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Effect of Si-addition as a grain refiner on microstructure and properties of Ti−6Al−4V Alloy

Khaled M. IBRAHIM[1], Abdel Hamied HUSSEIN[2], Mohamed ABDELKAWY[1]

1. Central Metallurgical R&D Institute, CMRDI, Cairo, Egypt;
2. Cairo University, Giza, Egypt

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Abstract: Two different Ti alloys were cast in a graphite mould using vacuum induction skull melting furnace. The first alloy was Ti−6Al−4V and the second was Ti−6Al−4V−0.5Si. Silicon as a grain refiner was added into Ti−6Al−4V alloy, and the effects of Si-addition on the microstructure and properties of the as-cast and swaged alloys were investigated. Hot swaging at 900 °C was performed on the cast samples and then two different thermal treatments were applied. The first treatment was done by heating the swaged samples at 1050 °C to produce fine lamella structure, while the second treatment was carried out at 1050 °C and then decreased the temperature to 800 °C for getting coarse lamella structure. An addition of 0.5% Si to Ti−6Al−4V alloy decreased the grain size of the as-cast sample from 627 to 337 μm. There was an increase in ultimate tensile strength of about 25 MPa for the as-cast Ti−6Al−4V−0.5Si alloy compared to Ti−6Al−4V due to the refinement effect caused by Si addition. A maximum ultimate tensile strength of 1380 MPa and a minimum corrosion rate (1.35×10^{-6} mm/a in Hank's solution and 5.78×10^{-4} mm/a in NaCl solution) were reported for the heat treated fine lamella structure of Ti−6Al−4V−0.5Si alloy. The wear rate was decreased to about 50% by adding 0.5% Si at low sliding speeds and to about 73% at high sliding speeds.

Key words: Ti−6Al−4V alloy; silicon; casting; grain refinement; heat treatment; wear

1 Introduction

Titanium has emerged as a very attractive metal for numerous applications. Ti−6Al−4V (Ti-64) is one of the most commonly used titanium alloys in the aviation industry and civil applications due to its high specific strength, high operating temperature and corrosion resistance. The excellent corrosion resistance of Ti-64 is due to the surface oxide film that protects it from corrosive agents such as seawater. Ti-64 is an important $\alpha+\beta$ titanium alloy with an interesting and challenging correlation between mechanical properties and its complex microstructure [1−4]. Titanium alloys normally have a coarse microstructure in the as-cast condition. This coarse microstructure could be attributed to different facts such as cooling rate, solidification, casting procedures and impurities. This condition affects mechanical properties, like strength, ductility and damage tolerance. Therefore, several thermo-mechanical processes are needed to obtain a good balance between static and dynamic properties, which in turn increases time and cost to obtain high quality billets. For other metals and alloys, it is well documented that inoculation using solute elements could refine the grains. A similar approach was used in titanium but there has not been extensive work carried out. BERMINGHAM et al [5] observed that small addition of silicon (<0.6%, mass fraction) produced a significant grain refinement in Ti-64 alloy, which later was observed by other researchers.

Refinement of prior β-grain in cast titanium alloys is believed to improve a number of properties including strength, ductility and fatigue resistance. Despite the associated benefits of controlling prior β-grain size in cast titanium alloys, relatively little research has been conducted into grain refinement of titanium alloys, and no commercial grain refiners currently exist. Some earlier work has reported the grain refinement with various elemental additions, such as B and Br [6,7].

In the present work, two different Ti-alloys were cast in a graphite mould using vacuum induction skull melting (ISM) furnace. The first one was Ti-64 and the

Corresponding author: Khaled M. IBRAHIM; Tel: +96-6558526682, Fax: +20-225010639; E-mail: khaledabouelela@yahoo.com
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second was Ti-64−0.5Si, where silicon was added to clarify its role as a solute element in Ti-64. Hot swaging accompanied with thermal treatment process was applied for studying microstructural characteristics and mechanical properties as well as corrosion behavior under all conditions (as-cast, hot swaged and heat treated) for both investigated Ti-alloys (Ti-64 and Ti-64−0.5Si).

