J Mater Sci (2008) 43:788–792
DOI 10.1007/s10853-007-2298-y

The effect of quenching medium on the wear behaviour of a Ti–6Al–4V alloy

C. Feng · Tahir I. Khan

Received: 5 December 2006 / Accepted: 9 April 2007 / Published online: 18 November 2007

Abstract The aerospace alloy, Ti–6Al–4V is a difficult material to machine, and, in general, shows poor wear resistance due to the soft, ductile properties of the alloy. In this study, the Ti–6Al–4V alloy has been heat treated to a temperature above and below the β-transus temperature and then quenched using a medium of oil, water or liquid nitrogen to change the surface wear behaviour of the alloy. The results showed that no significant change in microstructure and surface properties was achieved when the alloy was heated to 750 °C and then quenched in liquid nitrogen. However, when the alloy was heated to 1,000 °C (above the β-transus), the hardness of the titanium alloy significantly increased from 400 VHN to about 800 VHN, but the wear resistance of the alloy did not improve. In fact, the wear resistance of the alloy decreased as the surface hardness increased, and this change in wear behaviour was attributed to a change in the mechanism of wear from plastic deformation to brittle-fracture of the surface.

Introduction

In metals such as steels, it is well known that a quenching medium (e.g. oil or water) can be used to effectively increase the surface hardness, and, hence, the wear resistance of the steel. More recently, extensive research in the use of liquid nitrogen as a quenching medium has demonstrated a significant increase in the wear life of tool steels [1, 2]. The aerospace alloy Ti–6Al–4V is an $\alpha + \beta$ alloy, which is commonly used in the "mill annealed condition" so that when the alloy is solution-treated and aged, it possesses excellent yield, tensile and fatigue strength properties. However, these alloys are difficult to machine due to the ductile properties of these materials and this also results in significant wear of cutting tools used in machining. In an effort to counteract this problem, research has shown that a noticeable improvement in tool life can be obtained by using liquid nitrogen as a coolant during machining [3, 4]. This improvement has been attributed to liquid nitrogen lowering the temperature of the alloy, thereby reducing the frictional wear of tools by reducing adhesive wear mechanisms between the cutting tool and the titanium alloy surface. The general effect of cooling rate on the microstructural development and mechanical properties (such as the ductility, fatigue, tensile and yield strength) of Ti–6Al–4V has been [5, 6]. Work by Hong et al. [7] suggested that a surface quenching treatment using liquid nitrogen could also be used as a method of reducing the coefficient of friction between the cutting tool and chip interface and thereby change the wear resistant behaviour of these alloys. However, very little research has focussed on the effect of cooling rate on the changes in wear resistance of this alloy. It is well known that the inherent ductility of titanium alloys results in poor surface wear characteristics, and, therefore, it is normally accepted that by increasing the surface hardness, a corresponding increase in wear resistance can be expected. As a result, a number of different surface modification processes have been used to treat these alloys to increase hardness and, hence wear resistance [8, 9]. In this research study, quenching has been used as a method of modifying the wear resistance of the titanium alloy surface. Changes in wear

---

C. Feng · T. I. Khan (✉)
Department of Mechanical and Manufacturing Engineering,
University of Calgary, 2500 University Drive N.W,
Calgary, AB, Canada
e-mail: tkhan@ucalgary.ca

behaviour have been investigated as a function of different heating and quenching regimes using water, oil and liquid nitrogen. The changes in the wear resistance of the surface are explained in terms of microstructural development within the surface and changes in hardness after the quenching treatments.

Experimental procedure

Titanium alloy samples were cut from a forged Ti–6Al–4V plate into dimensions 2 cm × 1 cm × 1 cm. The effect of solution treatment at 750 °C and at 1,000 °C was compared, and the effect of using a mixture of water, oil and liquid nitrogen as quenching media was investigated. The titanium alloy samples were first solution-treated and left in the furnace in an inert atmosphere of argon for 30 min prior to quenching. The samples were quenched in either water, oil or liquid nitrogen, and left in the quenching medium for 24 h. Metallographic samples were prepared using conventional polishing techniques with a 3 μm final polish using a diamond suspension. The specimens were etched in a solution consisting of 85 H_2O, 10 HF and 5 HNO_3 to reveal grain boundaries. Optical micrographs were taken using the inverted Zeiss light microscope.

