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.

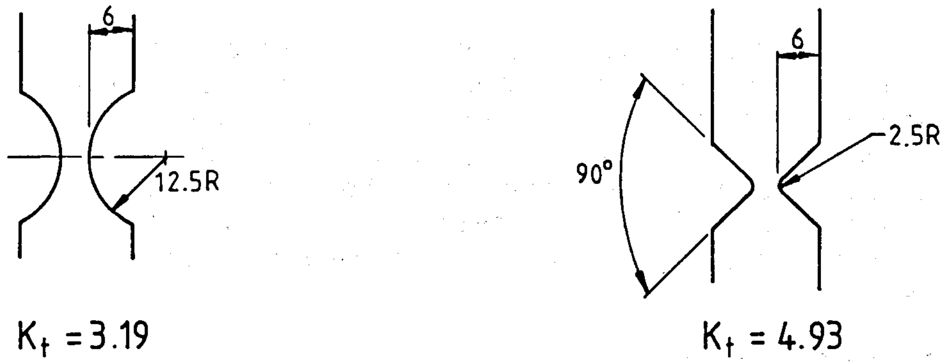

Figure 1 Specimen geometric configurations

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.

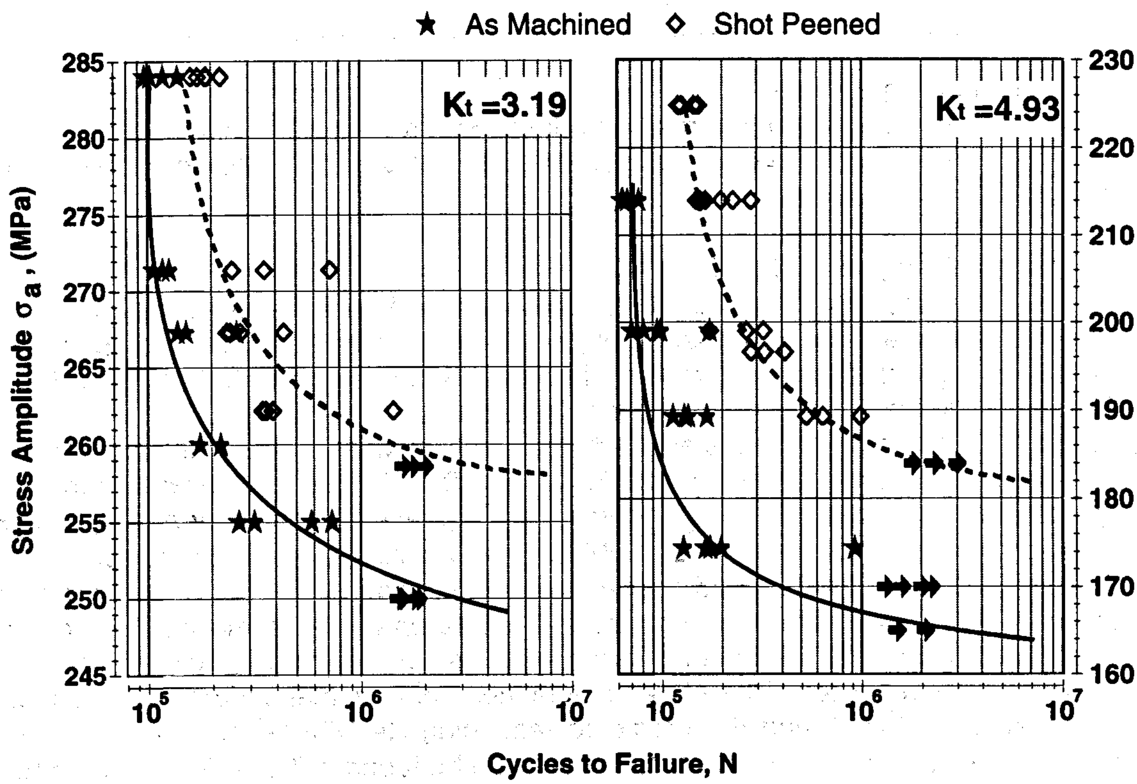

