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Understanding the properties of low-cost iron-containing powder metallurgy titanium alloys

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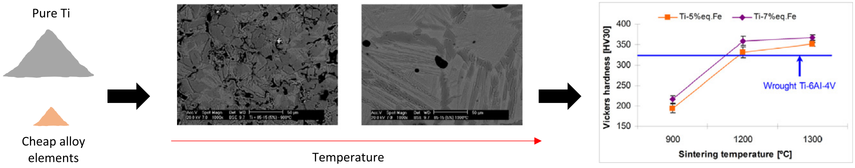
HIGHLIGHTS

- Low-cost iron-containing powder metallurgy Ti-5$\%_{\text{eq.}}$Fe and Ti-7$\%_{\text{eq.}}$Fe alloys are designed.
- Homogeneous microstructures are obtained using the appropriate sintering parameters.
- The materials studied show mechanical behavior comparable to wrought $\alpha + \beta$ alloys.
- The novel compositions are potential candidates for cheaper structural components.

GRAPHICAL ABSTRACT



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ABSTRACT

The high production costs of titanium in comparison to other structural metals is the main limiting factor for the wide employment of titanium. Cost reduction can be addressed considering creative fabrication methods and/or formulating new chemical compositions. In this work the fabrication of low-cost iron-containing powder metallurgy titanium alloys is studied by using a spherical 85Fe/15Ni powder whose small particle size and spherical morphology favours both the densification of the material and the diffusion of the alloying elements. The designed composition are obtained by the blending elemental approach and processed by means of the conventional powder metallurgy route. The high vacuum sintered $\alpha + \beta$ alloys show homogeneous microstructure and the formation of brittle intermetallic phases is prevented as checked by XRD and DTA analysis. Similar physical and mechanical behaviour to wrought-equivalent structural titanium alloys is obtained for these new low-cost alloys which, therefore, are potential materials for cheaper structural titanium components.

1. Introduction

Titanium has superior corrosion resistance in many aggressive chemical environments, is inert in contact with body fluids (biocompatible) and has the best specific mechanical properties among engineering metals (i.e. mechanical properties divided by density). For example, the specific strength of titanium (i.e. 288 kN m/kg) is 1.4 times and 4.5 times higher in comparison to aluminium (i.e. 204 kN m/kg) and stainless steel (i.e. 63 kN m/kg), respectively. Because of these aspects, titanium is usually employed in high demanding applications, such as in the aeronautic, naval, (petro)chemical and medicine sectors [1–3]. Nevertheless, titanium is also characterised by very high production costs which are approximately 6 times and 30 times higher, respectively, in comparison to those to obtain the same quantity of aluminium or steel [4] relegating titanium to high demanding sectors. These costs are due to the necessity to use special industrial processes to prevent the contamination of titanium from interstitials (especially oxygen and nitrogen) which are detrimental for its ductility [5,6]. Moreover, titanium is also classified as a difficult-to-machine materials as a result of its poor conductivity [7].

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The automotive industry is showing interest in the employment of titanium for the lightweighting of structural components which will eventually result in less oil consumption and lower emission of greenhouse gases [8,9]. The use of original techniques and cheap alloying elements are the two main factors which can lead to cost reduction for titanium parts [10]. Titanium and its alloys can be processed by powder metallurgy (P/M) taking advantage of the intrinsic benefits of these technologies among which the fact that they are near-net-shape methods with no need or limited need for machining operations as well as high yield (i.e. reduced generation of costly scraps). In most of the P/M methods the metal is processed well below its melting point which, in the case of titanium, is helpful to limit the reaction of titanium with the oxide- and nitride-based moulds and processing utensils. Lately, a lot of effort has been focused on developing new extraction processes, like the International Titanium Powder ITP/Armstrong [11–14], method which could be further favour the fabrication of titanium components by means of P/M techniques.

On the one hand, up to date, the titanium P/M industry has mainly focused on the production of titanium alloys whose composition is equivalent to that of commercial and well-developed wrought alloys, in particular Ti-6Al-4V. On the other hand, iron has not been completely accepted as alloying element for titanium because has higher density, and therefore tends to settle at the bottom of cast ingots and components, and the fact that is a eutectoid beta stabiliser. More in detail, above a certain percentage [15], iron forms Ti-Fe intermetallic phases which brittle the material. Nonetheless, iron is a highly desirable alloying element because stabilises the titanium beta phase (B.C.C.) and it is much cheaper than conventionally employed beta stabiliser (i.e. vanadium, tantalum and niobium). Attempts were made and some commercial wrought alloys which contemplate iron in their chemical composition can be found, such as the case of the low cost beta (LCB) developed by TIMETAL and the Ti-5Al-2.5Fe alloy. In the case of P/M processing, some few chemical compositions were studied [16–18] but the full potential of low-cost titanium alloys development has not been exploited yet. Examples are the study of Chen at al. about the effect of cooling rate on the microstructure and properties of Ti-xFe ($x = 3$, 5 and 7) produced using iron carbonyl powder [19]. Moreover, Chen and Hwang studied the formation of in situ synthesized TiC dispersoids in the sintered Ti—7Fe alloy [20].

