Microstructural Transformation by Compositional Modification of Ti-6Al-4V Alloy for Aerospace Applications

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Abstract

Ti-6Al-4V alloy has been extensively used in aircraft for lightweight structural applications including wings and fuselage. Similar to other Ti alloys, however, its major drawback is higher cost leading to limitation in its application. In this case, Iron (Fe) has been introduced to Ti-alloys as a replacement of expensive element like vanadium (V) and molybdenum (Mo) in order to lower cost. In this work, a new Ti-6Al-Fe alloy was developed through major composition modifications of Ti–6Al–4V alloy. The vanadium element in Ti–6Al–4V alloy was replaced by 1 to 3 wt. % Fe. It was found that Fe can be effectively act as a β-stabilizing element. Ti-6Al-Fe system bring a strong advantage over conventional Ti-6Al-4V alloy in many aerospace applications owing to outstanding mechanical and corrosion properties.

Keywords: *Ti-6Al-4V alloy; Iron (Fe); Microstructure; mechanical response, aerospace*

1. Introduction

Titanium production as a predominant material reaches to about 80% for aerospace and aviation industry. For instance, structural materials such as fuselage, wings, skins and load-bearing components is composed of Ti-alloys [1,2]. Ti-alloys are lightweight materials; not only do they possess excellent tensile and yield strength produced for higher strength-weight ratio of structures but also bring advantages of heat resistance and weight savings. The major advantage of Ti-alloy is to increase the strength in order to get good strength-weight ratio in structures and to increase temperature capabilities that have direct impact to heat resistance in engines. In addition, the corrosion resistance rendered Ti-alloys to be engaging structural materials for aircraft industry. These improvements allow Ti-alloys to substitute much heavier materials such as steels and superalloys for airframe structures and engine pars [3-5].

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Typically, Ti can be found in two different crystallographic forms: hexagonal close-packed (HCP) crystal and body-cantered cubic (BCC) structure. HCP structure which refereed as alpha (α) phase existed at room temperature. HCP structure transforms to BCC structure or beta (β) phase at temperature about 883 °C. These crystallographic variations can be subjected to manipulation through adding of alloying elements and/or heat treating to obtain an extended diversity of alloys and properties [4,6]. Based on the crystallographic structure they can be categorized as α alloys, β alloys and α+β alloys which widely used in aircraft structural applications. Proportions and morphologies of α and β phases, which exist in Ti-alloys, are governed by alloy composition and heat treatment. The proportion of α and β phases can be specifically adjusted using additions of alloying elements. These alloying elements preferentially stabilize either α or β phase. Generally, the two-phase (α+β) alloys are dominated on using for structural application among Ti-alloys which are widely used in aerospace with application in both engines and airframe structures. The mechanical behavior of Ti alloys is coherently related to their microstructures (proportions and distribution of α and β phases) which are strongly affected by the processing used to manufacture the structural components [7,8]. The (α+β) Ti-alloys can be usually found in for rotating and static components of aircraft. For example, they have been used in fan blade, compressor's parts (disc, blade and compressor case) as well as airframe parts which are affected by engine's temperature.

Dual phase (α+β) Ti-6Al-4V alloy is definitely one of the most extensively used Ti alloys in aircraft, where it has been commonly utilized as a structural material, airframes and engine components [7-9]. Similar to other Ti alloys, the mechanical response of Ti-6Al-4V is also influenced by its morphology and microstructure. It can be easily modified and coherently affected by adding alloying elements or altering its composition. For instance, any reduction in grain size of primary α and lamellar colony in (α+β) Ti-6Al-4V alloy provides higher strength properties specifically yield strength [10]. However, this alloy is expensive because of the expensive alloying elements such as vanadium (V). To lower material cost and improve properties, researchers have introduced the cheaper alloying elements as an alternative of more expensive elements. Addition of alloying elements has direct influence on microstructures that would positively reflect on mechanical response of these alloys leading to significant improvements. There are three different types of alloying element: α-stabilizers (such as Al) and β-stabilizers (such as V, Mo, Nb, Fe, Cr and Mn) and neutral additives (such as Sn and Zr). The α-stabilizers and neutral additives contribute towards solid solution strengthening of these alloys. The β-stabilizers are responsible to formation of β phase in (α) Ti alloys or stabilize or increase the proportion of β phase in a (α+ β) microstructure of Ti alloy [11-14].

