Influence of Shot Peening Treatment on the Fatigue Life of Ti6Al4V ELI Biomedical Alloy

S. Amin-Yavari, A.A. Ziaei-Moayed, H.R. Madaah-Hoseini

Materials Science and Engineering Department, Sharif University of Technology, P.O. Box 11365-9466, Tehran 14584, Iran- Tel: +98 9126180877- Fax: +98 2166022721

ABSTRACT

Fatigue lives of shot peened specimens have been evaluated by Rotating – Bending fatigue tests at two stress levels of 625 and 675 MPa. Combination of surface work hardening, compressive residual stresses and surface roughness were obtained by changing the bead size and peening time. Compressive residual stresses, hardness and roughness were measured by X-ray diffraction, microhardness and profilometry. Fatigue lives at the optimum combination of the as mentioned parameters increased by 2.7 and 1.9 times in compare to unpeened surface life. Fracture surfaces were evaluated by Scanning Electron Microscopy.

It is found that, the effect of surface roughness among the three variables is more pronounced. Fractography of fatigue fracture surfaces with high fatigue lives showed that while crack nucleation site was shifted to subsurface layers, the nucleation site for the roughened specimens was again at the surface.

KEY WORDS: Ti6Al4V ELI alloy, fatigue, shot peening, compressive residual stress, surface roughness.

INTRODUCTION

Titanium alloy Ti6Al4V ELI has applications in a number of industries, specially as medical implants. Fatigue strength is an important property of an implant material. An artificial hip joint is exposed to a cyclic loading of around 3.5×10^6 cycles per year. Ti6Al4V ELI with extra low interstitials is the first titanium alloy registered as an implant material in ASTM standard (F-136-84) [1, 2].

It is well known that almost all fatigue cracks that initiate at surfaces may be attributed to a variety of surface stress concentration features. Therefore, control of surface crack initiation and growth by surface treatments is an effective means to enhance the fatigue performance of implanted devices.

In a shot peening treatment, metal surface is stretched radially, plastically deformed to cause depressions on the surface and make it rough. The depth of penetration extends to 0.13 to 0.25 mm, but it may extend to as much as 0.50 mm below the surface. This residual compressive stresses compensate the service-imposed tensile stress encountered in engineering parts to improve fatigue life in service markedly [3].

Nakamura et al [4] implied that the resistance to crack propagation at the surface is more effective on fatigue strength as compared with the resistance to crack initiation or propagation below the surface at an early stage

Nalla et al [5] and Wagner et al [6] believed that since work hardening primarily retards crack initiation, it is especially effective if the fatigue damage process is crack initiation controlled. Conversely, if mechanically surface treated components exhibit very rough surfaces, the fatigue damage process can be considered crack propagation controlled, requiring pronounced and stable compressive residual stresses in order to improve fatigue strength and life significantly.

METHODS:

The chemical composition of (in Wt %) Ti6Al4V ELI alloy used in the present study (ZAP Company, Germany) is given in Table 1.

Table 1 Chemical composition of alloy Ti6Al4V ELI

Ti	Al	V	Fe	C	O	N	H
balance	5.98	4.02	0.17	0.02	0.11	0.01	0.005- 0.0125

The alloy in as-received condition has hardness of 34 HRC, yield strength of 806 MPa, ultimate tensile of 978 MPa and elongation to fracture of 12%. The material was solution treated at 1050˚C for 1 hr followed by air-cooling. Table 2 shows the three types of beads used in suction blasting process.

Table 2 Properties of peening beads

Name of beads	Type of beads	Hardness (HRC)	Average Size (mm)
WS110	Shot	46-51	0.3
WGP080	Grit	48-52	0.18
WGP050	Grit	48-52	0.35

The distance between the tip of nozzle to work piece surface, diameter of nozzle, peening pressure and peening angle were 300mm, 8mm, 4 bar and 70˚, respectively. Surface roughness and Vickers hardness were measured on both as-received and shot peened specimens. Residual stresses of peened surfaces were measured by X-ray diffraction and $\sin^2 \psi$ technique. For each specimen, nine residual stress measurements with an average error of 10 MPa were made at negative and zero degrees of ψ.

