COMPONENT LIFING BY SHOT-PEENING

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This investigation systematically approached the effect of peening and re-peening upon the fatigue life of partially fatigue damaged components made of high strength 7075 Al-Zn alloy.

Total fatigue life improvements better that 300% over the as machined condition and, >40% over the shot peened life were obtained when partially damaged material was shot peened. Maximum benefits were obtained for conditions where ≈60% of the life was used prior to peening. Re-peening of partially damaged specimens was also modestly beneficial. However, the results indicate the strong dependency of benefits on the degree of fatigue damage before re-peening, with a detrimental effect for partial fatigue damage $\lambda > 75\%$.

X-ray diffraction measurements of the residual stresses demonstrated that peening or re-peening following partial fatigue, did not produce residual stresses as intense as those associated with the peening of 'virgin' samples.

INTRODUCTION

Impact surface treatments have been known to provide a highly effective, versatile and relatively inexpensive method for combatting fatigue in metallic materials. The process is extensively used in industry for surface treatment of critical components as it has been proven to provide fatigue life improvements better than 200%. Furthermore, shot peen treated components have been found to outperform untreated ones under conditions that promote stress corrosion cracking and fretting fatigue wear. The treatment has been conveniently employed to process plain and curved surfaces, fillets, holes and, very complex component geometries.

The observed beneficial effects are due to surface work-hardening and the development of surface and subsurface compressive residual stresses induced by shot impact. The combination of work-hardening and compressive residual stresses, suppress fatigue crack initiation resulting to prolonged service lives. Traditionally, surface treatment processes have been implemented at the manufacturing stages and prior to service introduction. However, the question frequently arises as to potential benefits of peening components which are already in service and not previously treated. Moreover, could there be any gain from a second peening treatment after in service operation and, what would be the effects of re-peening upon the total service life of such parts.

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These questions become all the more relevant as engineers endeavour to develop optimal designs based upon reduced utilisation of expensive materials without loss of structural integrity. Such design schemes, dictate detailed understanding of design methods, manufacturing operations and the effects of processing on materials destined for machine elements. Moreover, many machine systems exist whose design fatigue life is soon to expire and maintenance methods are sought to extend their service beyond their design life, lifing.

The aim of this study was to investigate the aforementioned questions and provide information on the macroscopic effects of shot peening partially fatigued samples and, the benefits of re-peening partially fatigued peened specimens. The emphasis was on axial tension-tension cyclic loading of notched components and, x-ray diffraction measurements were employed as a means of determining the peening and re-peening residual stresses on the tested samples, aiming to ascertain the level of restoration of cyclically faded-out residual stresses.

EXPERIMENTAL PROCEDURES

Material Selection

The material used in the study was 7075 high strength aluminium alloy in extruded bar form. In order to eliminate the influence of production related residual stresses that could potentially cloud the experimental results, the T73511 temper condition was selected, Table 1. This temper, yields a material reasonably free of production related residual stresses for the machining of test specimens.

TABLE 1 - 7075-T73511 Mechanical Properties

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

Two specimen geometries were used, designed with the aid of Finite Element methods. The nominal specimen cross sectional dimensions were, width w=18.0mm and thickness t=6.0mm. Special discontinuity features were machined at the mid-length of samples introducing stress concentrations K_t=3.19 and 4.93. The specimens were CNC machined and cutting parameters were selected so as to impart minimal residual stresses on the finished specimens, Kyriacou et al (1). The machined surface residual stresses in the vicinity of the notches were measured by x-ray diffraction and were found to be ±5.0MPa and ±2.0MPa in the longitudinal and transverse directions respectively.

Fatigue Testing

A preliminary study evaluated the effect of shot peening on the total fatigue life of the two notched geometries and the results have been previously reported, Kyriacou et al (1). The current work focused 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.

Throughout the experimental programme a constant stress amplitude sinusoidal waveform was employed, with frequency f=25Hz and load ratio R=0.04, in air. The stress waveform parameters were closely monitored to assure repeatability.

Partially Fatigued - Shot Peened. The testing used specimens incorporating a notch with K_t=4.93. As machined samples were partially fatigued and load cycling was interrupted at predefined intervals $N^P=\lambda N_e^{AM}$. Where, λ is the partial fatigue factor and, N_e^{AM} being the experimentally determined endurance life - for the as machined condition - at the load amplitude employed. These partially fatigued samples were shot peen treated and subsequently fatigued to failure.

Shot Peened - Partially Fatigued - Re-peened. Specimens including a stress concentration factor K_t=3.19 were shot peened and partially fatigued to $N^P_{SP}=\lambda N_e^{SP}$. Where, λ is the partial fatigue factor and N_e^{SP} is the endurance life - for the shot peened condition - at the load amplitude used. Subsequently, these specimens were re-peened and fatigue tested to failure.

Shot Peening Treatment

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 peen treated by rotating the samples under the shot stream with a constant rotational speed of 20 rpm. Table 2, lists the shot peening process parameters used in the research programme.

