INFLUENCE OF STRESS GRADIENT ON FATIGUE BEHAVIOR OF SHOT PEENED TIMETAL 1100

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ABSTRACT

Fully lamellar as well as duplex (primary alpha phase in lamellar matrix) microstructures optimized for a good combination of LCF, HCF and creep strengths were produced in the high temperature near-α titanium alloy TIMETAL 1100. Shot peening was performed using various Almen intensities to evaluate optimum conditions for fatigue life improvements of smooth and notched components. The fatigue results are explained in terms of the resistance to crack nucleation and microcrack growth as affected by the shot peening induced changes in near surface properties and the actual applied stress gradient.

KEYWORDS

Fatigue behavior, TIMETAL 1100, shot peening; Almen intensity; residual compressive stress; crack nucleation, microcrack growth.

INTRODUCTION

Previous work on titanium alloys [1] has shown that shot peening can significantly improve the fatigue life. This was shown to be clearly related to the interaction of the shot peening induced residual compressive stresses and the crack tip stress field leading to a marked retardation of microcrack growth within near surface regions. On the contrary, the resistance to fatigue crack nucleation was only improved if the shot peening induced surface defects such as overlaps and dents were removed by an additional slight polishing (crack nucleation at the surface). In this case, the high dislocation density (surface strengthening) was found to be beneficial in increasing the resistance to fatigue crack nucleation. Similar as in high strength steels [2], subsurface crack nucleation was observed in shot peened titanium alloys under certain loading conditions [3]. Subsurface failure was favored by axial loading and testing in inert environments, while high applied stress gradients as for high amplitude bending loads and notched components led to a shift in crack nucleation site from subsurface to surface regions.

The present investigation on TIMETAL 1100 is part of a project that was initiated to study the effects of mechanical surface treatments, i.e., shot peening and deep rolling on ambient and elevated (600°C) temperature fatigue performance of high temperature near-α titanium alloys. At the time of writing, only room temperature fatigue results can be reported and interpreted. Emphasis is placed on the effect of stress gradient on fatigue performance after shot peening.

EXPERIMENTAL PROCEDURE

The TIMETAL 1100 material was received from Timet (USA) as 200 mm bar material which had been finally forged at 980°C and air cooled. The nominal composition of the alloy is given in Table 1.

Table 1 - Chemical composition of TIMETAL 1100 (wt.-%)

Al	Sn	Zr	Mo	Si	O	Ti
6.0	2.7	4.0	0.4	0.45	0.07	bal.

Fully lamellar and duplex microstructures were produced as described in [4, 5].

Shot peening was performed using spherical conditioned cut wire (SCCW) with a hardness of 50-55 HRC. The Almen intensity was varied between 0.03 and 0.20 mmA_2. The shot peening parameters are summarized in Table 2.

Table 2: Details of the injector type shot peening treatment utilized on TIMETAL 1100

shot size (mm)	shot type (sph. cond. cut wire)	inner nozzle diameter (mm)	working distance (mm)	revolutions/ time (s^{-1})	exposure time (s)
0.36	SCCW 14	7	35	1	60

Fatigue tests were performed in fully reversed loading (R = -1) on hourglass shaped specimens (gage diameter: 3.6 mm).Tests were done using a servohydraulic testing machine for axial loading and a rotating beam machine for rotation bending, respectively. In addition, circumferentially V-notched (K_t = 3.0) specimens were tested in rotating beam loading. In addition to the shot peened (SP) conditions, electrolytically polished specimens (EP) were tested as reference. Roughness profiles were measured by means of a profilometer. Fracture surfaces were investigated by SEM.

EXPERIMENTAL RESULTS AND DISCUSSION

Annealing the alloy TIMETAL 1100 at 1060°C and 1012°C resulted in fully lamellar structures (Fig. 1) with prior β grain sizes of 450 μm (Fig. 1a: LC) and 160 μm (Fig. 1b: LF), respectively [4, 5]. While the width of the α lamellae is somewhat smaller in LF than in LC, the length of the α lamellae and the colony sizes are much smaller in LF due to the finer prior β grains. The duplex microstructures with 60% (D60) and 20% (D20) primary alpha (α_p) volume fractions are also shown in Fig. 1. For both D60 (Fig. 1c) and D20 (Fig. 1d), the α_p size is about 15 μm. While the width of the α lamellae is about 1 μm for both, the length of the α lamellae and the colony sizes are larger in D20 (Fig. 1d) as opposed to D60 (Fig. 1c) due to the coarser prior β grains.