Of the interest of authors, Fe can be an attractive alloying element in (α+β) Ti-6Al-4V alloy as a potential β-stabilizers. It can be as a substitution to expensive β-stabilizing V element in order to lower alloy cost and simultaneously improve mechanical response [12,14]. An earlier investigation is carried on Fe containing Ti alloys by Hideki and Kazuhiro [13]. They reported that Ti-5.5Al-1Fe present remarkable strength, ductility and fatigue properties as well as super plasticity. It is also suggested that Fe containing Ti alloys alloy can be used in applications where Ti-6Al-4V are conventionally used [12]. However, there is restriction in the quantity of Fe addition due to possible formation of brittle FeTi intermetallic precipitates. According to Kadiri eta l. [12], Fe content can not excess from 3 wt. % in Fe containing Ti alloys. Therefore, a new Ti-6Al-xFe alloy (x=1, 2, and 3 wt. %) was developed in this study by compositional modification of of Ti-6Al-V alloy. In this regards, V as an expensive alloying element was replaced by Fe as a cost-effective β-stabilizing alloying element in Ti-6Al-4V alloy. Then, the effect of addition of Fe on the microstructures, mechanical and corrosion response of developed Ti-6Al-(1-3)Fe alloy was studied.

2. Methodology

Ti-6Al-Fe alloys containing up to 3 weight percentage (wt. %) were supplied from TIMET Co. Alloys were initially manufactured by melting in a vacuum arc melting technique using tungsten electrode. Three new alloys were designed through a major modification of Ti-6Al-4V alloy by introducing an inexpensive Fe alloying element. The as-received alloys were formed into bar shaped samples. Then, samples were heated above β-transus temperature at 1038 °C. Finally, samples underwent rolling process to obtain 35% thickness reduction where final dimensions of 160×60×6 mm was obtained.

An X–ray Diffractometer (XRD), BRUKER-D8 equipped with a 1-D (LYNXEYE) fast detector was used to record the XRD pattern of the investigated alloys. The samples were scanned using a 2θ scan configured in the general measurement mode to identify the existing phases, percentage of each phase, and their lattice parameters. The scans were performed with 0.025° step size, exposure time of 0.1 s/step and in the 2–theta (2θ) range of 29°- 85°. The x-ray source was Cu-Kα with a wavelength of 1.54060 Å. The resulting patterns were analysed using DIFFRACEVA V4.0 software based on its technical procedure. Following a standard metallography procedure, kroll solution was used as the etching reagent prior to microstructural observations. The morphological and microstructural features of Ti-6Al-(1-3)Fe were observed using optical microscope (NIKON Eclipse).

The micro-hardness of Ti-6Al-(1-3)Fe alloys were measured using a digital Micro-Vickers hardness tester (WOLPERT–Model: 401MVD). Three different measurements was carried out at a load of 1 kgf and a dwell time of 10 seconds on the randomly selected positions of each specimen and the average value was reported. Tensile tests were carried out using a 50 KN universal tensile testing machine (SHIMADZU). The tensile specimens were prepared in a form of square cross sections using a wire-cutting machining process.

Electrochemical test measurements were carried out using standard three-electrode system at room using AutoLab PGSTAT128N potentiostat supported with Nova 1.11 software programme. Silver chloride electrode (Ag/AgCl) was used as reference electrode while platinum (Pt) wire was the counter electrode. A 3.5% NaCl solution was prepared as an electrolyte solution. The corrosion rates were measured to identify the corrosion resistance using the linear polarization technique through the Tafel extrapolation method.

3. Data Results and discussion

Figure 1 illustrates the microstructure of Ti-6Al-4V and Ti-6Al-1Fe alloys. Optical micrographs reveals the fully equiaxed microstructure of Ti-6Al-4V alloy which is composed of a uniform structure of α grains and grain boundaries of β (Figure 1a). Based on XRD analysis, the equiaxed microstructure consists of 95.2% α-phase and 4.8% of β-phase. The average grain size of α phase is about 1.78 µm. The microstructures of Ti-6Al-(1-3)Fe alloys consist of as a basket weave-like structure which is well known as a typical fully lamellar microstructure as also reported earlier [14]. For instance, the microstructure of Ti-6Al-1Fe alloy is illustrated in Figure 1b. The lamellar colony size and the α-lamella width decreases by increasing Fe content. The average lamellar colony size of Ti-6Al-1Fe alloy is 780 µm which is larger than Ti-6Al-2Fe (644 µm) and Ti-6Al-1Fe (457 µm). In addition, the average lamella width of Ti-6Al-(1-3)Fe alloys decreases from 2.65 µm to less than 1 µm by increasing Fe content.