TABLE 2 - Shot Peening Parameters

Air Pressure (KPa)	Mass Flow Rate (Kg/min)	Almen-A Intensity (mm)	Coverage (%)	Shot Velocity (m/sec)
104	3.2	0.36	150	45

Shot velocity was measured using a laser transient anemometer system Akber (2). Coverage was evaluated by visual examination using a (x10) magnifying glass, a fluorescent tracer coating and ultraviolet illumination in accordance with MIL-S-13165C.

RESULTS AND DISCUSSIONS

Partially Fatigue Damaged - Shot Peened (PF-SP)

The specimens in the as machined condition, were partially fatigued by constant stress amplitude cyclic loading, $\sigma_a=0.53\sigma_{0.2\%}$. 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 $N_F=N_e'+N^P$ were recorded and, $N^R=(1-\lambda)N_e^{AM}$ the predicted remaining lives were computed. This allowed the evaluation of the effects of treatment, by comparing the expected total life in the un-damaged and as peened conditions, to the actual total life following partial fatigue damage and shot peening treatment.

The effects of peening following partial fatigue are depicted in Figures 1 & 2, as compared to N_e^{AM} and N_e^{SP} respectively. The life enhancements achieved through peening after consuming part of the as machined life, $\lambda>0$, were greater than the effect of peening before testing, $\lambda=0$, which yielded an enhancement of $\approx 200\%$. The results demonstrate the dependency of life improvement upon the degree of partial fatigue λ. The beneficial effect increased for $\lambda<65\%$ and peaked at $\lambda \approx 60\%$ where a 370% improvement over the life to failure recorded for the as machined condition. The benefits of shot peening gradually declined as partial fatigue increased beyond 65%. However, the observed improvements were consistently better than 300%, even when partial fatigue preceding treatment was 80% N_e^{AM}, Figure 1.

Comparison of the total life achieved following treatment with N_e^{SP} demonstrated further favourable results. In detail, the improvements over N_e^{SP} increase for $\lambda<65\%$. The beneficial effects peaked at $\lambda \approx 60\%$ and gradually reduced as the degree of partial fatigue increased. However, improvements were at least 40% higher than those achieved by peening before commission, Figure 2.

Therefore, peening of partially fatigued samples achieved an enhancement of the total fatigue life better than that obtained for the shot peened condition. The experimental results provide clear evidence that peening following partial fatigue is positively better than shot peening prior to service, even when partial fatigue is extended to 80% N_e^{AM}.

Shot Peened - Partially Fatigued - Re-peened (SP-PF-SP)

Shot peened specimens were partially fatigued by constant stress amplitude cyclic loading, $\sigma_a=0.58\sigma_{0.2\%}$ and after partial fatigue they were re-peened. During each test the number of endurance cycles following re-peening N_e^{RP} and the total number of actual endurance cycles of any one test $N_F^{RE}=N_{SP}^{P}+N_e^{RP}$ were recorded and the predicted $N_{SP}^{R}=(1-\lambda)N_e^{SP}$ remaining lives were computed. The effects of re-peening as a function of the partial fatigue factor λ, are presented in Figures 1 & 2, as compared to N_e^{AM} and N_e^{SP} respectively.

Evidently, re-peening extended the total fatigue life to failure by as much as 38% as compared with N_e^{SP} and 140% relative to N_e^{AM}. Significant life improvements were observed for $\lambda<25\%$ that quickly reduced with increasing λ. For $\lambda>25\%$, the beneficial effect rapidly faded and only small benefits were noted. Moreover, for $\lambda>70\%$, re-peening was detrimental with consistent failures below the N_e^{SP} endurance cycles. Evidently, re-peening achieved an enhancement however, this was reduced proportionally to λ.

Mechanism. Microscopic examination of the fractured surfaces revealed that fractures developed by initiation and propagation of sub-surface cracks, Kyriacou et al (1), Akber (2). In contrast, surface edge crack nucleation was found to dominate the fatigue failure of as machined samples. Shot impact causes localised plastic deformation of a finite layer and reorientation of the slip planes, thus, impeding surface crack initiation. Surface coverage with overlapping indentations obliterates any surface micro-cracks and initiation sites formed during load cycling. Moreover, assuming that the crack depth is small, i.e. well within the layers affected by shot peening, this crack remains engulfed within plastically deformed layers and a compressive residual stress field. Crack nucleation and early-stage propagation are therefore impeded and this is confirmed by the observed enhanced fatigue performance.

Residual Stress Measurements. X-ray diffraction evaluation of the residual stresses was carried out on specimens peened before service, after peening and partial fatigue and, partial fatigue and re-peening, Figure 3. The surface and sub-surface residual stresses for the re-peened condition are lower than the values obtained for the shot peened state. Clearly, re-peening did not rebuild the residual stresses to the original level. The lower values of residual stresses indicate that strain hardening of the material during fatigue loading prevented the formation of sufficient plastic deformation which could result to restoration of cyclically faded out residual stresses, Akber (2). Re-peening is detrimental for λ>70% caused by the material over-hardening - verified during the project - that, promoted surface micro-cracking due to increased dislocation density, Oshida et al (3), illustrated by early failure.

