Effects of Shot Peening on Fatigue of Ti-6Al-4V Powder Compacts

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ABSTRACT

The effects of shot peening on fatigue of both blended elemental and prealloyed Ti-6Al-4V powder compacts were studied. Low intensity (6N and 12N) shot peening was not successful in closing surface porosity in the blended elemental material. Fatigue strength improvement resulted from shot peening despite the fact that fatigue crack initiation occurred at surface and near-surface pores as was the case for unpeened material. High intensity (10-12A) shot peening followed by recrystallization annealing produced a desirable surface microstructural condition in the prealloyed material; however, the fatigue strength was lower than for the unpeened condition. Fractography and metallography were performed to aid in understanding of the influence of shot peening on fatigue crack initiation mechanisms.

Key words: shot peening, fatigue, titanium, powder.

INTRODUCTION

Titanium alloy powder metallurgy (PM) technology has matured to a state of availability of commercial products for aerospace and other industrial applications (Parsons, 1983). Prices and properties of such PM products are now competitive with articles produced by conventional ingot metallurgy (IM) technology (Froes, 1980; Eylon, 1983). Titanium alloy PM technology is subdivided into two major areas: Prealloyed PM which provides fully dense compacted materials with mechanical properties equal to or exceeding those of corresponding conventional IM materials and Blended Elemental (BE) PM which provides compacted materials with good static strength properties (Andersen, 1981) but somewhat lower fatigue strength than those of corresponding conventional IM materials. Both prealloyed and BE Ti-6Al-4V materials were employed in this study.

The overall objective in this work was to employ shot peening as a possible means for improving fatigue strength of PM Ti-6Al-4V materials. Because of different inherent microstructural features arising from processing, the purposes for and implementation of shot peening were different for the BE and prealloyed Ti-6Al-4V materials.

The objective in work performed on the BE Ti-6Al-4V was to determine whether shot peening would close surface porosity and, thereby, improve fatigue strength. The motivation for this is that BE technology offers a means to produce low cost components because low cost powder (sponge fines) is used with low cost processing by cold pressing and sintering (Froes, 1980). Also, production of close-to-net shape components eliminates much costly machining and finishing attendant with components produced by IM (Eylon, 1980); however inherent residual porosity currently limits application of BE materials to components wherein fatigue resistance is not of critical concern. Surface and near-surface porosity have been identified as the main factors resulting in low fatigue strength in BE relative to IM materials (Froes, 1981).

The objective in work performed on the prealloyed Ti-6Al-4V was to determine whether shot peening plus subsequent thermal treatment would produce a surface microstructure superior in fatigue resistance to the bulk microstructure since the bulk microstructure contains lenticular alpha-phase platelets which are undesirable for fatigue crack initiation resistance. The motivation for this was the observation in previous work that Ti-6Al-4V microstructures tending toward equiaxed primary alpha-phase platelets exhibit better fatigue crack initiation resistance than those with lenticular alpha (Kerr, 1976; Eylon, 1978). The possibility of such microstructural modification by shot peening to plastically deform surface layers followed by recrystallization annealing offered a potentially attractive means to improve fatigue strength.

MATERIALS AND PROCEDURES

Cold pressed and sintered BE Ti-6Al-4V compacts were produced by Imperial Clevite, Inc. High cycle fatigue specimens with threaded ends and cylindrical gage sections of 5 mm (0.2 in.) diameter x 31 mm (1.25 in.) long were machined from the compacts. The subsequent processing of the fatigue specimens is indicated in Table I. The baseline condition represents finish machining by gentle grinding and longitudinal polishing with successive grades of SiC abrasive papers down to 600 grit. Vacuum stress relief (620°C/2 hr) was performed on some of the shot peened specimens to check whether any fatigue improvement in shot peened specimens over baseline was the result of possible surface structural alterations or residual stresses.

The prealloyed Ti-6Al-4V material was compacted by Colt Crucible Corporation from rotating electrode process (REP) powder. High cycle fatigue specimens of the same geometry as for BE Ti-6Al-4V were machined from the compacts. The subsequent processing of the fatigue specimens is shown in Table II. The baseline condition represents the same finishing, grinding, and polishing procedures as employed for BE Ti-6Al-4V specimens. As mentioned previously the shot peening followed by recrystallization annealing (925°C/2 hr, slow cool) was performed to determine whether the resulting surface microstructural modification would improve fatigue resistance.

