THE EFFECT OF PEENING AND RE-PEENING UPON PARTIALLY FATIGUED COMPONENTS

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Industrial Summary

This investigation examines the respective effects of peening and re-peening upon the fatigue-life improvement of partially fatigued un-peened and previously-peened cylindrical V-notched specimens made of medium carbon steel En8. Room temperature rotating-bending fatigue tests conducted on initially un-peened and subsequently peened specimens, at various stages of their estimated fatigue life, generally revealed a substantial life improvement. This improvement is governed however, amongst other factors, by the depth of cracks measured prior to peening. Tests on previously-peened partially-fatigued and subsequently re-peened specimens indicated complete life recovery, even when the specimens had been partially fatigued by as much as 75% of their estimated fatigue life.

Detailed analysis of the results reveals that the recovery of the fatigue life of previously-peened partially-fatigued components is due mainly to the strengthening of the "faded" residual stresses in the compressed layer and to the improved peening-coverage.

Notation

M Total fatigue life of a peened specimen
M_i Initiation fatigue life of a peened specimen
M_{pr} Total propagation fatigue life of a peened specimen
N Total fatigue life of an un-peened specimen
N_{pr} Total propagation fatigue life of an un-peened specimen
R stress ratio ($\sigma_{min}/\sigma_{max}$)
W Chosen loading weight
σ_a Alternating stress
σ_{ep} Endurance limit for peened specimens
σ_R Residual stress distribution
σ_y Initial lower yield stress
σ_{yu} Upper yield stress

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Subscripts

a   indicates alternating
i   indicates initiation
o   indicates initial
pr   indicates propagation
R   indicates residual

Superscripts

b   indicates bulk material
cl   indicates compressed layer

1. Introduction

The problems associated with the behaviour of metals under repeated stresses are becoming more acute with the increasing demand for energy and weight savings, and the increase in the operational demands of machinery. Justification for the study of compressive stresses, and the processes which induce them, lies in the fact that compressive surface stresses have been found to be very useful in combating fatigue failure. Shot-peening is one of these processes: it uses a high velocity stream of hard spherical particles — such as cast-steel shot — to hammer the surface of a component, thus causing the surface regions to deform plastically. The objective is to impart compressive residual stresses in the surface regions large enough in magnitude to suppress the initiation and the subsequent growth of surface cracks. This is believed to be the basic mechanism of fatigue life improvement due to peening.

Several investigators [1—3] have demonstrated that these residual stresses are not permanent, but tend to fade with cyclic loading. Such a phenomenon was found to be greater at the surface than in the sub-surface layers, and due to high loads rather than low loads [1]. It is reasonable, therefore, to assume that this fading is attributable to the microscopic plastic deformation which takes place during the crack-initiation period and the early stages of growth. Other causes which might result in residual stress fade-out or even complete annihilation include: exposure to elevated temperatures; over-stressing; hostile environments; physical removal of the compressed layer by machining, wear, erosion or surface scratching; and finally through permanent distortion. These causes are indicative of the limitations imposed upon successful peening, unless some means is found to restore the faded-out compressive residual stresses. This can be achieved by re-peening the component. As far as the authors are aware, no attempt has been made to study the respective effects of peening and re-peening upon the fatigue life improvement of partially fatigued un-peened and previously-peened components, and for this reason the present investigation was undertaken.

Two aspects of the material behaviour are examined: (i) the response of

partially-fatigued components to peening treatment, and (ii) the response of partially-fatigued previously-peened components to similar re-peening treatment. In particular, it was desired to determine whether the cyclically faded-out residual stresses of previously peened components can be restored by the re-peening treatment.

For this purpose, room temperature rotating-bending fatigue tests were conducted on cylindrical V-notched un-peened, peened and re-peened specimens made of annealed medium carbon steel (En8).

2. Experimental analysis

2.1 Equipment and specimens

The experimental programme conducted utilised a rotating-bending fatigue-testing machine, and a direct-pressure air-blast peening system. A photograph of the fatigue-testing machine is presented as Fig. 1. One end of the machine is driven by a 3-phase, 7.5 HP(2.24 kW) induction motor operating at a constant speed of 2980 rev/min. The uniform bending moment acting on the specimen was generated by loading equal weights onto two pans attached to respective loading arms. This testing machine is equipped
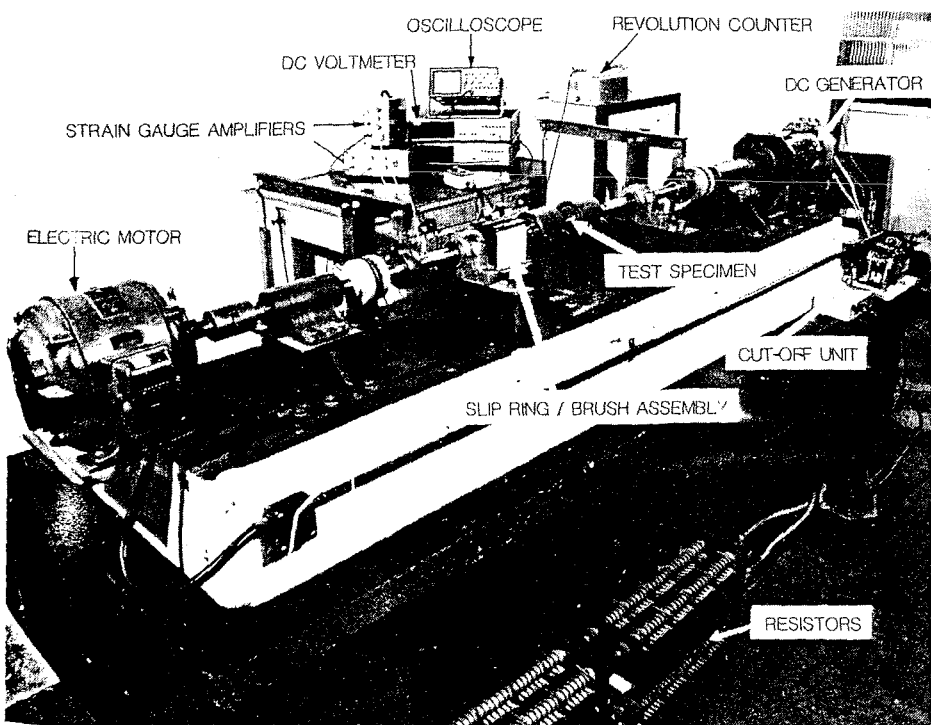