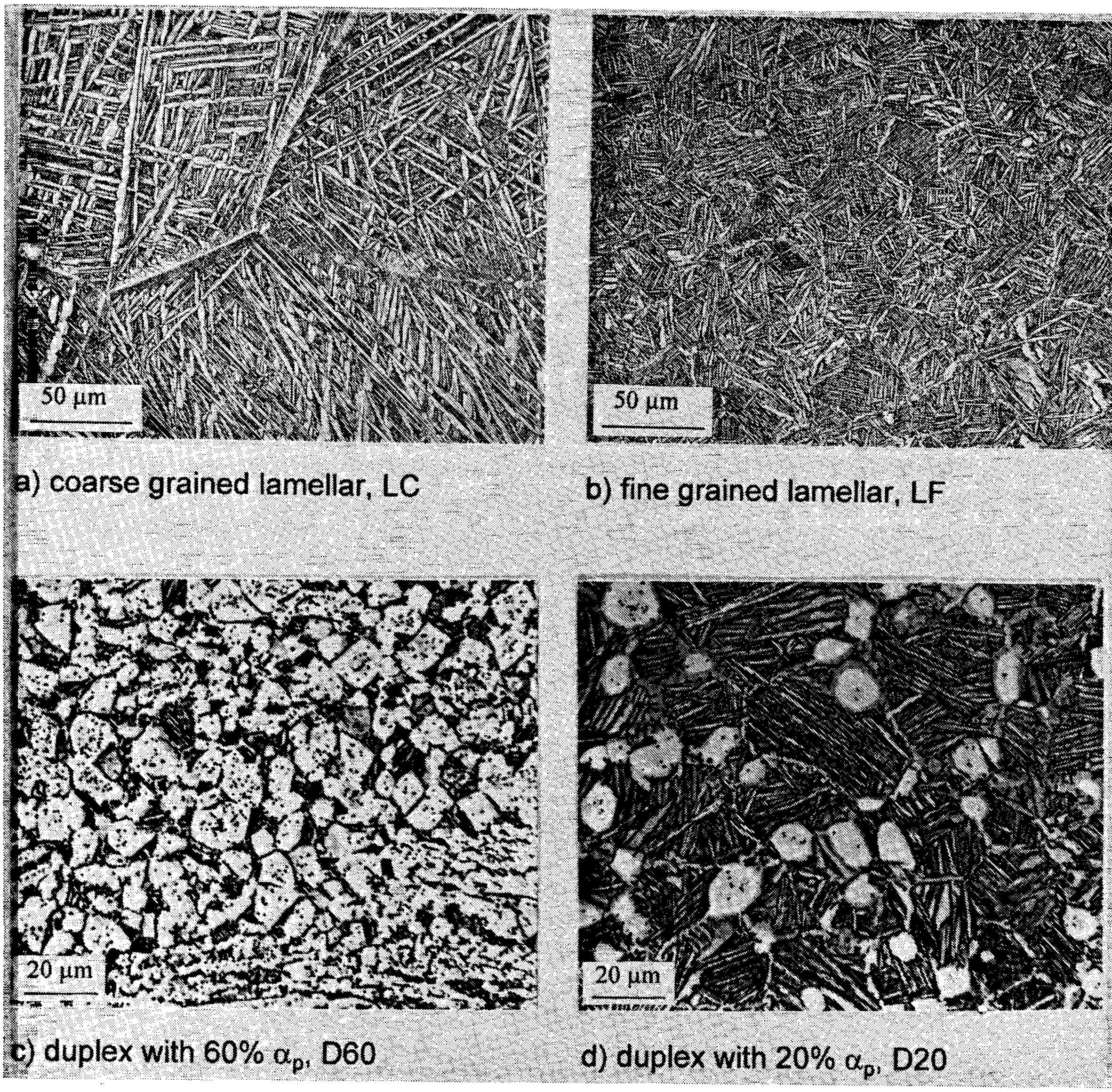


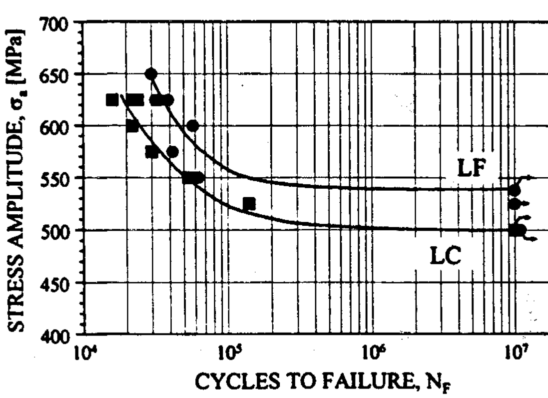
Fig. 1: Microstructures in TIMETAL 1100 [4, 5]

Tensile test results are listed in Table 3 comparing the data of the various microstructures. Yield stress values are similar between LC and LF, while LF is markedly superior to LC regarding tensile elongation to fracture El and ductility ε_F. Similarly, yield stress values are very similar between D20 and D60, while D20 is somewhat superior with respect to tensile strength.

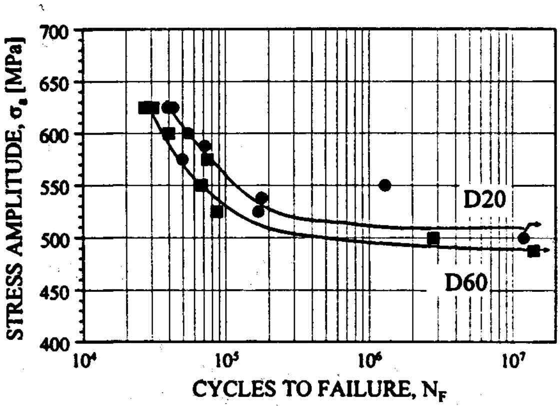
Table 3 - Tensile properties of TIMETAL 1100 [4, 5]

Microstructure	$\sigma_{0,2}$ MPa	UTS MPa	e_u %	El %	σ_F MPa	ε_F = ln A_0/A_F	E GPa
LC	955	1065	6.1	6.2	1170	0.10	116
LF	935	1040	4.8	11.1	1233	0.22	116
D20	965	1032	3.3	9.2	1341	0.32	113
D60	953	994	3.2	11.4	1320	0.36	113

The S-N curves of the reference conditions are shown in Fig. 2 comparing LC with LF (Fig. 2a) and D60 with D20 (Fig. 2b) [4, 5]. A decrease in prior β grain size from 450 (LC) to 160 μm (LF) significantly improves the fatigue life of the fully lamellar microstructures in the LCF regime while the 10^7 cycle fatigue strength is increased from about 500 to roughly 540 MPa (Fig. 2a). A decrease in the α_p volume fraction from 60 to 20% not only improves the LCF life of the duplex microstructures, but also increases the 10^7 fatigue strength from roughly 490 to 520 MPa (Fig. 2b).



a) Lamellar microstructures



b) Duplex microstructures

Fig. 2: S-N curves in TIMETAL 1100, rotating beam loading [4, 5]

From both lamellar and duplex microstructures, the superior structures, i.e., LF (Fig. 2a) and D20 (Fig. 2b) were chosen to study the influence of shot peening on fatigue performance. The effect of air pressure during injector type shot peening on the resulting arc height of Almen strips A_2 is shown in Fig. 3. The saturation values (= Almen intensities) are plotted in Fig. 4. The roughness profiles (Fig. 5) indicate a direct dependence on peening pressure or Almen intensity. The roughness value R_a clearly increases with Almen intensity (Fig. 6).

