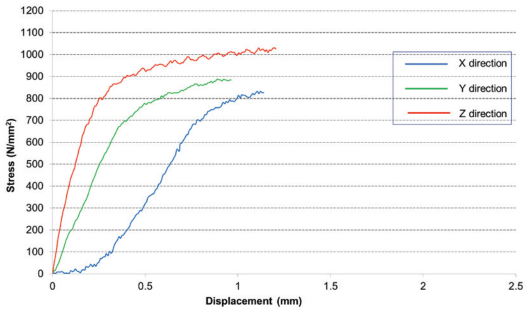

Figure 3. Stress-displacement graph of the tensile specimens fabricated by 55 W laser power.

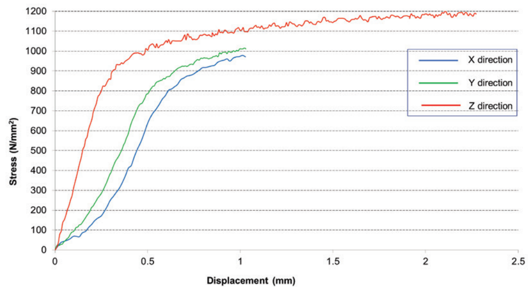

Figure 4. Stress-displacement graph of the tensile specimens fabricated by 75 W laser power.

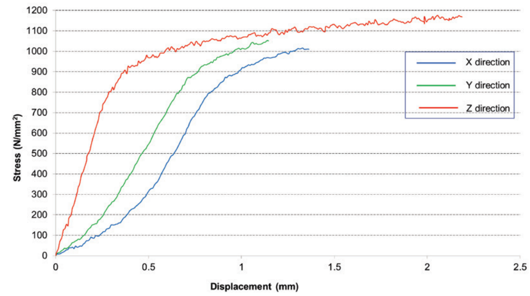

Figure 5. Stress-displacement graph of the tensile specimens fabricated by 95 W laser power.

Although densities are higher in X- and Y-oriented specimens fabricated at 75 W and 95 W laser power, tensile properties are significantly lower compared to those fabricated in the Z direction. At the applied laser power of 55 W, the Z-oriented samples have higher densities, but the tensile properties are not significantly different from those of the X- and Y-oriented samples.

4. Conclusions

Significant results have been observed in the densities and tensile properties of Co-Cr-W-Si samples prepared by selective laser melting considering different combinations of energy densities and buildup directions, which are as follows:

1. The product density differed due to the different directions as well as the energy density. The densities are also significantly lower than those of the cubic samples with larger scanning area prepared with the same laser parameters.

2. The specimens built in the Z direction exhibited higher strength and ductility compared to the X and Y oriented specimens, although they had comparatively lower density.

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