Fig. 1. Photograph of fatigue-testing machine.

with an automatic cut-out circuit, a digital revolution counter and a remote emergency shut-down facility. Linear (and torsional) strain-gauge bridges were installed on one of the flexure shafts and these, in turn, were connected to a series of slip rings, brushes and signal pick-up points, as depicted in Fig. 2. Adequate slip rings were also made available for picking-up the signals from strain-gauged specimens during the initial calibration of the testing machine.
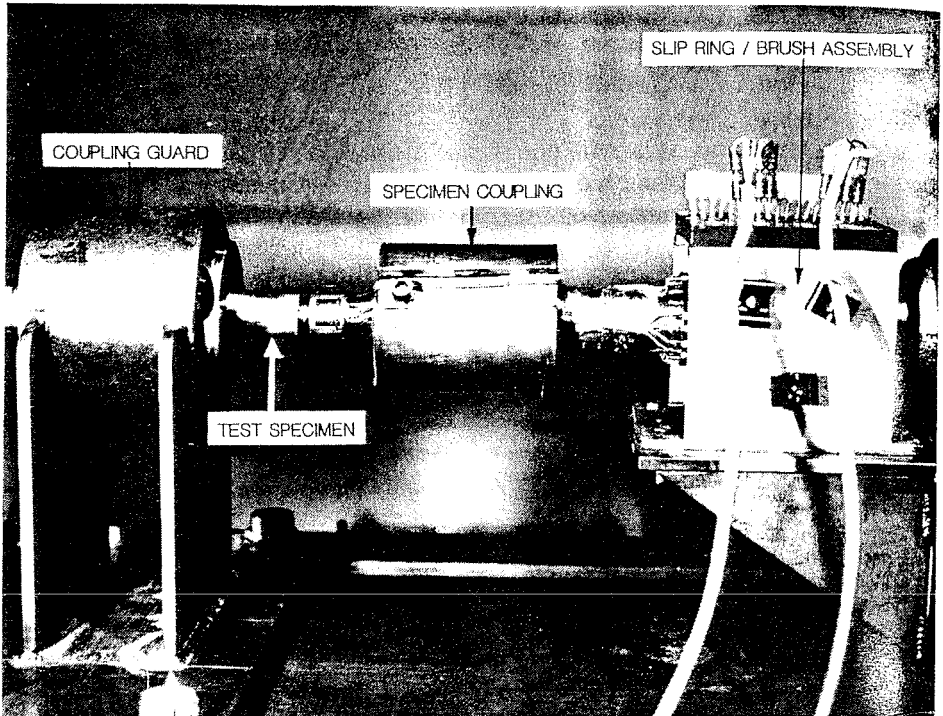

Fig. 2. Strain-gauged specimen and slip-ring assembly.

The fatigue machine was initially calibrated by strain-gauging one of the specimens and both static and dynamic calibrations were carried out. During the dynamic calibration use was made of an oscilloscope, not only to measure the magnitudes of the resulting bending stresses, but also to monitor the wave-form during testing.

The shot-peening system used in the present investigation is fully described in ref. 4. The shot-size used was mainly determined by the root radius of the notch and the surface conditions of the specimen. The "MIL-S-13165B" specification* on shot-peening recommends the use of a shot-diameter which is less than half of the notch root-radius to be peened. The

*U.S. Military specification

speci ication also recommends the use of peening intensities between 0.012 and 0.016 A (Almen Intensity) for mild steel having a minimum section diameter of 15 mm. It was therefore decided to use the following parameters for all the peening and the re-peening treatments: shot size = S170, peening intensity = 0.014 A, nozzle stand-off distance = 152 mm, and jet obliquity = 90°. Full coverage of the specimen was assumed to be 98%.

