FATIGUE BEHAVIOUR OF SHOT PEENED SURFACES

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Peening is a technique commonly used to improve fatigue resistance, but it is not always appreciated that excessive peening may be detrimental to fatigue behaviour. The present work demonstrates this effect in three different alloys: a mild steel, stainless steel, and a commercial copper alloy. The dependence of fatigue behaviour on peening intensity is shown to reach a maximum beyond which high intensity peening reduces fatigue life; at very high intensities the fatigue life can be reduced below the unpeened value. This reduction in fatigue life is shown to coincide with an increase in surface roughness, as measured by the parameter R_a, *and the onset of a distinct damage mechanism revealed by scanning electron microscopy. The varying effect of peening intensity in the different materials is related to their tensile, fatigue, and wear properties; a model is advanced to explain the observed behaviour, based on the change from an initiation dominated mechanism to a propagation dominated mechanism as peening intensity is increased. A limited number of results is also presented showing the effect of peening time on fatigue behaviour.*

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Peening techniques are commonly used to protect components against fatigue failure, and many of the principles and limitations of peening have been elucidated elsewhere.[1,2] The effectiveness of the peening operation is known to be due to the establishment of a surface layer of compressive residual stress and, to a lesser extent, to surface work hardening. It is often assumed that increasing the intensity of peening, as would be achieved by increasing the velocity or size of shot, for example, is always beneficial. While it is true that increased intensity will produce a deeper layer of residual stress, other effects come into play at high peening intensities which can be detrimental to fatigue life.[3,4] Simpson and Cammett, for example, have shown that high peening intensities can produce poor fatigue properties in aluminium alloys;[3] small scale surface damage in the form of extrusion folds was held to be responsible in this case. Likewise, Smith and Hirt[4] have suggested that the peening of a welded joint can lead to changes in the local geometry, resulting in increased stress concentration and, again, a lower fatigue life. Irving and Starkey[5] have shown that the fatigue properties of shot blasted surfaces decrease with increased surface roughness; a fracture mechanics approach was suggested in which the relevant parameter was the square root of the roughness value, approximating to the square root of depth for a sharp crack.

The present work demonstrates this roughness induced degradation in three materials: a low carbon mild steel, an austenitic stainless steel, and a complex commercial copper alloy. The fact that a similar effect can be demonstrated for materials with greatly differing mechanical and wear properties suggests that this problem is the rule rather than the exception, and should be investigated for all alloys that are subjected to peening.

EXPERIMENTAL DETAILS

Materials

Three materials were tested:

(i) a low carbon mild steel, in a normalized condition, containing a standard ferrite–pearlite microstructure with ~20% pearlite and a yield strength of 204 MN m^{-2}

(ii) a 316 austenitic stainless steel (18%Cr, 8%Ni) with a yield strength of 525 MN m^{-2}

(iii) a commercial copper alloy, denoted MZC, containing 0·6%Cr, 0·1%Zr, and 0·05%Mg. The microstructure consisted ~10% of intermetallic precipitates. The material has a yield strength of 455 MN m^{-2} and a tensile strength of 479 MN m^{-2}.

Peening operation

In all cases peening was carried out to saturation, i.e. until the residual stress pattern, as measured by Almen test strips, reached a plateau value. Peening intensity was varied by varying gun pressure, using

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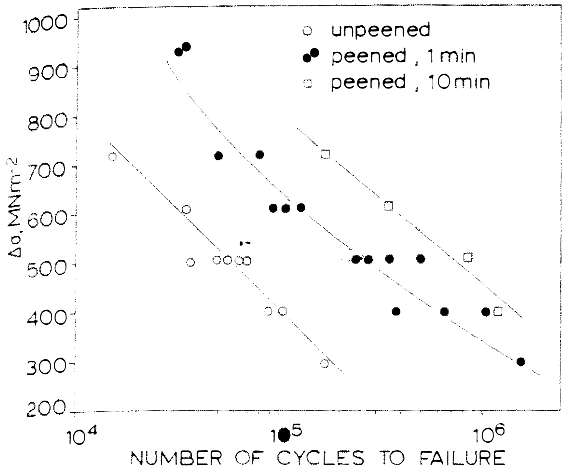


1 *Fatigue results for mild steel, showing effect of peening to saturation (1 min) and beyond saturation (10 min)*

steel shot and glass beads of average dia. 150 μm. In some cases peening was continued for extended times beyond that required for saturation. To limit variability in the data, all peening was carried out by the same operator.