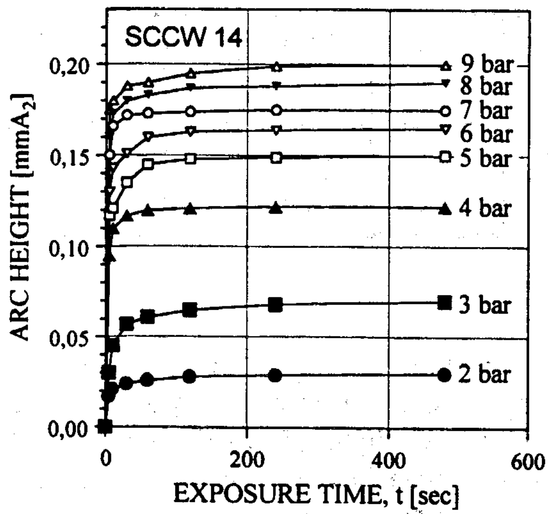


Fig. 3: Arc height vs. exposure time

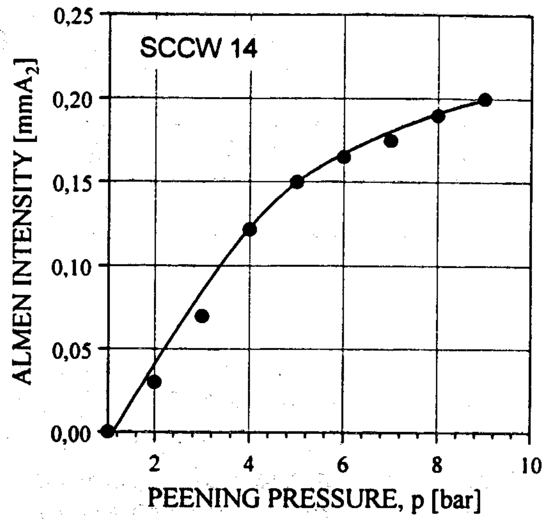


Fig. 4: Almen intensity vs. peening pressure

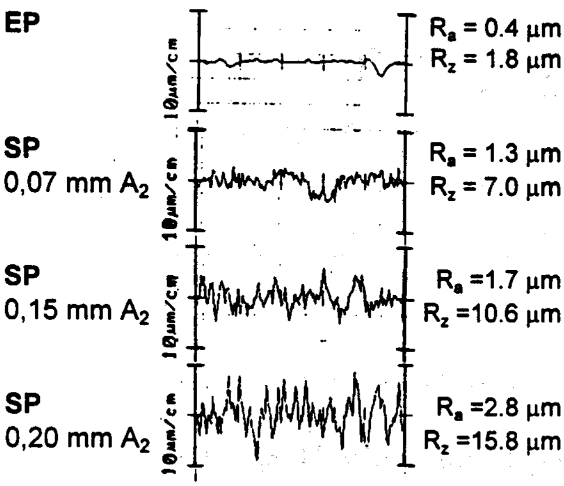


Fig. 5: Roughness profiles

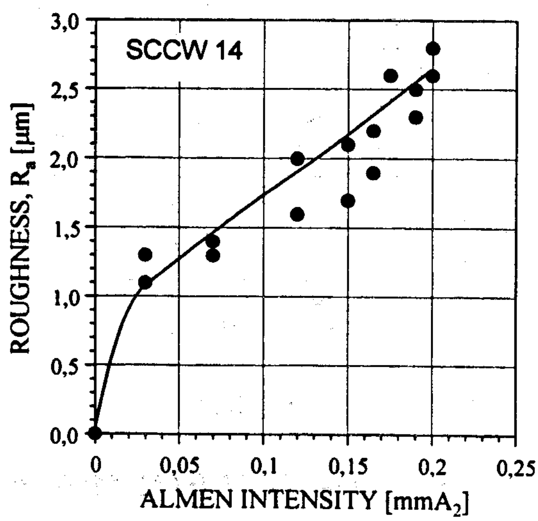


Fig. 6: Roughness R_a vs. Almen intensity

The effect of Almen intensity on the fatigue life was studied on smooth (K_t = 1.0) specimens of LF in rotating beam loading at a stress amplitude of σ_a = 750 MPa (Fig. 7). There is a marked increase in fatigue life from about $N_F = 1.2 \times 10^4$ for EP to more than 1×10^6 after shot peening with an intermediate Almen intensity of 0.07 mm A_2. A slight decrease in fatigue life and an increase of scatter occured by further increasing the Almen intensity. Fracture surface observation (Fig. 8) by SEM revealed that except of the reference EP (Fig. 8a) all shot peened specimen failed from subsurface regions. An example is shown in Fig. 8b. With increasing Almen intensity, the fatigue cracks nucleated in greater depths (Fig. 9). Due to the subsurface crack nucleation in shot peened specimens, the decline in fatigue life at high Almen intensities (Fig. 7) is not related to the concomitant increase in surface roughness (Fig. 6) However, local tensile residual stresses which balance the outer high compressive residual stresses may be responsible for this loss in fatigue life. Further fatigue testing was conducted with specimens shot peened with this optimum intensity of 0.07 mm A_2.

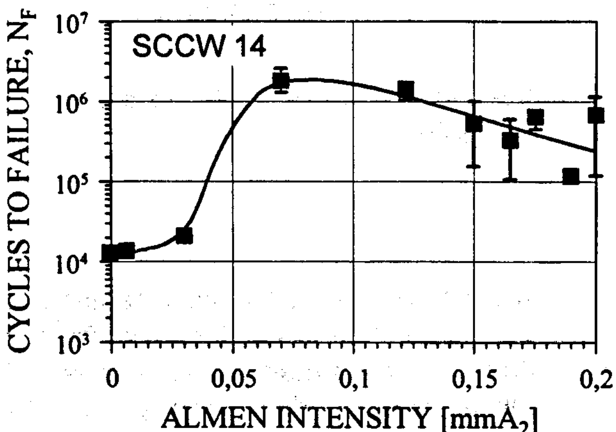
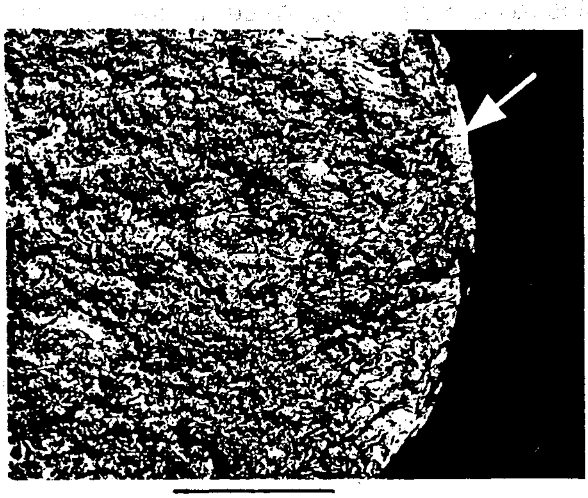
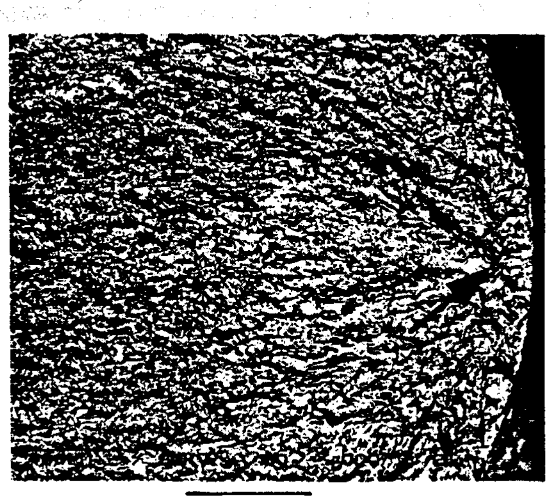


Fig. 7: Effect of Almen intensity on fatigue life (σ_a = 750 MPa) of LF in rotating beam loading



a) Crack nucleation at the surface (EP)



b) Subsurface crack nucleation (SP 0.07 mmA_2)

Fig. 8: Fracture surfaces (SEM) of LF in rotating beam loading (σ_a = 750 MPa)

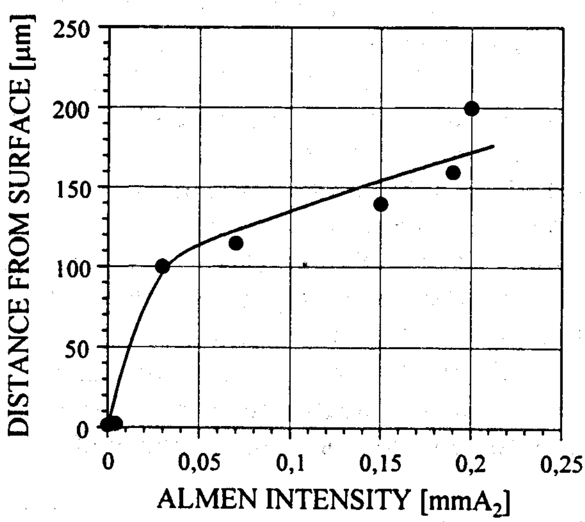
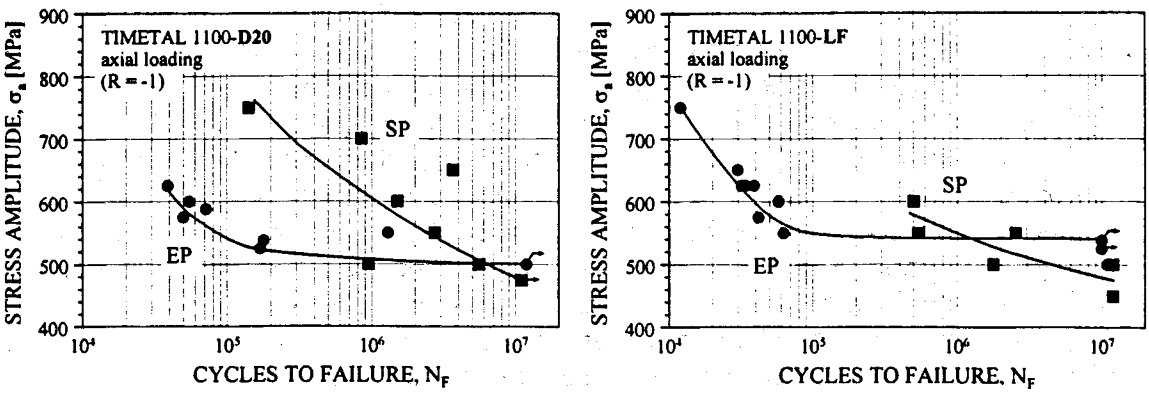