Most of the studies available in the literature considered the effect of the addition of iron to titanium when iron was the only alloying elements but not combined with nickel. Therefore, the aim of this work was to assess the fabrication of low-cost iron-containing P/M titanium alloys produced by alloying an irregular hydride-dehydride titanium with an 85Fe/15Ni powder. The development of low-cost titanium alloys would be beneficial to widespread to use of titanium in industrial applications and potentially help to stabilise the price of titanium which is currently still primarily dependent on the fluctuation of the demand from the aeronautical sector. The iron-containing master alloy was chosen because of: (1) it is a readily availably inexpensive commercial powder, (2) the elements constituting the powder are both β-stabilisers permitting to target the production of $\alpha \pm \beta$ titanium alloys and, (3) the powder particle features of the selected master alloy favour both the densification of the material and the diffusion of the alloying elements. The starting powders were mixed, cold uniaxially pressed and sintered under high vacuum. Physical and mechanical properties of the novel low-cost iron-containing P/M titanium alloys were studied as a function of the sintering temperature. Moreover, the effect of the presence of iron and nickel as alloying elements on the phases present was assessed by differential thermal analysis (DTA) and X-ray diffraction (XRD) analysis.

2. Experimental procedure

An irregular elemental titanium powder bought from GfE GmbH (which was obtained by means of the (HDH) hydride-dehydride process) and a commercial 85Fe/15Ni powder fabricated by electrolysis (H.C. Starck) were the raw materials of the study. Important characteristics of these raw materials as well as of the mixed powders (starting materials for the study) are reported in Table 1. Specifically, two low-cost iron-containing P/M titanium alloys were designed (Ti-5$\%_{\text{eq.}}$Fe and Ti-7$\%_{\text{eq.}}$Fe).

A previous study about the addition of iron to titanium indicated that the best mechanical performances are obtained for an iron content in between 5 wt.% and 7 wt.% [18]. Most of the elements of the period table are β stabilisers, such as molybdenum, iron, manganese, chromium, nickel and vanadium. The global β stabilising effect is defined by the formula proposed by Molchanova [21], which takes into account the pondered strength of the different alloying elements:

$$[\text{Mo}]_{\text{eq.}} = [\text{Mo}] + 0.67[\text{V}] + 1.25[\text{Cr}] + 1.25[\text{Ni}] + 2.5[\text{Fe}] \quad (1)$$

From Eq. (1), alloys with 5 wt.% and 7 wt.% of iron have $[\text{Mo}]_{\text{eq.}}$ parameter of 12.5 and 17.5, respectively. These values were used to calculate to total amount of 85Fe/15Ni powder to be mixed with elemental titanium to design the two low-cost iron-containing P/M titanium alloys with an equivalent $[\text{Mo}]_{\text{eq.}}$ parameter to those of Ti-5Fe and Ti-7Fe, respectively. Specifically, they were labelled as Ti-5$\%_{\text{eq.}}$Fe and Ti-7$\%_{\text{eq.}}$Fe and their relative amount of iron and nickel (β stabilisers) are reported in Table 1. The Ti-5$\%_{\text{eq.}}$Fe and Ti-7$\%_{\text{eq.}}$Fe alloys were produced by the blending elemental approach using a Turbula mixer (processing time: 30 min). The density values of these low-cost alloys were computed by considering the rule of mixture. The density of the 85Fe/15Ni powder is much greater than that of titanium, that is why the low-cost iron-containing P/M titanium alloys have slightly higher density with respect to elemental titanium, but any possible sedimentation of heavier particle was completely prevented by compacting the Ti-5$\%_{\text{eq.}}$Fe and Ti-7$\%_{\text{eq.}}$Fe alloys samples right after mixing. From Table 1, the elemental titanium powder has irregular morphology whilst the 85Fe/15Ni powder spherical. The irregular titanium powder, which represents the great majority of the alloy, is thought to provide the backbone of the green samples (compressibility) whereas the finer 85Fe/15Ni powder particles should sit in between the spaces left from the accommodation of the asperities of the irregular titanium particles. Another important difference between the two raw materials is their particles size. The much smaller particle size of the 85Fe/15Ni powder was chosen to promote and enhance the diffusion of the alloying elements into the titanium matrix and speed up the complete homogenisation of the microstructure. Due to the chemical composition of the raw materials, the Ti-5$\%_{\text{eq.}}$Fe and Ti-7$\%_{\text{eq.}}$Fe alloys have oxygen contents of 0.29 wt.% and 0.27 wt.%, respectively. The contents of nitrogen and carbon are lower than 0.050 wt.% and 0.080 wt.%, respectively, where these values are the limits specified by ASTM standards for many titanium alloys, such as Ti-6Al-4V [22].

Table 1
Characteristics of the raw materials and mixed powders (starting materials for the study).

Characteristic		Material			
		Elemental Ti	85Fe/15Ni powder	Ti-5$\%_{\text{eq.}}$Fe	Ti-7$\%_{\text{eq.}}$Fe
Density ($\rho_{\text{theoretical}}$) [g/cm^3]		4.51	7.96	4.70	4.77
Morphology		Irregular	Spherical	–	–
Particle size distribution [μm]	D_{MAX}	<90	<10	<90	<90
	D_{10}	21.45	2.16	19.63	18.10
	D_{50}	45.80	4.36	47.89	45.69
	D_{90}	85.01	9.13	88.52	86.45
Chemical composition [wt.%]	Ti	99.6	–	Balance	Balance
	Fe	0.027	85.00	4.60	6.43
	O	0.27	–	0.29	0.27
	N	0.0080	–	0.026	0.022
	C	0.0070	–	–	–
	Ni	–	15.00	0.81	1.14