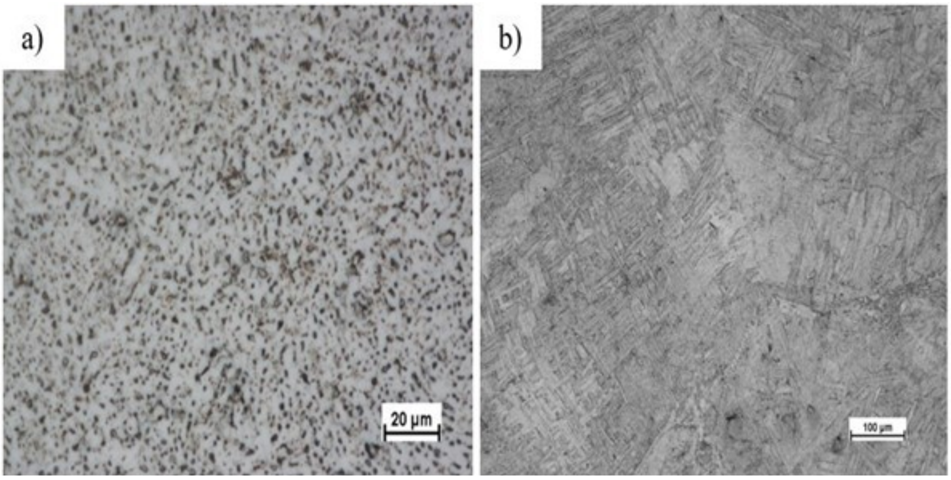

Figure 1. The optical micrograph of a) Ti-6Al-4V and b) Ti-6Al-1Fe alloys

Figure 2 shows XRD pattern of Ti-6Al-4V and Ti-6Al-(1-3)Fe alloys. The XRD patterns reveal that Ti-6Al-(1-3)Fe alloys are clearly dual phases that consist of coexistent α and β-phases. The percentages of α and β phases in Ti-6Al-(1-3)Fe alloys are listed in Table 1. Obviously, the percentage of β-phase increases by increasing Fe content. The results show that TiFe intermetallic compounds such as Ilmenite ($FeTiO_3$) and Rutile (TiO_2) did not detected as existing phases in Ti-6Al-(1-3)Fe alloys indicating that Fe is a strong β-stabilizer that can suppress TiFe formation.

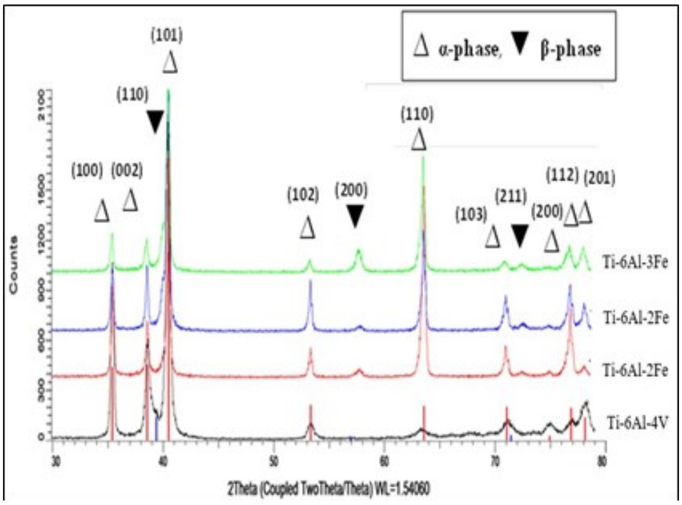

Figure 2. XRD patterns of Ti-6Al-4V and Ti-6Al-(1-3)Fe alloys.

It can be also clearly observed that Ti-6Al-(1-3)Fe alloys underwent allotropy phenomena, similar to Ti-6Al-4V alloy, where they possess two allotropic crystal structures. The crystalloghic structure of α-phase and β-phase are HCP and BCC, respectively. Fe as a β-phase stabilizing alloying element effectively reduces the β-transus temperature, then the formation of β-phase is consequently enhanced [15]. Table. 2 shows the lattice parameters of crystal structure of existing phases in Ti-6Al-4V and Ti-6Al-(1-3)Fe alloys.

Table 1. The percentage of α and β phases in Ti-6Al-(1-3)Fe alloys.

Specimen	Phase Percentage (%)		Increment percentage of β-Phase (%)
	α	β	
Ti-6Al-4V	95.2	4.8	0
Ti-6Al-1Fe	91.9	8.1	68.8
Ti-6Al-2Fe	89.6	10.4	116.67
Ti-6Al-3Fe	86.9	13.1	172.9

In Ti-6Al-(1-3)Fe alloys, it is observed that they have similar lattice parameters (a=2.92500 Å, c=4.66700 Å) in α-phase. Whereas, for the β-phase they have the same lattice parameter of 3.1800Å which is smaller than that of Ti-6Al-4V alloy (3.23220Å). This may be attributed to the effect of both alloying elements, Fe and V, on the crystal structure of titanium in the β form (BCC). Although Fe and V are β-stabilizing alloying elements, they behave differently when they are added as solute atoms to titanium as a host material to form a solid solution. V is an isomorphous β-stabilizer where its atoms introduce to the crystal structure of titanium to substitute titanium's atoms that are located at their normal sites in the cubic structure. While the atoms of Fe fill up the voids or interstices among the host atoms to be inserted into the interstitial sites of β-titanium's crystal structure (BCC). In addition, iron's atom is smaller than vanadium's atom, which lead to a smaller lattice parameter (a) for Ti-Al-Fe system.

