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Effect of Fabrication Method and Heat Treatment on the Properties of Co-Cr Bio Alloy

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Abstract

Co-Cr alloys are widely used in dental and medical equipment since the development of the first cast Co-Cr-Mo alloy. This is due to its high mechanical properties and high resistance to wear and corrosion. This research aims to study the effect of the fabrication method (Investment Casting and Selective Laser Melting SLM by 3D printing) and heat treatments on the mechanical and tribological properties of Co-Cr-Mo alloy. It was found that the Selective Laser Melting method in general increases the ultimate tensile strength, strain and hardness compared to the Investment Casting method. Also, solution treatment and aging reduce the strength and strain values of the SLM samples and have no obvious effect on the casting samples. The wear test shows that wear rate of casting samples is lower than that of SLM samples.

Keywords: Co-Cr-Mo alloy, Investment casting, Selective laser melting, hardness, wear, ultimate strength.

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1. Introduction

Co-Cr alloys have been discovered since the beginning of 1900s and the Stellite alloys manufactured by Haynes became important materials for wear-resistant applications [1]. Due to their exceptional mechanical, wear and corrosion properties, Co-Cr alloys are considered as effective biomaterials and have been used in applications of medical and dental parts. Since the development of the cast Co-Cr-Mo alloy in the 1930s and the use of the lost-wax method in its manufacture, its commercial use has become widespread [2-3]. The lost wax method suffers from the problem that it is sensitive to human error [4].

Recently, advanced manufacturing methods using computer-aided design / computer-aided manufacturing (CAD/CAM) for the production of biomedical devices and dental prostheses have been established [5-7].

A CAD/CAM technology-based Additive manufacturing is an excellent alternative to the traditional Investment wax casting method in producing restorations. One of the additive manufacturing methods is selective laser melting (SLM), in which parts can be made directly from a three-dimensional CAD model by fusing metal powder and building layers using a focused laser beam [8]. Also, many researchers have found that SLM-manufactured parts have higher mechanical properties than those manufactured by the casting method [4].

Figure 1 includes the equilibrium phase diagram for the Co-Cr system. It shows that pure cobalt undergoes martensitic change at 417° C from **γ**-phase (FCC) to ε-phase (HCP) [10-11].

The transformation temperature is changed by the addition of alloying elements to Co., So it changes to 900° C for Co-Cr alloys.

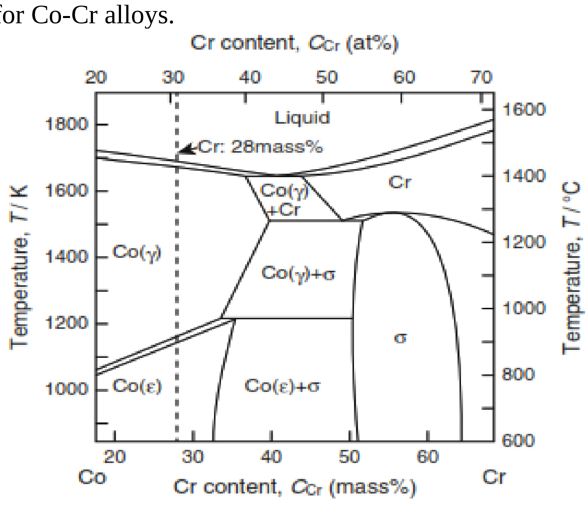

Fig.1 Equilibrium phase diagram of Co-Cr alloys [9]

Co-Cr alloys manufactured with conventional casting have a dendritic structure. The dendritic and interdendritic regions are of γ-phase and ε-phase respectively. Although the phase diagram specifies that there is only a ε-phase at room temperature, in fact there is a residual γ-phase due to the slow γ-ε transition. [12]. X-ray diffractrometry shows that the amount of ε-phase increases significantly from 2% for the Laser surface processing to 13% in the as cast specimen, 24% in the annealed specimen, and 51% for the TIG surface processing [13].

