International Conference on Shot Peening and Blast Cleaning

SHOT PEENING AND ITS IMPACT ON FATIGUE LIFE OF ENGINEERING COMPONENTS

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INTRODUCTION

Shot Peening is a method of cold working in which compressive stresses are induced in the exposed surface layers of metallic parts by the impingement of a stream of shots directed at the metal surface at high velocity under controlled conditions. The shot peening can be applied to various materials and their weldment like steels cast steels, cast iron, Cu alloys, Al alloys. Ti alloys and some plastics. The major applications are related to improvement and restoration of fatigue life and reliability of machine elements by increasing their fatigue strength, straightening and forming of machine elements(metal parts), pretreatment prior to plating, pretreatment for components to be metallized or coated with plastics, enhancement of resistance to stress corrosion cracking and corrosion fatigue etc. In the review presented, the role of shot peening on the service life of engineering components and materials subjected to cyclic loading and also to aggressive environment has been discussed.

SHOT PEENING PARAMETERS

The outcome of shot peening is the result of interaction between two sets of parameters namely (i) the shot peening parameters and (ii) the material parameters. These are outlined below :

Shot peening parameters

- the shot speed
- the dimensions, shape, nature and hardness of the shot
- the projection angle
- the exposure time to the shot peening
- surface coverage
- Peening / repeening cycle

An important factor in peening operation is known as the "peening intensity" which is governed by the velocity, hardness, size and width of the shot pellets and-the angle of projection against the surface of the workpiece. Peening intensity decreases with decreasing velocity, decreasing shot size and decreasing angle of impingement (below 90^0).

Material parameters

These include microstructure, hardness, surface condition and hardening characteristics of the material. The result of their interaction with the shot peening parameters is:

- generation of residual stresses
- strain hardening of the surface and sub-surface layers
- changes in microstructure and substructure of material
- change in surface conditions

The beneficial effect of shot peening depends on the following effects:

- nature of distribution of induced residual stress
- level of maximum compressive residual stress(CRS)
- location of the maximum CRS
- depth of plastically deformed layer
- minimum possible sruface roughness caused by shot peening
- stability of residual stresses during loading
- type of metallurgical changes

SOME COMMON EFFECTS OF SHOT PEENING

Surface / Subsurface deformation

When individual particles in a high velocity stream contact a metal surface, they produce slight rounded depressions in the surface, stretching it and causing plastic flow of surface metal at the instant of contact.The effect usually extends to about 0.12-0.25mm below the surface. The metal beneath