In order to compare changes in surface hardness before and after the quenching treatment, micro-hardness measurements were obtained using a Lietz micro-hardness tester using a load of 200 g. Wear assessment of the surfaces was performed using a pin-on-plate reciprocating wear test rig. The pin in this study was a diamond tip, and, can be considered as a cutting edge. The diamond tip will not be expected to show plastic deformation or wear loss, and, hence, wear measurements can be considered as being from the titanium alloy surface. The wear tests were performed at room temperature in air under dry sliding conditions. A constant sliding speed of 50 revs/min was used and an applied load of 5 N. The wear rate of the surfaces was measured dynamically by recording the change in wear depth as a function of sliding distance. The average surface roughness (R_a) value was measured from the wear tracks using a Mitutoyo SJ-301 surface profilometer in order to compare changes in surface condition after the wear tests. Further examination of the wear tracks was performed using light microscopy and a JEOL 840A scanning electron microscope (SEM).

Results and discussion

As a control experiment the as-received titanium alloy was heated to 750 °C for 30 min, and then quenched in liquid nitrogen for a 24 h soak. Figure 1 contains optical micrographs of the (a) as-received (baseline) alloy and (b) the alloy after the 750 °C heat-treatment and liquid nitrogen quench. There was no significant change in the microstructure of the titanium alloy after the quenching treatment and the typical $\alpha + \beta$ phase structure was visible in both samples. The result indicated that the solution treatment at 750 °C for 30 min was far below the β-transus temperature and in the α phase range; thus, a phase transformation is not expected during the quenching stage. When the titanium alloy was solution-treated at 1,000 °C (above the β-transus (980 °C)) for 30 min, and then quenched in either liquid nitrogen, oil or water, a noticeable change in microstructure was observed as shown in Fig. 2a, b and c. The samples that were quenched in water or oil were characterized by a microstructure consisting of α' martensite with some primary α grains in the matrix. In the case of samples quenched in liquid nitrogen, the microstructure also consisted of α' martensite, but the primary α grains were not observed, since liquid nitrogen is a more effective quenching medium. It is known that α phase formation is associated with a slow cooling rate [10]. The microstructures did not show any significant change in the size of the α lamellae with respect to the different quenching media used in this study.

The hardness values measured from the surface of the quenched samples are presented in Fig. 3. These results correspond to the microstructural changes and show a

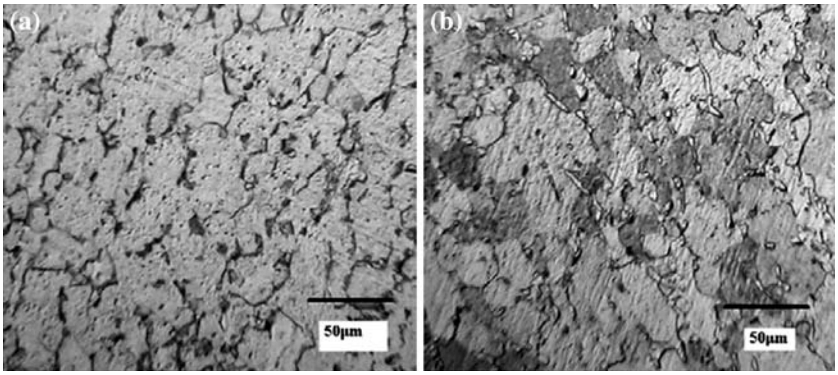


Fig. 1 Light micrographs showing: (**a**) as-received Ti–6Al–4V alloy ($\alpha + \beta$ microstructure); (**b**) after heat treatment at 750 °C for 30 min and quenched in liquid N_2