Fig. 9: Depth of crack nucleation site of LF in rotating beam loading (σ_a = 750 MPa) for various Almen intensities

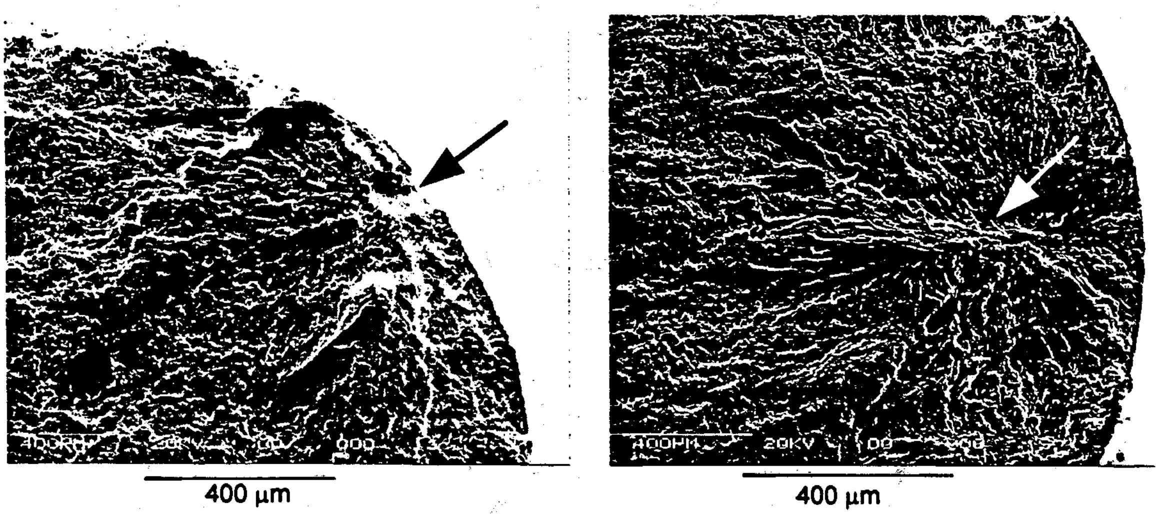
S-N curves of shot peened specimens tested in axial loading are compared in Fig. 10 with the references for D20 (Fig. 10a) and LF (Fig. 10b) from rotating beam results. This comparison can be done, since no marked differences in fatigue strength were found for EP between axial and bending loading [6]. While the fatigue life improvement at high stress amplitudes is very pronounced, no improvement (Fig. 10a) or even a deterioration (Fig. 10 b) of the 10^7 cycles fatigue strength was found after shot peening. Similar as found in the rotating beam tests (Fig. 8b), fatigue testing of shot peened specimens in axial loading led to subsurface failure (Fig. 11). The distance of the crack nucleation site to the surface was somewhat higher in axial loading compared to rotating beam loading for the same Almen intensity (compare Fig. 11b with Fig. 8b). Since the 10^7 cycles fatigue strength in titanium alloys is significantly higher in vacuum than in air, the detoriation of the fatigue strength despite the change in nucleation site from surface (air) for EP to subsurface (vacuum) for SP indicates marked tensile residual stresses at the crack nucleation site in SP specimens.

For estimating the tensile residual stresses in shot peened specimens which cause a detoriation in fatigue strength in axial loading, both the fatigue strength of the reference EP in vacuum and the mean stress sensitivity of the particular microstructure must be known.



a) D20 *b) LF*

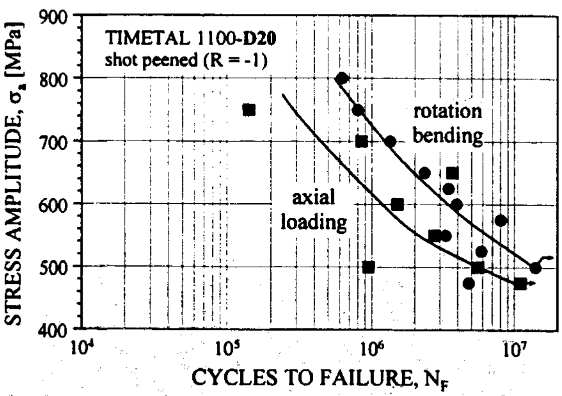
Fig. 10: S-N curves of D20 and LF in axial loading



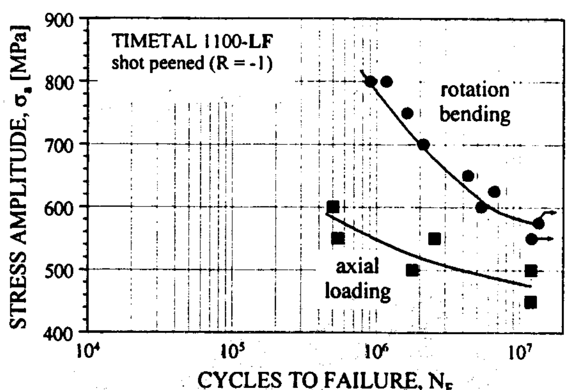
a) Crack nucleation at the surface (EP) *b) Subsurface crack nucleation (SP 0,07 mmA$_2$)*

Fig. 11: Fracture surfaces (SEM) of LF in axial loading (σ_a = 750 MPa)

The S-N curves of shot peened specimens in rotating beam loading are compared with the corresponding data from axial loading in Fig. 12. For both D20 (Fig. 12a) and LF (Fig. 12b), the slight stress gradient in bending leads to somewhat higher fatigue life compared to axial loading. This can be explained in part by the lower applied stress amplitude in rotating bending at the location of subsurface crack nucleation. On average, this stress amplitude in bending is about 6 % lower than that in axial loading. In addition to crack nucleation, crack propagation in bending is also slower due to the stress gradient. The rotating beam fatigue results of notched electrolytically polished specimens (K_t = 3.0) are compared with those of the smooth (K_t = 1.0) specimens in Fig. 13. For reasons of comparison, the maximum stress amplitude at the notch root, i.e., $\sigma_a \times K_t$ is plotted. Notched specimens have longer lifetimes in the finite life regime while the 10^7 fatigue strength is roughly the same for notched and smooth specimens (Fig. 13). The longer lifetimes of notched specimens in the finite life regime is due to crack propagation being slower in notched than in smooth specimens once the crack has left the stress field of the notch [6]. Since no difference in the 10^7 cycles fatigue strengths was found between smooth and notched specimens, the resistance to crack nucleation must be very similar [7]. Shot peening of notched (K_t = 3.0) specimens (Fig. 14) improves the fatigue performance much more than that of smooth (K_t = 1.0) specimens (compare Fig. 14 with Fig. 10). Fatigue cracks in the notched specimens generally nucleated at the surface of the notch root for both the reference and the shot peened conditions.