Fatigue testing was performed axially on servo-hydraulic universal test systems at room temperature in ambient air under constant load amplitude triangular waveform cycling at a frequency of 5 Hz with a load ratio, R, of 0.1. The BE Ti-6Al-4V specimens were tested at various maximum stress levels to produce S-N curves representing each condition. Because of the relatively small number of prealloyed Ti-6Al-4V specimens available for study, two specimens in each condition were tested all at a maximum stress level of 550MPa (80ksi). After fatigue testing all fracture surfaces were examined by scanning electron microscopy (SEM) to study the nature of crack initiation sites. SEM was also employed to examine the external surfaces of specimens. In addition, optical metallographic examinations were performed on selected specimens.

RESULTS AND DISCUSSION

Fatigue S-N curves for the BE Ti-6Al-4V material in various conditions are shown in Figure 1. The data representing the baseline condition (gently ground and polished) were found to be in agreement with data from previous work (Froes, 1980; Andersen, 1981; Froes, 1981). Both the 6N and 12N shot peened conditions generally exhibited higher fatigue strength than the baseline condition with the 12N shot peening condition exhibiting higher fatigue strength than the 6N condition. On the other hand, the two shot peened plus stress relieved conditions exhibited lower fatigue strength than the baseline condition. This finding indicates that the fatigue strength improvement from shot peening is the result of compressive residual stresses in the surface layers as found previously (Koster, 1981). Further support for this argument arises from the observation of greater fatigue strength improvement with the higher (12N) shot peening intensity over the lower (6N) shot peening intensity. Measurement of residual stresses was not included in the scope of this work.

Despite the definite indication of a favorable influence of residual stresses in surface layers on fatigue strength, SEM fractographic evaluation of the specimens revealed that a clear majority of specimens failed as a result of surface crack initiation. Also, crack initiation in nearly all specimens was associated with surface or near-surface pores regardless of surface condition. Fractographic observations are summarized in Table III. A typical example of fatigue crack initiation from a surface pore is shown in Figure 2.

Comparison of photomicrographs in Figures 2b and 2c indicate that shot peening induced no surface microstructural alterations beyond slight surface plastic deformation. The shot peening did, however, tend to close surface porosity as may be seen in Figure 3. Figure 3a illustrates the baseline condition with roughly spherical surface pores. Figure 3b depicts the 6N shot peened condition with partially closed surface porosity while Figure 3c depicts the 12N shot peened condition with nearly fully closed surface porosity. As noted above, despite this observed influence of shot peening on closure of porosity, fatigue crack initiation in shot peened specimens still occurred principally at surface or near surface pore locations.

The stress relief thermal treatment (620°C/2 hr) after shot peening appeared to give rise to morphological surface changes. As illustrated in Figure 3d, no evidence of deformed surface pores remained after stress relief. This may be the result of localized recrystallization and/or pore healing. Fractographic observations (Table III) indicated that early fatigue crack progression in shot peened plus stress relieved specimens was associated with subsurface pores. Micrographs of a section normal to a fatigue crack shown in Figure 4 indicate that such cracks initiated at surface alpha grains in what appears to be a shear across the grains. Some of these cracks appeared to link with near-surface pores resulting in crack tip blunting.

While the intended purpose of shot peening the BE Ti-6Al-4V material was to close surface porosity, the intended purpose of shot peening the prealloyed Ti-6Al-4V material was to produce sufficient surface plastic deformation which would promote recrystallization upon subsequent thermal treatment (925°C/2 hr, slow cool). As may be noted from Figure 2, the 6N and 12N shot peening produced very little detectable plastic deformation in BE material. Subsequently, it was found that shot peening of the prealloyed Ti-6Al-4V material at high intensity (10-12A) followed by the recrystallization anneal thermal treatment would result in formation of a recrystallized surface layer of the order of 20-30μm in depth. The appearance of such a layer is illustrated by the micrograph in Figure 5. Note the presence of roughly equiaxed alpha grains near the surface as contrasted with the lenticular alpha platelets more than 30μm from the surface. In the absence of other influences, e.g., residual stresses, the surface microstructure is considered to be more resistant to fatigue crack initiation than the bulk.

Fatigue results for the prealloyed Ti-6Al-4V material are presented in Table IV. Comparisons among conditions lead to the following observations:

(1) The 10-12A shot peened condition (No. 2) resulted in lower fatigue life than the baseline condition (No. 1) despite the presumed favorable residual stresses induced by shot peening.