The depth of plastic deformation of shot peened surfaces were evaluated base on hardness measurements on the cross sections.

Standard dog bone fatigue specimens were tested in rotating bending fatigue tests (R=-1) at frequency of 50 Hz at room temperature. The fracture surfaces of the fatigue specimens were studied by Scanning Electron Microscopy.

RESULT:

Table 3 shows the exposure time, Almen intensity and roughness of the shot peened surface with different types of beads.

Table 3 Properties of peened surfaces

Specimen Name	Name of Beads	Exposure Time (seconds)	Almen Intensity (N)	Surface Roughness (µm)	
				R_a	R_z
A	WS110	5	20	1.17	9.07
B	WGP080	5	15	1.91	15.7
C	WGP050	5	21	2.77	20.9
D	WS110	30	26	1.2	8.78
E	WGP080	30	22	1.83	15.8
F	WGP050	30	37	2.75	19.5
as received (Unpeened)				0.095	1.1

Almen intensity at two shot peening times for three shot peening beads is shown in Fig 1.

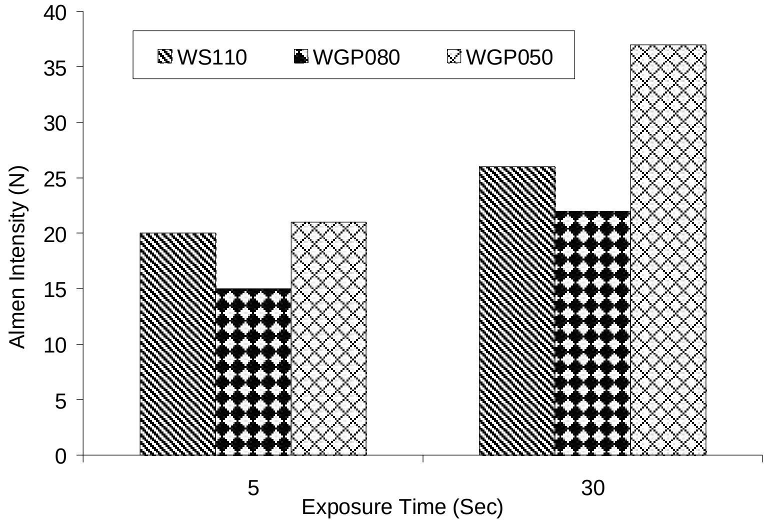

Fig 1 Almen intensity versus exposure time for various beads

At 30 seconds using the greater size of beads, WGP050, leads to a higher Almen intensity. Surface roughness of shot peened specimens at 5 and 30 seconds using three different blasting beads WS110, WGP080 and WGP050 are shown in Fig 2.

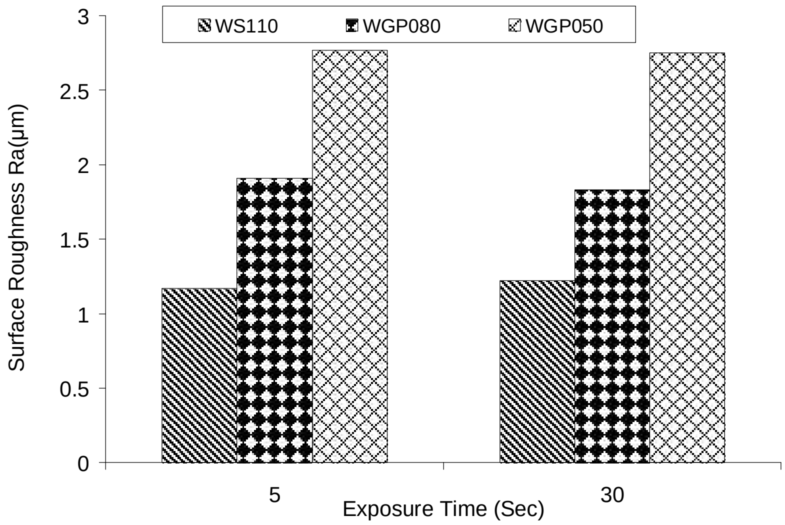

Fig 2 surface roughness versus exposure time for various beads

As illustrated, surface roughnesses of shot peened specimens are mostly influenced by the size of blasting beads including size and geometry of grits [8, 9]. Among the three grits were used, WGP050 with the largest sizes with sharper edges produce the most roughened surface. The specimen A exhibits the lowest value of surface roughness while specimens C and F possess the highest value of surface roughnesses.