On the other hand, the structure of Co-Cr alloys produced by SLM is homogeneous comprised of fine cellular dendrites [14]. The average hardness was higher than that of other fabrication processes. Some investigators have studied Co-Cr-Mo alloy devices manufactured by direct laser sintering. They found that the microstructure consists of γ and ε phases. Whereas, ε phase consists of a network of thin layers within γ phase. They explained the high hardness of the alloy as being due to the obstruction of the ε phase layers to the movement of dislocations in the γ phase [15].

The γ-phase is ductile, while the ε-phase is hard, so increases wear and corrosion resistance [16]. Therefore, the properties of Co-Cr alloys depend on the ratio of γ to ε as well as the percentage of carbides present [17].

Heat treatments are usually used to relieve stresses and improve the mechanical properties of traditional casting parts [18-20]. AM parts also employ heat treatment for reduction of internal stresses but improvement in their elongation and the fatigue performance is also possible [21]. Its conditions affect the size, shape, and distribution of precipitates [22-24], size and shape of grains [25-27], and **γ**/ε fraction [24-28].

The following heat treatment for the investment cast alloy includes the solution treatment at a temperature of 1200 to 1255 ° C for a period of 1-3 hours, followed by cooling with water and then aging at a temperature of 800 to 900 ° C [29]. The objective of this heat treatment is to homogenize the cast structure, eliminate segregation, enhance martensitic change, and deposit fine carbides [30]. As for the SLM, its resulting microstructure differs greatly from the investment as cast structure, and therefore it needs a different heat treatment to improve its properties. SLM involves local melting of small areas of metal powder, which solidifies at a very high out-of-equilibrium speed, which results in a very fine supersaturated microstructure of products [31-32]. Therefore, the heat treatment should take those structural characteristics in consideration and avoid the growth of the fine microstructure.

The aim of this research is to study the effect of fabrication method and heat treatments on the mechanical properties of Co-Cr alloys.

2. Experimental Procedure

2.1 Samples Preparation

Two sets of samples were prepared for each of the investment and SLM processes. Each including three individual samples (see Fig. 2). These samples belong to the class of mediloy® S-Co of standards; ISO 22674 and ISO 9693. The chemical composition of this alloy is in table 1.

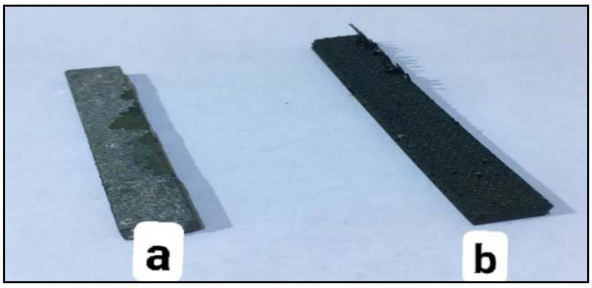

Fig.2 a) Investment casting sample (10X4X65 mm) b) Selective Laser Melting sample (10X4X80 mm)

Co	Cr	Mo	W	Si
63.9	24.7	5	5.4	1

2.2 Processing Conditions

Table 2 includes the various conditions of the processes conducted on the samples for this research.

Table 2 Samples conditions

Sample code	conditions
La	SLM as prepared samples
Lhs	SLM + Solution treated at 1100°C for 3 hrs.
Lha	SLM + Solution treated at 1100°C for 3 hrs. + Aged at 800°C for 2 hrs.
Ca	Investment As Cast samples
Chs	Inv. Casting + Solution treated at 1100°C for 3 hrs.
Cha	Inv. Casting + Solution treated at 1100°C for 3 hrs. + Aged at 800°C for 2 hrs.

2.3 Study Testing

Three types of tests were performed on all samples under the conditions mentioned in table 2. These tests include tensile, hardness and wear testing. Each test was repeated three times on three samples from the same conditions, and the average of the test results was taken for them. The tensile test was carried out with a universal tensile device. The tensile samples were prepared in accordance with ASTM Standard (E8-91) [33]. (Fig.3) shows two tensile samples after testing. The hardness test was performed by the Vickers hardness device. The wear test was carried out with a pin-on-ring device (Fig.4). Diameter of the ring was 4.6 cm. The wear rate was measured by measuring the weight lost during rubbing divided by the rubbing distance.