Fatigue testing

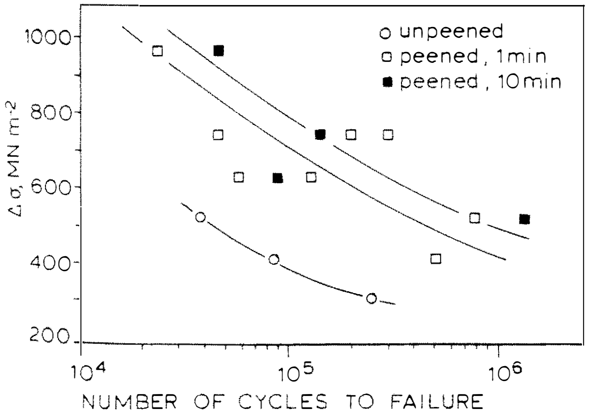
Standard rotating–bending fatigue tests were carried out using waisted specimens with threaded ends tested in fully reversed four point bend loading at a frequency of 46 Hz. The number of cycles to failure was recorded as a function of peak to peak stress range.

Surface roughness measurements

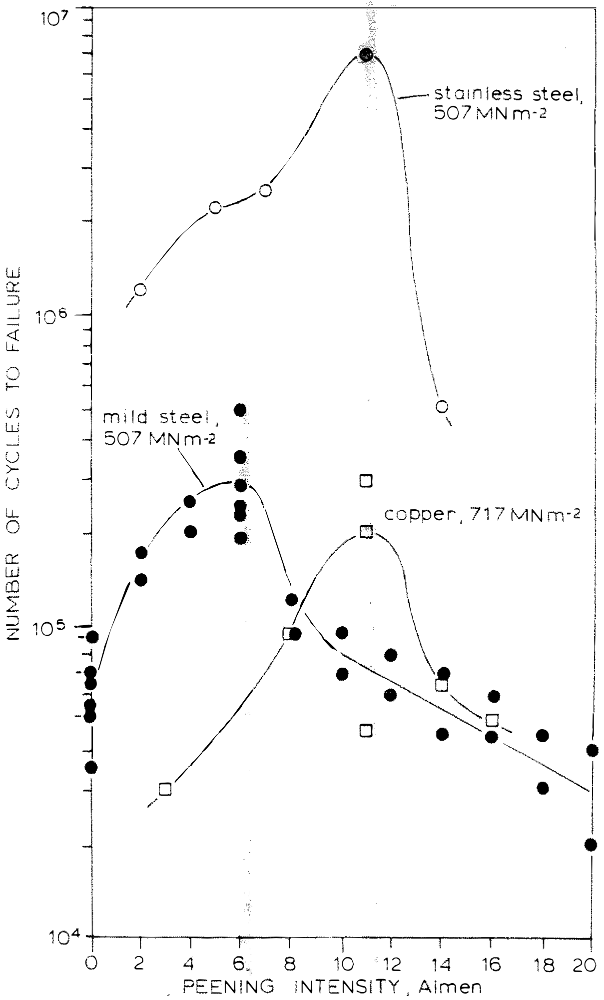
Surface roughness was measured using a Hommell Tester; the parameter recorded was R_a, the average deviation from the mean surface height. Five R_a values were measured at different points within the gauge length of each specimen. Surface condition was also assessed by examination in a scanning electron microscope (SEM).

RESULTS

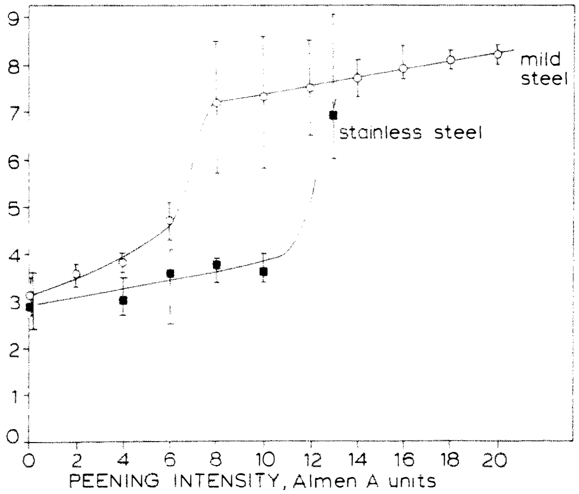
Figures 1 and 2 illustrate the effect of peening at a fixed intensity on fatigue behaviour for the mild steel and the copper alloy respectively. Standard S–N fatigue plots show that there is a significant increase in the number of cycles to failure at a given stress range after peening for 1 min at this intensity. This represents peening just beyond the time for saturation. Specimens peened for 10 min showed a further small increase in fatigue life. The amount of



