Influence of heat treatments on mechanical properties of a biocompatility alloy ASTM F75

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ASTM F75 alloy (Co-Cr-Mo) has widely used in surgical implants manufacturing. Due to morphology and large carbide content in the as-cast conditions, brittleness is the main problem in this alloy. In this work, mechanical properties were studied as microstructure change with heat treatments. Samples were obtained from a "keel block" design (ASTM E8/08) poured; then, the heat treatments were partial solution and a combined of aged and solution. Tensile and hardness tests were made. Metallographies were analyzed by Optical Microscope (OM) and Scanning Electronic Microscope (SEM). Results showed that partial solution treatment at one hour promoted carbide morphology change that generates good mechanical properties to the material be implanted in human body. On the other hand, almost total carbide solution showed that was not beneficia to mechanical properties since it produces hardness increase into the matrix.

Keywords: ASTM F75; Co-Cr; cobalt alloys; prosthesis.

La aleación ASTM F-75 (Co-Cr-Mo-C) ha sido ampliamente utilizada para la fabricación de implantes quirúrgicos. Uno de los problemas más importantes en esta aleación es la fragilidad, la cual está fuertemente influenciad por la morfología, tipo y distribución de carburos. En el presente estudio se analizaron las propiedades mecánicas obtenidas al variar la microstructura por medio de tratamientos térmicos. Para ello se obtuvieron muestras vaciadas mediante el diseño de "keel block" (ASTM E8/08) a las que se les efectuaron tratamientos térmicos de solución parcial y un tratamiento combinado envejecimiento y solución. Se realizaron pruebas de tracción y dureza además de análisis mecalográfic en microscopio óptico y microscopio electrónico de barrido. Los resultados revelan que el cambio morfológico de carburos propiciado al disolverlos parcialmente genera propiedades mecánicas adecuadas para que el material sea implantado en el cuerpo humano; por el contrario, disolverlos casi completamente mostro ser contraproducente al obtenerse propiedades mecánicas muy pobres debidas al excesivo endurecimiento de la matriz.

Descriptores: ASTM F75; Co-Cr; aleaciones base cobalto; prótesis.

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1. Introduction

The Co-Cr-Mo-C alloys are widely used in orthopedics and dentistry application due to its great biocompatibility and spontaneous chromite formation of a passive layer which gives to the material high corrosion resistance [1]. The Cobalt base alloy ASTM F-75 satisfy with the requirements of biocompatibility; however its mechanical properties are highly affected by chemical composition and process parameters, having as a consequence that results achieved by different researchers [2-4] show a great discrepancy among them, being no possible even to have a satisfactory explanation for this phenomenon. On the other hand, studies have shown that solidificatio defects, as microshrinkages, are causing fatigue failures in joint implants, specificall in the hip [5]. It is also known that the ASTM F-75 alloy microstructure in as cast conditions is constituted of an α-Cobalt dendritic matrix FCC structure and a secondary $M_{23}C_6$ carbides phase which are segregated to the grain boundaries having a block and lamellar morphology [4]. Such carbides are the main mechanism of alloy resistance; they are originated by a reaction of the intermetallic σ + C [6,7]. The size, distribution, morphology and extension of this phase to the grain boundaries impacts on the mechanical properties [3,4,7-10]. On the other hand, matrix can be hardened by a solid solution treatment with elements such as Cr and Mo mainly [7].

Failures on femoral steam in hip replacement have been associated with the low ductility in the Co-Cr alloy; this has motivated to researchers to study the effect of different heat treatments on microstructure and mechanical properties of this alloy. Heat treatments commonly used in these alloys

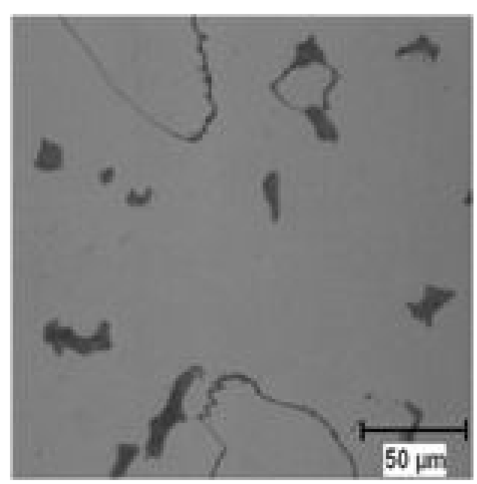

FIGURE 1. Optical micrograph of the sample I, as cast.