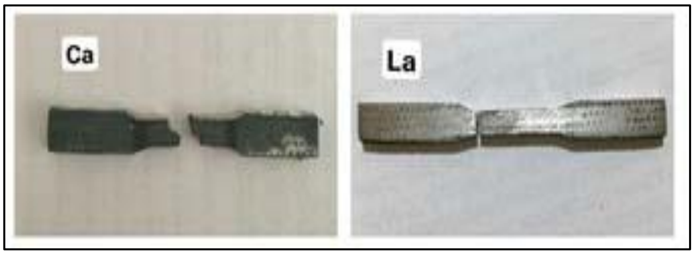

Fig.3 Two types of Tensile samples after Testing

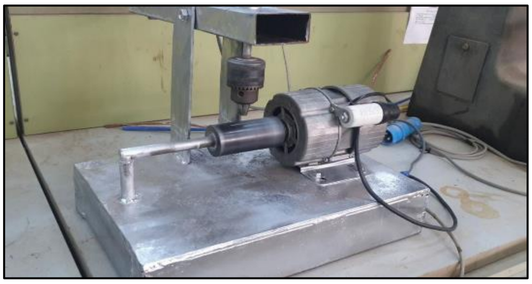

Fig. 4 Pin on Ring device of Wear Testing

3. Results and Discussion

3.1 Tensile Test

Figures 5 and 6 show the tensile strength and Max. strain bar charts of the SLM and Investment casting samples in different conditions respectively. They show that the ultimate tensile strength and strain values of the samples manufactured by SLM are much higher than that of the samples manufactured by the investment casting. This can be explained by the fact that the samples manufactured with SLM have a fine dendritic and homogenous structure compared to those manufactured with casting [14]. They also show that the solution treatment and aging of the SLM-manufactured samples cause a decrease in the ultimate tensile strength and strain values, but they do not have a clear effect on the samples manufactured by investment casting. This is because these heat treatments lead to the growth of grains and a decrease in the strength and strain.