Preliminary experiments were conducted on the steel investigated (En8) in order to determine the specimen dimensions. The design requirement of the notch and overall dimensions of the specimens were dictated by the need to er sure (i) elastic loading conditions, (ii) rigidity during dynamic loading, (iii) that no distortions resulted ffom the peening treatment, and (iv) that the number of grains existing across the reduced section was sufficient, so that the experimentally determined properties were representative of a poly-crystalline material behaviour. As a compromise, is was decided to choose the dimensions given in Fig. 3 for the steel specimens, the composition of which is given in Table 1. In order to minimize experimental scatter and ensure repeatability, a complete manual of the manufacturing procedure was laid down, and the guide lines given in refs. [5] and [6] were followed wherever possible.

P. or to testing, the specimens were annealed for 90 min at 850°C in a vacuum furnace and then furnace cooled. In order to quantify the mechani-
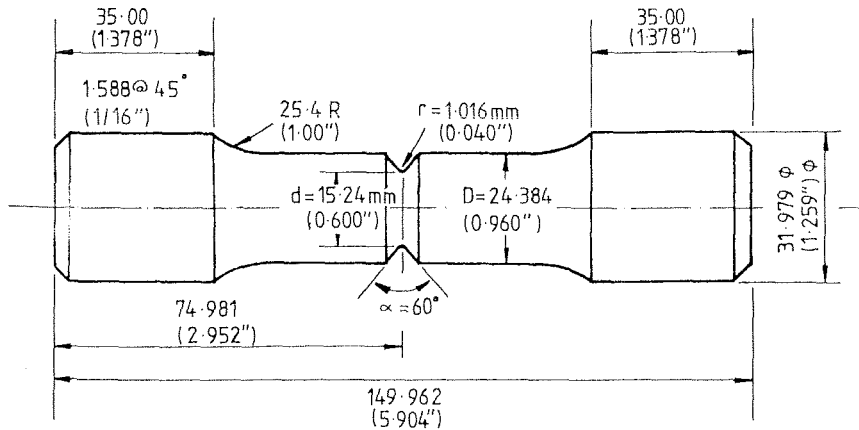

Fig. 3. Details of the fatigue-test specimen.

TABLE 1

Chemical composition of En8 Steel as provided by the manufacturer

Element	C	Si	Mn	S	P	Fe
Percentage (wt)	0.43	0.26	0.78	0.033	0.028	rem.

cal and microstructure properties of the resulting specimens, a comprehensive test programme was undertaken, the details of which are given in ref. [4]. The microstructure studies revealed that there exist no directionality effects in the grain structure. The average grain-size of the specimen was found to be 20 μm giving about 760 grains across the reduced section of the specimen. The mechanical properties of the specimens which are listed in Table 2 were the averages of five tests. Finally, the hardness measurements indicated a random distribution of values across the face of the specimens examined. The overall mean value of hardness was Hv 194 using an indenter load of 30 kgf (294 N).

TABLE 2

Mechanical properties of the test material determined from quasi-static tensile tests performed at a constant deformation rate of 10^{-5} s^{-1}, and from hardness tests with an indenter load of 30 kgf (294 N)

Material	Lower Yield Stress, σ_y (MPa)	Upper Yield Stress, σ_{yu} (MPa)	Ultimate Tensile Strengh, σ_{uts} (MPa)	Elongation At Fracture (%)	Hardness (Hv)
Medium Carbon Steel (En8)	411	422	660	29	194

The crack detection and measuring equipment used was the "Crack Micro Gauge — Type U7G 300 Series" (a.c. field measuring) together with a 10 mm probe. It is worth noting that the smallest crack depth measurable using this equipment is 0.03 mm and the largest depth is 45 mm. Post-mortem examinations were carried out to ensure that the actual crack depths were in agreement with those as measured by the above equipment.

2.2 Experimental programme

The experimental work consisted of preliminary and main test programmes. The preliminary tests involved the determination of the σ_a–N curves for peened and un-peened "virgin" specimens with the aim of establishing the improvement in the fatigue life due to peening for varying applied alternating stress, σ_a, and to establish the appropriate test load for the main tests. The test requirements of the appropriate fatigue load were dictated by the need to ensure: (i) elastic loading conditions, thus ensuring high cycle fatigue testing; (ii) avoidance of endurance (or fatigue) limit; and (iii) appropriate testing time. As a compromise, it was decided to choose a test load of 170 N.

The main test programme comprised two sections. In the first, virgin specimens were partially fatigued to 25%, 50% and 75% of their mean un-peened fatigue life N (which could be estimated from σ_a–N curves derived from the preliminary test results at the chosen value of σ_a). The initial

crack depths of these partially fatigued specimens were measured using the a.c. field crack-measuring equipment, described earlier. The specimens were then peened, according to the previously specified conditions, and re-tested to fracture. The fatigue life thus obtained was compared with N and M, where M is their mean *peened* fatigue life. In the second, previously peened specimens were partially fatigued to 25%, 50% and 75% of M. The specimens were then re-peened using the same conditions — thus ensuring the same coverage and intensity — and re-tested to failure. Again the fatigue life was compared with N and M.

3. Results and discussion

3.1 Preliminary tests

Figure 4 shows the σ_a–N curves for peened and un-peened specimens. It appears from these curves that the number of cycles which corresponds to the appropriate test load of 170 N for peened and un-peened specimens is approximately $M = 4.8 \times 10^5$ cycles and $N = 1.5 \times 10^5$ cycles, which is equivalent to 160 min and 50 min of testing time, respectively.

