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Investigation of mechanical properties for open cellular structure CoCrMo alloy fabricated by selective laser melting process

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Abstract. Orthodontic implants have been a major focus through mechanical and biological performance in advance to fabricate shape of complex anatomical. Designing the part with a complex mechanism is one of the challenging process and addition to achieve the balance and desired mechanical performance brought to the right manufacture technique to fabricate. Metal additive manufacturing (MAM) is brought forward to the newest fabrication technology in this field. In this study, selective laser melting (SLM) process was utilized on a medical grade cobalt-chrome molybdenum (CoCrMo) alloy. The work has focused on mechanical properties of the CoCrMo open cellular structures samples with 60 %, 70 %, and 80 % designed volume porosity that could potentially emulate the properties of human bone. It was observed that hardness values decreased as the soaking time increases except for bottom face. For compression test, 60 % designed volume porosity demonstrated highest ultimate compressive strength compared to 70 % and 80 %.

1. Introduction

Dental implant consists of parts such as crown, abutment and bridge where is restored in the interior or posterior region of human jaw or skull. There are two factors that must take into consideration for the purpose to produce the dental implants product that are mechanical performance and also the surface properties of the finished product [1]. Selective laser melting (SLM) process has been proven best to produce a dental implant as a ready used product with better stress distribution and also the primary stability [2]. SLM has been widely used in the application of medical implants manufacturing as this process can produce complex geometry that impossible to fabricate using conventional manufacturing processes [3].

Cobalt chromium molybdenum (CoCrMo) has been widely utilized in orthodontic application nowadays due to its high corrosion resistance and biocompatibility. The biocompatibility of CoCrMo is due to exhibition of spontaneous formation of a passive oxide film layer and thus results a barrier for metal ion release [4]. A study on CoCrMo has been performed on the human body and it has been proven to be a preferred alloy for the application of the metal-on-metal contact [5]. From EOS datasheet, this material possess excellent characteristics as it able to stands to Young modulus of 200 – 210 GPa, tensile strength at 1150 – 1400 MPa and yield strength of 880 – 980 MPa [6].

The size of pore in a finished part plays an important role in biomedical applications. In medical term, osseointegration is significantly in strengthening the internal fixation by allowing the bone ingrowth into the implant in order to enhance the functionality and longevity of the dental implants [7]. The pores distribution and the shape of the pore must emulate natural porous structure like sandstone that is mimicking the human bone as they exhibit the fractal characteristics [8]. In the human nature, there are complex ways to determine the pore-structure completely as it has a character of abnormity, uncertainty, and intangibility. Accuracy description of the pore structure has led to a scientific issue and experimental method cannot be available for the natural porous structure [9].

Cellular structures of natural orthodontic such as cellular biomaterials device comes from either two dimensional unit cells or also three dimensional unit cells. Honeycomb is an example of two dimensional unit cells and tetradecahedron and cubic is example of three dimensional unit cells [10]. The mechanical properties of the specimen are based on the type of unit cell and its dimensions [11].

An idea of introducing porous structure in biomedical application is to minimize the stress shielding effect that occurred between the bones and also implant due to mismatch of stiffness characteristics. Therefore, this study is conducted to define the mechanical properties of open cellular structure CoCrMo alloy sample with different designed volume porosity that could mimic the bone.

2. Experimental Set Up

2.1 Sample Design

Three (3) groups of samples were prepared based on the designed volume porosity namely 60 %, 70 % and 80 % that were being designed by aid of Solid Works® 2013 software. Wall thickness of open cellular structures samples were fixed at 0.80 mm with pore sizes in square shape ranging between 1.20 and 1.80 mm within 15 mm cubic. Detailed specifications of individual CAD models are shown in Table 1. The models were exported from CAD software in STL file format into Materialise Magics 17.01 software. The models were then positioned on the build platform (substrate) and sliced files were generated to enable physical sample fabrication process by SLM followed. Typical CAD model of a sample is shown in figure 1.

Table 1. Dimensions and volume based porosity of open cellular structure samples.