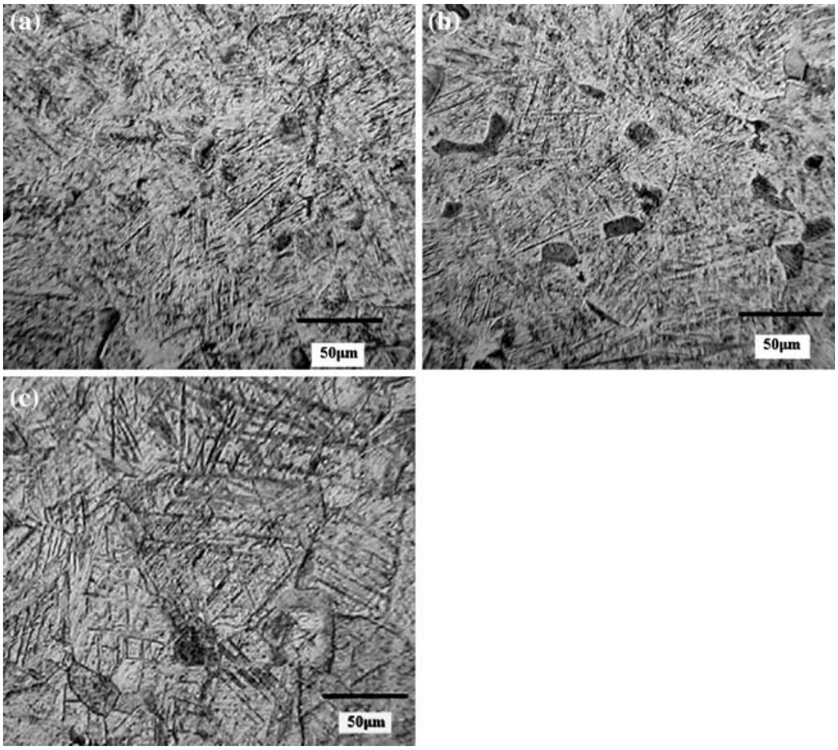


Fig. 2 Light micrographs showing microstructure after heat treatment at 1,000 °C for 30 min and quenching in: (**a**) oil; (**b**) water; (**c**) liquid N_2

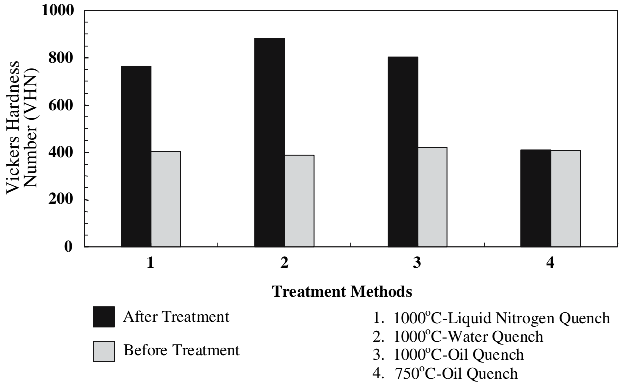


Fig. 3 Comparison of surface hardness values before and after quenching treatment

significant increase in hardness for all quenched samples when compared with the as-received alloy and the control sample, which was solution-treated at 750 °C. The hardness increase was greatest for the water-quenched (883 VHN) followed by oil quenched (802 VHN) and then liquid nitrogen quenched samples (746 VHN). The use of water and oil quenching mediums is well established, but the use of liquid nitrogen as a quenching medium is a relatively recent development. The hardness results clearly show that quenching with liquid nitrogen is effective although it rapidly evaporates upon contact with the hot titanium surface.

Wear tests were performed in order to examine the change in wear behaviour of the titanium alloy surfaces before and after quenching. A reciprocating diamond pin was used to move across the titanium alloy surfaces. The pin simulated the action of a cutting tool and provided data, for comparing the wear rate of the titanium surfaces. The volume of material removed during the wear test was calculated using an expression, which takes into account the shape of the diamond pin and is given as:

$$\text{Volume loss} = 12.375 \times (\text{scar depth})^2$$

The wear test results presented in Fig. 4a and b provide a comparison of the wear depth and volume of material removed as a function of sliding distance. The wear results showed that the surfaces quenched using liquid nitrogen exhibited the greatest wear loss with increasing sliding distance. Interestingly, the least change in wear depth was for the as-received alloy. These results are in contrast with normal wear resistance behaviour as defined by the Archard wear equation [11]. In normal cases, as the hardness of a surface increases, a corresponding increase in the wear resistance can be expected due to a decrease in the plasticity of the surface and absence in adhesive wear mechanisms. The results from this study show that the inverse is observed. As the surface hardness of the titanium alloy increased after quenching in liquid nitrogen, a decrease in the wear resistance of the surface was observed.