At this chosen test load, the fatigue life achieved by the peened specimens is 333% of that achieved by the un-peened specimens, i.e. an improvement of 233%. This improvement is considered modest, and is attributed to the high alternating stress, σ_a, used. Another contributing factor is the use of reversed bending with $R = -1$: the residual stress pattern tends to fade out
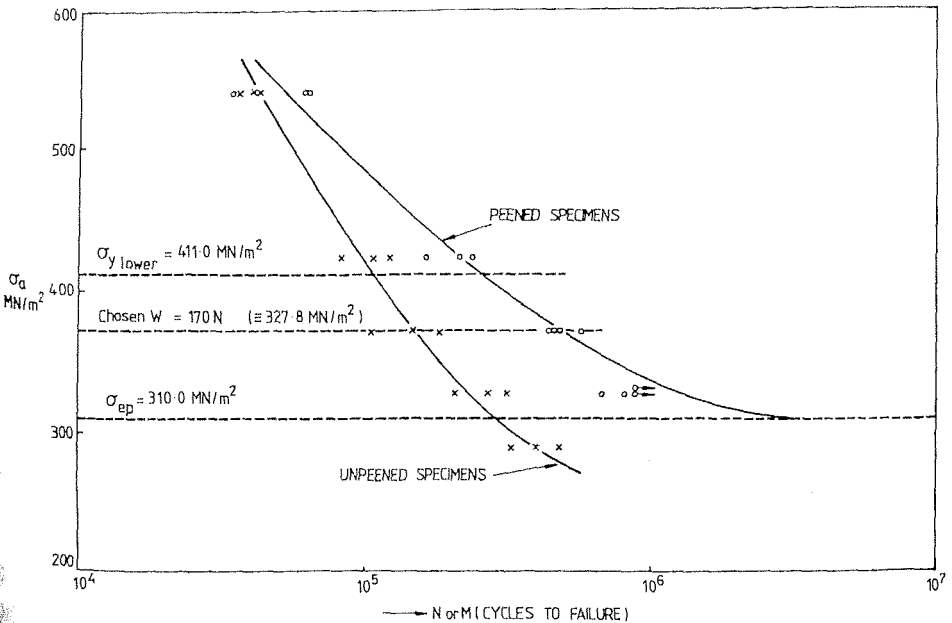

Fig. 4. σ_a–N curves for peened and un-peened specimens.

with increasing number of cycles [7]. Finally, the use of normalised speci-
mens which are relatively soft and of low strength could also contribute to
this modest improvement [8].

The $\sigma_a - N$ curves also indicate that the improvement in the fatigue life
could still be achieved even for an alternating stress, σ_a, exceeding the initial
yield stress of the material, σ_y. This could be explained by the fact that the
compressed layer, which is work-hardened by peening, attains a new, higher,
yield value.

3.2 Main tests

Effect of peening upon partially fatigued un-peened specimens

The results obtained from these tests are summarized in Table 3. The
crack readings given in Column (e) represent the mean of the crack depth
measurements taken at four different positions 90° apart around the notch.
Post-mortem examinations were also carried out to ensure that the cracks
were central, and that their depths were in agreement with those as measured
using the a.c. field measuring equipment. The results were very satisfactory
and in agreement to within 3%.

Despite the statistically intensive crack readings taken during this study,
the results show some scatter in the initial crack depth measurements of par-
tially fatigued specimens. However, if the mean of the crack depth of the
four different specimens for each experimental group was taken into ac-
count, the following results were obtained: mean crack depth = 0.145 mm
for 25% N, 0.335 mm for 50% N and 0.683 mm for 75% N, thus indicating
a consistent crack growth as the fatigue lives of the test specimens were ex-
pended (see Column (d) of Table 4). The standard deviation of the readings
was admittedly still high; a larger test sample could probably yield a smaller
deviation.

Closer study of the initial crack depth prior to peening and the corre-
sponding fatigue life obtained after peening (Column (d) of Table 4) reveals
good correlation between these two, regardless of the pre-fatigue conditions.
Figure 5 shows a rapid decrease in the available fatigue life with the in-
creased depth of cracks prior to peening. Hence, it can be deduced that the
fatigue life improvement achievable by peening depends to a large extent
upon the crack depth existing prior to peening.

Figure 5 also indicates that if the specimen has no detectable engineering
cracks (i.e. <0.03 mm) the fatigue life obtained is equal to about 160 min,
which is almost equal to the mean fatigue life of a specimen peened when
"new". In other words, the partially fatigued material behaves as though it
has never been subjected to cyclic loading. This implies that if a component
is run for part of its fatigue life, peening of such components yields a much
better overall fatigue life improvement than peening while new, the gain
being the partial fatigue life already accrued by the component at the time
of peening. This can be explained as follows. The bombardment of high

TABLE 3

Fatigue lives of specimens peened after being partially fatigued to 25%, 50% and 75% N

