ELSEVIER

Materials Science and Engineering A 394 (2005) 220–228

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Effect of alloying time and composition on the mechanical properties of Ti alloy

Margam Chandrasekaran*, Zhang Su Xia

Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, 638075 Singapore

Received 19 November 2003; received in revised form 8 November 2004; accepted 12 November 2004

Abstract

Titanium and its alloys find wide applicability in aerospace and medicine. The key restricting factor in using the Ti-based alloys is the difficulties associated with the processing of the alloy as they are forged at temperatures >800 °C. In the current work, Ti was mechanically alloyed in a tumbler mixer with Al, Fe and Zr with a charge to ball ratio of 1:2. The mechanical properties such as tensile and compression strengths and the hardness profile were evaluated as per the ASTM/MPIF standards. SEM analysis of the fracture surfaces indicated that samples sintered in vacuum exhibited brittle failure while those sintered in argon exhibited ductile–brittle failure. The tensile strengths ranged from 300 to 850 MPa for the samples tested. The alloying time affects the fracture mode and the strength of the alloy. Strain in excess of 20% was obtainable during upsetting samples alloyed for 48 h which is comparable to the conventional Ti–6Al–4V alloy.

Keywords: Titanium alloy; Mechanical alloying; Tensile strength; Sintering atmosphere; Sintering time

1. Introduction

The use of titanium and its alloys in the aerospace and biomedical industries is well known due to their high strength to weight ratio and excellent biocompatibility. The market for titanium alloys is fast expanding with applications ranging from aerospace, automobiles, and biomedical to even electronic applications such as hard disk bases or hand phone covers. The most common alloy currently being used is the Ti–6Al–4V because of its performance. However, despite the advantages of Ti alloys and their application potential, the growth in the application of Ti alloys has been rather slow. This is due to the difficulty associated with the processing of Ti alloys at room/warm temperature ranges. Another significant disadvantage associated with titanium alloys is that they become highly reactive at temperatures higher than 600 °C and undergo rapid oxidation. Thus, Ti components are either fabricated by investment casting or by forging to near net shape at elevated temperatures in a controlled environment. This contributes to the increase in processing cost and most of the research works on titanium are aimed at development of microstructure useful for easier processing of the Ti alloys.

Forging and mechanical working Ti alloys occupy a principal position in processing of titanium alloy components owing to the properties achievable of alloys [1–5]. Due to high flow stress and limited elongation of titanium alloys at room temperature, titanium and its alloys are normally processed at elevated temperatures close to 900 °C to enable forming the desired shape of the component. Moreover, Ti alloys are highly sensitive to strain rate during processing and require careful control of parameters to minimize hardening due to strain rate sensitivity. Both the requirements of controlled environment and strain rates during forming contribute to higher processing costs of Ti alloys. Titanium exhibits polymorphism at different temperatures and its room temperature phase (alpha) has a hexagonal closely packed (HCP) structure while the high temperature phase (beta) has body centered cubic (BCC) crystal structure [6]. The hexagonal closely packed

* Corresponding author. Tel.: +65 67932730; fax: +65 67925362.
E-mail address: chandram@simtech.a-star.edu.sg (M. Chandrasekaran).

0921-5093/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2004.11.056

structure has only three slip systems active at room temperature which affects the plastic deformation while the high temperature phase of BCC has about 48 slip systems thus aiding plastic deformation upon application of stress. Addition of certain alloying elements to titanium results in stabilization of the phase and the elements can be broadly classified in to alpha stabilizers and beta stabilizers. One of the ways to improve the processability is to use beta phase stabilizers to facilitate forging at lower temperatures. The elements used for stabilizing the particular phase can be further classified into 'isomorphous' and 'eutectoid' stabilizers depending on the crystal structure of the alloying elements and the type of resulting compounds upon cooling from an elevated temperature. Isomorphous stabilizers do not form brittle intermetallics as on slow cooling, the beta phase does not transform in to alpha Ti + alloying elements, but are expensive. On the other hand, the eutectoid stabilizers have limitation on the percentage that can be used. Typical isomorphous stabilizers include, molybdenum, vanadium, tungsten, tantalum while iron, chromium, nickel, cobalt, manganese are termed as eutectoid stabilizers. The critical minimum percentage for the eutectoid stabilizers required goes as low as 3.5% in iron to as high as 13% in case of copper [4]. Moreover, the addition of vanadium in titanium has been found to retard the bone mineralization and formation in patients with implants and the bone growth is found to be lower with the presence of V and Al. Vanadium has higher toxicity compared with Al on the biocompatibility chart [14]. The alloying elements were selected based on the earlier works on cold forgeability of Ti alloys [7–14]. In the current work, mechanical alloying of the powders was performed for different lengths of times to improve the processability of the Ti alloys at lower temperatures. The present work studies the effect of alloying time and composition on the properties of Ti–Al–Fe–Zr alloy.