Figure 2 (σ_a-N) Curves for as Machined and Shot Peened Notched Specimens

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

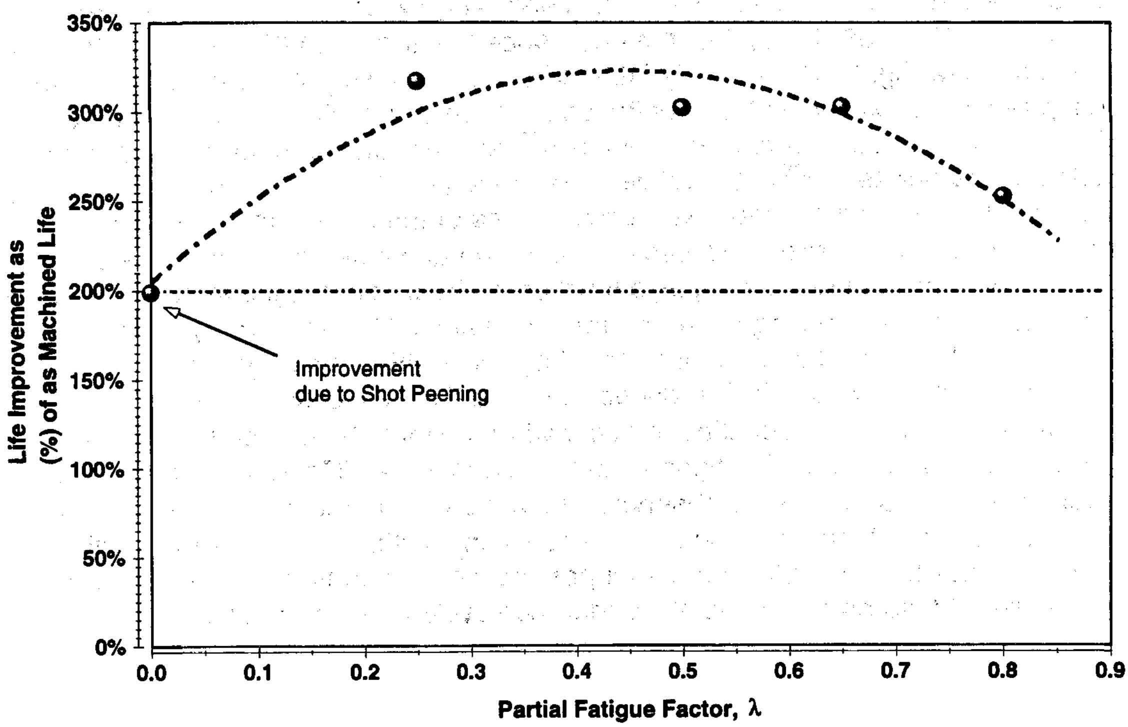

Figure 3 Total Life Improvement due to Shot Peening on Partially Fatigued Specimens