Sample Group	Strut Thickness (mm)	Pore Size (mm)	Porosity (%)
1	0.80	1.20	60
2	0.75	1.60	70
3	0.50	1.80	80

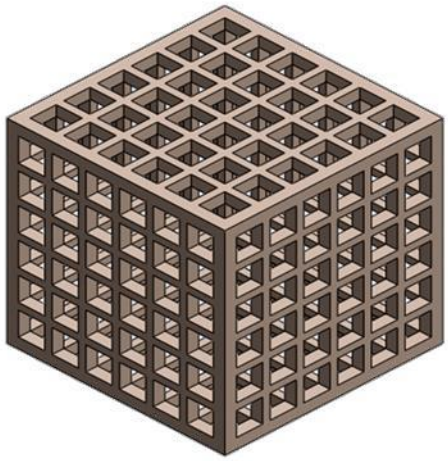

Figure 1. The CAD model of sample with designed volume porosity 80 %.

2.2 Fabrication Process

The material used for this study was EOS CobaltChromeMP1^{TM} supplied by EOS GmbH, Germany. This powder consist mainly element of Co, Cr, and Mo equipped with fine spherical morphology and average particle size of 25 µm. Figure 2 shows the shape of each particle of the powder that was obtained by scanning electron microscope (SEM). The chemical composition of the powder is summarizes in table 2.

Table 2. Chemical composition of CoCrMo alloy.

Element	Mass (%)
Co	60-65
Cr	26-30
Mo	5-7
Si	1.0
Mn	1.0
Fe	0.75
C	0.16
Ni	0.10

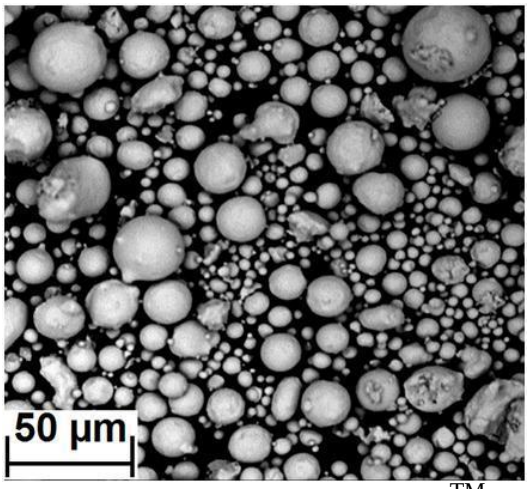

Figure 2. SEM image of EOS Cobalt Chrome MP1^{TM} powder particles.

All of the samples were fabricated by EOSINT M280 machine that was operated on PSW 3.06 software. The powder was manually sieved into the dispenser platform to avoid any powder that agglomerate to each other. Substrate dimension was 250 × 250 × 36 mm and made from tool steel plates. Table 2 summarizes the parameter that is set for the machine during fabrication process. The fabrication chamber was filled by nitrogen gas with less than 1.3 % oxygen present. Figure 3 shows the virtual process inside the fabrication chamber.

Table 3. Setting parameters of SLM process.

Process parameters	Parameters Value
Layer Thickness	20 µm
Laser Power	195 W
Scanning Space	0.1 mm
Laser Scan Speed	800 mm/s

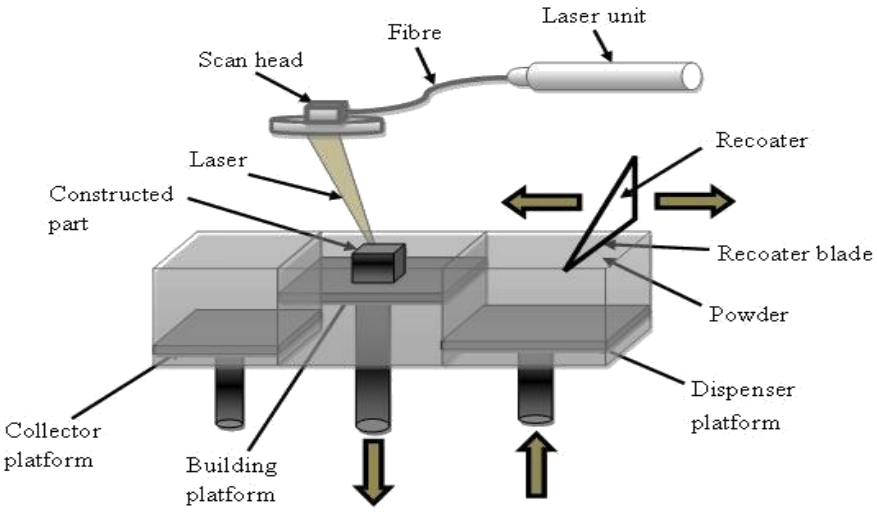

Figure 3. Schematic diagram of SLM process.