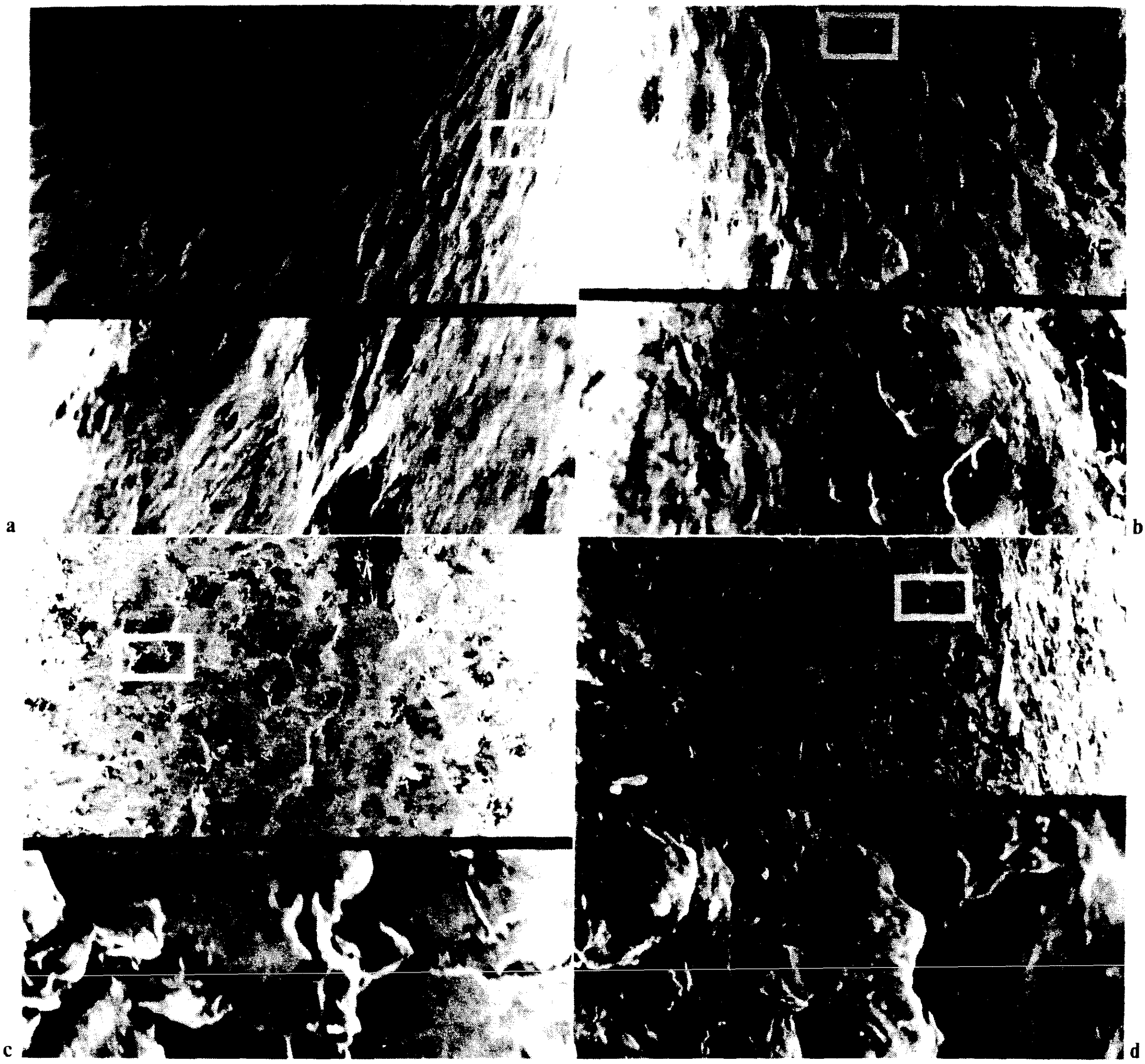
2 *Fatigue results for MZC copper, showing effect of peening to saturation (1 min) and beyond saturation (10 min)*



3 *Effect of peening intensity (Almen A units for steels, N units for copper) on number of cycles to failure for three materials, tested in fully reversed cycling: peak to peak cyclic stress is indicated for each material*



4 *Effect of peening intensity on measured surface roughness* R_a*: scatter bands show range of* R_a *values for five measurements taken on each specimen*



a 4A, 1 min; *b* 6A, 1 min; *c* 8A, 1 min; *d* 6A, 10 min

5 *Scanning electron micrographs showing surface roughness produced after peening mild steel specimens at given intensities for periods indicated: in each case magnification is 63 for upper part of micrograph and 630 for lower part*

scatter in results is typical for fatigue testing of this kind.