2. Experimental methodology and materials used

Pure elemental powders of Ti, Al, Fe, Zr were obtained from different sources and their size distribution and morphology are provided in Table 1. The alloying addition of Fe and Zr were kept lower to minimize their adverse effects on the creep resistance and oxidation resistance, respectively [6]. Fe has a higher interdiffusion coefficient in Ti and has a retained beta phase on cooling. Moreover, alloying of Fe contributes to increase in the proof strength of the alloy, but on the other hand, decreases the cryogenic toughness of the alloy [4,12,13].

The flowability tests were conducted under normal atmosphere. The resistance to free flow in the Carney flow meter is due, possibly, to the low particle size and high relative humidity. The powders were weighed in their respective proportions and filled in a plastic container, which was filled with Al_2O_3 balls with a charge to ball ratio of 1:2 (v/v) and were mechanically alloyed from 8 to 48 h using a tumbler mixer. After alloying, the containers were carefully opened to avoid any oxidation of the powders and the contents were sieved to remove the balls and collect the powder blend. About 4–7 g of powders was used to prepare tensile bars and pellets of 11 mm diameter × 10 mm height specimens. In order to ascertain the effect of sintering temperature and sintering atmosphere, samples alloyed for 8 h were sintered in vacuum for 2 h at 1150 and 1250 °C, respectively. The optimum sintering conditions were identified based on the tensile strength and the strain at fracture besides the phases formed during sintering. The samples alloyed for 8 h were also sintered in argon at 1250 °C. The optimum conditions were used for sintering of the compositions alloyed for different time durations and the properties such as tensile strength, strain at failure, fractograph and hardness were evaluated.

The alloyed samples were compacted to form tensile specimens (MPIF 10) and pellets of 12 mm diameter × 9 mm height. The green pellets were used to countercheck the repeatability of results obtained from powder X-ray diffraction. The pellets and the tensile specimens were then sintered at respective conditions as described in the experimental methodology. The density of the alloyed powder, green pellets and the sintered compacts were identified using a pycnometer. The X-ray phase analysis was done using a Philips X-ray Diffractometer with 2θ values ranging from 20 to 120°. The reason for the wider scan angle is basically to identify any stray phases that might form in the new formulation. The tensile tests were performed on the sintered samples as per ASTM E8-03/MPIF 10 at room temperature while the compressive strengths were evaluated as per procedures in ASTM E9-89a. The hardness of the samples was evaluated using the Vickers micro hardness tester at a load of 300 g. A minimum of three samples were used for each of the tests to confirm the repeatability of the results within ±5% and the average values were plotted. One pellet sample in each condition was polished and etched with Keller's reagent for approximately 30 s to reveal the grains and phases present. Scanning electron microscopy was performed on the fractured samples and the etched samples for identifying the fracture mode. EDX was performed on individual grains on samples to identify the elements present to be used as indicative evidence of spe-

Table 1
Morphology/size of the powders used for the study and the compositions studied

Powders	Titanium	Aluminium	Iron	Zirconium
Size/morphology	−270 Mesh/irregular	−325 Mesh/rounded	−270 Mesh/irregular	−325 Mesh/rounded
Flowability	Non-flowing	Non-flowing	Non-flowing	Non-flowing
Alloy composition (wt.%)	Bal.	2	1	1