(2) Longitudinal polishing sufficient to remove visible surface roughness after shot peening (No. 4) restored fatigue life to at least the baseline level. This and the previous observation are consistent with previous work (Mahajan, 1980) in which it was indicated that surface damage from 10-12A shot peening lowered the fatigue strength of Ti-6Al-2Sn-4Zn-2Mo material. It should also be noted that the 10-12A shot peening intensity is above the 6-8A intensity level commonly employed for shot peening Ti-6Al-4V components in the aerospace industry. Despite this knowledge, the 10-12A intensity was employed in the current work because the 6-8A intensity level did not produce sufficient surface plastic deformations to give a uniformly present recrystallized surface layer after thermal treatment.

(3) Recrystallization annealing (925°C/2 hr, vacuum, slow cool), after shot peening (Conditions 3 and 6) after shot peening and polishing (Condition 5) and after baseline grinding and polishing (Condition 7) resulted in much lower fatigue strength than the baseline condition. Apparently, the removal of compressive residual stresses resulting from shot peening is much more detrimental to fatigue resistance than is the intended favorable influence of surface microstructural alteration. In view of the limited quantity of data, not too much should be made of difference in fatigue life among these conditions; however, a ranking in descending order of fatigue life (Condition 7, Condition 5, Condition 3, Condition 6) does support the argument of influence of surface damage (in the presumed absence of residual stresses) on the results.

SEM fractography revealed that surface fatigue crack initiation had occurred in all prealloyed Ti-6Al-4V PM specimens regardless of condition. A typical fracture initiation site is shown in Figure 6a. Shown in Figure 6b is the appearance of the shot peened surface adjacent to the fracture origins. The much greater surface roughening and deformation associated with 10-12A shot peening of the prealloyed PM Ti-6Al-4V than with 6N or 12N shot peening of the BE PM Ti-6Al-4V may be seen by comparing Figure 6b with Figures 3b and 3c.

SUMMARY

The overall objective in this work was to employ shot peening as a possible means for improving fatigue strength in BE and prealloyed Ti-6Al-4V compacted materials. In the BE material shot peening was employed specifically in an attempt to close surface porosity which is responsible for early crack initiation. In the prealloyed material, shot peening plus a recrystallization thermal treatment was employed to produce a surface layer with a microstructure of equiaxed alpha grains.

Specific findings from BE material were:

(1) Shot peening at 6N and 12N intensities resulted in partial closure of surface porosity and in improved fatigue strength relative to unpeened material.

(2) Despite fatigue strength improvement, fatigue crack initiation in peened material still occurred at surface and near-surface porosity.

(3) Thermal stress relief at 620°C after shot peening appeared to heal surface porosity; however, fatigue strength was lowered relative to shot peened and unpeened material.

Specific findings from prealloyed material were:

(1) Shot peening at 10-12A intensity followed by recrystallization annealing at 925°C produced a surface layer of equiaxed alpha grains about 20-30μm in thickness.

(2) Despite the microstructural modification, fatigue life after shot peening and recrystallization annealing was degraded relative to the unpeened condition.

(3) Shot peening at 10-12A intensity lowered fatigue life slightly relative to the unpeened condition. Polishing to remove surface roughness from shot peening restored fatigue life to at least the same level as the unpeened condition.

(4) Fatigue crack initiation occurred at specimen surfaces for all conditions.

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TABLE I. BE Ti-6Al-4V Specimen Conditions

Condition No.	Almen Intensity[a]	Thermal Stress Relief	Condition
1	-	-	Baseline
2	6N	-	6N shot peen
3	12N	-	12N shot peen
4	6N	620°C/2 hr (vacuum)	6N shot peen + stress relief
5	12N	620°C/2 hr (vacuum)	12N shot peen + stress relief

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[a] 100% coverage, S110 hardened steel shot.

TABLE II. Prealloyed Ti-6Al-4V Specimen Conditions

Condition No.	Almen Intensity[a]	Recrystallization Anneal	Condition[b]
1	-	-	Baseline
2	10-12A	-	10-12A shot peen
3	10-12A	925°C/2 hr (vacuum)	10-12A shot peen + Rx anneal
4	10-12A	925°C/2 hr (vacuum)	10-12A shot peen + polish + Rx anneal
5	5-7C	925°C/2 hr (vacuum)	5-7C shot peen + Rx anneal
6	10-12A	-	10-12A shot peen + polish
7	-	925°C/2 hr (vacuum)	Baseline + Rx anneal

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[a] 125% coverage, S110 hardened steel shot.

