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The effect of adding Sn on the mechanical properties and microstructure of the titanium

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ABSTRACT

Ti-XSn (X = 0, 5, 10, 15) (wt. %) alloys were prepared by blending TiH_2 and Sn powder compact extrusion. The effect of adding tin (Sn) on the microstructure and mechanical properties of titanium has been investigated by optical microscopy and tensile tests. The lamellar thickness (10 to 6.6 μm) of the Ti reduced after adding Sn and according to the Hall-Petch equation the yield strength (548.2 to 801.3 MPa) and microhardness (233.2 to 310 HV) of the Ti is increased with increasing the tin (Sn) content.

1. Introduction

Titanium (Ti) and its alloys are useful for the orthopedic and dental applications because of having high corrosion resistivity and biocompatibility with the low elastic modulus [1]. The ratio of the tensile strength and Young's modulus is used for determining the materials are suitable for the biomedical applications [2]. The CP Ti and Ti-6Al-4V alloy because of having excellent biocompatibility, high corrosion resistivity, high strength and low elastic modulus are used as traditional Ti biomaterials [3]. In addition, the Ti-6Al-4V alloy in the long-term efficiency has a toxic effect on human body by dissolution of the passive film on the surface and erosion the agglomerate of the V and Al ions are increased in blood of the human makes problem [1]. With adding Sn to the Ti as an alloying element, the alloy can be biocompatible because Sn is a neutral stabilizer (only have a slight effect on the β-transus temperature) and non-toxic element in human body [4]. Generally, the Ti alloys implants are fabricated by casting and powder metallurgy [5]. The main advantages of implant production via powder metallurgy are reduction in machining and post processing comparing with the casting process which different alloying elements can be added [6].

Nowadays, the Ti implants are also fabricated by the additive manufacturing [7,8]. The Ti-XSn alloys were fabricated by cold isostatic pressing for biomedical applications and the researchers recognize that by increasing amount of the Sn, the mechanical properties of the Ti-XSn alloys are increased [9].

2. Materials and methods

The studied alloys were prepared using elemental powders of TiH_2 and Sn. TiH_2 powder (<75 μm, 99.5% pure) and Sn powder (<75 μm, 99.9% pure) were supplied by Beijing Xing Rong Yuan Technology Co., Ltd, PR China. All powders were heated for removing the absorbed moisture (100 °C, 2 h, in vacuum oven). The mixtures were blended in a tumbler mixer (24 h, in Ar) before cold pressing in a die (200 ton press, ϕ 25 mm, 1000 MPa, >5 min holding, in air). The pressed sample was extruded (in Ar, 200 ton, 1200 °C, 5 min, ratio 9:1, and 500 °C heated die and holded).

The microstructure of the extruded rod was characterized by optical Microscopy (OM, Olympus BX51M) and the specimen was etched for 10 s (HF: HNO_3: H_2O = 3: 6: 91) for observing microstructure. In order to run perform tensile test, three samples were cut in the extrusion direction with $15 \times 3 \times 2$ mm^3 dimension with (Zwick/Roll Z20) machine and the strain rate was 5×10^{-4} s^{-1} with the gauge length of 10 mm. Also, the Vickers micro-hardness (402SXV SCTMC) was measured (500 gr load, 10 s, 10 point).

