*Materials Science Forum Vol. 690 (2011) pp 69-72*
*Online available since 2011/Jun/14 at www.scientific.net*

*doi:10.4028/www.scientific.net/MSF.690.69*



# Mechanical Properties of Mill-Annealed Ti6Al4V Investment Cast

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**Keywords:** Ti6Al4V alloy, investment casting, mill annealing, mechanical properties

**Abstract.** Ti6Al4V alloy, produced by investment casting using yttria stabilized zirconia, was machined and then mill-annealed in vacuum furnace. The ultimate strength, yield strength and percentage elongation were largely improved compared to the same alloy in the as cast condition. The mill annealing temperature and time strongly affected the ultimate strength, 0.2% yield strength and the percentage elongation.

## Introduction

The used of Titanium and its alloys in military and civil applications requires excellent mechanical properties, good corrosion resistance and excellent biocompatibility. Generally these properties change considerably according to the manufacturing process and subsequent heat treatment, as shown by Li et al [1]. Investment casting is the main route and the most fully developed net-shape technology compared to precision forging and powder metallurgy processes. Therefore, heat treatment process, contrary to the wrought Titanium and Titanium alloys, is the only one possibility of improving properties.

Although the effect of annealing temperature on the tensile properties, of Ti6Al4V investment cast, has been discussed [2], the synergic effect of Hot Isostatic Pressing (HIP), mill-annealing temperature and mill-annealing time on the ultimate tensile strength, the 0.2% yielding stress and the percentage elongation of the investment cast Ti-6Al-4V need to be addressed.

This work investigated the effect of HIP and mill annealing treatment on the mechanical properties of Ti6Al4V investment cast.

## Experimental Procedure

The Ti-6Al-4V alloy (chemical analysis shown in the Table 1) was investment cast, after induction melting, using fully yttria stabilized zirconia ($Y_2O_3$-$ZrO_2$) face-coat. The ceramic shell mould was made by alternate dipping of wax patterns into a colloidal $ZrO_2$ and subsequent stuccoing with $ZrO_2$ stucco, Fig.1a. The entire tree mould was first dried for 24 hours at 22°C, then de-waxed using a LBBC steam boiler clave at 200°C and 8 bars for 15 minutes and fired at 800°C for 2 hours.

Some of investment cast Ti-6Al-4V samples (Fig.1c) were HIPed and then machined for tensile test specimens (5mm of diameter and gage length of 30mm, Fig. 1d). Tensile specimens, previously cleaned in ethanol, were mill-annealed in the XERION vacuum furnace. All specimens were cooled to room temperature before been removed from the furnace.

The metallographic analysis and Vickers hardness were performed on polished and etched specimens. Tensile tests were carried out in the air laboratory, on the servo-hydraulic Instron testing machine. Specimens were pulled at a strain rate of 5mm/min. The environment temperature was around 21°C.

Polished surface and fractures were analyzed using the optical microscope and Scanning Electron Microscopy (SEM), respectively.

### Results and Discussion

**Table 1**. Chemical composition of the investment cast Ti6Al4V

| *Elem.* | *Ti* | *Al* | *V* | *Zr* | *Si* | *Fe* | *C* | *N* | *O* | *H* |
|---|---|---|---|---|---|---|---|---|---|---|
| Wt% | Bal. | 5.7 | 4.2 | 0.041 | 0.02 | 0.01 | 0.069 | 0.013 | 0.171 | 0.002 |

The microstructural analysis revealed blocky and plate-like acicular α (transformed β), with α (black area) at prior β (bright area) grain boundaries in the as cast (Fig. 2b) and mill-annealed (Fig. 2c). Almost no change in grain size of after mill-annealing treatment was observed. The grain size was about 2.22mm (Stdev=1.03), Figure. 2a. The as cast Ti6Al4V was characterized by coarse alpha plate-like phase of 5.26μm (Stdev=1.21) and relatively wide grain boundaries of about 16.83μm (Stdev=7.72). However fine alpha plate-like of 3.24μm (Stdev=0.57) and narrow grain boundaries of 6.48μm (Stdev=1.85) were noticed in the Ti6Al4V mill-annealed structure.