Identifier	Running Time Prior to Peening (Min)	Expected Remaining Life Prior To Peening $\{N-(b)\}$ (Min)	Specimen Number	Crack Depth Prior to Peening (mm)	Fatigue Life Obtained After Peening (Hrs: Mins: Secs)	Total Life Since New $\{(b) + (f)\}$ (Hrs: Mins: Secs)	Improvement Over Remaining Life $\dfrac{(f)-(c)}{(c)} \times 100\%$	Overall Improvement Over N $\dfrac{(g)-N}{N} \times 100\%$
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
1	12.5 (25% N)[a]	37.5 (75% N)	4.14	0.00	2 : 50 : 49	3 : 03 : 19	356	267
			5.13	0.05	2 : 40 : 03	2 : 52 : 33	327	245
			6.05	0.30	2 : 09 : 47	2 : 22 : 17	246	185
			6.17	0.23	0 : 50 : 47[b]	—	—	—
2	25.0 (50% N)	25.0 (50% N)	6.09	0.13	2 : 31 : 14	2 : 56 : 14	505	252
			5.04	0.23	2 : 15 : 43	2 : 40 : 43	443	220
			5.08	0.88	1 : 50 : 00	2 : 15 : 00	340	170
			4.07	0.10	2 : 11 : 12	2 : 36 : 12	425	212
3	37.5 (75% N)	12.5 (25% N)	4.02	0.35	1 : 55 : 43	2 : 33 : 13	826	206
			6.15	0.86	1 : 34 : 52	2 : 12 : 22	659	164
			5.06	1.05	0 : 42 : 54	1 : 20 : 24	243	60
			4.05	0.47	1 : 33 : 22	2 : 10 : 52	647	162

[a] N = 50 min.
[b] Specimen accidentally overloaded — data rejected.

TABLE 4

Mean values of fatigue-life improvement of partially-fatigued un-peened specimens. All mean-life calculations assume log-normal distribution.

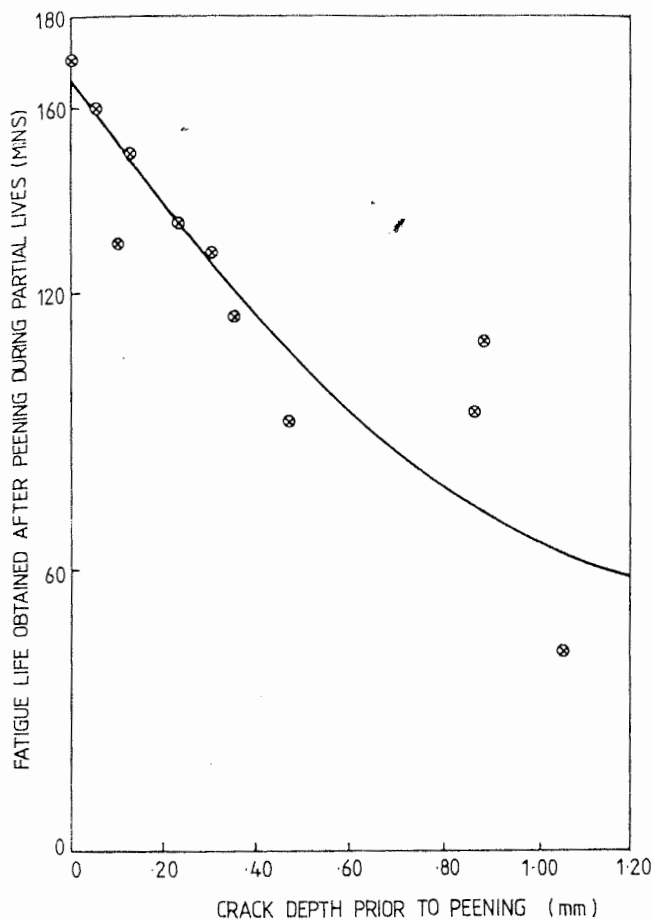| Identi-fier	Running Time Prior to Peening (Min)	Expected Remaining Life Prior to Peening $\{N-(b)\}$ (Min)	Mean Crack Depth Prior To Peening (mm)	Mean Fatigue Life Obtained After Peening (Hrs:Mins:Secs)	Total Mean Life Since New (b) + (e) (Hrs:Mins:Secs)	Improvement Over Remaining Life $\frac{(e)-(c)}{(c)} \times 100\%$	Overall Improvement Over N $\frac{(f)-N}{N} \times 100\%$
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
0	0 $(0\% N)$[a]	50 $(100\% N)$	—	2 : 42 : 12	2 : 42 : 12	224	224
1	12.5 $(25\% N)$	37.5 $(75\% N)$	0.145	2 : 33 : 33	2 : 46 : 03	309	232
2	25.0 $(50\% N)$	25.0 $(50\% N)$	0.335	2 : 12 : 03	2 : 37 : 03	428	214
3	37.5 $(75\% N$	12.5 $(25\% N)$	0.683	1 : 50 : 27	2 : 27 : 57	594	148

[a] $N = 50$ min.

Fig. 5. Relationship between crack depth prior to peening and fatigue life available after peening.

velocity shots onto the exposed surface regions causes a finite layer of the surface to be plastically deformed, which upon unloading introduces a compressive residual stress system at the top layers. If all the initiation sites are obliterated or at least disrupted by the peening action, the entire initiation and early-stage propagation has to be restarted all over again, hence accounting for this improvement in the fatigue life of such components.

