APPLICATION OF MICROSTRUCTURAL FRACTURE MECHANICS TO SHOT-PEENED COMPONENTS

C. Vallellano*, A. Navarro* and E. R. de los Rios†

Shot-peening is a classical method of surface engineering frequently applied to increase the fatigue resistance of metallic components. The macroscopic effects of this process are the creation of a cold work-hardened surface layer and a compressive residual stress field. These macroscopic effects are the consequence of microstructural changes within the surface layer, such as an increase in the density of dislocations and high deformation of the original grains.

In this paper a first attempt is made to analyse the enhancement of fatigue resistance in shot-peened components based on the present understanding of microstructural fracture mechanics principles. The model developed reproduces the behaviour of small cracks growing in a notched shot-peened component, incorporating the influence of the residual stress field and the microstructural distortion in the surface.

INTRODUCTION

The fatigue behaviour of engineering components is known to be strongly dependent on the properties of the surface and subsurface layers. One of the treatments more widely used in industry to improve endurance of metallic components is shot-peening, the bombardment of the surface with hard shot. The effectiveness of the shot peening operation depends upon a number of parameters, particularly the energy of the incident jet (shot diameter and material, velocity and incident angle), the coverage (which must be bigger than 100% to ensure a uniform distribution of residual stresses) and the shot hardness. Combinations of such parameters produce different residual stresses and hardness profiles, which must be optimised for each particular material and application. There is, however, no generally accepted theory to determine either the residual stress field or the hardness profile from data defining the shot-peening operation.

Experimental evidence shows that this treatment is most effective in components

* E.S.I., Department of Mechanical Engineering, University of Seville.
† SIRIUS, University of Sheffield.

subjected to bending and torsional loads where the highest applied stresses appear at the surface, and is less effective in situations where the applied load is uniform straight through the section. Thus, the interaction between the gradient of the applied stress and the compressive residual stresses seems to play an important role in the process. A case of real practical interest, in which steep stress gradients are involved, is that of fatigue at sharp notches. In these cases, the residual stresses induced by shot-peening may provide a substantial improvement in the fatigue strength.

It is now well established that the fatigue resistance of metallic materials is governed by the interaction of small growing cracks with plastic slip barriers such a grain boundaries. Microstructural Fracture Mechanics techniques (1) are capable of describing such interactions and have recently proved their usefulness in the study of notch fatigue limits and notch sensitivity (2). The aim of the present work is to give a first account of the application of such techniques to the analysis of the behaviour of notched shot-peened components.

SHORT CRACK GROWTH IN PEENED SURFACES

There are two basic effects of shot-peening. First, the creation of a highly distorted surface layer (*Zone 1*, see Figure 1). This is the result of the intense plastic deformation induced by the shot impacts. Many dents, micropits and folds, which can lead to early fatigue crack nucleation, are typically found in this region. The second effect is the setting up of compressive residual stresses, noticeable over a distance called the shot-peening depth. Below *Zone 1*, the material begins to show a texture similar to the virgin material, where grains, although slightly distorted, are clearly distinguishable (*Zone 2* in Figure 1).

Experimental studies carried out by Miller and co-workers (3) show that fatigue crack growth in *Zone 2* (and beyond) corresponds to the characteristic short crack growth pattern in the unpeened material, displaying the well known retardations and subsequent accelerations at microstructural barriers. Both the compressive residual stress field and the microstructural barrier strength influence the crack propagation rate in this region. This behaviour was not observed in *Zone 1*. In this case, the severe grain distortion and work hardening reduce the capacity of the crack to generate an extended plastic zone. Thus, the cracks follow very tortuous paths, giving rise to a predominantly faceted type of fracture. The critical issue of crack propagation in the hardened layer does not seem to be the overcoming of barriers, since the latter entails the generation of plastic slip beyond the barriers in an undeformed grain, while in shot-peened material this region should have a high dislocation density. It is, therefore, argued that cracks initiated at micropits or folds will zigzag through the distorted layer and will meet with the first significant barrier at the first grain boundary beyond the hardened layer. Experimental work on high strength aluminium alloys (4) supports the above assumption. Cracks arrested at distances of the order of the hardened layer depth were reported at applied stress levels just below the fatigue limit.

MODELLING

In the short crack propagation model developed previously by Navarro and de los Rios (1), the resistance of the material to crack propagation, as represented by the well-known Kitagawa-Takahashi diagram, is expressed through the following equation

$$\frac{\sigma_{Li}}{\sigma_{FL}} = \left(\frac{m_i^*}{m_1^*}\right)\frac{1}{\sqrt{i}} \tag{1}$$

where σ_{FL} is the plain fatigue limit which represents the maximum applied stress required for a crack growing within a grain of size D to propagate past the grain boundary (or the main microstructural barrier). Likewise, σ_{Li} is the minimum stress required to propagate an initial crack spanning over i half grains. The m^* 's are factors incorporating orientation and other local parameters controlling the strength of the barrier at the microscopic level.

