Influence of shot peening on tension–tension fatigue property of two high strength Ti alloys

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Surface roughness, residual compressive stress caused by shot peening and the effect of shot peening on fatigue property of Ti–5Al–5Mo–5V–1Cr–1Fe (TC18) and Ti–10V–2Fe–3Al (TB6) titanium alloys were investigated. The results show that fatigue limit for 1×10^7 cycles can be increased by 27 and 29% for TC18 and TB6 titanium alloys respectively. By comparing fatigue life under the same stress for different shot peening regimes treated specimens, the optimum shot peening process was determined. For a given material, there is an optimal shot peening intensity, and insufficient shot peening and over shot peening will not result in good fatigue performance. However, double shot peening, a shot peening process by which parts are peened initially with cast iron shot to induce a deep residual compressive stress field, followed by shot peening with glass shot to decrease the surface roughness and to remove the contaminants caused by the cast iron shot, can significantly improve fatigue performance.

Keywords: Titanium alloy, Shot peening, Fatigue, Residual stresses

Introduction

Titanium alloys are widely applied in aerospace industry because of their remarkable characteristics: high strength to weight ratio, excellent corrosion resistance and good fatigue performance. Ti–6Al–4V (TC4) alloy is the most widely used titanium alloy and it occupies 80% in titanium industry.[1] To increase the strength and fatigue limit of titanium alloys and decrease the weight of airplane, high strength titanium alloys (when the tensile strength of a titanium alloy is >1000 MPa, it is called as high strength titanium alloys) were developed.[2,3] Among these high strength titanium alloys, there are two titanium alloys named Ti–5Al–5Mo–5V–1Cr–1Fe (TC18) and Ti–10V–2Fe–3Al (TB6), which are employed in aeronautical engineering. Ti–5Al–5Mo–5V–1Cr–1Fe (TC18) was produced in Russia in 1970s and it has a tensile strength as high as 1080 MPa under the annealed condition. Ti–10V–2Fe–3Al (TB6) was designed by TIMET Company in USA and it is a near β type of age hardened titanium alloy. TC18 and TB6 have similar features regarding composition design, processing and mechanical properties, but both of them have their own advantages: TC18 can be used to make heavy forgings because of its outstanding quenching performance and TB6 has a higher fracture toughness K_{IC} and lower forging temperature.

Surface modification is used to increase fatigue and stress corrosion cracking properties by the aeronautical industry.[4] Shot peening, hole cold expansion and screw or bolt cold rolling are cold work surface modification processes which are widely applied. In the present paper, the surface integrity change including surface roughness, surface residual stress and residual compressive stress in the surface layer and the effect of shot peening on tension–tension fatigue properties of TC18 and TB6 titanium alloys have been investigated.

Experimental

The two titanium alloys, TC18 and TB6, were employed and their chemical compositions are Ti–0·021C–5·06V–0·98Fe–5·10Al–0·020N–0·0027H–0·150O–5·14Mo–0·93Cr and Ti–0·014C–10·45V–1·70Fe–3·02Al–0·011N–0·0018H–0·086O respectively. Table 1 illustrates the tensile properties of these two titanium alloys after heat treatment. The microstructure of two titanium alloys is $\alpha+\beta$ but the β content for TB6 is higher.

The tension–tension fatigue specimens are notched specimens with a theoretical stress concentration factor $K_t=3$. The fatigue tests were performed with a 10 t type fatigue test equipment at a stress ratio $R=0{\cdot}06$, with a minimum stress to maximum stress at room temperature and at a frequency of 150 Hz. Comparing the fatigue life of specimens after different shot peening conditions with unpeened material under the same stress provides the optimum shot peening technique to improve the fatigue properties. Three specimens as a group were selected to get the mean fatigue life. The fatigue life comparison tests were performed under the same stress 520 MPa. The fatigue limit for 1×10^7 cycles was determined by the push–pull method.[5] Relevant parts of the specimens were correctly shot peened (with Almen strip A arc height of 0·35 mm/0·15 mm and coverage of 200%) with a pneumatic machine.