In order to investigate the change in wear mechanisms during the wear tests, the wear tracks produced on the titanium alloy surface were examined using scanning

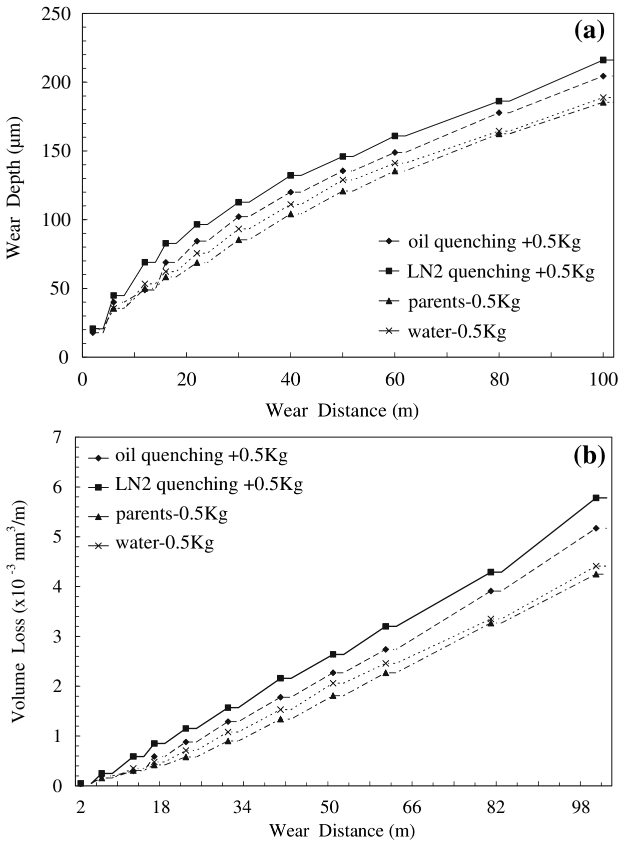


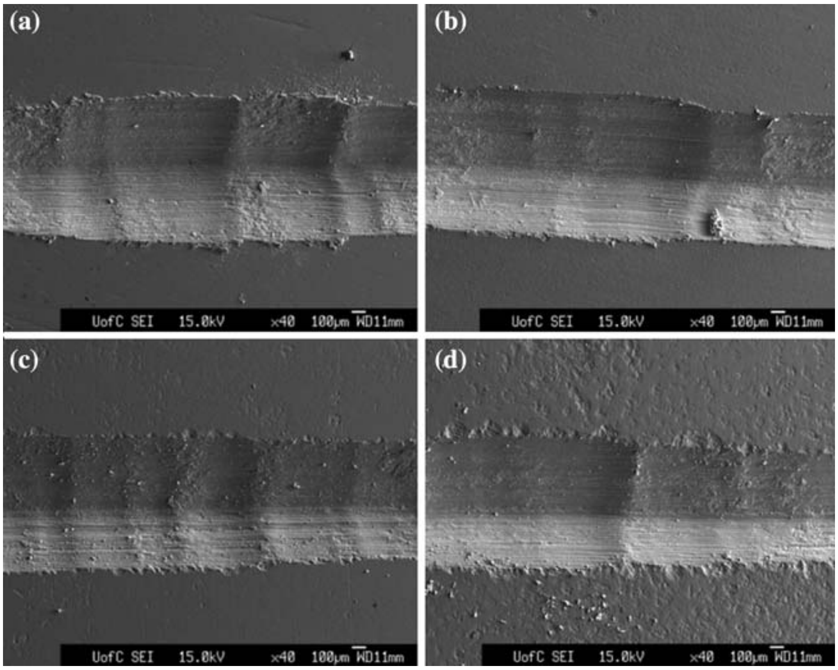
Fig. 4 Graphs showing the effect of quenching medium on wear resistance behaviour of the titanium alloy

electron microscopy (see Fig. 5). All wear tracks revealed micro-cutting and a ploughing action by the diamond tip as material was removed from the surface. However, closer examination of the edges of the wear tracks also revealed considerable plastic deformation in the as-received alloy, which exhibited a distinct "deformation lip" at the edge of the wear track. In comparison, the edges of the wear tracks for the quenched samples were straight and did not show excessive deformation. Instead, there was evidence of a "chipping" effect at the edges of the wear tracks. This was particularly noticeable for samples quenched in water and liquid nitrogen (see Fig. 5c and d). These observations suggest that the titanium alloy undergoes a change in wear behaviour from plastic deformation in the untreated condition to a more brittle-fracture of surfaces in the quenched condition. A comparison of average surface roughness (R_a) values taken from the as-received metal surface and wear tracks are shown in Table 1. These results indicate that the R_a values tend to increase with the severity of the quenching medium. The larger R_a values for the alloy quenched in water and liquid nitrogen indicate a rougher surface due to brittle-fracture of the surface. These changes in surface morphology were also evident in SEM analysis

Table 1 A comparison of surface profile measurements

Quenching medium	Average surface roughness (R_a/µm)
Surface of sample	0.09
Parent metal wear track	0.12
Oil quench	0.31
Water quench	0.56
Nitrogen quench	0.86

Fig. 5 Scanning electron micrographs taken from the wear tracks produced during the pin-on-plate wear test: (**a**) Untreated as-received alloy; (**b**) Sample quenched in oil; (**c**) Sample quenched in water; (**d**) Sample quenched in liquid N_2



of the wear tracks. This type of wear transition is well established in the literature, and has been identified as a cause for the increase in wear rate in ceramic materials [12].