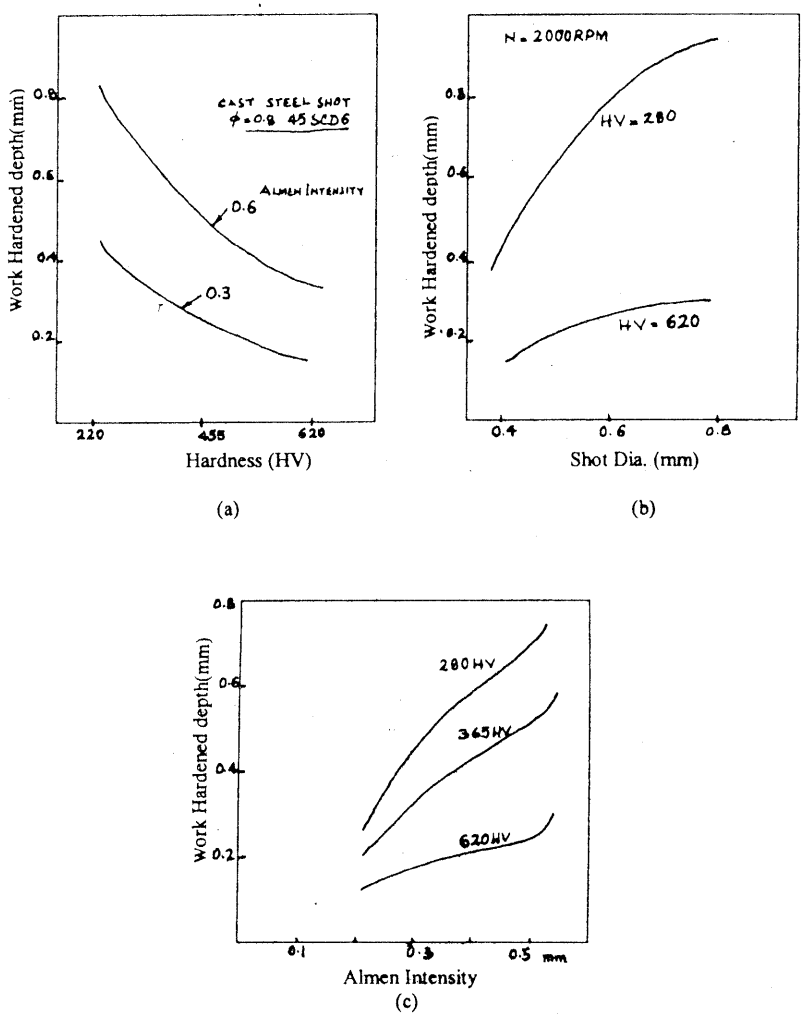

Fig.1. Effect of Material Hardness, Shot Dia, Almen Intensity on Work Hardening Depth.

this layer is not plastically deformed. In the stress distribution that results, the surface metal has induce residual compressive stress parallel to the surface, while metal beneath has reaction induced tensile stress. The surface compressive stress may be several times greater than the subsurface tensile stress[1]. The depth of plastically deformed layer is influenced by:

- the nature of material shot peened
- the projection velocity
- shot size
- hardness of material

The depth of deformed layer decreases with increasing hardness of the material treated. Also the depth increases with increasing projection velocity (i.e. the Almen intensity) (Fig.1a). The increasing diameter of the shot increases the work hardened depth and the effect saturates at a limiting diameter (Fig.1b). Furthermore, the work hardened depth increases more rapidly with a progressive reduction in the hardness of the material shot peened (Fig.1c)[2].

Surface Finish

Shot peening may also be used to enhance the surface finish of a component. It is known that the surface finish has considerable effect on fatigue strength and corrosion cracking resistance of alloys. To improve the surface finish a double shot peening operation may be required in which a heavy shot peening operation is followed by a micro-ball shot peening operation. Sometimes the surface is also subjected to chemical or electrochemical polishing after shot peening to improve the surface finish. The surface roughness increases with increase in Almen intensity caused by increasing velocity(Fig.2a). Also a greater increase in surface roughness is noticed in the material with lower hardness level. The effect of shot size on surface roughness, however, is not very clear. For any given material hardness, there is

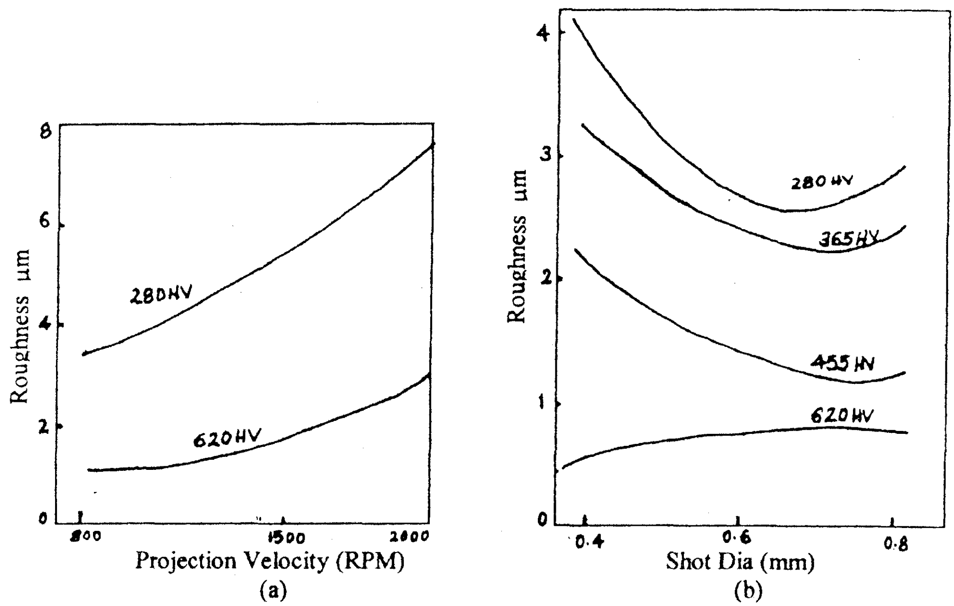

Fig.2. Effect of (a) Projection Velocity 9b) Shot dia, on the surface finish

an optimum ball diameter(shot size) that represents the best surface finish obtainable(Fig.2b)[3].