The residual stress was measured using the Stress Tech X-stress 3000 equipment (Stresstech, Finland). The

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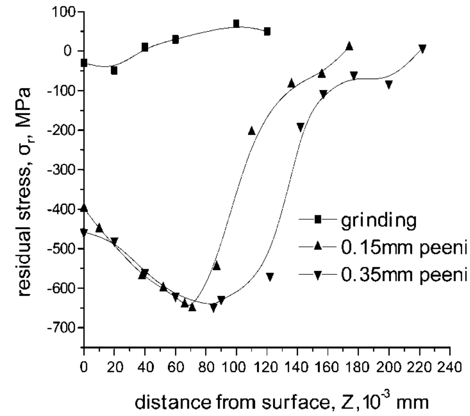
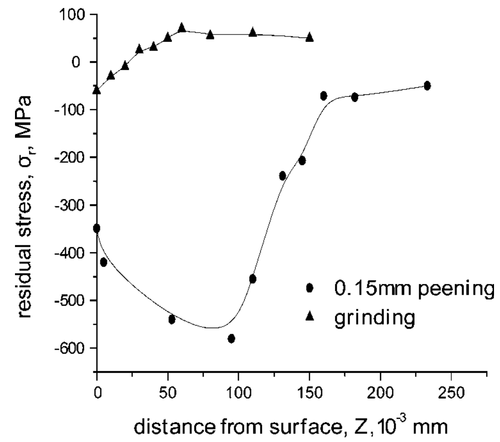
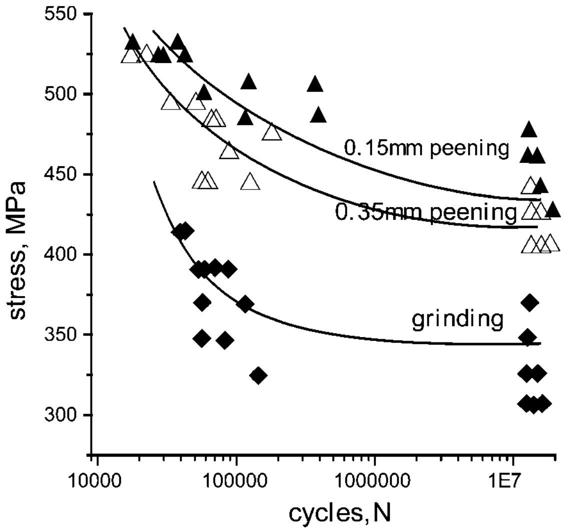


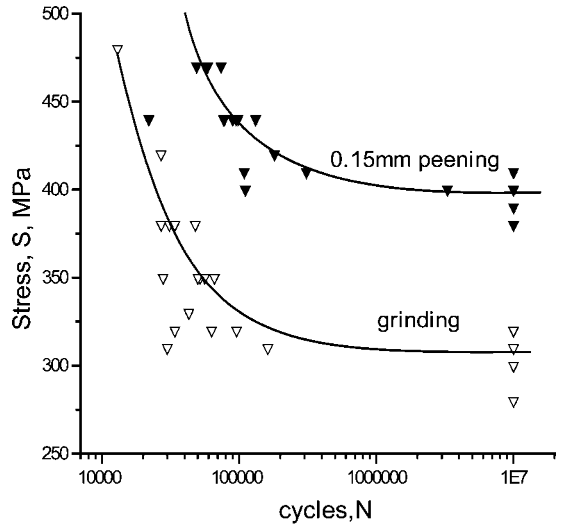
1 Residual stress field in TC18 alloy



2 Residual stress field in TB6 alloy



3 S–N curves in TC18 alloy



4 S–N curves in TB6 alloy

diffraction crystal line is (110) and X-ray tube is Ti K_α target. The residual stress field was determined by measuring layer by layer using the electropolishing method.[6] The surface topography and fracture surfaces of broken specimens which were tested under a stress level a little higher than the apparent fatigue limit and with a fatigue life of $\sim 5\times 10^5$ cycles were analysed by SEM.