TABLE I. Chemical composition of the alloy and ASTM standard (wt%).

Alloy	Cr	Mo	C	Si	Ni	Fe	Mn	N	W	Co
ASTM F-75/06	27-30	5-7	0.35	1	0.5	0.75	1 max	0.25	0.20	Bal.
Obtained	28.3	6.25	0.21	0.66	0.43	0.8	0.24			Bal.

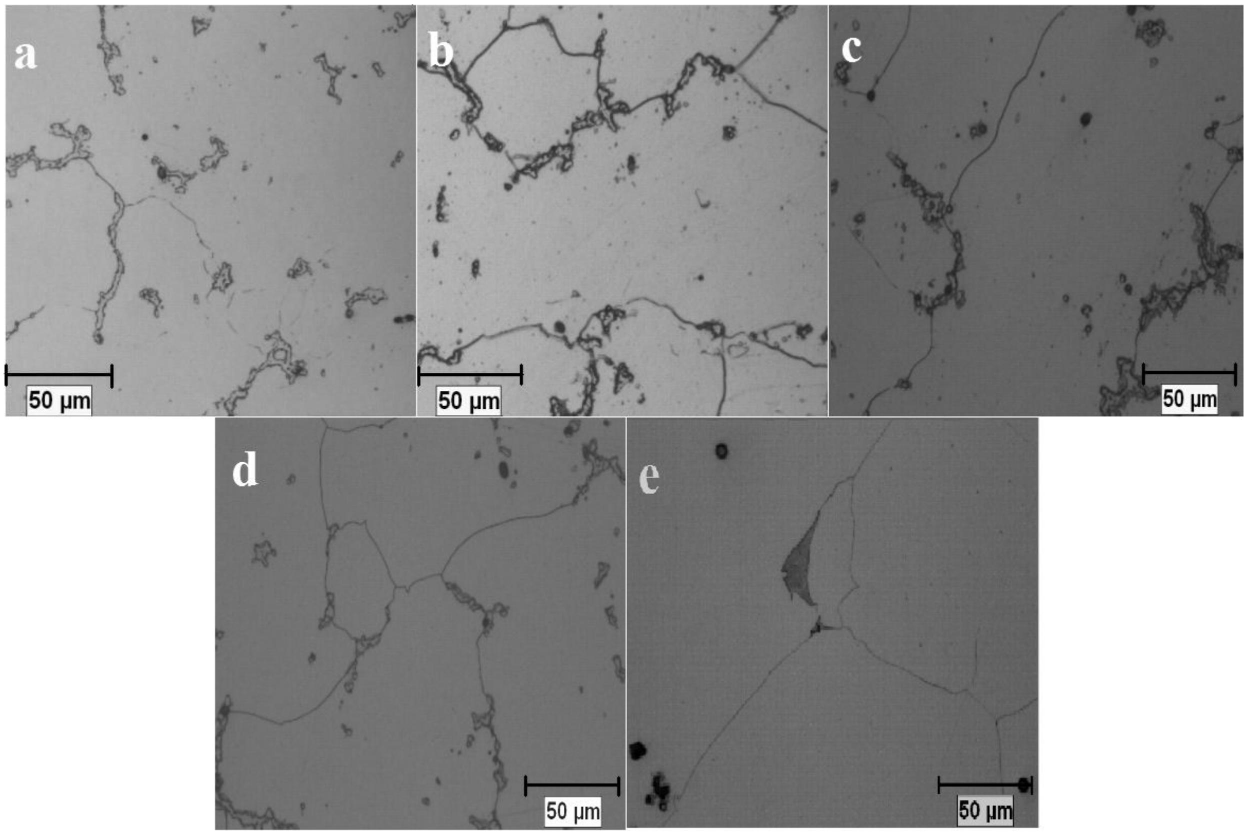

FIGURE 2. SEM images showing the progressive carbides dissolution according heat treatment time in CT; carbides change from lamellar to a round-like morphology before being dissolved. a) Sample II. b) Sample III. c) Sample IV. d) Sample V. e) Sample VI.

TABLE II. Samples identificatio and applied heat treatments for different samples studied.