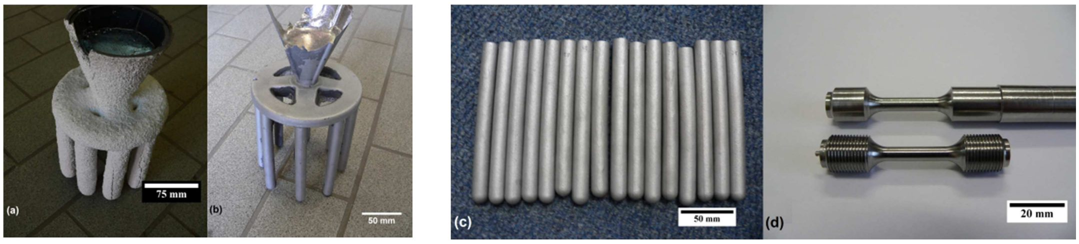


**Figure 1**. Ti6Al4V investment samples and tensile specimens

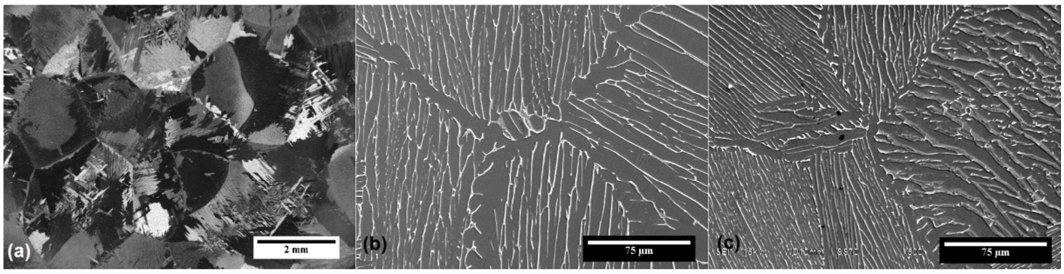


**Figure 2**. Ti6Al4V a) grain structure and blocky and plate-like α (transformed β) b) as cast and c) milled annealed

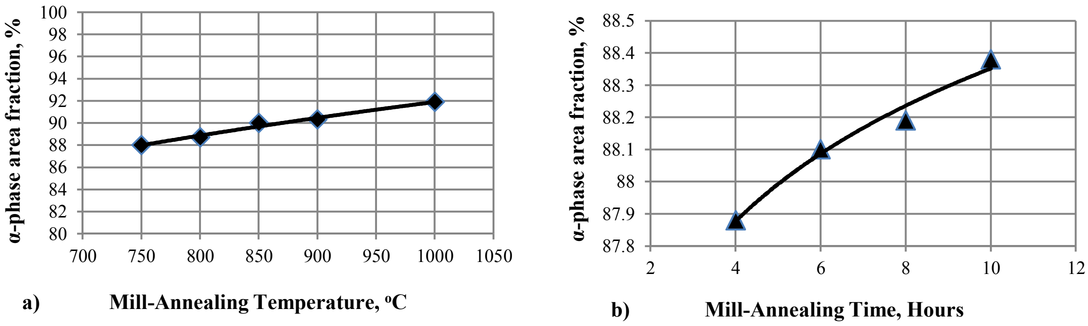


**Figure 3**. Variation α-phase area fraction with mill-annealing temperature and time

Mill-annealing Ti6Al4V investment cast, at high temperature and furnace cooling, increased the volume fraction of α-phase transformed from β-phase (Fig.3a). Similar phenomenon was observed when the exposure time became longer, Figure 3b.

The hardness was high in the as cast alloy (about 450 HV3), however relatively lower in the HIPed and mill-annealed Ti6Al4V (380 HV3).

The mill-annealing treatment considerably improved the UTS, 0.2%Ys and the total elongation (Fig. 4), as results of α-phase transformation, fine α-phase plate-like formation and HIP process. Defects were sensibly reduced after HIP [3], as it sintered the internal-connected voids

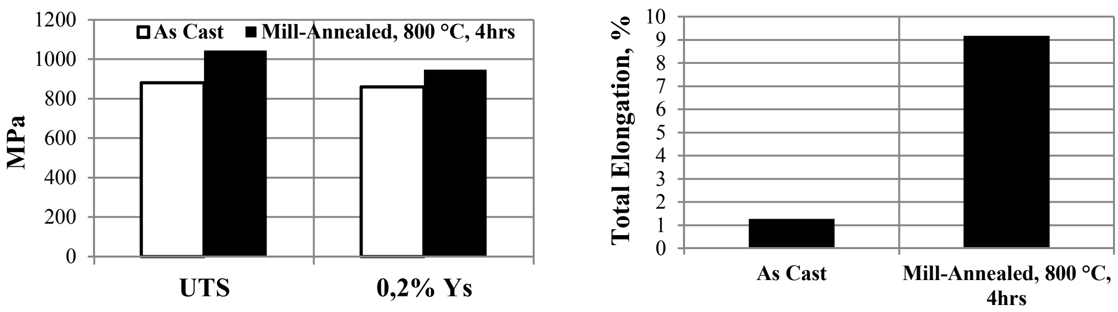


**Figure 4**. UTS, 0.2% Ys and % elongation of the as cast and mill-annealed Ti6Al4V

The as cast specimens have fractured with no permanent deformation or necking (about 1% elongation) (Fig. 5a), whereas the mill-annealed fractures exhibited some ductility with about 10% elongation. These fracture surfaces revealed the presence of dimples, which are different in size and shape, see Figure 5b, 5c and 5d.