a) D20



b) LF

Fig. 12: S-N-curves of shot peened TIMETAL 1100

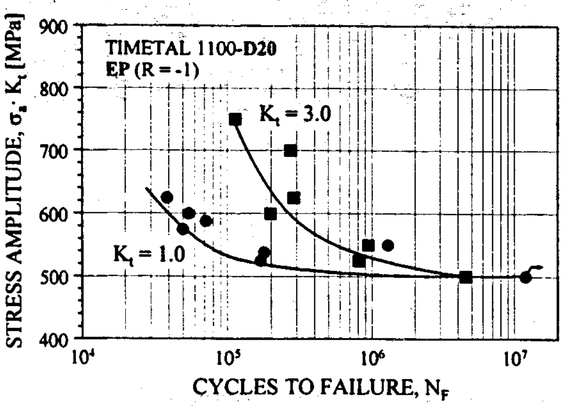


Fig. 13: S-N curves of notched EP (K_t = 3.0) and smooth (K_t = 1.0) specimens

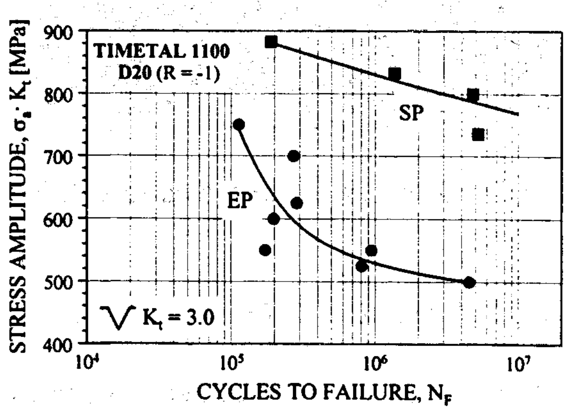


Fig. 14: S-N curves of notched (K_t = 3.0) EP and SP specimens

SUMMARY

The results of the present study clearly indicate the prounounced effect of an applied stress gradient on the fatigue performance of the shot peened TIMETAL 1100. With an increase in stress gradient, a shift in fatigue crack nucleation site from subsurface to surface nucleation was observed. In the latter case, early crack propagation is drastically retarded through the interaction of the crack front with the residual compressive stress field. As a result, the 10^7 cycles fatigue strength significantly increases after shot peening.

In bending of smooth specimens and even more pronounced in axial loading, the fatigue crack beeing nucleated below the residual compressive stress field does not have to interact directly with the residual compressive stress field because it can first propagate rather easily deeper into the specimen interior. Aside from mechanical aspects, environmental effects should therefore be considered since subsurface cracks nucleate and propagate under vacuum conditions until they reach the surface. For fatigue testing in air, the local tensile residual stresses at the subsurface crack nucleation site, the mean stress sensitivity of the particular microstructure and its sensitivity to the environment determine whether the fatigue strength increases or decreases after shot peening.

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INVESTIGATION OF SHOT-PEENING AND RE-PEENING EFFECTS ON PARTIALLY FATIGUED NOTCHED COMPONENTS

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ABSTRACT

This investigation systematically approached the effect of peening and re-peening upon the fatigue life of partially fatigued notched components made of high strength 7075 Al-Zn alloy, loaded under axial tension-tension conditions. It has been found that peening partially fatigued specimens not previously shot peen treated can be beneficial as the total fatigue life to failure extends by as much as 115% under certain conditions, as compared to the shot peened life. However, re-peening was found to provide little benefits and in some cases it had a detrimental effect. X-ray diffraction measurements have shown that peening after partial fatigue and re-peening induced residual stresses were not as intense as those induced on 'virgin' material.

KEYWORDS *Shot peening, re-peening, tension-tension axial loading, life improvement, partial fatigue, X-ray diffraction, aluminium 7075-T73511.*

INTRODUCTION

Impact surface treatments have been shown to provide a highly effective method for fatigue alleviation. Shot-peening is extensively utilised in many industrial applications for the purpose of providing fatigue life improvements, which depending upon component service loading and material behaviour have been found to be better than 200%. Further, shot peening has been shown to enhance the stress corrosion cracking resistance and fretting performance as well as providing prolonged fatigue lives and fatigue strength enhancement. The treatment can be conveniently employed to process plain surfaces, fillets, and bores of components.

The beneficial effects of the treatment have been attributed to surface work-hardening and the development of surface and subsurface compressive residual stresses as a result of shot impact. The combination of work-hardening and compressive residual stresses cause suppression of the fatigue crack initiation stage and thus the total fatigue life is extended. The process has traditionally been employed at the manufacturing stage, prior to the component been introduced to service. Frequently, the question arises as to whether the process could be of benefit when employed on components which are already in service. Furthermore, could components that have been peened benefit from a second peening operation during their service life, and what would be the effects of re-peening on the total service life of such machine parts. Although there has been a wide industrial acceptability of shot-peening, these questions remain poorly answered. Only a limited number of small research studies have partly dealt with these questions [1-3].

The aim of this study was to investigate the aforementioned questions, and provide information on the macroscopic effects of re-peening on the total fatigue life of 7075-T73511 high strength aluminium-zinc alloy. In the present investigation the emphasis was on axial tension-tension cyclic loading of notched components, which has not been previously utilised for such a study. X-ray diffraction measurements have been employed as a means of determining the peening and re-peening residual stresses on the tested samples.

EXPERIMENTAL ANALYSIS

Material Selection and Specimen Design

The material used for the machining of test specimens was 7075 high strength aluminium alloy in extruded bar form. In order to avoid the influence of production related residual stresses that could potentially cloud the experimental results, the T73511 temper condition of the alloy was selected. The basis for the selection of this temper was that it provides a material which is solution heat-treated, stress relieved by controlled stretching of 1-3% and stabilised. Thus the material for the machining of samples was reasonably free of production related residual stresses. The composition and mechanical properties of the material are shown in Tables 1 and 2 below.

Table 1 7075 T73511 Chemical Composition as provided by the supplier

Al	*Zn*	*Mg*	*Cu*	*Cr*	*Fe*	*Si*	*Ti*	*Zr*	*Mn*
Balance	5.96	2.39	1.29	0.19	0.17	0.09	0.05	0.04	0.04

Table 2 7075 T73511 Mechanical Properties measured by the authors

$\sigma_{0.2\%}$ (MPa)	σ_{UTS} (MPa)	e_f (%)	Hardness (Hv)
488	545	10.5	150-155

Two special specimen geometries were used in this investigation and were designed with the aid of Finite Element analysis. The nominal cross section dimensions of the specimens were, width w=18.0mm and thickness t=6.0mm. Special discontinuity features were machined at the mid-length of samples detailed in Fig.1, that introduced stress concentrations K_t=3.19 and 4.93 for notches 1 and 2 respectively. The machining of the specimens was carried out by CNC and the cutting parameters (depth of cut, feed rate etc.), were carefully selected so as to impart minimal residual stresses on the surface of finished specimens [4,5,7]. The machined surface residual stresses in the vicinity of the notches were measured by X-ray diffraction and were found to be small, ±5.0MPa in the direction of the machining marks and ±2.0MPa at 90° to the machining marks.