[b] Rx denotes recrystallization.

TABLE III. Nature of Fatigue Crack Initiation in Ti-6Al-4V BE PM Specimens

Cond No.	Number of Specimens Examined	Pore[a] Initiation No.	(%)	Contaminant Initiation No.	(%)	Microstructural Initiation[b] No.	(%)	Surface Initiation No.	(%)	Near Surface[c] Initiation No.	(%)
1	8	8	(100)			-	-	7	(88)	1	(12)
2	8	7	(88)			1	(12)	6	(75)	2	(25)
3	6	6	(100)			-	-	3	(50)	3	(50)
4	8	8	(100)			-	-	7	(88)	1	(12)
5	7	6	(86)	1	(14)	-	-	4	(57)	3	(43)
TOTAL	37	35	(94)	1	(3)	1	(3)	27	(73)	10	(27)

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[a] Includes also pores with contaminants.

[b] No relation to pore or contaminant.

[c] 10 to 100 microns below surface.

TABLE IV. Prealloyed Ti-6Al-4V Fatigue Results

(550MPa maximum stress, R = 0.1)

Condition No.	Condition[a]	Cycles to Fracture
1	Baseline	2,500,000[b] 2,500,000[b]
2	10-12A shot peen	1,569,000 1,238,000
3	10-12A shot peen + Rx anneal	64,500 42,500
4	10-12A shot peen + polish	2,500,000[b] 2,500,000[b]
5	10-12A shot peen + polish + Rx anneal	49,700 89,500
6	5-7C shot peen + Rx anneal	38,300 33,400
7	Baseline + Rx anneal	78,100 591,400

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[a] Rx denotes recrystallization.

[b] Specimen did not fracture; test terminated after indicated number of load cycles.

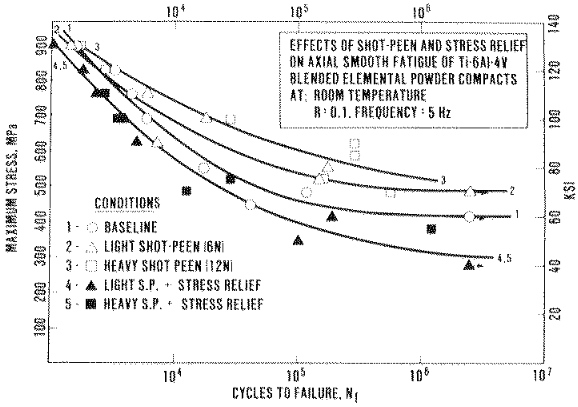

Figure 1. Fatigue S-N curves for BE Ti-6Al-4V.