Id Samples	Heat treatment
I	As cast
II	CT - 30 min of solution
III	CT - 1 hr of solution
IV	CT - 2 hrs of solution
V	CT - 4 hrs of solution
VI	CT - 6 hrs of solution
VII	PST 1hr
VIII	PST 2 hrs

are solution, partial solution and aging [2-4,11]. The purpose of this study was to assess the influenc of solution and ageing heat treatments time on microstructure evolution, morphology and dissolution of carbides, as well as the influenc on the mechanical properties.

2. Experimental

Nineteen samples of ASTM F-75/06 alloy [13] were obtained by investment casting following a design of ”keel block” according to the ASTM E8/08 specification which promotes slow solidificatio rates and good cast ability avoiding defects. The chemical analysis obtained in the samples is presented in Table I, which also shows the specificatio for ASTM F-75/06 alloy.

Two different heat treatments were carried out: 1) combined treatment (CT) and 2) partial solution treatment (PST), see Table II. The CT was performed by an aging treatment at 815°C, during 4 hours followed by solution treatment at 1220°C for different times (0.5, 1, 2, 4 and 6 hours). The PST was carried out at 1220°C for 1 and 2 hours. All heat treatments were finishe with quenching in water.

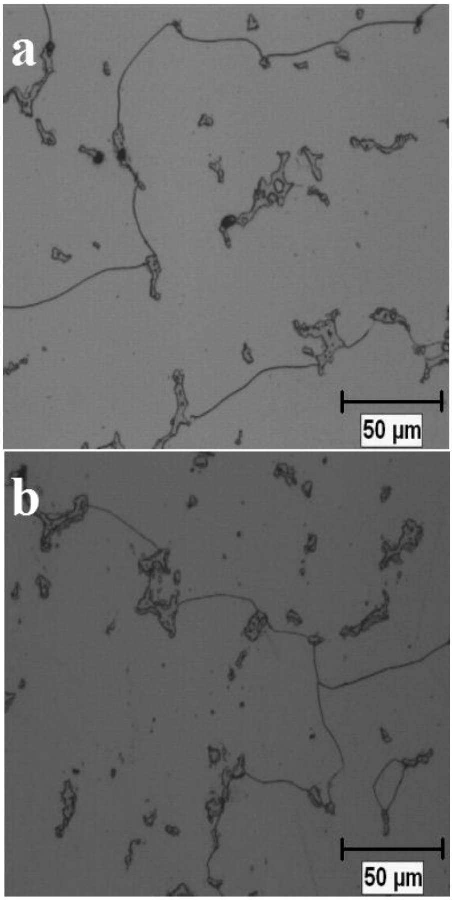

FIGURE 3. Optical micrographs showing the carbide dissolution according to time of PST. Carbides did not dissolve completely; only change its morphology from lamellar to globular. a) Sample VII. b) Sample VIII.

Samples in as cast condition were used for comparison. Afterward all samples were machined in cylindrical shape with 0.250 inch diameter according to ASTM E8/08 in order to be characterized by tensile tests on an Instron machine model 8502 and hardness on a Wilson machine series 50 tester. Microstructural analysis was made using an OM Nikon Epiphot and SEM LEO model 440. Percentage carbide in all conditions of heat treatments was obtained by measuring area fraction of this phase with the image analyzer Clemex adapted to the OM.

TABLE III. Mechanical properties and carbide percentage obtained for different samples studied after heat treatments.

Samples	YTS (MPa)	UTS (MPa)	%ε	HRC	% Carbides
ASTM F-75	450	655	8%	-	-
I	542	670	6.37	28	9
II	482	684	7.8	32	7.2
III	615	745	8.5	31	3.7
IV	610	741	8.3	21	2.2