Table 2. The lattice parameters of crystal structure for existing phases of Ti-6Al-4V and Ti-6Al-(1-3)Fe alloys.

Specimen	Phase	Crystal Structure	Lattice Parameters (Å)	
			a	c
Ti-6Al-4V	α	Hexagonal	2.92500	4.66700
	β	Cubic	3.23220	-
Ti-6Al-1Fe	α	Hexagonal	2.92500	4.66700
	β	Cubic	3.18000	-
Ti-6Al-2Fe	α	Hexagonal	2.92500	4.66700
	β	Cubic	3.18000	-
Ti-6Al-3Fe	α	Hexagonal	2.92500	4.66700
	β	Cubic	3.18000	-

The physical and mechanical properties of Ti-6Al-(1-3)Fe alloys is tabulated in Table. 3. First of all, density of Ti-6Al-(1-3)Fe alloys have almost similar densities to the Ti-6Al-4V reference alloy. The density values in Ti-6Al-(1-3)Fe alloys increase as Fe content increases. Ti-6Al-3Fe alloy has the highest density value of 4.386 (g/cm^3) which is slightly higher than Ti-6Al-4V (4.374 g/cm^3). It can be due to higher density of Fe element compared to other composing element such as Ti, Al, and V. Substitution of Fe in Ti-6Al-4V alloy has significant impact on the mechanical properties of resultant Ti-6Al-(1-3)Fe alloys. Ti-6Al-(1-3)Fe alloys have higher micro-hardness (HV) and ultimate tensile strength (UTS) but lower ductility (%) than Ti-6Al-4V alloy. In addition, HV, UTS and elongation % values increase by increasing Fe content. For example, the as-received Ti-6Al-3Fe alloy revealed the highest tensile strength of 1069 MPa, while tensile strength of 833 MPa was demonstrated by Ti-6Al-4V. The higher mechanical response of Ti-6Al-(1-3)Fe alloys is attributed to the fine lamellar microstructure. The lamellar colony size of Ti-6Al-(1-3)Fe alloys decreases and the lamella width becomes finer with increasing Fe content. The grain size of Ti-6Al-(1-3)Fe alloys decreases from 13.17 µm to 8.60 µm by increasing Fe content from 1 wt.% to 3 wt.%. Therefore, this microstructural variations exerts the improved mechanical response in Ti-6Al-(1-3)Fe alloys. Moreover, the electrochemical responses of Ti-6Al-4V and Ti-6Al-(1-3)Fe alloys are almost similar. However, Ti-6Al-1Fe shows excellent corrosion resistance of 1.77E-5 mm/year, the lowest corrosion rate in 3.5% NaCl solution, while higher corrosion rate of 2.1E-5 mm/y was recorded by its counterpart, Ti-6Al-4V alloy.

Table 3. The physical, mechanical and corrosion properties of Ti-6Al-(1-3)Fe alloys.

Specimen	Density (g/cm^3)	HV	UTS (MPa)	Elongation (%)	Corrosion Rate (mm/year) * 10^{-5}
Ti-6Al-4V	4.374	302	833	12.5	2.10
Ti-6Al-1Fe	4.338	327	897	11.3	1.77
Ti-6Al-2Fe	4.369	338	974	10.4	2.09
Ti-6Al-3Fe	4.386	370	1069	8.1	2.29

4. Conclusion

In this work, vanadium (V) element was replaced by different percentage of Iron (Fe) in a commercial Ti-6Al-4V alloy in order to develop Ti-6Al-(1-3)Fe alloys. This compositional modifications results in the improvement of density, strength, hardness as well as corrosion resistance of Ti-6Al-(1-3)Fe alloys compared to Ti-6A-4V alloy owing to developed bi-modal α+β microstructure. Ti-6Al-(1-3)Fe alloys contain a lamellar α+β microstructure wherein size of lamellar colonies and the lamellae width gradually decrease by increasing Fe content. It can be concluded that Fe can be used as a potential a β-stabilizing alloying element. Therefore, Ti-6Al-(1-3)Fe can be considered as promising alloys and also competitors to Ti-6Al-4V in many engineering applications.

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