The effect of peening intensity on the number of cycles to failure for all three materials is shown in Fig. 3, using in each case a fixed stress range which is shown on the plots. Peening intensity is measured here in arbitrary Almen gauge units. Improvements in fatigue life of almost an order of magnitude can be achieved, but in all cases there is an optimum intensity beyond which the fatigue life decreases. There is a particularly sharp dependence of fatigue life on intensity for the stainless steel.

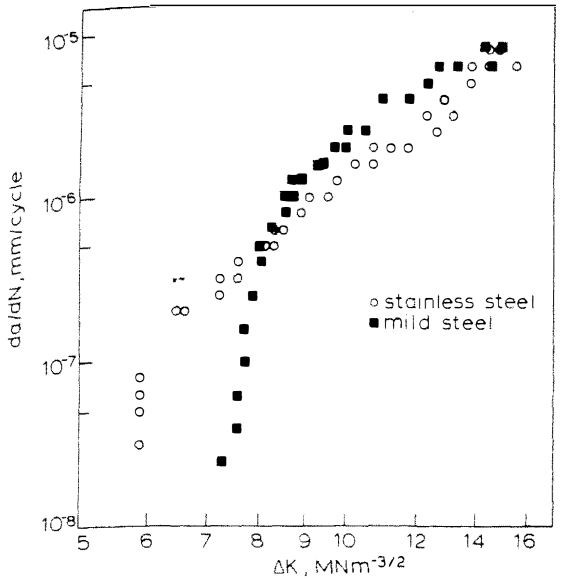
The surface roughness of the two steels, measured as a function of peening intensity using the same units, is shown in Fig. 4. In both materials there is a sudden increase in the average roughness above a given intensity value, which corresponds closely to the intensity value at which the fatigue properties begin to deteriorate.

SEM micrographs of the surfaces of some mild steel specimens are illustrated in Fig. 5. Two types of surface feature are evident: first, there is a general waviness composed of gradual surface undulations; and second, there are dark patches which, at higher magnification, are shown to consist of sharp sided pits and particles of extruded metal. The number of these latter features increases with increasing intensity. In the case of the stainless steel these dark features are fewer in number but have the same characteristics.

DISCUSSION

It is evident from the results presented above that peening intensity affects fatigue behaviour in a complex manner; there is a distinct optimum intensity which produces the best fatigue properties in each material tested, but the variation close to the peak can be quite steep, so that small changes in intensity may have a strong effect. A similar dependence has been demonstrated by Simpson and Cammett[3] for two aluminium alloys which are used in airframes; in their case it was pointed out that peening intensities beyond the optimum value were being used in practice for these alloys.

It has been shown here that the decrease in fatigue life beyond the optimum value coincides with a



6 *Typical fatigue crack propagation rate (d*A*/d*N*)–stress intensity (*ΔK*) behaviour for a 316 stainless steel and a low carbon mild steel:* R = *0·3–0·35; after Ref. 6*

sudden increase in surface roughness. For both steels tested there was an increase in R_a from an almost constant value of 3–4µm to a value of 7–8 µm. SEM observation linked this change to an increase in the number and size of sharp damage features. Simpson and Cammett[3] referred to the presence of surface extrusion folds on their materials; they would appear to have been observing the same features as shown here, though no micrographs appeared in their paper.

These sharp surface features appear to be caused by local removal (or wear) of material as a result of impingement by individual shot particles; material seems to be 'ploughed up', leaving an extrusion in the vicinity of the pit. The size of the features is approximately the same as the size of the shot used. On the whole, the size of the defects does not seem to change with increasing intensity, but there is a sudden increase in their number, which presumably occurs because, as the velocity of the shot is increased, a larger number of shot particles possess the energy necessary to cause this particular wear process.

Though the typical size of these features is 50–100 µm, the measured R_a values are much smaller than this. This is because R_a measures an average deviation for a large area of the sample surface, over which defects occur only occasionally. The lower roughness value of 3–4 µm measured at low intensities is assumed to be the background roughness resulting from a combination of the machining process and the dimpling produced by shot which do not plough up the surface. This dimpling is quite evident in the SEM micrographs. It is significant that when the average roughness increases, the scatter in roughness values also increases, since in this case some sampled surfaces contain few or no defects, whereas other samples may contain several defects. In this case R_a is clearly not the best parameter to describe the surface; other parameters can be developed which concentrate on larger surface features. However, R_a is at least sufficient to indicate the increase in surface damage, though not to quantify it.

