MATERIALS CHARACTERIZATION 62 (2011) 53–61

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Microstructural characterization of as-cast biocompatible Co–Cr–Mo alloys

J.V. Giacchi[a,c,*], C.N. Morando[a,c], O. Fornaro[a,c], H.A. Palacio[b,c]

[a]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, (C1033AAJ) Buenos Aires, Argentina
[b]Comisión de Investigaciones Científicas de la Provincia de Buenos Aires (CICPBA), Calle 526 e/10 y 11 (B1096APP) La Plata, Argentina
[c]Instituto de Física de Materiales Tandil (IFIMAT–FCE–CICPBA) Facultad de Ciencias Exactas, Universidad Nacional del Centro de la Provincia de Buenos Aires, Pinto 399 (B7000GHG) Tandil, Argentina

ARTICLE DATA

Article history:
Received 4 November 2009
Received in revised form
12 October 2010
Accepted 14 October 2010

Keywords:
Biocompatible alloys
Microstructure
Solidification
Co–Cr–Mo
Carbides

ABSTRACT

The microstructure of a cobalt-base alloy (Co–Cr–Mo) obtained by the investment casting process was studied. This alloy complies with the ASTM F75 standard and is widely used in the manufacturing of orthopedic implants because of its high strength, good corrosion resistance and excellent biocompatibility properties. This work focuses on the resulting microstructures arising from samples poured under industrial environment conditions, of three different Co–Cr–Mo alloys. For this purpose, we used: 1) an alloy built up from commercial purity constituents, 2) a remelted alloy and 3) a certified alloy for comparison. The characterization of the samples was achieved by using optical microscopy (OM) with a colorant etchant to identify the present phases and scanning electron microscopy (SE-SEM) and energy dispersion spectrometry (EDS) techniques for a better identification. In general the as-cast microstructure is a Co-fcc dendritic matrix with the presence of a secondary phase, such as the $M_{23}C_6$ carbides precipitated at grain boundaries and interdendritic zones. These precipitates are the main strengthening mechanism in this type of alloys. Other minority phases were also reported and their presence could be linked to the cooling rate and the manufacturing process variables and environment.

1. Introduction

The Co–Cr–Mo as-cast alloys conforming to the ASTM F75 standard are widely used in the manufacturing of orthopedic implants made with investment casting techniques. Because of these alloys' hard workability and the shape complexity of the prostheses, this process reduces the high cost of machining operations by producing pieces whose dimensions are close to final ones. However, this method of fabrication leads to poor mechanical properties compared to other manufacturing processes such as powder metallurgy or forging [1].

It is well known that the main defects present in the as-cast state are: porosity, chemical inhomogeneity, large grain size and a microstructure with hard precipitates in interdendritic zones [2,3]. Also due to the casting process, inhomogeneities in carbide morphology and their size and distribution may lead to low ductility and low fatigue strength.

Nevertheless, the mechanical properties can be improved with ulterior heat treatments by dissolving the large carbide network and produce a more homogeneous structure. It was demonstrated that by dissolution of the dendritic structure an isotropic behavior is obtained, particularly with respect to plastic deformation [4,5].

Pure cobalt has a hexagonal close-packed (hcp) structure at room temperature, and it shows an allotropic transformation to face centered cubic (fcc) structure at 400 °C. The addition of

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[*] *Corresponding author.* Instituto de Física de Materiales Tandil, Universidad Nacional del Centro de la Provincia de Buenos Aires, Pinto 399 – (B7000GHG) Tandil, Argentina.
E-mail address: jgiacchi@exa.unicen.edu.ar (J.V. Giacchi).

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doi:10.1016/j.matchar.2010.10.011

Table 1 – Chemical composition (wt.%) of the as-cast alloys.

Sample	Co	Cr	Mo	C	W	Si
C1	60.75	30.60	6.14	0.13	0.36	1.29
C2	62.99	28.93	5.83	<0.021	0.38	1.05
C3	64.13	27.01	6.30	<0.021	0.40	1.08
F75	59.0/69.0	27.0/30.0	5.0/7.0	Max 0.35	Max 0.2	Max 1

alloying elements such as chromium (Cr) and tungsten (W) increases this transformation temperature. Co-base alloys exhibit a dendritic α-fcc metastable matrix due to the sluggish nature of the fcc→hcp transformation [6], and a precipitate formed mainly by $M_{23}C_6$ carbides, an intermetallic σ compound and a lamellar phase formed by interlayed plates of $M_{23}C_6$ carbide and a phase that has not been clearly identified yet, possibly a σ phase, both α and σ phases and either α or M_6C carbide phases, as has been proposed by several authors [7–11]. This lamellar structure is formed during cooling at temperatures under 990 °C, and it has been found to be the most detrimental feature of the microstructure [12] because once this grain boundary precipitate was dissolved, the fatigue life improves.