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

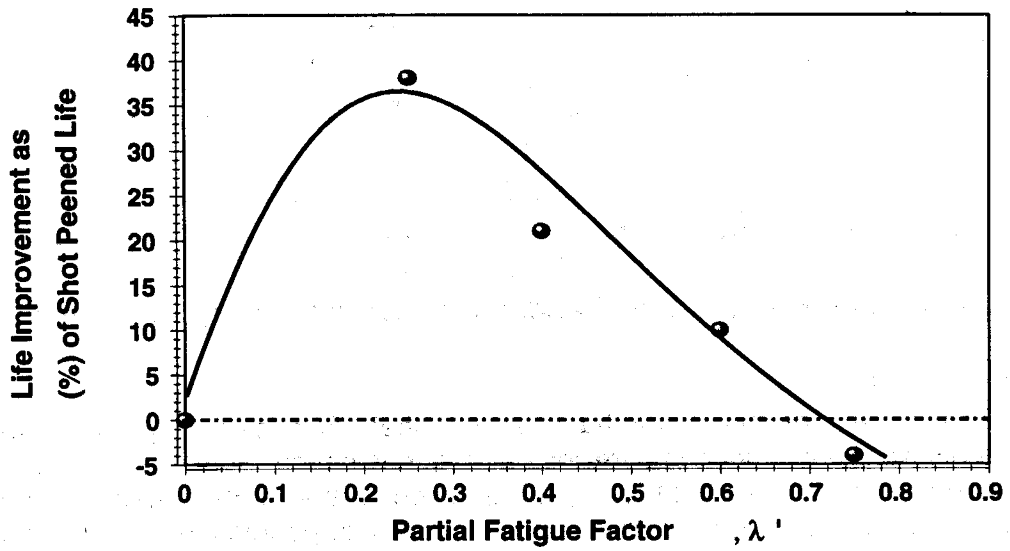

Figure 4 Effect of Re-Peening Partially Fatigued Specimens

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 $\lambda' > 0.6$, 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.

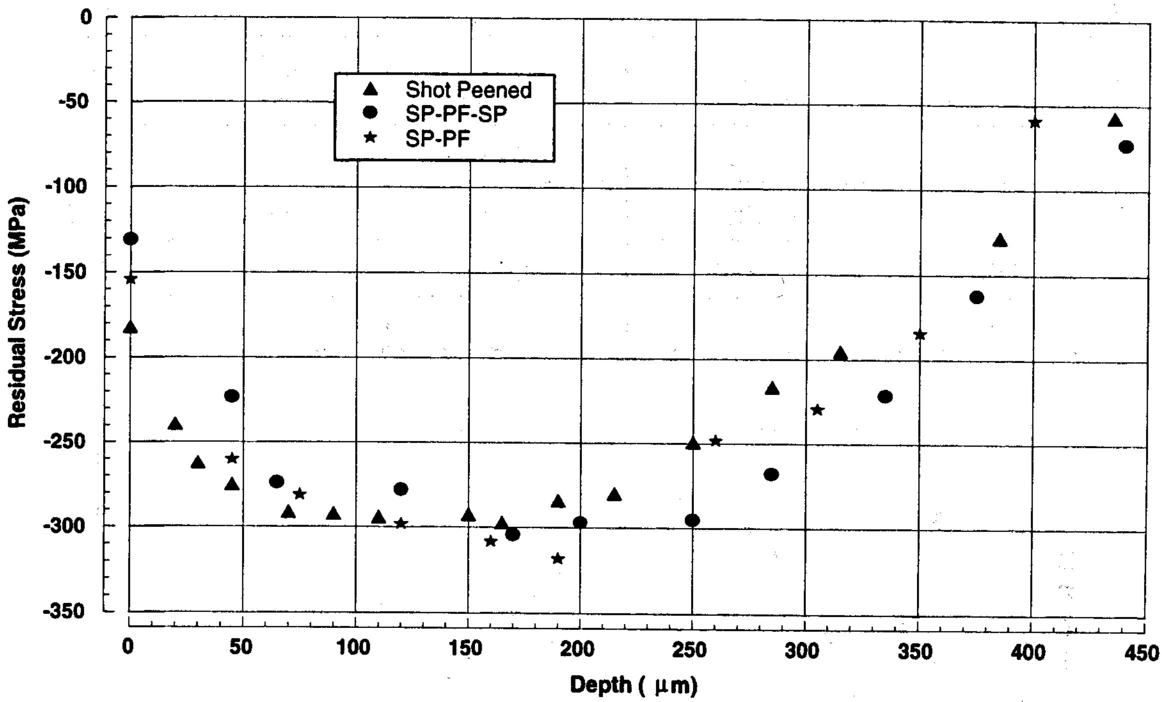

Figure 5 Shot Peening Induced Residual Stresses obtained by X-ray Diffraction

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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