Alternatively, if an engineering crack has already been formed at the time of in-service peening, it is unlikely that the crack can be obliterated by the peening action. Assuming that the crack depth is still *small*, i.e. well within the depth of the compressed layer, this crack will be engulfed in a compressive residual field. The effect of this on the rate of growth depends to a large extent upon the resultant state of stress at the crack region. Figure 6 shows a gradual decline in the fatigue-life improvement as the peening of the par-
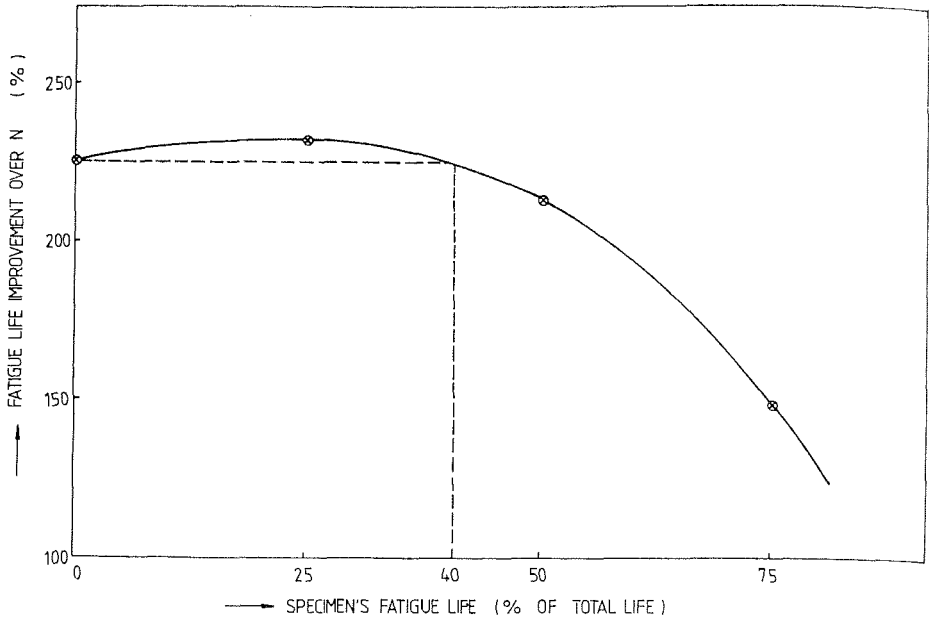
Fig. 6. Fatigue life improvement (over N) due to the shot-peening of partially fatigued un-peened specimens.

tially fatigued specimens is performed progressively later in their lives. It is believed that as the cracks grow deeper into the specimen, the peening treatment becomes less effective.

Effect of re-peening upon partially-fatigued previously-peened specimens
Peened specimens were tested for part of their estimated fatigue lives M, and then re-peened and re-tested to complete fracture: the results obtained are given in Table 5. It is worth noting that the fatigue life quoted after re-peening does not include that part of the life which has already been accrued by the specimen at the time of re-peening.

Attempts were made to measure the crack depth of the specimens before and after they had been partially fatigued but the readings obtained were found to be inconsistent: this is probably due to the poor probe-tip contact with the somewhat rough and irregular peened surfaces.

Results of Table 5 indicate a tremendous improvement in the fatigue lives of peened specimens after they had been partially fatigued to 25%, 50% and 75% of M, and then re-peened using the same peening treatment. For all cases considered, complete rejuvenation has been accomplished, even in cases where the specimens were partially fatigued to 75% M.

The following model is proposed to explain the recovery of the fatigue life of a previously-peened partially fatigued component. In this model, shown schematically in Fig. 7, it is assumed that the initial fatigue life of a component is N and that upon initial peening it becomes M, where $M >> N$.

TABLE 5

Fatigue lives of re-peened specimens after being partially fatigued to 25%, 50% and 75% M

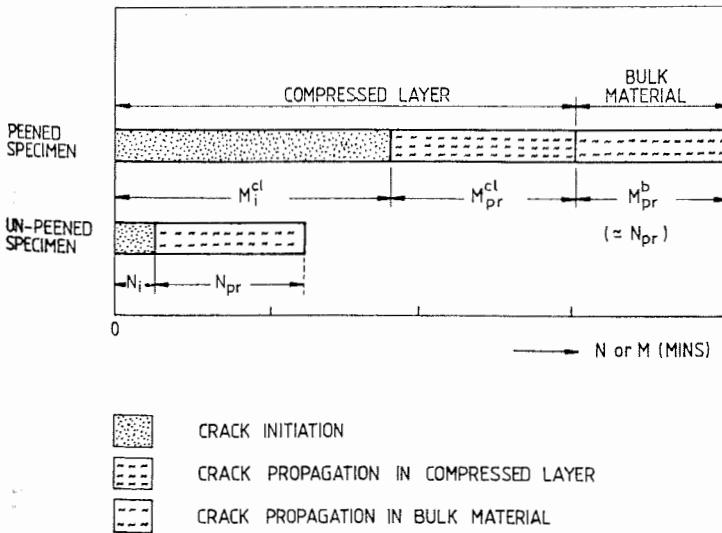| Identi-fier	Running Time Prior To Re-Peening (Min)	Expected Remaining Life Prior To Re-Peening $\{M-(b)\}$ (Min)	Fatigue Life Obtained After Re-Peening (Hrs:Mins:Secs)	Mean Fatigue Life Obtained After Re-Peening (Min)
(a)	(b)	(c)	(d)	(e)
1	40 $(25\% M)^a$	120 $(75\% M)$	4 : 03 : 11 3 : 40 : 27 3 : 12 : 15	218
2	80 $(50\% M)$	80 $(50\% M)$	3 : 50 : 27 3 : 12 : 51 3 : 05 : 42	203
3	120 $(75\% M)$	40 $(25\% M)$	4 : 20 : 15 3 : 15 : 17 3 : 39 : 18	224

[a] M = 160 min

Fig. 7. Schematic showing the crack initiation and crack propagation segments in peened and un-peened specimens.