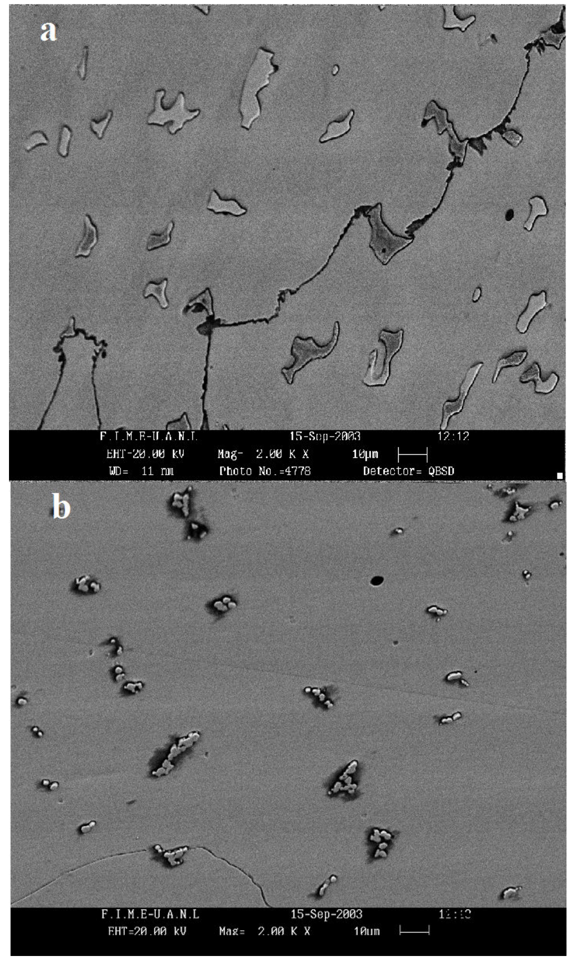

FIGURE 4. SEM images showing the carbides morphological evolution on PST. a) As cast lamellar carbide. b) Round-like carbides after PST.

3. Results and discussion

Figure 1 shows the typical microstructure of as cast condition with a cobalt matrix (FCC) containing primary lamellar and blocky carbides. Figure 2 shows the microstructural evolution for CT (samples II to VI). It is showed a solid solution of Co α as a matrix and also carbides as secondary phase. Figure 3 illustrates the microstructure of the alloy after PST; due to the short time of heat treatments, there is still an important content of carbides. Figure 4 shows a comparison between carbides before and after partial solution heat treatments. Figure 4a shows the typical carbides in as cast conditions. Figure 4b shows the morphology change of the carbides after PST.

Table III contains average results of mechanical properties from the tests performed and carbide percentage in all conditions of heat treatments. All samples, except sample VI, satisfy the minimum ASTM F75/06 standard required in yield strength (YTS) and ultimate tensile strength (UTS). Carbide content decreases progressively according to the time of solution treatment.

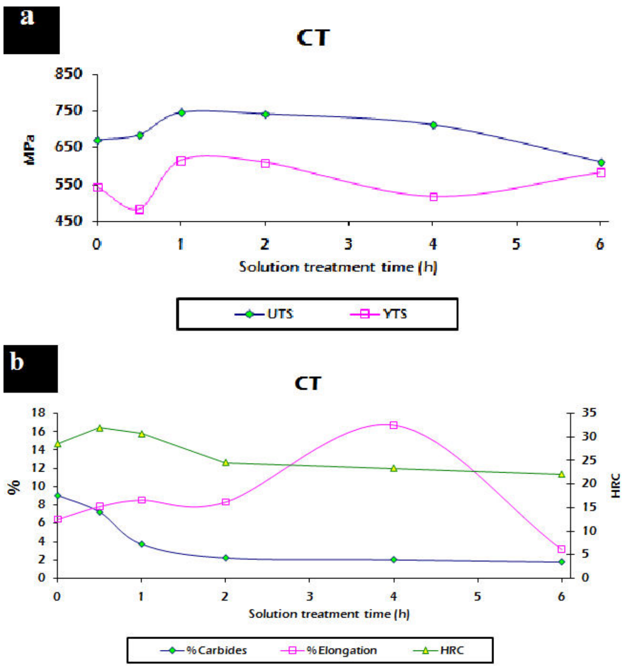

FIGURE 5. Mechanical properties behavior and relation between carbides percentage, elongation and hardness in function of the heat treatment applied for CT. a) YTS and UTS. b) Carbides content, elongation and HRC.