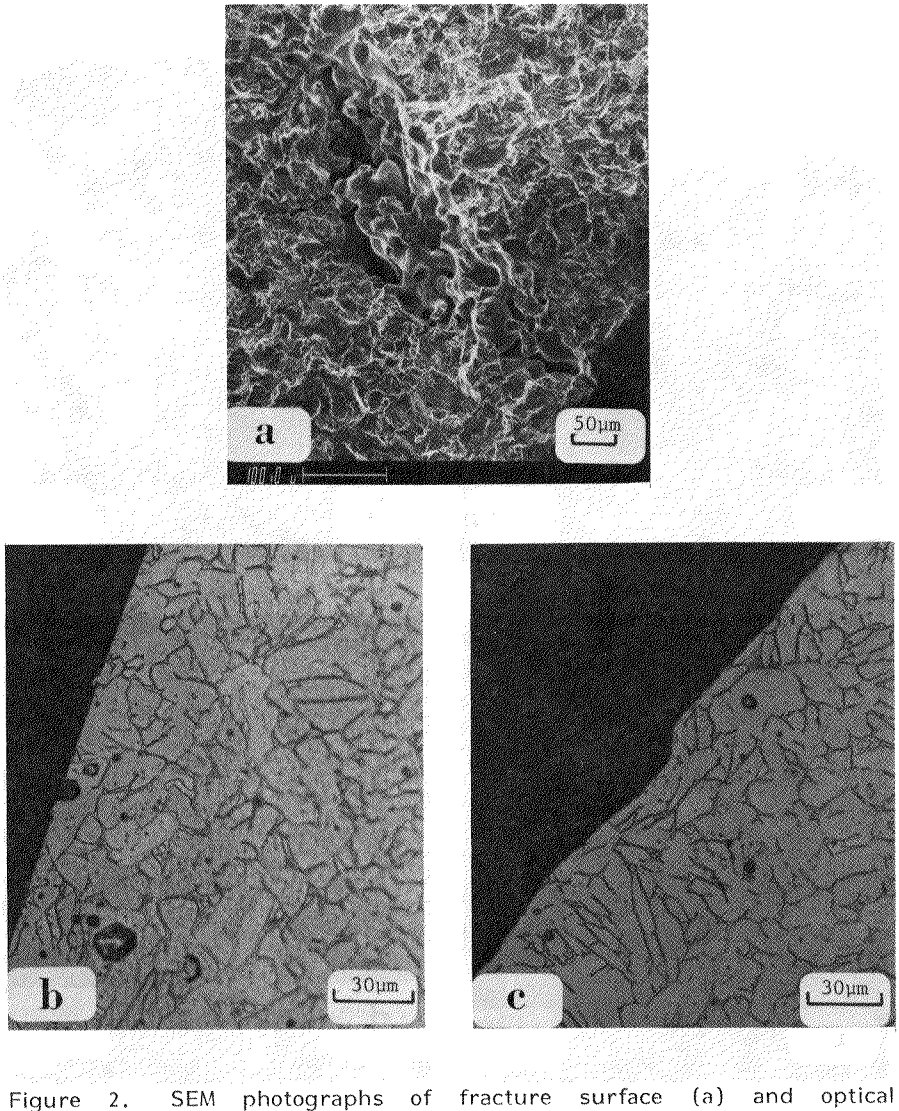

Figure 2. SEM photographs of fracture surface (a) and optical photomicrographs of BE Ti-6Al-4V; (b) unpeened; (c) shot peened, 12N.