In this work it was not possible to measure the depth of the layer of residual stress produced by the various peening intensities, but it is estimated that the largest of these surface defects may be able to penetrate beyond the protective influence of the residual stress layer. This, combined with the fact that the defect itself is a stress concentrator, serves to explain why very high peening intensities can cause fatigue behaviour which is worse than that of the base metal.

The practice of electropolishing the surface after peening has been shown to improve the fatigue life;[1] this is presumably a result of the removal of surface roughness, and may be an effective line of action for the high intensity peening reported here. However, if the damage features do indeed penetrate the layer of compressive residual stress, then polishing will not be effective, since it will not be possible to remove the defects without removing the residual stress.

Effect of material type

Comparing the stainless steel and the mild steel, it can be seen that, for the same stress range, the stainless steel has a longer fatigue life and appears to respond more to shot peening at low intensities. These properties can be attributed to its higher yield strength, which would be expected to produce improved fatigue properties if the fatigue process were controlled by crack initiation or by the growth of very small cracks. Likewise the higher yield strength will result in a compressive residual stress of greater magnitude and a smaller population of the sharp defects discussed above. On the other hand, the stainless steel showed a more rapid decrease in fatigue life for peening intensities above the optimum value. This may be accounted for by its relative brittleness and poor fatigue crack propagation properties as compared to the mild steel. Typical fatigue crack propagation data for materials of this type (from Ref. 6) are shown in Fig. 6. In this case the low crack growth rates ($<10^{-6}$ mm/cycle) are of interest, since these would be experienced by components for which a high cycle fatigue life was required. The stainless steel shows a lower stress intensity threshold and corresponding higher crack growth rates in the near threshold region. In situations, then, where crack propagation behaviour is dominant, as may be the case when these large, sharp defects are present, the stainless steel will behave poorly in comparison to the mild steel.

The MZC copper alloy is known to have relatively high strength and low toughness; fatigue crack propagation data are not available for this material, but it would seem to be demonstrating similar behaviour to the stainless steel. To summarize, it is postulated that yield strength dominates at the low peening intensities where fatigue crack initiation from a compressive residual stress layer is the relevant mechanism, but good crack propagation properties are required when the mechanism changes to that of crack growth from existing defects.

Finally, in the present work, peening for a longer time at a relatively low intensity caused a slight improvement in fatigue life. This may be attributed to two effects: a statistical factor, namely that further peening covers the surface more thoroughly and reduces the chance of there being any region of the surface not protected; and a defect controlled factor, namely that long times of peening tend to flatten any surface irregularities, eventually producing a polished surface. This may not be the case for long peening times at high intensities, where the dominant effect may be to produce more sharp, wear type defects to act as sites for crack growth.

Further work is planned, concentrating on more detailed characterization of the surfaces produced by high intensity peening and of the processes of crack initiation and growth. It is felt that this problem merits more attention than it has received to date, considering that the effect is common to many different materials and that very careful control of peening intensity is needed to realize the optimum improvement in fatigue behaviour.

CONCLUSIONS

1. The dependence of fatigue life on peening intensity has been shown to display similar characteristics for three different alloys. The initial increase in fatigue life with increasing intensity is followed by a decrease which proceeds to values lower than the fatigue life of unpeened material. In some materials the variation in properties can be very steep, so that careful control of peening intensity is needed to achieve optimum fatigue life.
2. The decrease in fatigue behaviour can be linked to a sudden increase in surface roughness R_a and to the onset of a wear damage process which produces sharp, crack like defects on the material surface. The defect size may be large enough to penetrate the compressive residual stress layer, which would account for the rapid decrease in fatigue life.
3. Stainless steel shows superior behaviour to mild steel at low intensities owing to its high yield strength, which creates a large residual stress and confers good resistance to crack initiation. At higher intensities the stainless steel loses its fatigue resistance more rapidly, having poorer crack propagation resistance than the mild steel. This implies a change from an initiation or 'short crack' dominated fatigue mechanism to a propagation dominated mechanism with increasing intensity. MZC copper behaves in a similar manner to stainless steel.
4. The use of longer peening times at lower intensities improves fatigue life, but this may not be the case if higher intensities are employed. More research is required in this area.

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