In the case of a short crack growing from a notch, the propagation condition depends on the stress field around the notch. The expression equivalent to equation 1 is

$$\int_0^1 \frac{\sigma(\zeta)}{\sqrt{1-\zeta}\sqrt{1+\zeta+2t^*/i}}\,d\zeta := \left(\frac{i}{i+t^*}\right)^{\frac{1}{2}}\frac{\pi}{2}\sigma_{FL}\left(\frac{m_i^*}{m_1^*}\right)\frac{1}{\sqrt{i}} \tag{2}$$

where ζ is a dimensionless coordinate measuring distances from the notch root, $\zeta = z/D/2$ and $t^* = t/D/2$, t being the notch depth. $\sigma(\zeta)$ is the stress field in front of the notch. The above equation gives the expression of the Kitagawa-Takahashi diagram for notched components.

It is well established that, if no relaxation of residual stresses occurs during cyclic loading, the effect of residual stresses on the fatigue behaviour of a component cannot be accounted for by simply superposing them linearly with the applied stresses (5). It has, therefore, been suggested that the assessment of residual stresses be carried out by combining them with the applied stresses by means of the expressions traditionally used when dealing with applied mean stresses in fatigue, for instance, the well known Goodman expression. According to this, the effect of the residual stresses produced by shot-peening is introduced in the equations by defining at every point an equivalent alternating applied stress $\sigma_{eq}(\zeta)$ through the relationship:

$$\frac{\sigma_a(\zeta)}{\sigma_{eq}(\zeta)} + \alpha\frac{\sigma_m(\zeta)+\sigma_R(\zeta)}{\sigma_u(\zeta)} = 1 \tag{3}$$

and substituting it for $\sigma(\zeta)$ in equation 2. Here $\sigma_a(\zeta)$ and $\sigma_m(\zeta)$ are the alternating and mean stresses induced by the applied load, $\sigma_R(\zeta)$ is the residual stress and $\sigma_u(\zeta)$ represents the tensile strength of the material, which will be correlated with the local hardness. α is equal to one when $\sigma_m(z)+\sigma_R(z)$ is positive (the original Goodman line for positive mean stress) and should be somewhat less that one in the region of negative mean stresses in the Goodman diagram. In the simulations below it has been taken as equal to 0,5.

RESULTS AND DISCUSSION

The above equations have been applied in the study of the effect of shot-peening in the propagation of short cracks in notched components. The intensity of the shot-peening has been included indirectly by considering different shot peening depths.

In order to carry out the calculations, the residual stress and hardness profiles and the shot-peening depth must be specified. It has been observed that variations in the shot peening process have little effect on the maximum value of the compressive residual stress, as long as the shot used is at least as hard as the material being peened. Its magnitude is primarily a function of the material itself and has a value of the order of 60% of the ultimate tensile strength, and usually occurs slightly below the surface, at about 25% of the shot-peening depth d (6). The shot peening depth d and the hardened layer depth $d1$ depend on the mechanical properties of the material. Both increase with the kinetic energy of the shot jet. To simplify the calculations, a typical value of $d1 = 0.2\ d$ has been used. Also, slightly beneath the surface an increment in hardness of 1.2 times the nominal hardness of the bulk material has been assumed, which leads to a similar increment in the local ultimate tensile strength (7).

Figure 2 shows threshold stresses in an unpeened and peened-notched specimen as a function of the stress concentration factor. In both cases, the upper line corresponds to the applied stress necessary to propagate cracks up to failure (propagation limit). The lower line represents the condition of cracks that are able to initiate but will stop at the first significant barrier (initiation limit). The region between the two lines corresponds to cracks that grow over a number of grains and then become non-propagating. For simplicity the simulation has been carried out for zero mean applied stress and no relaxation of the residual stresses has been considered.

The model corroborates the expected increase in propagation limits in peened notches as compared to unpeened ones. It also predicts substantial differences between initiation and propagation limits, especially in sharp notches, which is in accordance with the experimental evidence. It can also be observed that the non-propagating crack region is narrower in the peened condition. This reflects the assumption that cracks will always grow through the highly distorted superficial layer.