Micro-hardness measurements were also taken from transverse sections through the wear tracks to compare the effect of strain hardening of the material due to changes in the plastic deformation behaviour between the as-received alloy and the samples quenched in liquid nitrogen. For these micro-hardness measurements, a load of 50 g was used to reveal surface hardening effects due to strain hardening. For the as-received alloy, a value of 553 VHN was measured from the region just below the wear track; in contrast, a value of 381 VHN was measured approximately 40 μm below the surface. In comparison, for the nitrogen-quenched surfaces a value of 407 VHN was recorded below the surface and a value of 391 VHN at 40 μm below the surface. These results suggest that the as-received alloy showed a greater strain hardening effect than the quenched surfaces. This strain hardening of material below the wear track will contribute to the wear resistant behaviour of the untreated titanium alloy. The SEM micrographs from the wear tracks, and micro-hardness measurements taken from under the wear tracks support the wear test results. The plasticity of the untreated titanium alloy and hence the strain hardening effect within the surface during wear tests will show an increase in wear resistance. Whilst the quenched surfaces show reduced plasticity within the surface and wear is dominated by brittle-fracture which results in a reduction in wear resistance of the surfaces. The effect of oxygen diffusion into the sub-surface structure could also contribute to a higher surface hardness value. In order to investigate the extent of oxygen diffusion into the titanium alloy, wavelength dispersive spectroscopy using an accelerating voltage of 15 kV (a depth of 1.5 μm) and 25 kV (a depth of 4 μm) was used to measure the oxygen concentration. Values of 10.4 wt% and 8.4 wt% were detected for the 15 kV and 25 kV analyses, respectively, showing that oxygen had diffused into the surface. However, the oxygen content will have decreased to an insignificant concentration at a depth of 40 μm, which is the point at which surface micro-hardness measurements were taken. This suggests that the hardness measurements taken from the treated surfaces reflect changes in strain hardening of the metal. These results indicate that quenching the titanium alloy reduces the wear resistance of the surface so that material loss by brittle-fracture dominates.

Conclusions

The use of a quenching medium such as water, oil and liquid nitrogen can be used to increase the surface hardness of a Ti–6Al–4V alloy from 400 VHN in the as-received condition to a value of 750–800 VHN depending on the quenching medium used. However, the increase in surface hardness does not result in an increase in the wear resistance of the alloy, but decreases it noticeably. This decrease in wear resistance is attributed to a change in wear mechanism from plastic deformation to a more brittle-fracture behaviour of the surface.

Acknowledgements One of the authors, C. Feng, would like to thank the Government of China for a Visiting Scholarship.

References

1. Huang JY, Zhu YT, Liao XZ, Beyerlein IJ, Bourke MA, Mitchell TE (2003) Mats Sci Eng A 339:241
2. Molinari A, Pellizzari M, Gialanella S, Straffelini G, Stiasny KH (2001) J Maters Process Techn 118:350
3. Uehara K, Kumagai S (1969) J Jpn Soc Precis Eng 35(9):73
4. Wang ZY, Rajurkar KP, Fan J (1996) Trans NAMRI/SME 24:3
5. Gill FJ, Manero JM, Ginebra MP, Planell JA (2003) Mats Sci Eng A 349:150
6. Jovanovic MT, Tadic S, Zec S, Misokovic Z, Bobic I (2006) Mater Design 27:192
7. Hong SY, Ding Y, Jeong W (2001) Int J Machine Tools Manufact 41:2271
8. Elder JE, Thanburaj R, Patnaik PC (1989) Surf Eng 5:55
9. Siahshani P (1990) JOM 3:30
10. Ahmed T, Rack HJ (1998) Mats Sci Eng A 243:206
11. Archard JF (1953) J Appl Phys 24:981
12. Conway JC, Pangborn RN, Cohen PH, Love DA (1988) Wear 126:79