Results and discussion

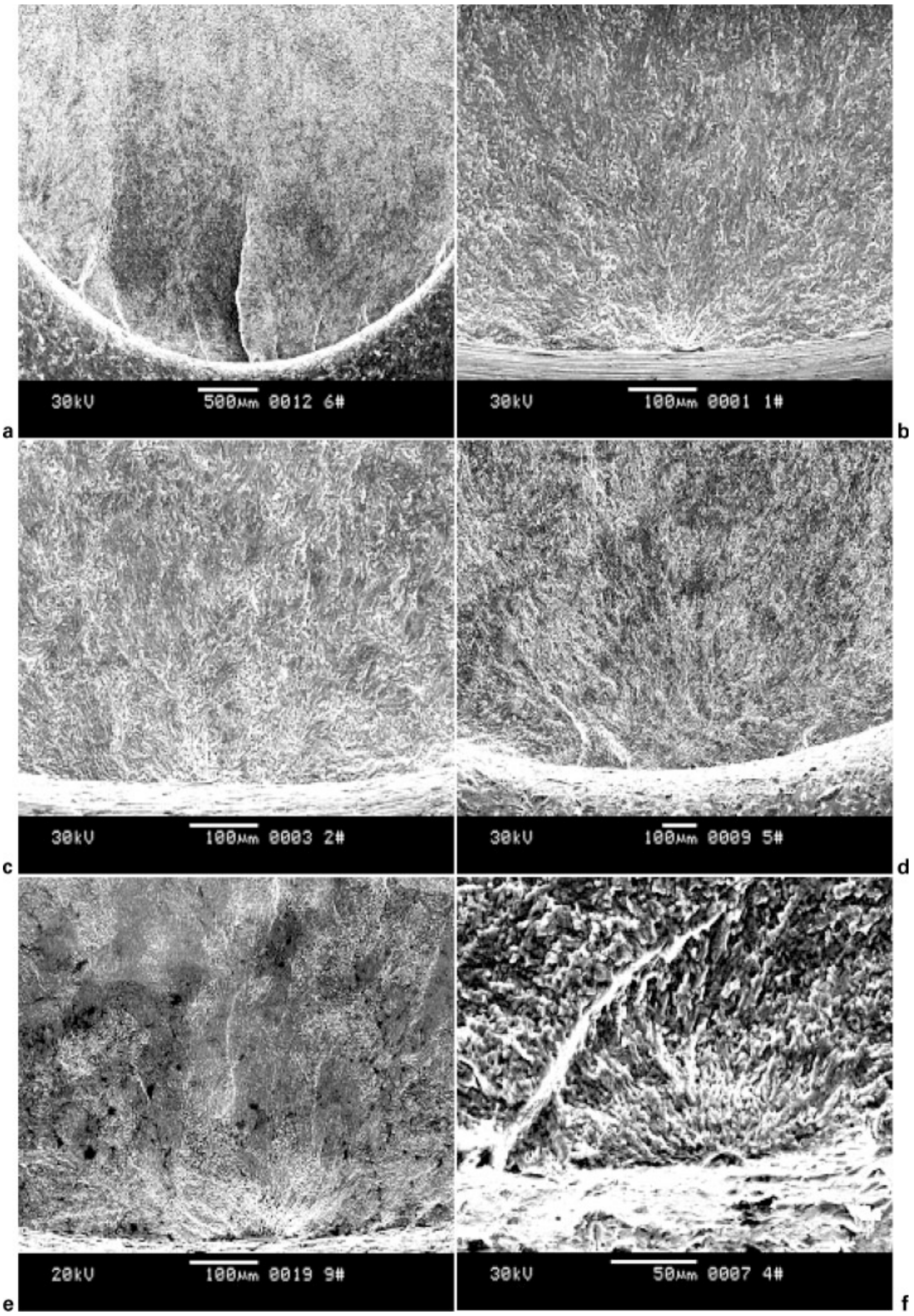
Some typical residual stress fields are shown in Figs. 1 and 2. Figures 3 and 4 illustrate the effect of shot peening on the improvement in fatigue properties of TC18 and TB6 titanium alloys. Residual compressive stresses in the surface layer induced by shot peening is the main factor which can increase the fatigue life and fatigue limit,[10–12] but surface roughness also affects fatigue life, as shown in Table 3. Specimens peened preliminarily by cast iron shot and following by glass shot have the longest fatigue life under the same stress 520 MPa.