One of the most important parameters in the model is the shot-peening depth; Figure 3 shows its effect. The relative improvement in notch fatigue resistance for a number of stress concentration factors and different dimensionless shot-peening depths are represented. In every case the maximum compressive residual stress value was kept constant, which seems to be a realistic assumption as long as d extends over a relatively large number of grains, typically more than 10. It can be observed that the beneficial effect of peening is greater for notches with higher stress concentration factors. This is in agreement with the experimental tendencies reported in the literature. For example, Akber et al. (8) found a substantially greater fatigue improvement as the notch stress concentration factor increased from around 2 to 5 in tension-tension fatigue specimens of Al-Zn alloy. The figure depicts also a typical pattern in the shot-peening process. As can be seen, the curves show an optimum range of peening intensity. The improvement in fatigue resistance tends to decrease as the shot peening depth increases over a certain point. This represents the detrimental effect of overpeening, associated with the production of a too severe surface damage.

CONCLUSIONS

A model based on Microstructural Fracture Mechanics principles has been presented to study the short crack propagation in peened-notched components. The model reflects the typical features of the shot peening process, such as the relative fatigue resistance improvement, the existence of an optimum range of applicability and the detrimental effect of overpeening. At the current state of the work such conclusions are necessarily qualitative in nature; but they are, nevertheless, in substantial agreement with the experimental tendencies reported in the literature. More experimental work on short crack growth at peened surfaces and the shot-peening process itself will be required to produce better models with reliable quantitative capabilities.

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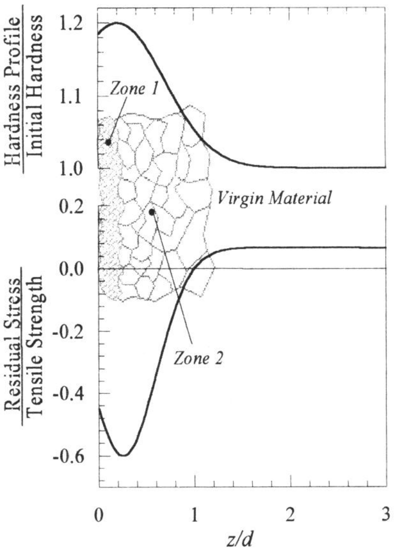

Figure 1: Surface changes due to shot-peening

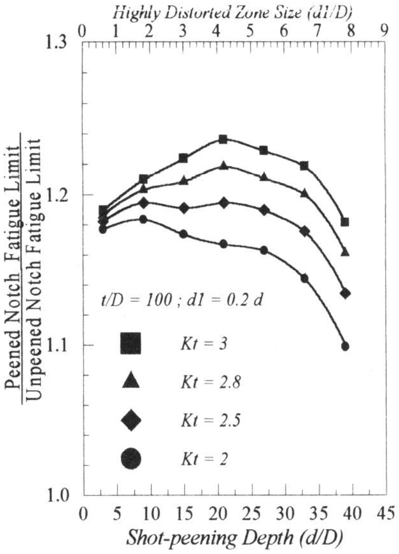

Figure 3: Effect of peening intensity and notch geometry on endurance limit.

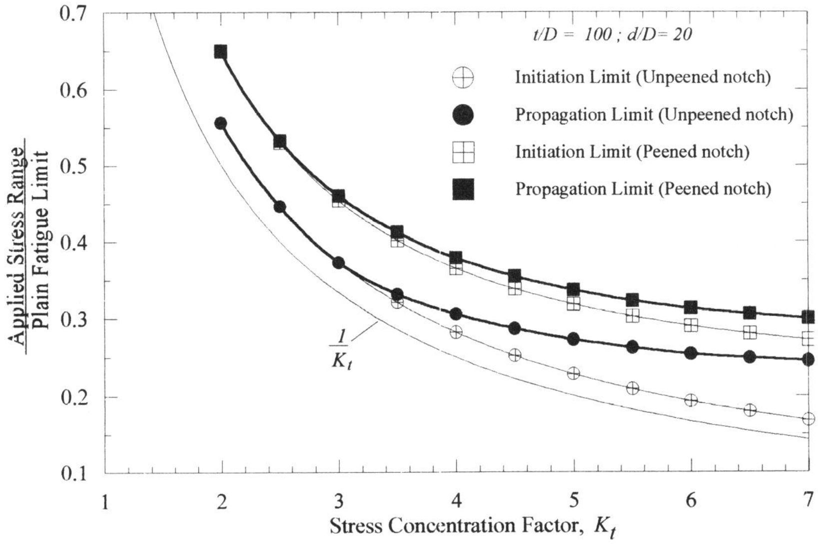

Figure 2: Crack initiation and propagation limits as a function of notch geometry