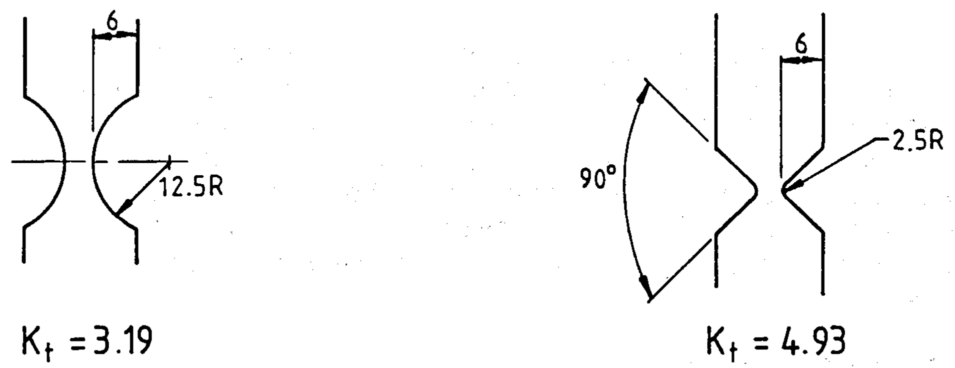

Figure 1 Specimen geometric configurations

Experimental Programme

The experimental programme comprised preliminary and main fatigue tests. The aim of preliminary testing was to establish the fatigue life characteristics of the material in the form of (σ_a-N) curves, for the material in the *as machined* and *shot peened* conditions, and for both notched geometries. The results of the preliminary test programme facilitated evaluation of the effect of shot peening on the total fatigue life of the two notched geometries selected. The main testing concentrated on the two areas of principal interest: **a.** The determination of experimental data associated with peening of partially fatigued as machined specimens, and **b.** The re-peening of partially fatigued shot peened specimens. The experimental testing made use of a ±100KN uniaxial servo-hydraulic testing machine, and throughout the experimental programme a constant stress amplitude sinusoidal waveform was employed with a load cycling frequency f=25Hz, and load ratio R=0.04, in air. These stress waveform characteristic parameters were kept constant in order to maintain test condition uniformity and assure repeatability.

Shot peening and re-peening treatments were performed in-house, under controlled conditions, utilising a direct pressure blasting cabinet and S-230 steel shot with an average hardness 630Hv. All specimen surfaces were shot peened and this was achieved by rotating the specimen under the shot stream with a constant rotational speed of 20 rpm. Table 3, lists the detail shot peening process parameters used in the research programme.

Table 3 Detail Shot Peening Parameters

Air Pressure	Mass Flow rate	Shot Velocity	Stand-off Distance	Duration	Almen A Intensity	Coverage
104 KPa	3.2Kg/min	45 m/s	145 mm	60 sec	0.36 mm	150%

Shot velocity was measured using a laser transient anemometer system, and the coverage was examined with a (x10) magnifying glass in conjunction with a fluorescent tracer surface coating and ultraviolet illumination, as per MIL-S-13165C.

RESULTS AND DISCUSSIONS

Preliminary Tests

Two series of fatigue tests to failure were performed utilising both notch geometries. Series 1, utilised specimens in the as machined condition, and series 2 made use of specimens that were shot peen treated. The results of these tests were plotted in the form of (σ_a-N) curves, and are shown in Fig.2, for K_t=3.19 and 4.93 respectively.

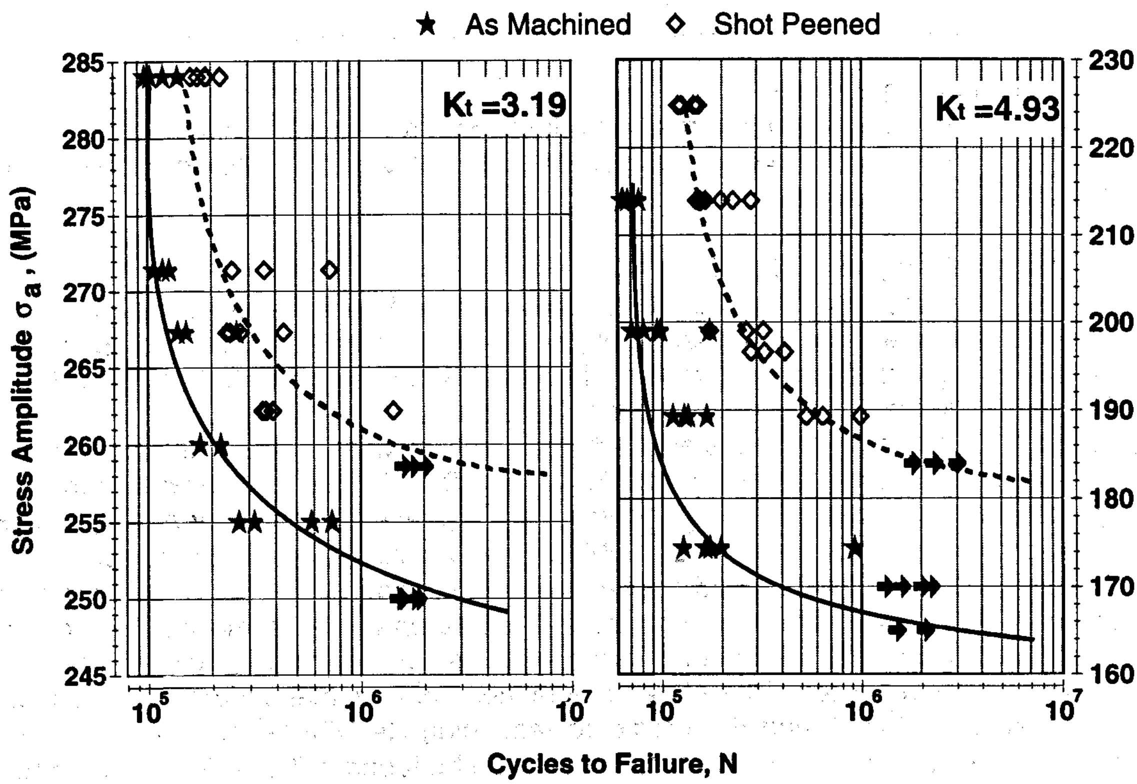

Figure 2 (σ_a-N) Curves for as Machined and Shot Peened Notched Specimens

The preliminary testing results, Fig.2, clearly demonstrate that the shot peening treatment was highly bebeficial. It extends the total fatigue life to failure whilst simultaneously provides an enhancement of the fatigue strength [5,7]. Comparison of the fatigue strength at 10^6 endurance cycles indicates that the observed fatigue strength enhancements were more pronounced for higher stress concentration values as shown in Table 4.

Table 4 Fatigue Strength Enhancement on 7075T73511 Aluminium due to Shot Peening Treatment

Stress Concentration Factor, K_t	Fatigue Strength at 10^6 Cycles (MPa)		Fatigue Strength Enhancement (%)
	As Machined (Series 1)	Shot Peened (Series 2)	
3.19	252	260	3.2
4.93	168	188	10.6

Main Testing Programme

The main test programme comprises two investigations namely, study of shot peening effects on partially fatigued specimens, and of re-peening on partially fatigued specimens.

1. Partially Fatigued ➪ Shot Peened

The first part of the main investigation focused on the effect of peening partially fatigued specimens not previously shot peen treated. The testing utilised specimens of the notch 2 geometric configuration, Fig.1, with a stress concentration factor K_t=4.93. These fatigue tests were conducted in two phases.

Phase 1. The specimens in the as machined condition were partially fatigued by constant stress amplitude cyclic loading, $\sigma_a=0.53\sigma_{0.2\%}$, R=0.04. Fatigue cycling was interrupted at pre-determined intervals $N^P=\lambda N_e^{AM}$, where λ is the partial fatigue factor and $N_e^{AM}=6.4\times10^4$ cycles, the endurance life at σ_a=214.0MPa in the *as machined* condition, see Fig.2.