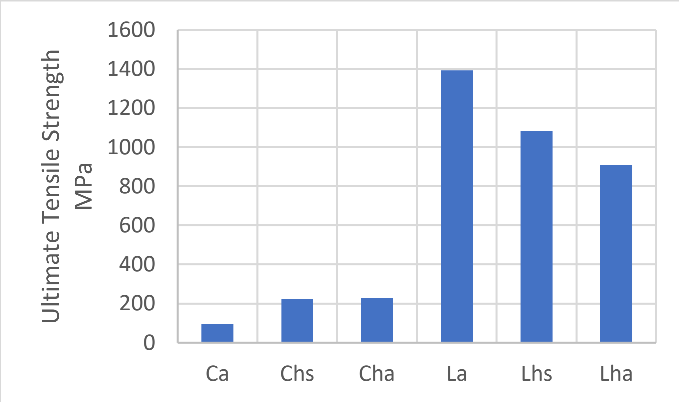

Fig.5 Ultimate tensile strength value of samples

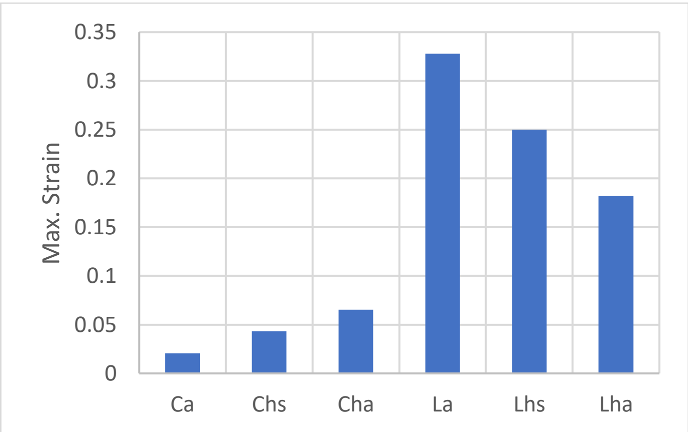

Fig. 6 Maximum strain value of samples

3.2 Hardness Test

Figure 7 includes a bar chart for the Vickers hardness values for all conditions of manufacturing and heat treatments. It shows that the samples manufactured with SLM have a higher hardness than those manufactured with casting. This is due to the same reason mentioned in the previous paragraph, which is the fine dendritic structure resulting from the high freezing rate in the SLM method compared to the slow rate of freezing in the casting method. The figure also shows that there is no significant effect of heat treatments on the hardness values of the two manufacturing methods.

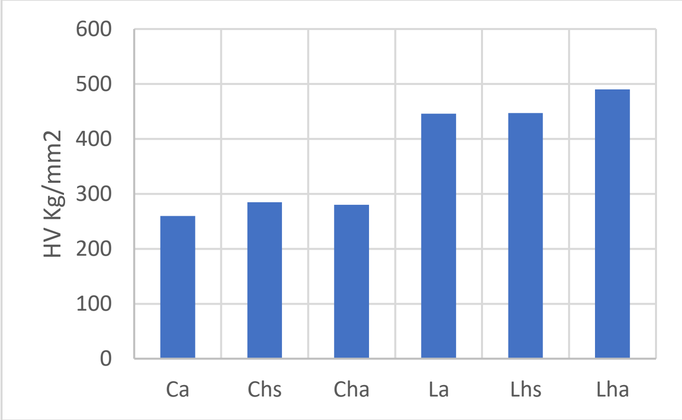

Fig.7 Vickers Hardness values of samples

3.3 Wear Test

Figure 8 includes the wear rate values for all conditions of manufacturing and heat treatments. The figure shows that the wear rate resulting from the weight loss of the cast-manufactured samples is generally lower than that of the SLM-manufactured samples. This is illogical if we take the hardness values of these samples (Fig.7) into consideration. Because it is known that the wear rate of the metal decreases with increasing hardness. This can be explained by the fact that the cast samples are so soft that there will be plastic deformation of the rubbing surfaces instead of removing the metal. Therefore, wear rate values for cast samples cannot be reliable.

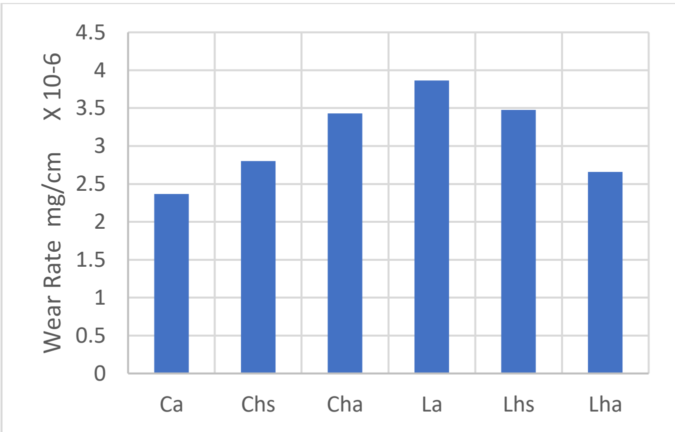

Fig. 8 Wear rate value of samples

4. Conclusions

1- Samples manufactured by SLM method have much higher tensile strength and strain than samples manufactured by the traditional method of investment casting.
2- Heat treatments such as solution treatment and aging caused a decrease in the tensile stress and strain values of the SLM-fabricated samples, but they had no significant effect on the cast-fabricated samples.
3- The samples manufactured with SLM have a higher hardness than those manufactured with investment

casting, but heat treatments have no significant effect on the hardness values of the two manufacturing methods.

4- The wear rate of the cast-fabricated samples is generally lower than that of the SLM-fabricated samples.

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