2.3 Heat Treatment

Samples from each group was subjected to stress relieve process for 8 and 20 hour of soaking time at 250 ^{o}C and pressure at -0.1 bar. The samples were then oven-cooled to room temperature. Figure 4 shows the oven used for the stress relieves process.

Figure 4. Vacuum oven for stress relieve.

2.4 Hardness

Hardness test was conducted on the sample from each group. The measurement involved samples with and without stress relief process. Each measurement was subjected to five (5) indentations that were on top, bottom, inner, and side face. The setting for hardness measurement was 10 seconds contact for the indentation with 500 gram applied load.

2.5 Compression

Uniaxial compression test was conducted in this study using Shimadzu materials testing machine that possess the capability of 100 kN maximum applied load. The test was performed to determine the effect of different soaking time on mechanical properties of the sample. The tests were performed with stroke of 8 mm and test speed of 0.5 mm/min. The samples were being tested until failure or until the maximum load capacity of the machine was reached. The stress strain relationship for each individual component was calculated from the real time force versus displacement data obtained from the test machine.

3. Results and Discussion

3.1 Hardness

Figure 5 concludes the result for hardness testing on all surfaces using Vickers hardness test. We can clearly observed that hardness values for top, inner, and side faces shows decrease trend as the soaking time increased. At high temperature, the grain size will be increased and deformation occurred which will promote recrystallization process accompanies with softening due to formation of new grains free of dislocations. Recrystallization resulted in reduction of strength and hardness of a material and a simultaneous increase in the ductility. Nonetheless, bottom face has shown distinctive trend, where instead of decreasing, the hardness values on this face keep increasing as the soaking time increased. The phenomenon was due to presence of heat affective zone (HAZ) as a result from electro discharge machining (EDM) wire-cut process to detach samples from the substrate. The rapid rate of cooling during the cutting process favours the formation of hard and brittle martensite in all the sub zones of the HAZ. The presence of martensite in the HAZ results in a very high hardness value for the heat affected zone. Figure 6 shows the effect of HAZ on bottom face of the sample.

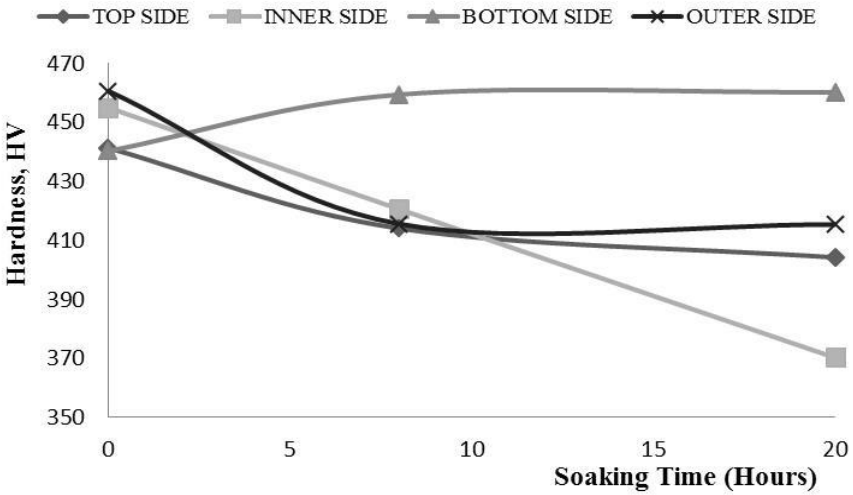

Figure 5. Hardness values for different surfaces.