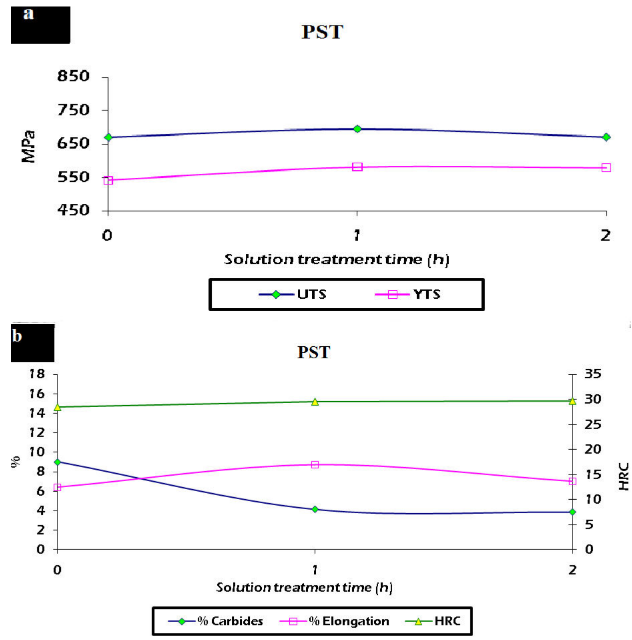

FIGURE 6. Mechanical properties behavior and relation between carbides percentage, elongation and hardness in function of the heat treatment applied for PST. a) YTS and UTS. b) Carbides content, elongation and HRC.

Figure 5a shows the YTS and UTS for CT. It can be observed that YTS follows almost the same behavior that UTS, excluding for 30 minutes. At 30 minutes of solution, the carbides size is similar to the as cast condition, producing low YTS; anyway further work will be necessary to explain the effect of short dissolution time in mechanical properties. As it is known, carbides are the principal strength of the material; it was found that after 6 hours of solution almost all carbides were dissolved, so it results in low mechanical properties. The plot of figur 5b summarizes carbides, elongation and HRC for CT. It can be seen that carbides percentage decreases due to a progressive dissolution by diffusion mechanism in function of the time. During the firs hour, elongation and hardness increase while the fraction carbide decreases. Moreover, hardness starts to decrease and continues with this trend until six hours. On the other hand elongation continues to raise until reaches its maximum value at 4 hours after which reduces drastically.

Figure 6 shows results obtained from analysis of samples with PST. Figure 6a presents the YTS and UTS, it can be noted that these values increment slightly with respect to as cast. It can be explained by the morphology change and dissolution of carbides. Figure 6b shows a plot that relates carbide content, elongation and hardness. Elongation and hardness are increased during the firs hour and after decrease.

In a previous study which combined heat treatments of ageing and solution, the following results were obtained: 498 MPa YTS, 1149 MPa UTS and 25% elongation [12]. Those results are completely different of that obtained in the present study even when conditions of heat treatments were very similar.

The results suggest that long heat treatment times are not beneficia to improve the YTS and UTS, similar results were found also by Herrera [4] and Sang-Hak Lee [6].

Other authors [6,11] have found that the elongation increases as the time and temperature of solution treatment increase. On the other hand, the results achieved in this study coincide with those of Herrera [4], where elongation grows during the firs step of heat treatment (before 4 hours) and then decrease significantl . This can be explained by two mechanisms: (a) at short solution times up to two hours, there is still a high volume fraction of round-like carbides having as a result a good ductility due to difficultie for cracks to grow through the round-like carbides as in the as cast condition where lamellar carbides are located on boundary grains promoting a fracture; and (b) after 2 hours of solution treatment, most of the round-like carbides are dissolved into the matrix having a 1.76% volume resulting in an excessive matrix hardness, leading a low ductility and low plastic deformation.

From obtained experimental results, it was proved that carbides morphological changes due to the solution heat treatments for periods of time up to 1 hour, increases the ductility, UTS and YTS which makes material satisfy the ASTM F-75/06.

4. Conclusions

There is a microstructure morphological change from lamellar to a more round-like form carbides M23C6; during the solution and partial solution heat treatments. Carbides start to get more rounded and decrease in percentage from 9 to 1.76%

volume as solution time increases from 0 to 6 hours respectively.

The samples with short time solution treatments due to microstructure changes, led to obtain appropriate mechanical properties, enough to satisfy ASTM F75 requirements. Considering feasibility and beneficia of carried out treatments, the optimal results were obtained for CT consisted of aging at 815°C for 4 hours and solution at 1120°C for 1 hour of solution.

The mechanical tests showed that an excessive time of dissolution, reduces considerably mechanical properties having values of UTS from 745 to 611 MPa for 1 and 6 hours of solution time respectively.

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