Carbide precipitation at grain boundaries and interdendritic regions is the major strengthening mechanism in the as-cast condition [13] but also by dislocation interactions with stacking fault intersections [14,15]. Coarse blocky carbides play an important role acting as sources of dislocations and stacking faults when stresses are applied [15]. Due to the intrinsic low cooling rates of the manufacturing process, two carbide morphologies can coexist, a “blocky type” and a “pearlitic type” as a result of the eutectoid reaction [16,17]. Other authors have reported that the formation of lamellar “eutectoid” carbides occurs for cooling rates varying from 8 to 16 °C/min [18] and previous results that established that the maximum cooling rate possible for the eutectoid phase precipitation is 35 °C/min [7]. Also, the precipitate size and density of both blocky and lamellar phase, was found to increase with the carbon content [17], whilst the ductility is not significantly affected.

On the other hand, the metallographic analysis showed that the nitrogen content has a little effect on the grain size. As the nitrogen content increases, it promotes the formation of finer M_6C carbides instead of $M_{23}C_6$ carbides that tend to accumulate along the grain boundaries. When present in solution, nitrogen might act as a solid solution strengthener, resulting in improved mechanical properties [1], at the expense of other properties which often turn out insufficient to satisfy the requirements of the aforementioned standard.

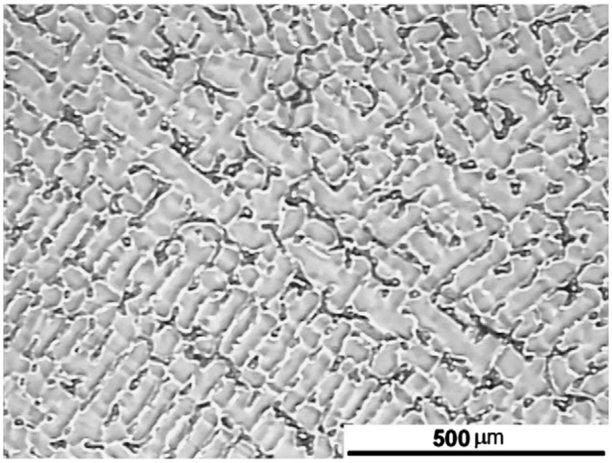

Fig. 1 – Optical micrograph of the as-cast microstructure of C1 at the upper section.

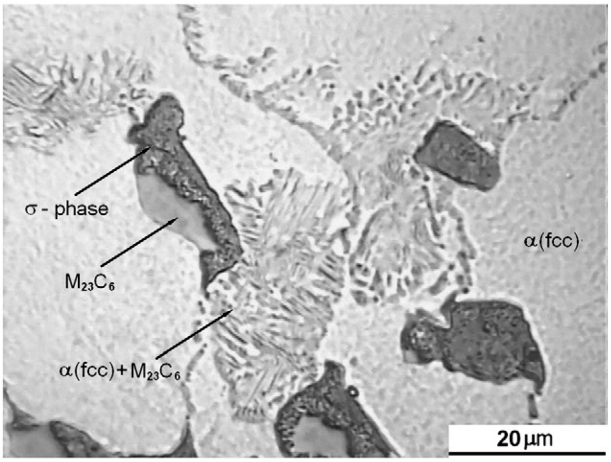

Fig. 2 – OM for C1, color detected phases are shown.

Kilner et al. [19], suggested the possible precipitation of the M_7C_3 carbide during solidification of an ASTM F75 alloy and its dissolution by diffusion during the subsequent cooling, since it was not observed at room temperature. Clemow and Daniell et al. [20] stated that the reactions during solution heat treatments at temperatures above 1300 °C include carbide incipient melting and that $M_{23}C_6$ carbide initially present in the alloy tends to transform into M_6C carbide and σ phase. It is important to mention that this type of heat treatment requires a precise control of the variables involved, due to the narrow range of temperature at which carbide dissolution takes place [21].

On the other hand, Opris et al. [6] confirmed the presence of a complex combination of Co_3Mo/W_3C, $M_{23}C_6$ and Cr_7C_3 carbides embedded in the Co-rich matrix since the metal carbides may actually have a ternary solid solution composition [22]. Besides the interdendritic phases, some of which should be avoided because they negatively affect some

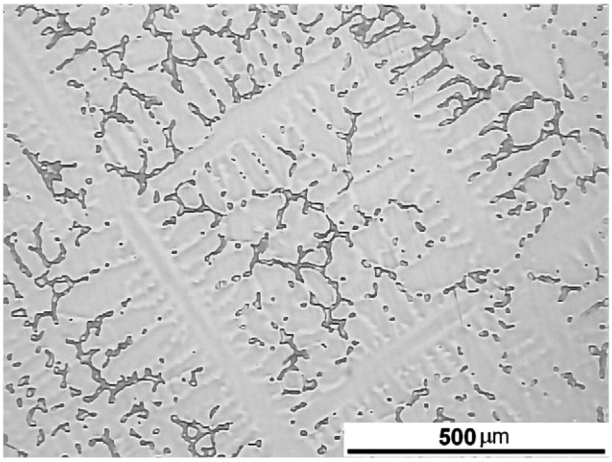

Fig. 3 – Optical micrograph of the as-cast microstructure of C1 at the bottom section.