Phase 2. The partially fatigued specimens were subsequently shot peen treated using the parameters of Table 3, and tested to fracture under the same loading conditions described above. The number of endurance cycles after peening N_e' and total endurance cycles N_F were recorded. Therefore the total number of actual endurance cycles of any one test $N_F=N^P+N_e'$, and the predicted remaining life $N^R=(1-\lambda)N_e^{AM}$ were calculated. Numerical values of the experimental results can be found in Table 5, where the results represent the log-mean values for a sample size of four.

The influence of λ, the partial fatigue factor, on the life improvements observed over the *as machined* condition is shown in Fig.3. It is clear from the results that the shot peening treatment enhanced the total fatigue life to failure, and the degree of enhancement is dependent on λ and gradually declined as λ increased. Evidently the life enhancement achieved through peening after consuming part of the total life, $\lambda>0$, was greater than the effect of peening prior to testing i.e. $\lambda=0$ which provides a life enhancement of 198% for σ_a=214.0MPa. Thus, the effect of peening partially fatigued specimens achieves a better enhancement of the total fatigue life than the one determined for the shot peened condition, even when the partial fatigue extended to 80%

of N_e^{AM}. The experimental results provide a clear indication that peening partially fatigued components is positively more beneficial than shot peen treatment before use. Furthermore, the results have shown that the beneficial effect is maximised for λ values between 0.25 and 0.6, as indicated by the trend line in Fig.3.

Table 5 Predicted and Actual Endurance Cycles for Partially Fatigued and Peened Specimens

Predicted Life Based on as Machined Data, N_e^{AM}=63793 cycles			Actually Obtained Endurance Data	
λ	N^P (cycles)	N^R (cycles)	N_e' (cycles)	N_F (cycles)
0.27	17220	46570	266000	283600
0.47	29980	33810	256880	287930
0.63	40190	23600	257260	298070
0.80	51000	12760	225240	276480

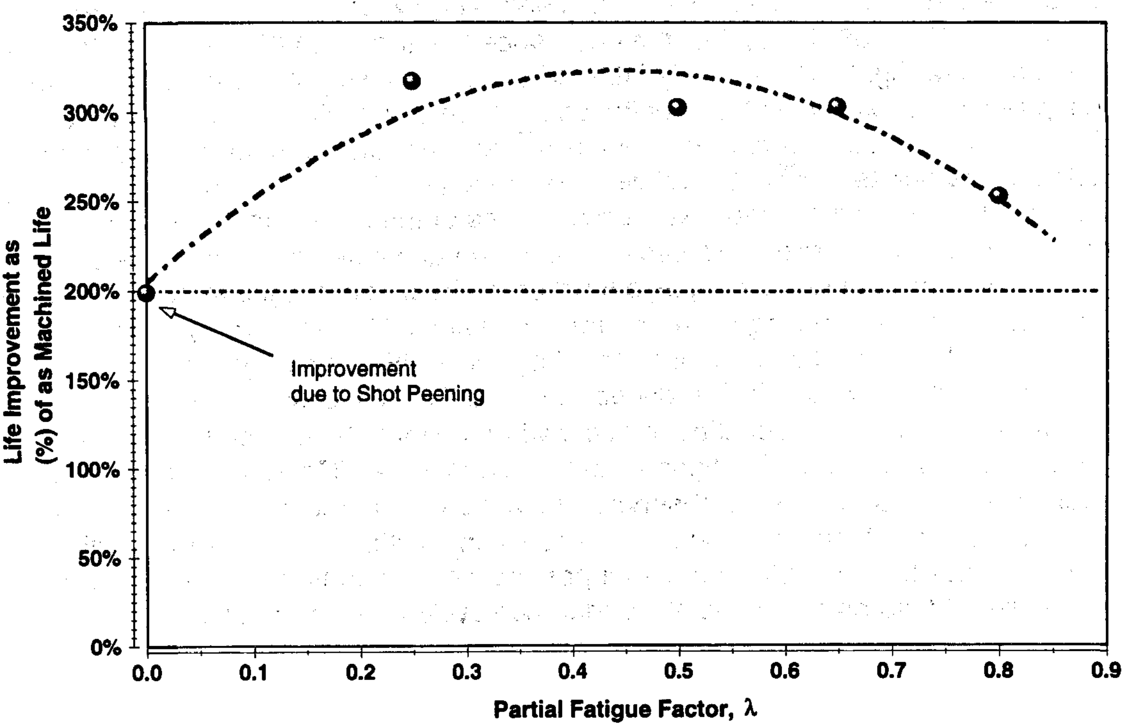

Figure 3 Total Life Improvement due to Shot Peening on Partially Fatigued Specimens

Microscopic examination of the fractured surfaces for partially fatigued and peened samples revealed that fracture occurs due to the initiation and propagation of corner sub-surface cracks, which is in agreement with the observations reported in [3]. In contrast surface edge cracks were found to dominate the fatigue failure of as machined samples. In view of these observations the beneficial effects of peening partially fatigued specimens could be attributed to the following mechanism. Shot impact with the surface, causes localised plastic deformation of a finite layer. This causes reorientation of the slip planes thus obstructing surface crack initiation, and further, the surface coverage with overlapping indentations causes obliteration of any surface micro cracks already formed which are engulfed within the plastically deformed layer and a field of compressive residual stresses. Whilst the partial fatigue factor λ, is increased the subsequent shot peening protection progressively declines, and this could be attributed to the fact that the material exhibits cyclic strain hardening, thus peening induced plasticity is smaller as the partial fatigue period is prolonged.

2. Shot Peened ⇨ Partially Fatigued ⇨ Re-Peened

The objective of this investigation was to ascertain the effectiveness of re-peening. Testing was carried out utilising the notch 1 geometric configuration, Fig.1, with a stress concentration factor K_t=3.19. Shot peened specimens, treated as per Table 3, were partially fatigued by constant stress amplitude cyclic loading, $\sigma_a=0.58\sigma_{0.2\%}$, R=0.04. The fatigue cycling was interrupted at preset intervals $N^P_{SP}=\lambda' N^{SP}_e$, where λ' is the partial fatigue factor and $N^{SP}_e=1.838\times10^5$ cycles, the endurance life at σ_a=284.0MPa in the shot peened condition, see Fig.2. The partially fatigued specimens were re-peened using the same shot peening conditions as those of the original treatment. During each test the number of endurance cycles following re-peening N^{RP}_e and the total number of actual endurance cycles of any one test $N^{RE}_F=N^P_{SP}+N^{RP}_e$ were recorded and thus the predicted remaining life $N^R_{SP}=(1-\lambda')N^{SP}_e$ was calculated. Numerical values of the experimental results are shown in Table 6, where the results represent the log-mean values for a sample size of five.

The effects of re-peening as a function of the partial fatigue factor λ', is shown in Fig.4. Evidently, re-peening extended the total fatigue life to failure by as much as 38% as compared with N^{SP}_e, the endurance life at σ_a=284.0MPa. Although the life improvement was significant, this was quickly reduced as the partial fatigue factor λ' increased. Fatigue life improvements were identified to occur when a small fraction of the shot peened life was used i.e. for $\lambda'<0.25$. For higher values the beneficial effect rapidly vanishes and only small apparent benefits were observed. In fact as the partial fatigue period λ' extends beyond 0.3 the effects of re-peening become insignificant, and as the partial fatigue period extends beyond 60% of the shot peened life, re-peening has a detrimental effect as consistent failures below the N^{SP}_e endurance cycles were recorded.