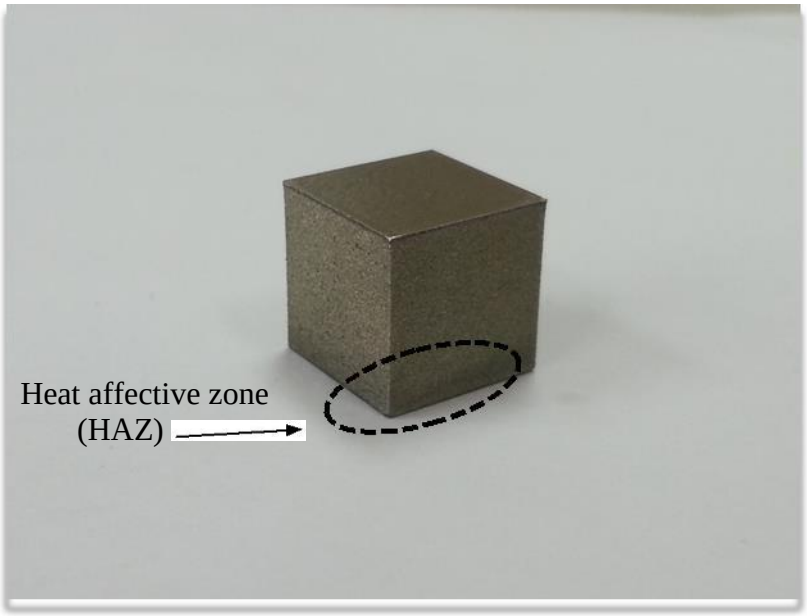

Figure 6. Heat affective zone (HAZ) on the sample.

3.2 Compression Test

Compression test data for all samples are presented in figure 7 to figure 9. As expected, 60 % designed volume porosity possess the highest value of ultimate compressive strength compared to 70 % and 80 % in all conditions. Samples with higher porosity will show lower mechanical characteristics. In general, the stress-strain curves can be divided into three (3) distinct regions. First, a quasi-elastic linear increase of the stress-strain curve, which is controlled by cell-wall bending and cell-face stretching. Next region is a deformation "plateau" characterized by a small or vanishing slope of the stress-strain curve with nearly constant flow stress to a large strain. This region is associated with cell collapse. The third region involved of rapidly increasing stress, where the cell walls touch each other and the material is densified.

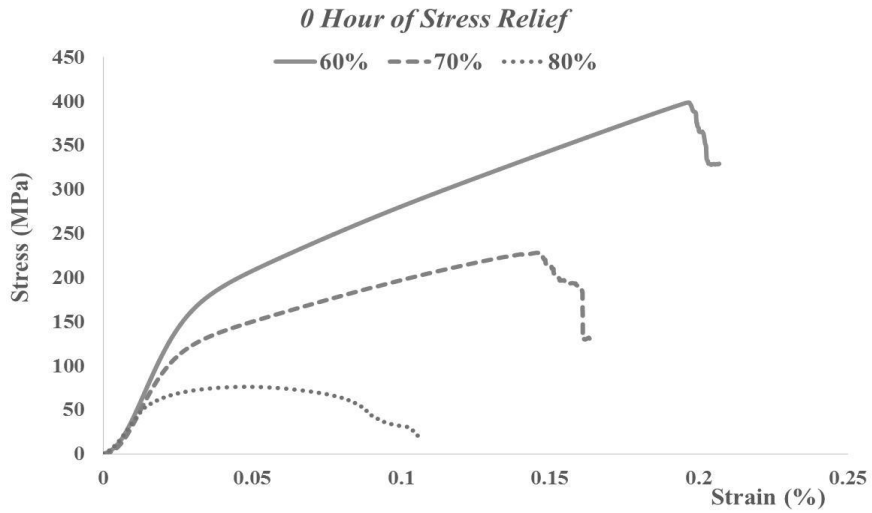

Figure 7. Without stress relief process.