It is generally accepted that the total fatigue life N is made up of initiation and propagation segments. It is reasonable therefore to assume that for an un-peened specimen

$$N = N_i + N_{pr} \tag{1}$$

where N_i is the initiation fatigue life and N_{pr} is the propagation fatigue life, while for a peened specimen

$$M = M_i + M_{pr} \tag{2}$$

where M_i is the initiation fatigue life and M_{pr} is the total propagation fatigue life.

Now, if M is segregated into fatigue damage taking place in the compressed layer (denoted by the superscript cl) and fatigue damage taking place in the bulk material of the specimen (denoted by the superscript b), eqn. (2) becomes

$$M = M_i^{cl} + M_{pr}^{cl} + M_{pr}^{b} \tag{3}$$

The above equation implies that the initiation fatigue life for the peened component M_i^{cl} takes place wholly in the compressed layer, while the propagation life M_{pr} takes place in the compressed layer as well as in the bulk material. This assumption is only valid for cracks initiated from the top surface layers of the component. Cracks initiated within the bulk of the material (e.g. porosities or voids, hydrogen embrittlement) cannot be helped by the localised effects of shot-peening.

Once a crack has propagated beyond the compressed layer into the bulk material, its rate of propagation approaches that of an un-peened specimen. Now, since the depth of the compressed layer is relatively much smaller than that of the bulk material, it is then reasonable to assume that under the same cyclic loading conditions

$$N_{pr} \approx M_{pr}^{b} \tag{4}$$

and eqn. (3) becomes

$$M = M_i^{cl} + M_{pr}^{cl} + N_{pr} \tag{5}$$

Equation (5) implies that a large proportion of the fatigue life (at least $M-N$) is spent in the initiation and propagation of cracks in the compressed layer.

It is worth noting that the results of this study (Table 5) reveal that re-peening is most effective when the crack is still at the initiation and/or early propagation stages, i.e. where a large proportion of the fatigue damage is spent in combating the residual stresses in the compressed layer. Bombarding high-velocity shots onto the surface of a component would harden, would re-orientate the initiation slip planes and, in some instances, would obliterate surface microcracks already formed during dynamic loading. Further, because the fatigue activities are localised in the compressed layer for a considerable

rtion of the total fatigue life, rejuvenation by re-peening could be carried
it most effectively at a relatively later stage of the specimen's residual
tigue life.

Surprisingly, the results of Table 5 indicate that the fatigue life obtained
ter re-peening is more than the original fatigue life of a peened component
. There are three possible factors which could account for this, namely:
strengthening of the compressed layers; (ii) improved coverage after re-
ening; and (iii) experimental scatter; all of which need to be explored in
ture research. However, from the results obtained in both the peening and
-peening experiments, it can be confidently concluded that complete re-
venation can be achieved even for specimens fatigued by up to 75% of their
timated peened fatigue life M, or their un-peened fatigue life, N.

One interesting aspect of the present study is the effect of the re-peening
eatment upon the formation of sub-surface cracks. As pointed out in ref. 9,
ib-surface cracks have been found in peened components subjected to a
w-load high-cycle type of fatigue loading. Their locations and depths are
ndom, and are mainly determined by the metallurgical weaknesses in the
ib-surface structure and the corresponding state of stress in that layer. It is
fficult to see how re-peening using the same peening treatment can help in
juvenating the fatigue life of a component having sub-surface cracks, es-
ecially if these cracks initiate from locations slightly below the existing
ompressed layer. One possible way to overcome this problem is to re-peen
ie component using higher intensities.

Effect of applied stress upon the compressed layer of peened components
Figures 8 and 9 illustrate the effect of the magnitude of the applied stress
pon the resultant state of stress at the notch of a cylindrical specimen sub-
cted to pure bending. The initial magnitude of the compressive residual
ress pattern is assumed constant.

If the resultant surface stress in a peened component is compressive for
oth the upper and lower faces of the specimen as depicted in Fig. 8 (b) (this
appens if the applied stress is low or moderate), the small surface cracks
ill obviously be subjected to "compressive—compressive" cyclic stresses.
he behaviour of a crack under such conditions is difficult to predict (LEFM
oes not apply). It is anticipated, however, that under these circumstances
he crack will be non-propagating, resulting in an improved fatigue life.

If, on the other hand, the applied stress is relatively high in magnitude the
esultant surface stress will be in a tensile—compressive mode as depicted in
ig. 9(b). Large tensile stresses will be generated at the crack tip, thus prom-
ting the growth of the crack.