Table 6 Predicted and Actual Endurance Cycles for Partially Fatigued and Re-Peened Specimens

Predicted Life Based on Shot Peened Data, N_e^{SP}=183800 cycles			Actually Obtained Endurance Data	
λ'	N_{SP}^{P} (cycles)	N_{SP}^{R} (cycles)	N_e^{RP} (cycles)	N_F^{RE} (cycles)
0.25	45950	137850	207560	253850
0.40	73520	110280	151140	224200
0.60	110280	73520	88480	203200
0.75	137850	45950	39340	177200

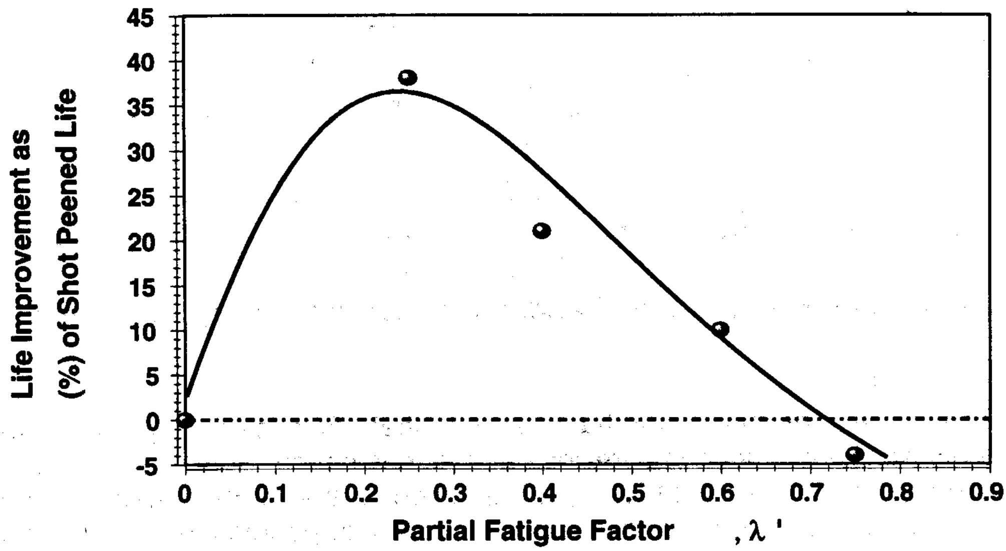

Figure 4 Effect of Re-Peening Partially Fatigued Specimens

X-ray diffraction evaluation of the residual stresses was carried out on specimens after re-peening, Fig.5. The surface and sub-surface residual stresses (up to 100μm depth) for the re-peened condition are lower than the values obtained for the shot peened state. Clearly, the re-peening process (•) has not re-built the residual stresses to the original level (▲). The lower values of residual stresses indicate that the strain hardening of the material during fatigue loading prevents the formation of sufficient plastic deformation which could result to re-juvenation of the residual stresses. The fact that re-peening is detrimental for λ'>0.6, is believed to be caused by the material over-hardening which induces surface micro-cracking due to increased dislocation density [3,6], as a result of re-peening, which accelerates failure.

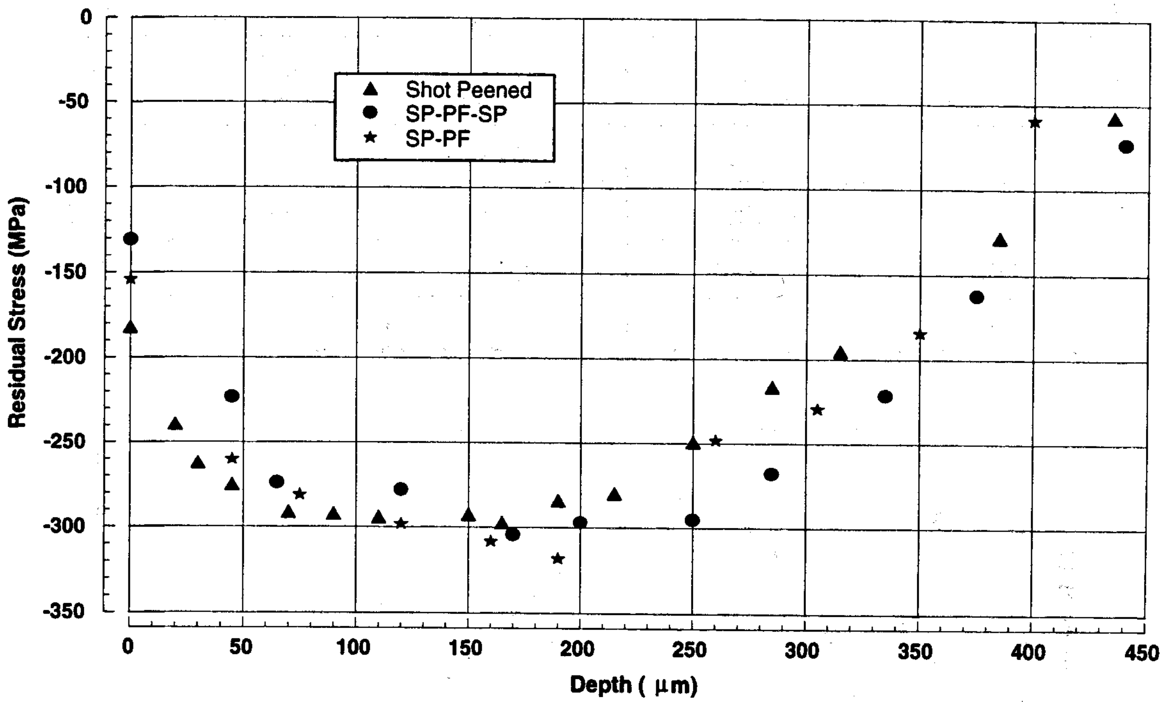

Figure 5 Shot Peening Induced Residual Stresses obtained by X-ray Diffraction

CONCLUSIONS

The results of the study have shown that shot-peening partially fatigued components which have not been previously peened is beneficial as the total fatigue life is extended by as much as 115% by comparison to the shot-peened and fatigued condition. Clearly this improvement implies that shot-peening of partially fatigued components can be beneficial and better than peening prior to commencement of service. Furthermore, it has been found that this beneficial effects were dependent upon the degree of fatigue life consumed prior to surface treatment. For the material in question there exists strong evidence that the effects of shot peening are maximum for partial fatigue in the range $0.25<\lambda<0.6$. Even when 80% of the fatigue life has been used, the material's total fatigue life to failure is extended by 50% more than the endurance achieved by peening before commission.

X-ray diffraction measurements of the residual stresses indicate that peening after partial fatigue does not produce residual stresses as intense as the peening of 'virgin' samples, demonstrating partial rebuilding of beneficial compressive residual stresses.

Re-peening was also found to be potentially beneficial. However, the benefits are strongly dependent on the percentage of shot-peened life consumed prior to re-peening. The results indicate that the effects of shot-peening can be detrimental if re-peening is performed at stages when the partial fatigue life has exceeded 75% of the shot-peened life. Some rather minor benefits could be obtained if the re-peening operation is carried out when a small percentage of the shot peened life is used by partial fatigue. Further, X-ray diffraction measurements of the residual stress levels following re-peening indicate that beneficial compressive residual stresses have not been fully rebuilt. Re-peening although it could yield benefits, should be employed with extreme caution and only following laboratory testing of the material.

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