Residual Stress Distribution

With increasing projection velocity (i.e. Almen intensity), the residual stress gradient decreases. The hardness of shot peened material also affects the residual stress distribution. In a material with lower hardness, the maximum compressive residual stress increases with projection velocity more significantly than the material with high hardness as shown in Fig.1c.[2].

The effect of shot size on residual stress distribution is similar as that of the projection velocity. Also the maximum stress increases with increasing hardness of the shot material and stabilizes at a certain level of shot hardness as shown in Fig.1b,[2].

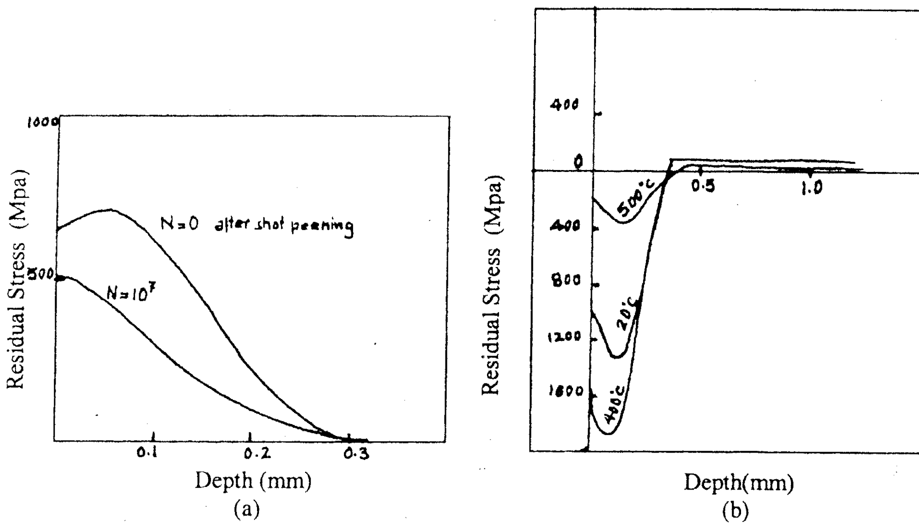

Fig.3. Stress relaxation after shot peening due to (a) fatigue cycling (b) tempering

The residual stress level decreases as well as the value of maximum residual stress reduces after fatigue cycling(Fig.3a),[4]. Similarly, when a shot peened component is subjected to tempering there is a decrease in the level of compressive residual stress. However the depth of plasticized metal remains unchanged after stress relieving(Fig.3b),[4,5].

SHOT PEENING AND DEFORMATION CHARACTERISTICS

The nature of deformation during shot peening is somewhat similar as the deformation during cyclic straining(fatigue cycling). During the cyclic straining of soft materials, the subgrain size is decreased with increase in straining[6]. Lattice distortion and dislocation density is increased and thus 'cyclic hardening' occurs. However, for hardened (or cold worked) materials, during cyclic straining the excess dislocations are annihilated, the growth of subgrain occurs and decrease of lattice distortion and dislocation density takes place. Consequently, cyclic softening is developed. The nature of plastic deformation in case of shot peening has two important differences with respect to the cyclic deformation. These are as follows:

(i) In case of hard materials, the "cyclic softening' is further followed by "cyclic rehardening" at a later stage of shot peening. This results in a "hardened" layer at the surface and "softened" layer beneath the surface. The hardened surface layer helps to improve the fatigue life when combined with residual compressive stress.

(ii) In case of the soft materials, (annealed steels, Al-alloys, stainless steels), the plastic deformation due to cyclic loading is inhomogeneous in nature and can produce microcracks. On the other hand, the slippage during shot peening is of homogeneous type in the surface layer and thus promotes hardening without tendency for crack nucleation.

SHOT PEENING AND MICROSTRUCTURAL CHANGES

The deformation produced by shot peening may bring a favourable or unfavourable phase transformation. The resulting microstructure may improve the desired properties or cause deterioration. A few examples from different materials are discussed below.

Effect of Shot Peening on a Carbonitrided case

The carbonitrided case of typical low alloy steel (e.g. 16Mn Cr1) contains substantial proportion of retained austenite (50%) after the treatment besides the martensite. With increasing duration of shot peening of the case, the austenite is converted into martensite(M) and compressive residual stresses are generated due to this transformation. The hardness of the case increases due to M formation as well as due to work hardening of austenite and martensite. The surface roughness is also found to decrease from 7 to 3μm. All these factors lead to substantial improvement in the fatigue life of the case.