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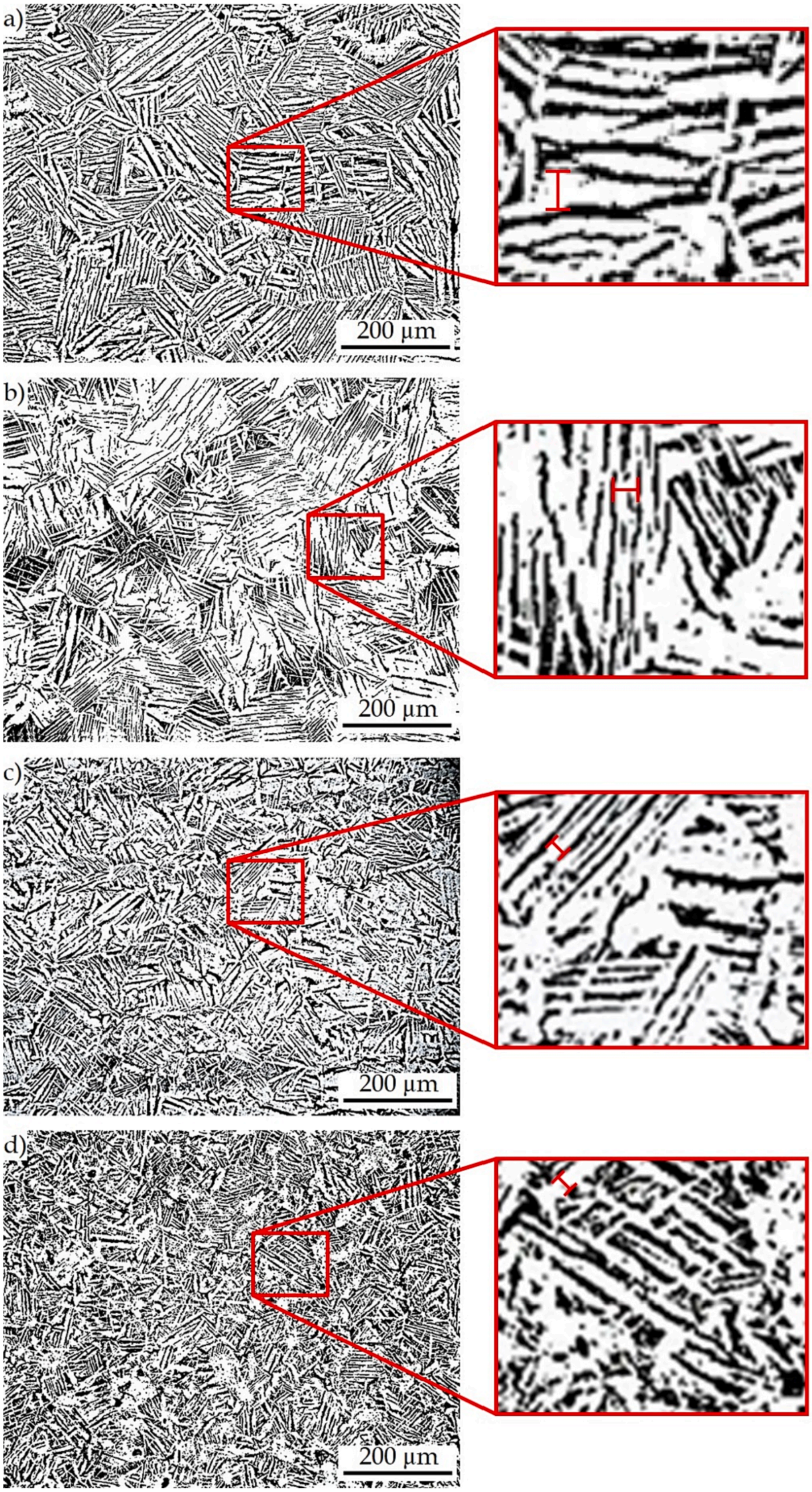

Fig. 1. Microstructure of the CP Ti and Ti-XSn alloys: a) CP Ti, b) Ti-5Sn, c) Ti-10Sn and d) Ti-15Sn.