During overpeening, (increase in shot peening time), the surface roughnesses of two specimens prepared by two beads are almost equal.

Residual stress and surface hardness of shot peened specimens are shown in Table 4. The specimens A, D and E, have the highest residual stresses. But the amount of surface hardness is highest only for specimens A and D in specimens B, C and F, either the residual stress or the surface hardness is low.

Table 4 surface compressive residual stress and microhardness of specimens A to F.

Seri of Specimens	Surface Compressive Residual Stress (MPa)	Surface Microhardness (HV)
A	-702	397
B	-424	354
C	-515	351
D	-786	407
E	-823	374
F	-631	360
as received	-12	336

Table 5 shows the number of cycles to failure (N_f) of shot peened specimens with as-received microstructure at applied stresses of 625 and 675 MPa.

Table 5 Number of failure cycles for different specimens

Specimen	Number of Failure Cycles	
	σ = 625MPa	σ = 675MPa
A	5.2×10^6	3.6×10^6
B	3.6×10^6	1.5×10^6
C	3.4×10^6	3.6×10^5
D	5.3×10^6	5.2×10^6
E	5.1×10^6	3.6×10^6
F	1.8×10^6	4.8×10^5
as	2.8×10^6	1.9×10^6

DISCUSSION:

Fatigue performance of shot peened surfaces is influenced by the surface work hardening, surface compression residual stresses and surface roughness [10, 11]. Specimens A and D on their surface have the highest amount of work hardening and compressive residual stress (Table 4). Therefore, it is expected the fatigue lives of specimens A and D to be the highest at applied stresses of 625 and 675 MPa in compare to as-received one (Table 5).

For these two specimens, the amount of surface roughness is at the lowest possible value of 1.17 and 1.22 µm, respectively, which reflect the important effect, that surface roughness on the fatigue performance. Beside that, the amount of Almen intensity were 20 and 26 for specimens A and D, respectively, are in the medium range of Almen intensities are used in this study (15 to 37). This reflects the importance to achieve best fatigue performance at medium shot peened surfaces at medium Almen intensities.

Also fatigue life of specimen D at applied stress of 675MPa is very close to 625 MPa. This is the result of optimum combination of surface work hardening, surface compression residual stresses and surface roughness (lowest value) in specimen D. Fatigue lives of specimens A and as-received, both show decrease in fatigue lives with increase in stress from 625 to 675 MPa.

Specimen E exceptionally at 625 MPa has the same life as specimens A and D. This can be attributed to the presence of the highest value of surface compression residual stresses. The fatigue life of specimen E at 675 MPa decreased due to the relaxation of surface compression residual stresses. In the high range of applied stress close to LCF[1], due to the presence of high roughness and stress concentration, the stress exceeds the yield stress. Local plastic deformation occurs and leads to

[1] Low Cycle Fatigue

recovery of the work hardened surface and relaxation of surface compression residual stresses.
Specimen C has comparable life to as-received one at 625 MPa, but its fatigue life at 675 MPa has reduced significantly. This may be attributed to the presence of low surface work hardening and low amount of surface compression residual stresses (Table 4). Above considerations show that the fatigue strength or fatigue life of shot peened surfaces are influenced by the three main features of surface work hardening, surface compression residual stresses and surface roughness. In specimen F, although the amount of surface work hardening and surface compression residual stresses is not as low as specimen B, but the surface roughness is so great that it overrides the effects of the other two existing features. In other words, while fatigue strength/ fatigue life is "nucleation of crack" control at the surface, the prerequisites to have optimum fatigue life is to have low or medium value of surface roughnesses along with highly work hardened surface and presence of high surface compression residual stresses.

Fractographic study of fatigue fracture surface of as-received and shot peened specimens at different shot peening conditions shows typical fatigue fracture surface with striations and crack nucleation at the surface (Fig 3).