Comparison of the fatigue life under the same stress but for different shot peening regimes allows the optimum shot peening process to be determined. For a given material, there is an optimal shot peening intensity and insufficient–shot peening and over shot peening will not show good fatigue performance.[13] However, double shot peening, that is a shot peening process by which parts are peened initially with cast iron shot to induce a deeper residual compressive stress field followed by shot peening with glass shot to decrease surface roughness and remove the contaminants caused by cast iron shot can significantly improve fatigue performance as in Tables 2 and 3[13]

The fracture surfaces of the specimens are shown in Fig. 5. The fatigue cracks initiate in surface for all type of specimens, but for ground specimens, there are several cracks not just one in the surface and for shot peened specimens, there are one or two cracks in the surface, as shown in Fig. 5*a–f*. Although there are less

Table 1 Tensile properties of TC18 and TB6 titanium alloys

Material	Yield strength, MPa (0·2 offset)	Tensile strength, MPa	Percentage elongation, %	Percentage reduction of area, %
TC18	1172	1220	17·6	48·4
TB6	1082	1145	11·1	64·4



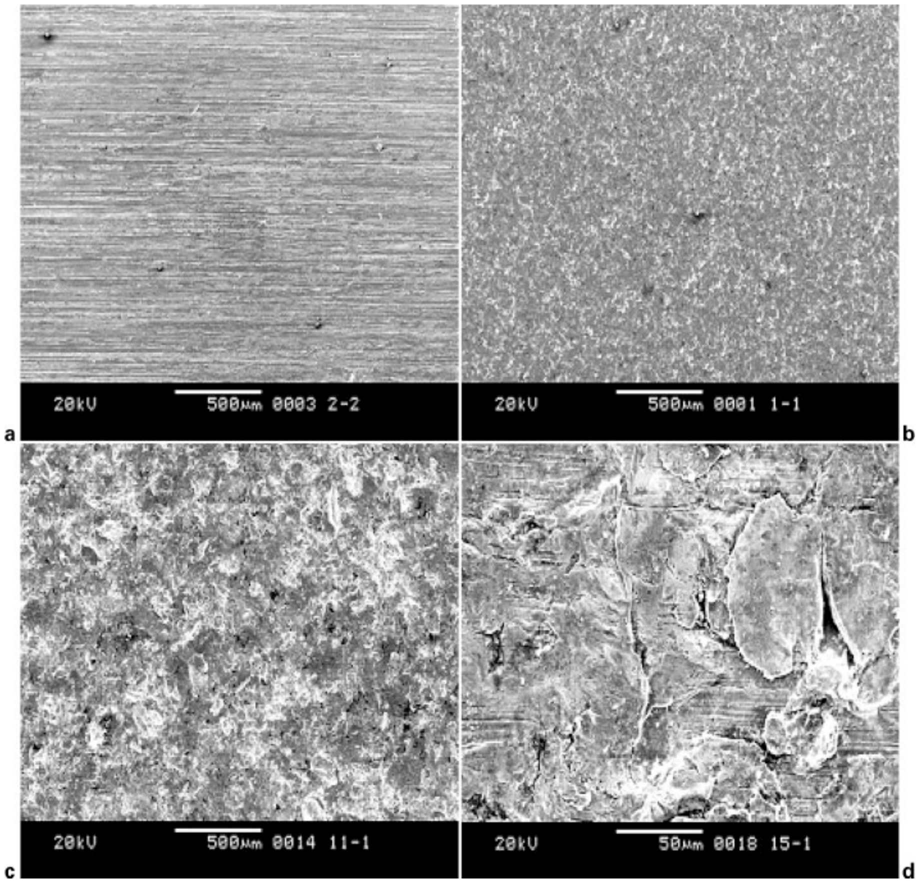
a **ground specimens;** ***b*** **TC18 double shot peened specimens;** ***c*** **TB6 double shot peened specimens;** ***d*** **TC18 0·15 mm glass shot peened specimens;** ***e*** **TC18 0·35 mm cast shot peened specimens;** ***f*** **TC18 0·45 mm cast peened specimens**