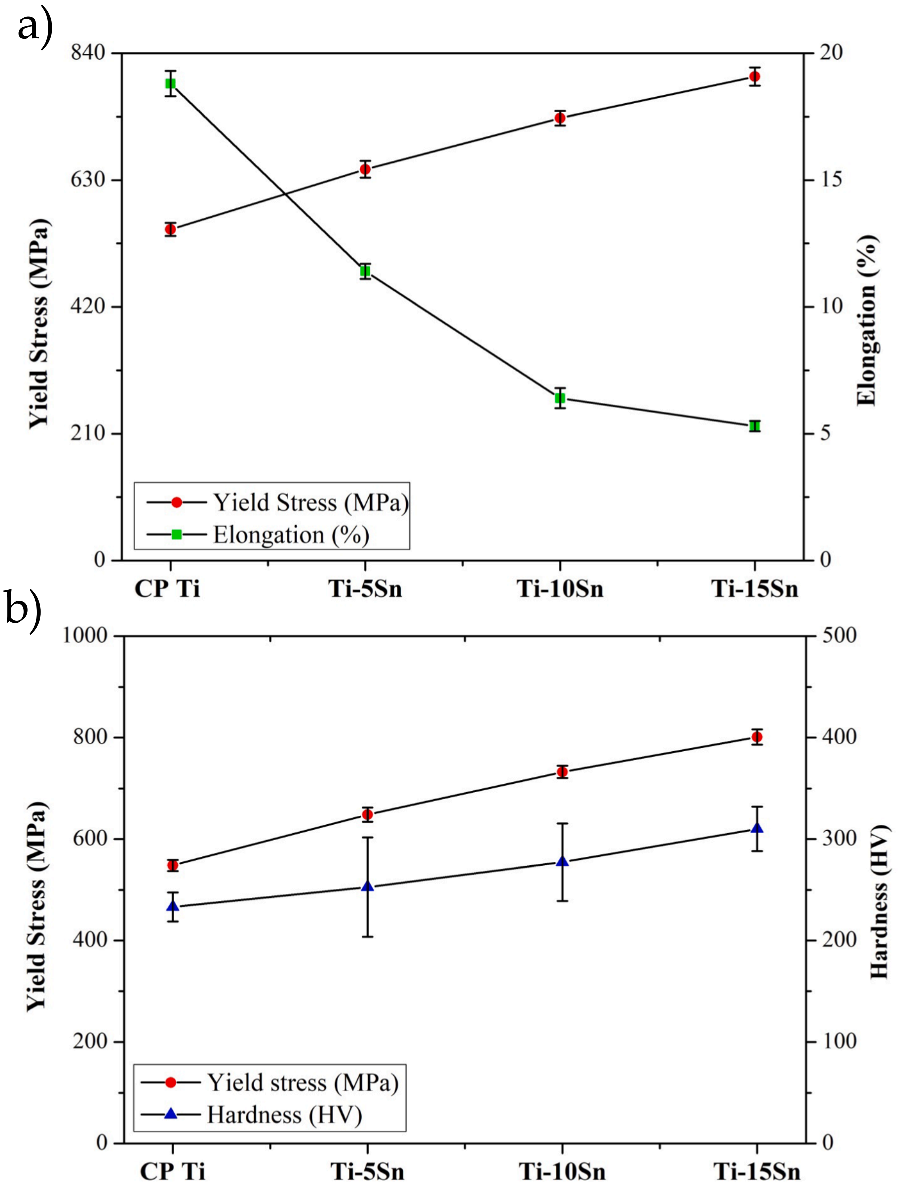

Fig. 2. A) yield strength and elongation, b) yield stress and hardness of Ti-XSn (x = 0, 5, 10, 15) alloys.

3. Results and discussion

Fig. 1 shows the microstructure of the Ti-XSn (X = 0, 5, 10, 15) (wt. %). The average lamellar thickness of the CP Ti is 10 μm. The average lamellar thicknesses of the Ti-XSn alloys after adding 5 wt%, 10 wt% and 15 wt% of Sn is reduced from 8.4 μm to 7.3 μm and to 6.6 μm respectively. The microstructure of the CP Ti after adding different wt. % of the Sn is changed from α lamellar to the α'/α lamellar [10].

The effect of adding different Sn percentage to the CP Ti as an alloying element on the elongation and yield strength is shown in Fig. 2a. By increasing the percentage of the Sn as an alloying element to the CP Ti, the lamellar thickness and elongation were decreased, whereas the yield strength of the alloys increased significantly. The effect of the adding different Sn percentage to the CP Ti as an alloying element on the yield strength and hardness is shown in Fig. 2b. The hardness of the Ti-15Sn is significantly higher than the 10, 5 and CP Ti. According to the Fig. 2b, by enhancing the hardness, the yield strength of the CP Ti after adding Sn from 5 to 15 wt% increased significantly. The hardness and yield strength have direct effect on each other [1]. Moreover, the hardness of the CP Ti is increased by adding Sn to the CP Ti from 5 to 15 wt% and the average lamellar size of the CP Ti after addition of the Sn form 5 to 15 wt% reduced. As shown in Fig. 2b, the lamellar thickness has direct effect on the hardness [11].

Generally, the strength mechanism is related to the different parameters such as crystal lattice friction stress σ_0, dislocation strengthening σ_d, solute atoms strengthening $\Delta\sigma_s$ and grain and sub-grain boundaries strengthening σ_λ. The yield strength of the all the materials can be calculated by the Eq. (1) [12], as follow:

$$\sigma_y = \sigma_0 + \sigma_\lambda + \sigma_s + \sigma_b \tag{1}$$

The grain boundaries strengthening and dislocation strengthening are the important mechanisms in this research for comparing the theoretical and experimental strengthening. The relationship between the yield strength (σ_y) and grain size (λ) is illustrated by the Hall-Petch equation for measuring the grain boundaries strengthening [13]. The correlation between the dislocation strengthening and grain boundaries strengthening is explained by the Eq. (2) [14], as follow:

Table 1

Participation of grain boundary strengthening and dislocation strengthening, the measured yield strength and calculated yield strength of the Ti-XSn alloys.