2 Experimental

Pure graphite mould was used for casting cylindrical titanium samples with dimensions of 30 mm in diameter and 300 mm in length each. Casting design was made before machining the graphite mould for getting four sound bars. Before melting the titanium alloys, the graphite mould was preheated in a heating chamber inside the ISM furnace to about 900 °C. Hereafter, 10 kg raw material of Ti-64 was heated to reach 1700 °C to melt it under vacuum that reached to 4 Pa. As soon as the charge was melted, a flow of argon was released into the chamber in order to prevent any possible chemical reaction with crucible. Then the molten metal was poured into the graphite mold after holding for 2 min in the crucible. For the second alloy of Ti-64 containing 0.5% Si, the amount of silicon was firstly weighed and ground to <45 μm and then inserted at the bottom of the sprue of the graphite mould. The molten metal was poured into the graphite mould to distribute this amount of silicon homogenously into the four cast Ti-bars. The chemical composition of both investigated Ti-alloys is given in Table 1. To remove the residual stress existing on the surface of the cast bars due to casting, 2.5 mm was removed by turning. The final dimensions of the cast rods became 25 mm in diameter and 250 mm in length which was suitable for the hot swaging process. Swaging was achieved at 900 °C to reduce the cast bars diameter from 25 mm to 8.5 mm in 11 steps. After that two kinds of thermal treatment processes were applied to the swaged samples (Fig. 1). The first treatment was done at 1050 °C for getting fine lamella structure and the second process was applied using step thermal cycle at 1050 °C and then quenching from 800 °C for getting coarse lamella structure. Finally, aging was carried out at 500 °C for 24 h for both samples.

Table 1 Nominal chemical composition of experimental castings

Alloy	Chemical composition/%						
	Al	V	C	O	F	Si	Ti
Ti-64	6.37	4.12	0.02	0.25	0.24	0.02	Bal.
Ti-64−0.5Si	6.26	4.10	0.02	0.25	0.24	0.53	Bal.

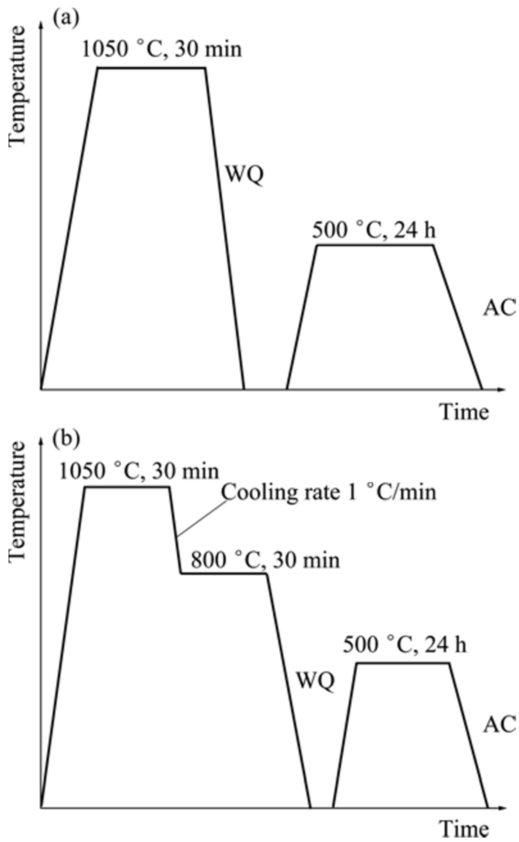

Fig. 1 Heat treatment cycles for getting fine lamella (FL) structure (a) and coarse lamella (CL) structure (b)

Cast and deformed samples were cut out from the rods and polished using conventional techniques. Grain size was also estimated after etching (3 mL of HF, 30 mL of HNO_3, and 67 mL of H_2O). Specimens were photo micrographed using light microscope and scanning electron microscope (SEM). Micro-analysis was carried out using X-ray diffraction (XRD), PC based image analyzer and energy-dispersive spectrometer (EDS). In order to determine the beta transus of each alloy, the solidification path of both Ti-alloys was monitored using heat-flux differential scanning calorimetry (DSC). Mechanical properties including hardness and tensile properties of the different investigated conditions were carried out according to ASTM standards. Further, wear testing was carried out on a pin-on-ring wear testing machine. The wear samples had a rectangular shape of 8 mm×12 mm×12 mm. The test was performed against a stainless steel ring with surface hardness of HRC 63, which was rotated at variable speeds of 270, 330, 400, 465 and 530 r/min and a constant applied load of 90 N for 1 h. After wear testing, the samples were weighed using 0.1 mg precision digital scale to determine the average mass loss of two samples for each condition. The wear rate was then calculated by dividing the mass loss by the testing time. The worn surface of some selected samples was examined using SEM to determine