5 Fracture surfaces of broken specimens by SEM

cracks in the surface for shot peened specimens, the crack initiates either in a surface crater caused by the shot peening when the shot peening intensity is larger, i.e., as shown in Fig. 5*e* and *f*, or in a surface dent when the intensity is lower. Figure 6 shows the surface topography of the specimens. It can be seen that there are some microcracks caused by shot peening in the surface when the specimens are shot peened at shot peening intensity equal to 0·45 mm, as shown in Figs. 5*f* and Fig. 6*d*. Table 2 illustrates that the TC18 and TB6 titanium alloys are sensitive to surface roughness and residual stress. It is very difficult to separate quantitatively the effect of factors including cold work, cyclic hardening or softening and surface roughness or surface dents (caused by shot peening) on the fatigue properties, so the present paper only investigates the qualitative influence of shot peening on the fatigue properties.

Conclusions

1. The fatigue limit at 1×10^7 cycles can be increased by about 27 and 29% by shot peening for TC18 and TB6 titanium alloys respectively.
2. The fatigue properties of TC18 and TB6 titanium alloys are sensitive to surface roughness and residual stress and by employing surface modification processes such as shot peening can change the surface integrity of parts to improve fatigue performance.
3. Comparing the fatigue life under the same stress conditions for different shot peening regimes allows the



a ground specimens; *b* double shot peened specimens; *c* 0·35 mm cast shot peened specimens; *d* 0·45 mm cast shot peened specimens

6 Surface topography of specimens

Table 2 Fatigue life of different surface treated specimens under 520 MPa

Material	Surface Roughness Ra, 10^{-3} mm	Almen intensity (arc height of A type strip), mm	Shot type	Coverage, %	Fatigue life, $\times 10^4$
TC18	2·55–3·50	unpeened	–	–	2·6
TC18	5·42–6·84	0·45	Cast shot (CS)	200	1·3
TC18	4·18–5·27	0·40	CS	200	1·8
TC18	3·55–4·81	0·35	CS	200	2·5
TC18	2·80–3·48	0·30	CS	200	4·7
TC18	2·23–3·61	0·25	CS	200	4·1
TC18	2·35–3·52	0·20	CS	200	3·6
TC18	2·21–3·24	0·15	CS	200	3·6
TC18	2·25–3·48	0·10	CS	200	3·1
TC18	2·14–3·40	0·35	Glass shot (GS)	200	4·8
TC18	1·52–2·61	0·15	GS	200	9·5
TC18	1·45–2·57	0·10	GS	200	4·5
TC18	2·91–3·58	0·3+0·35	CS+GS	200	5·6
TC18	1·35–2·84	0·3+0·15	CS+GS	200	4·9
TB6	2·62–3·47	unpeened	—	—	2·1
TB6	2·72–3·40	0·3+0·35	CS+GS	200	5·0
TB6	1·48–2·61	0·3+0·15	CS+GS	200	7·3

Table 3 Fatigue limits for TC18 and TB6 titanium alloys

Material	Almen intensity, mm	Fatigue limit, MPa	Fatigue limit increment, %
TC18	Unpeened	343	Base value
TC18	0·3(CS)+0·35(GS)	422	23
TC18	0·3(CS)+0·15(GS)	436	27
TB6	Unpeened	313	Base value
TB6	0·3(CS)+0·35(GS)	379	21
TB6	0·3(CS)+0·15(GS)	403	29

optimum shot peening process is determined. For a given material, there is an optimal shot peening intensity. Insufficient shot peening and over shot peening will not produce good fatigue performance. However, double shot peening, can significantly improve fatigue performance.

4. TC18 and TB6 titanium alloys have similar features regarding composition, processing and mechanical properties, but the fatigue property of TC18 alloy is somewhat better than that of the TB6 alloy

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