CONCLUSIONS

The results of the study provide strong evidence that shot peening of partially fatigued components yields significant fatigue life enhancements. Beneficial effects depend upon the degree of fatigue life consumed prior to treatment. For the material tested, that exhibits work-hardening behaviour, the beneficial effects were maximum when 60% of the as machined life was exhausted. Even when 80% of the fatigue life was used, the benefits were significant and at least 40% higher than the endurance achieved by peening before commission.

Re-peening partially fatigue damaged specimens was found to be potentially beneficial. However, benefits were strongly dependent upon the percentage of shot peen life expended prior to re-peening. Some modest benefits could be obtained by a re-peening treatment carried out when a small percentage of the shot peened life has been consumed by partial fatigue. The effects of re-peening are detrimental if performed at an instant where partial fatigue life has exceeded 75% of the shot-peened life.

X-ray diffraction measurements of the residual stresses demonstrated that peening or re-peening following partial fatigue, did not produce residual stresses as intense as those associated with the peening of 'virgin' samples. This demonstrates partial rejuvenation of compressive residual stresses. It is believed that restoration of the residual stresses could be achieved if higher re-peening intensities were used . That is the subject of further research.

Finally, it has been demonstrated that shot peening could be employed as a means of extending the design fatigue life of damaged un-peened components and, parts that were shot peened before use. It is hoped that the findings presented will assist engineers in developing maintenance strategies that would yield lifing of machine components.

REFERENCES

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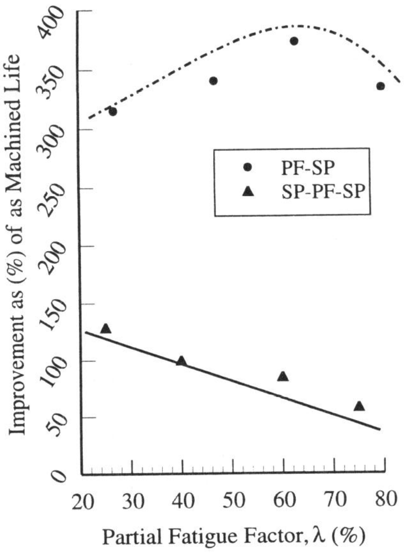

Figure 1 Life Enhancements as Compared to N_e^{AM}

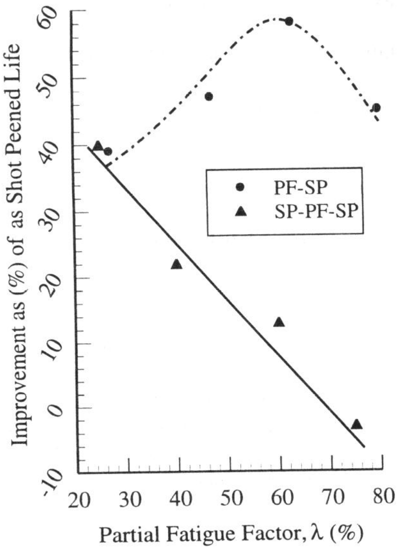

Figure 2 Life Enhancements as Compared to N_e^{SP}

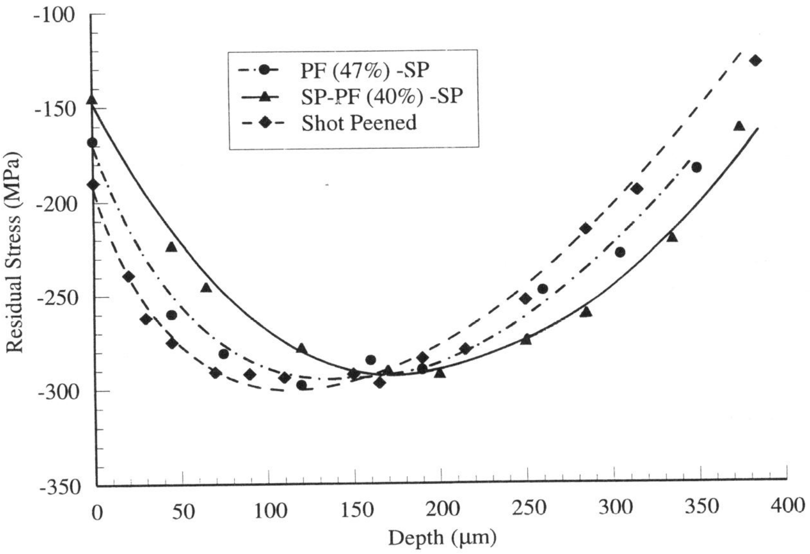

Figure 3 Residual Stress Profiles Induced by Shot Peening at various Stages of Partial Fatigue