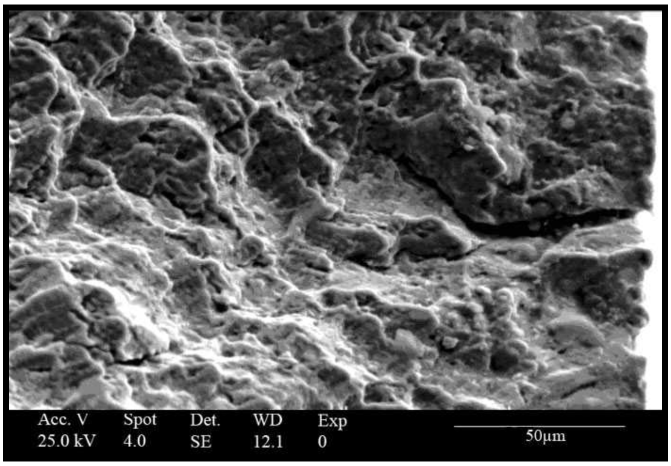

Fig 3 Crack nucleation on the surface of the specimen as received

For shot peened specimens at optimum peening condition (specimen D), crack nucleation site is transformed to the subsurface layers (Fig 4). The place crack nucleation is accompanied by subsurface crack branching. In specimens with the low roughened surface, crack nucleation is transferred to subsurface layers.

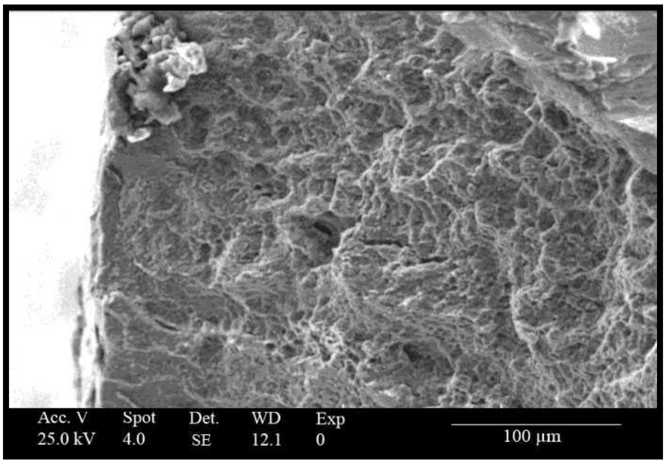

Fig 4 Crack nucleation beneath the surface of the shot peened specimen

The combined beneficial effects of surface work hardening, compressive residual stresses up to certain levels along with moderate surface roughness under a threshold value are responsible to increase the fatigue life of a peened surface such as specimen D.

CONCLUSION:

The results of present study are summarized as follows:

1- The optimum combination of surface work hardening (or work hardened surface), surface compressive residual stresses and roughness of 1.2 and 1.17 µm in peening of Ti–6Al–4V ELI alloy specimens A&D leads to an increase in fatigue lives by 1.9 and 1.8 times compare to fatigue life of as-received specimen, respectively, at applied cyclic stress of 625 MPa.

2- Fatigue life of shot peened Ti–6Al–4V ELI alloy specimens D and A at applied cyclic stress of 675 MPa with optimum combination of work hardened surface, surface compressive residual stresses at roughness of 1.2 and 1.17 µm is increased by 2.7 and 1.9 times, respectively, compared to fatigue life of as-received specimen.

3- Fatigue lives at 625 and 675 MPa of shot peened Ti–6Al–4V ELI alloy, specimens E, with combination of moderate surface work hardening , moderate surface compressive residual stresses and high roughness of 1.83 are increased only by of 1.8 and 1.9 times, respectively, compared to fatigue life of as-received specimens.

4- Fatigue lives of shot peened specimens C and F, due to high value of surface roughness, even in the presence of suitable combination of surface work hardening and surface residual compressive stresses are even lower than as-received specimen.

5- Fractography of fatigue fracture surfaces of specimens with high fatigue lives show that crack nucleation site is switched to subsurface layers, while nucleation site for the roughened specimens is again at the surface.

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