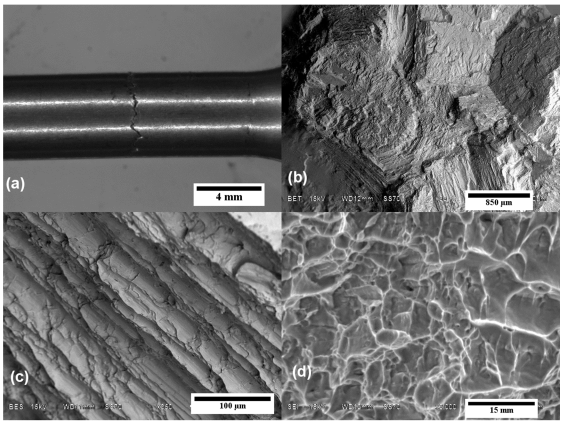


**Figure 5**. Tensile fractures of Ti6Al4V alloy

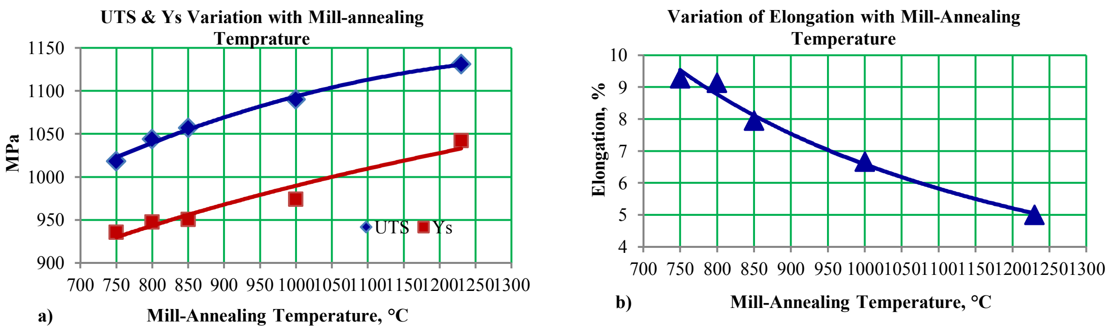


**Figure 6**. Effect of mill-annealing temperature on mechanical properties of Ti6Al4V

The increase of mill-annealing temperature, directly increased the UTS and 0.2% Ys (Fig. 6a), whereas increasing the temperature has negative effect on the total elongation of the Ti6Al4V (Fig. 6b). The strength increased as the amount of α-phase increased and α-phase plate-like became fine in the Ti6Al4V structure. However as a rule of thumb, the ductility decreases as the strength of the material increases.

UTS and 0.2% Ys increased as tensile specimens last for longer in the vacuum furnace (Fig. 7a), however inversely the total elongation decreased with mill-annealing time, as shown the Figure 7b.

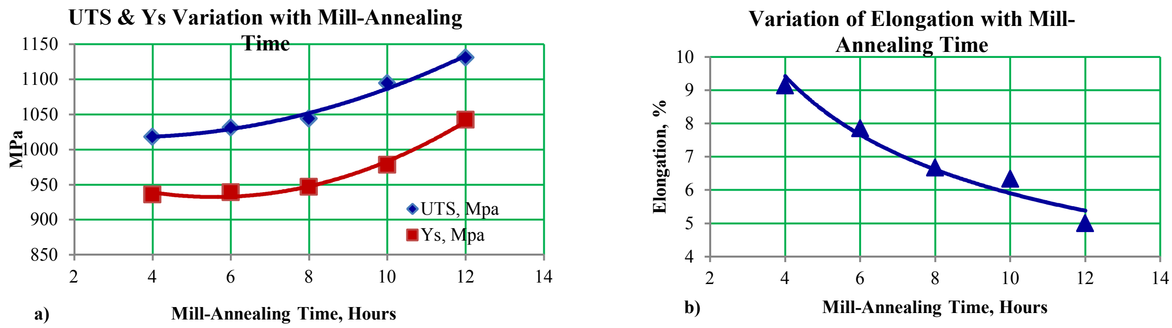


**Figure 7**. Effect mill-annealing time on mechanical properties of Ti6Al4V

## Conclusions

The mill-annealed and furnace cooled Ti6Al4V has the most acceptable combination of strength and ductility. The tensile properties of the as cast Ti6Al4V may be improved by hot isostatic pressing and mill-annealing treatment.

The mill-annealing temperature and time affect positively the ultimate tensile strength and the yielding stress. However the total elongation is negatively affected.

## Acknowledgments

Authors acknowledge the financial support of DST (Department of Science and Technology) and CSIR (Council for Scientific and Industrial Research).

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doi:10.4028/www.scientific.net/MSF.690

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