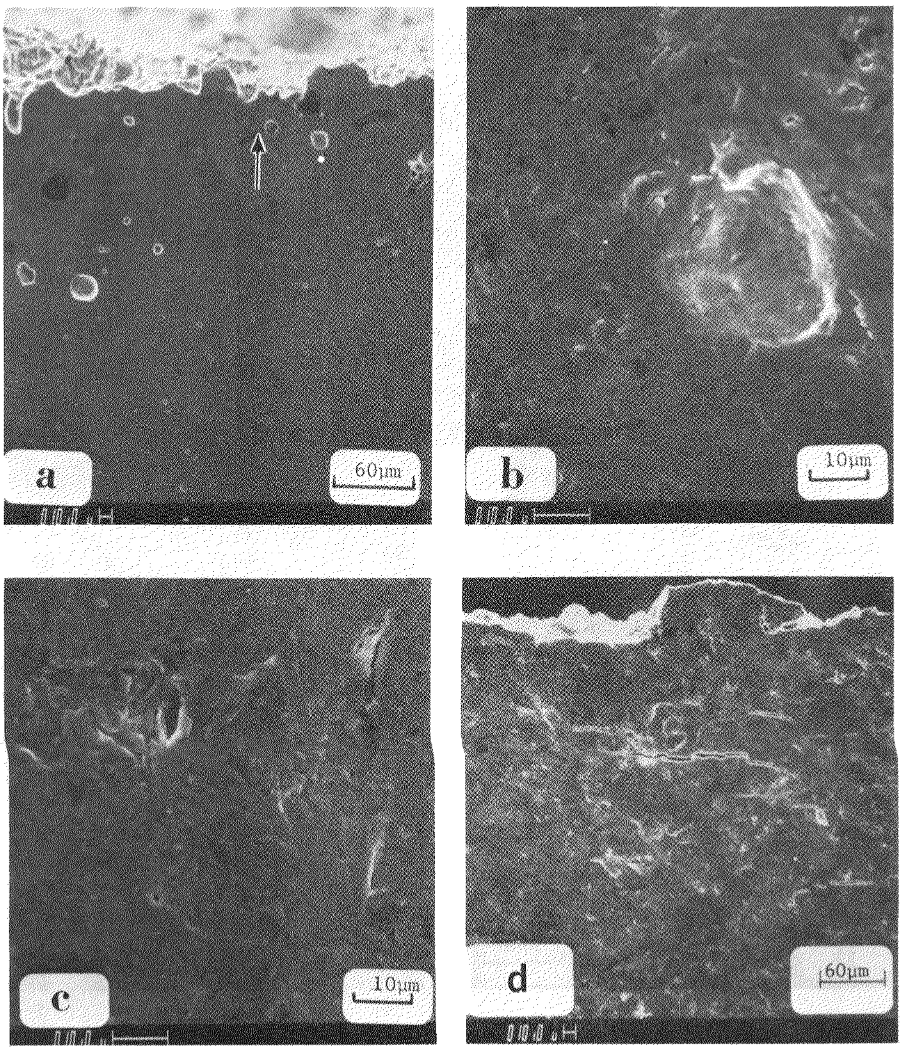

Figure 3. SEM photographs of BE Ti-6Al-4V fatigue specimens. (a) unpeened; (b) shot peened, 6N; (c) shot peened, 12N; (d) shot peened, 6N plus stress relief (620°C/2 hr.).

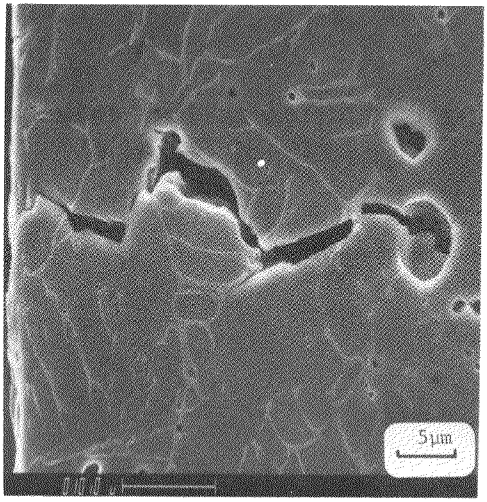

Figure 4. SEM photograph of section normal to small fatigue crack in BE Ti-6Al-4V specimen.

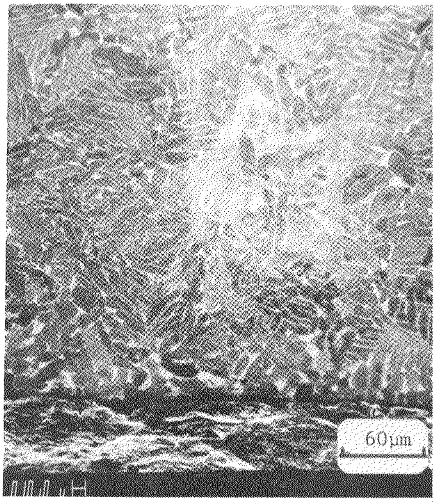

Figure 5. SEM micrograph of metallographic section of prealloyed Ti-6Al-4V showing recrystallized surface after 10-12A shot peening and annealing.

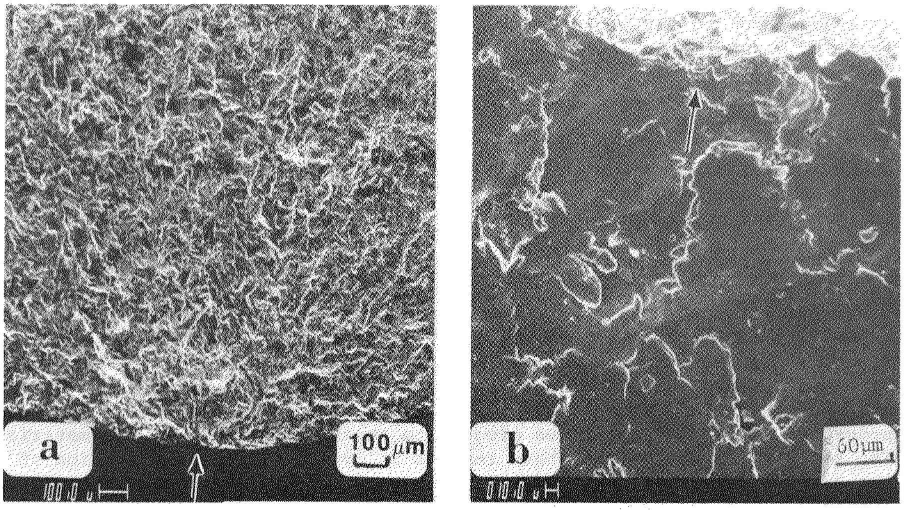

Figure 6. SEM photograph of fracture surface (a) and adjacent external shot peened surface (b) of prealloyed Ti-6Al-4V fatigue specimen.