It is therefore reasonable to conclude that the resultant state of stress
lays an important role in the assessment of the effect of the peening and re-
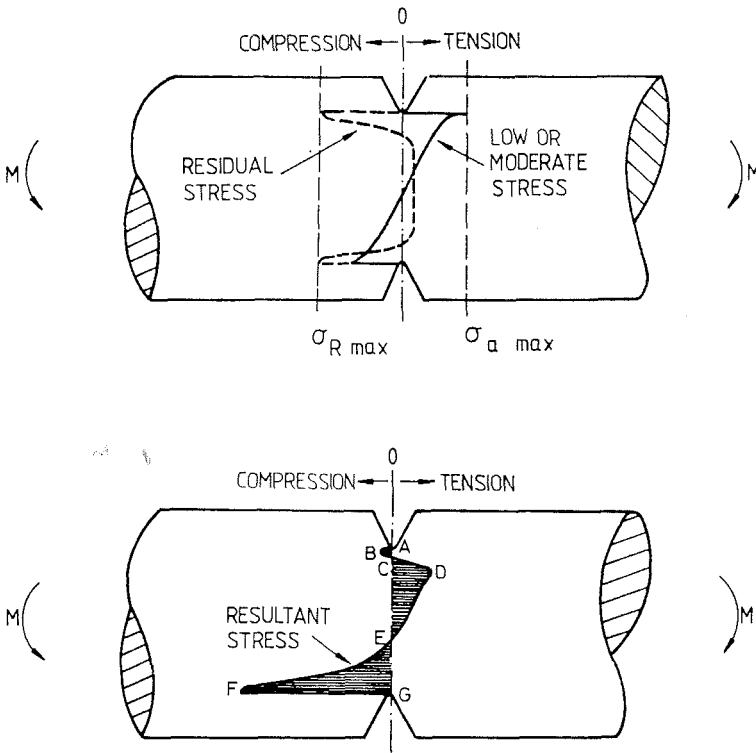eening treatments upon the resulting improvement in the fatigue life of the
omponent.

Fig. 8. Schematic of stress pattern of a shot-peened notched specimen subjected to a relatively low-to-moderate applied bending stress: (top) before superposition and (bottom) after superposition.

4. Conclusions

Both peening of partially fatigued un-peened specimens and re-peening of partially-fatigued previously-peened specimens, even at up to 75% of their estimated mean lives, yielded a considerable improvement in their respective fatigue lives. The results indicate that there exists a definite correlation between the initial crack depth prior to peening and the corresponding residual fatigue life achievable after peening. Specifically, a rapid decrease in the available fatigue life was promoted by the presence of increased depth of cracks prior to peening.

It was also demonstrated, using a simplified model, that the recovery of the fatigue life of a previously peened partially-fatigued component is most effective when the crack is still at the initiation and/or early propagation stages.

It is worth noting that the sample size for each experimental point was only four for the peening experiments and three for the re-peening experi-
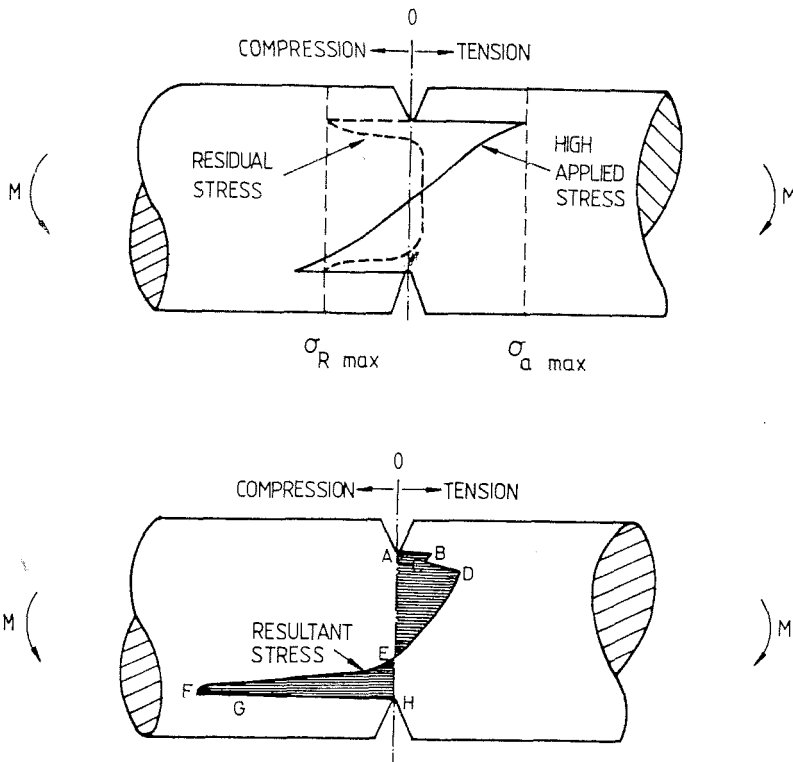
Fig. 9. Schematic of stress pattern of a shot-peened notched specimen subjected to a relatively high applied bending system: (top) before superposition and (bottom) after superposition.

ments. In view of the scatter inherent in all fatigue testing, a larger sample size per point is required. However, from the data available, this investigation consistently showed the effectiveness of the peening and re-peening treatments of partially fatigued specimens.

The objective of this study was to provide experimental results relating to the response of real materials to peening and re-peening of in-service components. It is believed that this is the first study of the effects of peening and re-peening upon partially fatigued components, and it is hoped that the information provided will guide the designer and the user of shot-peening towards the more effective use of both material and process.

Acknowledgement

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