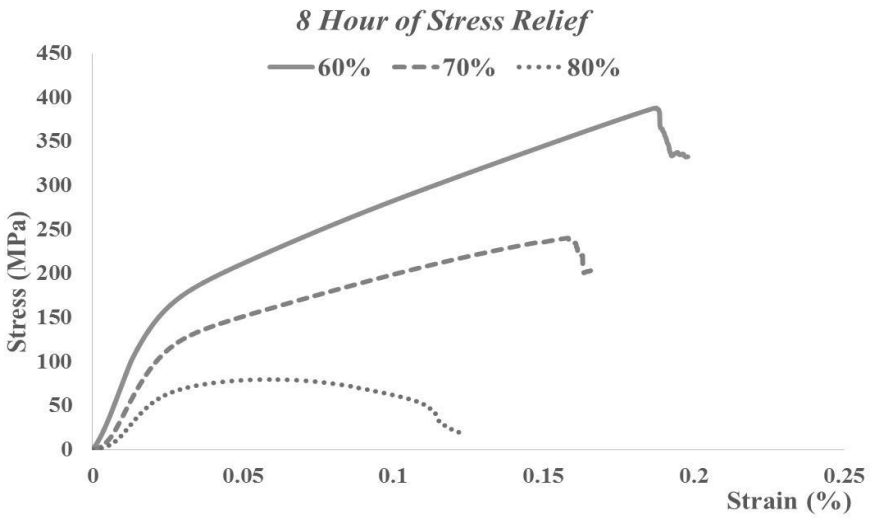

Figure 8. 8 hour of stress relief process.

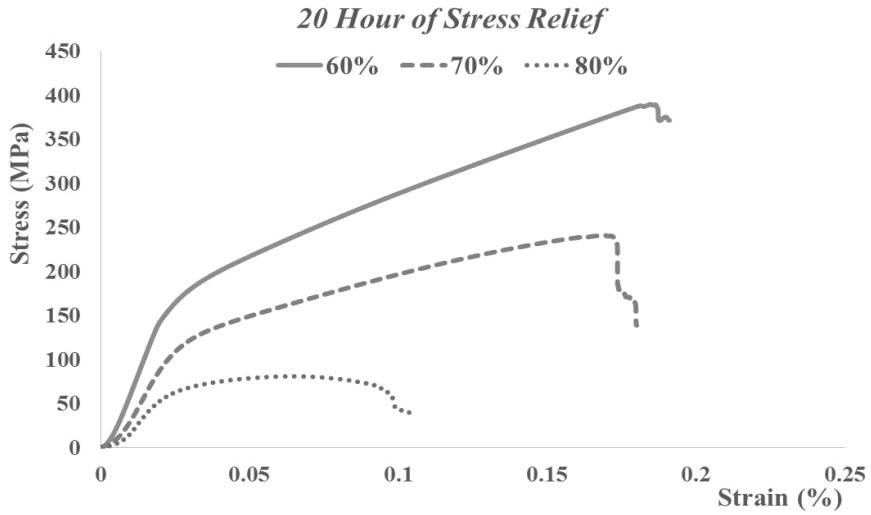

Figure 9. 20 hour of stress relief process.

Table 4 summarizes the ultimate compressive strength along with its strain values in bracket at different condition of soaking time. As mentioned earlier, 60 % designed volume porosity demonstrated the highest ultimate compressive strength and strains for all conditions compared to 70 % and 80 %. In general, prolong the soaking time to 20 hour resulted in improvement of ultimate compressive strength for all samples. It indicates the effectiveness of stress relief process regarding to its function which is to eliminate any residual stress that contained in the samples. However, low-temperature stress relief seem does not give any significant effect to the compressive strength. Therefore, a study will be conducted in future to investigate the differences in compressive strength values at higher temperature of stress relief.

Table 4. Ultimate compressive strength for different soaking time.

Porosity (%)	0 Hour	8 Hour	20 Hour
60	398.49 MPa (0.1967 %)	387.66 MPa (0.1876 %)	389.62 MPa (0.1846 %)
70	228.52 MPa (0.1458 %)	240.14 MPa (0.1583 %)	241.42 MPa (0.1688 %)
80	76.42 MPa (0.0486 %)	79.10 MPa (0.0594 %)	81.00 MPa (0.0649 %)

4. Conclusions

The effects of different designed volume porosity; 60 %, 70 %, and 80 % on mechanical properties were successfully identified. Hardness values showed decrease trend as soaking time increased for all surfaces except for bottom face. Samples with higher porosity demonstrated lower mechanical properties. 60 % designed volume porosity exhibit the highest ultimate compressive strength compared to 70 % and 80 %. Meanwhile, higher soaking time seem to give positive impact to the mechanical properties of the samples.

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