Alloy	Dislocation density (ρ/m^{-2})	$\Delta\sigma_\lambda$ (MPa)	$\Delta\sigma_{\mathbf{d}}$ (MPa)	Measured YS	Calculated YS	Deviation
CP Ti	$(3.38 + 0.6) \times 10^{13}$	548 + 6.1	10.97 + 2.1	558.97 + 8.2	548.2 + 11	10.77
Ti-5Sn	$(3.79 + 0.8) \times 10^{13}$	647.5 + 7.8	11.62 + 1.5	659.12 + 9.3	647.9 + 14	11.22
Ti-10Sn	$(4.341 + 0.9) \times 10^{13}$	734.1 + 5.3	12.44 + 3.2	746.54 + 8.5	732.5 + 12	14.04
Ti-15Sn	$(5.12 + 0.9) \times 10^{13}$	800.5 + 8.5	13.53 + 2.3	814.03 + 10.8	801.3 + 15	12.73

$$\sigma_y = \sigma_0 + k\lambda^{0.5} + \Delta\sigma_d \tag{2}$$

Where σ_y is the yield strength,σ_0 is the lattice friction stress which includes solution hardening contribution,k is a Hall-Petch coefficient and λ is the average lamellar thickness. Based on Eq. (2), by reducing the lamellar thickness, the yield strength increased. The values of the lamellar thickness of the CP Ti after adding different percentage of Sn to the Ti as an alloying element reduced. According to the Hall-Petch equation and Figs. 1 and 2, the Yield strength of the Ti-XSn alloys after increasing the Sn percentage because of the lamellar thickness reduced [1,14].

The correlation between hardness and grain size (lamellar thickness) is explained by the Eq. (3) [12], as follow:

$$H = H_0 + k_H\lambda^{0.5} \tag{3}$$

Where H is hardness, H_0 is friction hardness,k_H is the Hall-Petch coefficient and λ is the average lamellar thickness. According to the Eq. (3) and Figs. 1 and 2b, the lamellar thickness of the Ti-XSn alloys is reduced with the increasing Sn percentage and the hardness of the Ti-XSn alloys increased by reducing the lamellar thickness [15].

The correlation between hardness and dislocation density is explained by Eq. (4) [12], as follow:

$$H = H_0 + 3\alpha MGb\sqrt{\rho} \tag{4}$$

Where H is hardness, H_0 is friction hardness,M is the Taylor factor of Ti ($M = 3$),α is the coefficient of strength of the dislocation work of Ti with a value of 0.5,G is the shear modulus of Ti ($G = 44GPa$) and b is the burgers vector of Ti ($b = 0.286nm$) [1]. The dislocation density of the Ti-XSn alloys is shown in Table 1. According to the Eq. (4) and Fig. 2b, the dislocation density of the Ti-XSn alloys are increased by increasing the hardness.

The Taylor equation is used for calculating dislocation density as follows [1,14]:

$$\Delta\sigma_d = M\alpha Gb\sqrt{\rho} \tag{5}$$

Where M is the Taylor factor of Ti ($M = 3$),α is the coefficient of strength of the dislocation work of Ti with a value of 0.5,G is the shear modulus of Ti ($G = 44GPa$) and b is the burgers vector of Ti ($b = 0.286nm$) [1]. The calculated values of the grain boundaries strengthening (σ_λ) and dislocation strengthening (σ_d) are shown in Table 1. As can be seen from Table 1, the calculated values of the yield strength for the Ti-XSn alloys are close to the measured values. The Yield strength and the hardness of the Ti-XSn alloys are affected by the lamellar thickness and dislocation density [14]. By decreasing lamellar thickness the yield strength and dislocation density of the Ti-XSn alloys are increased [1,14].

4. Conclusions

The microstructure and mechanical properties of the Ti-XSn (X = 0, 5, 10, 15) alloys fabricated by hot extrusion of the blended TiH_2 and Sn elemental powders are investigated. The following conclusions can be remarked:

1. The lamellar thickness of the Ti-XSn alloys were reduced by increasing Sn from 0 to 15 wt%.
2. The microstructure of the CP Ti after adding Sn from lamellar α phase change to the α/α' lamellar structure.
3. Increasing the Sn percentage in Ti-XSn alloys was increased the yield stress and hardness, according to the Hall-Petch equation.
4. The elongation of the Ti-XSn alloys was increased by reducing the Sn content.

CRediT authorship contribution statement

Mojtaba Najafizadeh: Formal analysis, Investigation. **Mansoor Bozorg:** Formal analysis, Investigation, Data curation. **Mehran Ghasempour-Mouziraji:** Formal analysis, Investigation, Data curation. **Constantions Goulas:** Formal analysis, Investigation, Data curation, Visualization. **Pasqual Cavaliere:** Supervision, Validation, Data curation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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