Effect of Shot Peening in a Carburized Case and in an Austenitic stainless steel.

In a carburized steel (4320 steel), some of the retained austenite is converted to martensite by shot peening and introduces a compressive residual stress. This increases the fatigue strength as described earlier. In an austenitic stainless

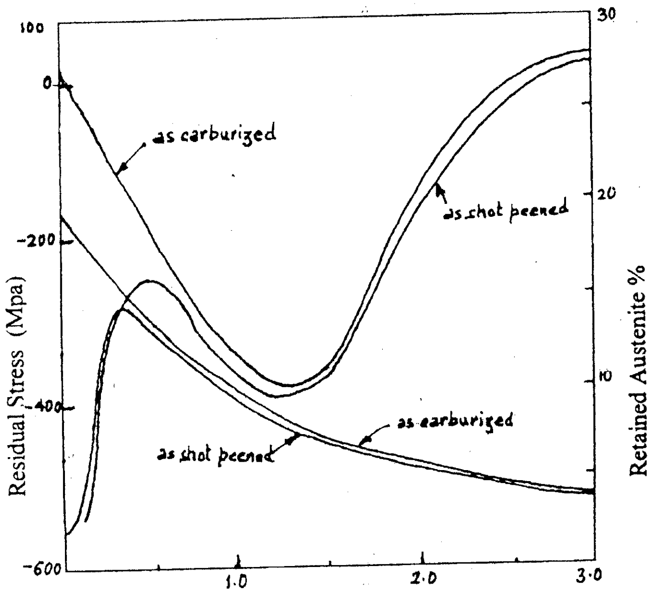

Fig.4 Distribution of residual stresses and retained austenite in as carburized and shot peened-carburized steel.

steel, on the other hand, the shot peening brings A $\rightarrow$ M transformation resulting in two phase structure. This decreases the corrosion resistance. Improvement in fatigue and corrosion fatigue properties due to shot peening canbe expected when relatively low cyclic stresses are involved. At high cyclic stresses, the compressive residual stresses are remove due to strain induced relief(accentuated by heating of specimen) and tensile stresses are generated which is undesirable(Fig.4),[7].

SHOT PEENING AND FATIGUE LIFE

The Surface characteristics

The nucleation of fatigue crack generally occurs at the surface because this is the layer experiencing greatest stresses owing to presence of micro-notches, surface flaws, changed physical and chemical properties etc. The shot peening can influence the surface characteristics in the following manner:

Work hardening of the surface layer: The micro hardness of surface increases with peening intensity due to work hardening. For an optimum depth of hardened layer, the initiation of fatigue crack over the surface can be delayed or prevented.

State of internal stress: In case of hardened components,(nitrided, carburized), the changeover from compressive to tensile stress field is rather steep. A fatigue crack is initiated just below the hardened layer. On the other hand, the stress gradient is much less steep in a shot peened case causing a steady change in mechanical properties within the cross section and reduced stress concentration at the interface.

Fatigue life depends on the position and magnitude of the maximum compressive stress and the thickness of the compressive layer. The studies in a high strength Al-alloy(7075-T6) indicated that if the surface and the maximum compressive stress is of higher level, located near the specimen surface and possesses a thick (compressive stress) layer, a crack initiated at the surface propagates very slowly through this region. On the other hand, if the maximum compressive stress is of smaller magnitude, located far below the surface in a relatively thin layer, the crack propagation rate increases.

Structural changes of material: Conversion of austenite to martensite and carbide dispersion caused by shot peening in surface layer is beneficial to fatigue life.

State of surfaces: Peening may favourably modify the surface roughness, anisotropic structure may change and radii of micronotches may be increased.

Yield Strength v/s Fatigue Life of Materials

This fatigue initiation life can be enhanced by increasing the allowable strain (by using high strength materials) or by decreasing the strain due to external loads in the critical section. The first option leads to reduced fracture toughness, K_{Ic} and increased crack propagation rate. The second option can be fulfilled by design improvement (avoiding stress concentration etc.), decreasing strain amplitude and by generating compressive stresses (through shot peening). Shot peening, in this respect, is preferred to thermal means for generating residual stresses.

The higher yield strength material is found to respond better to shot peening for improvement in fatigue initiation life especially for high cycle fatigue situation. This is because a high residual stress level can be maintained in these materials. Besides, higher value of strain hardening exponent(n) appears to have a favourable effect as follows:

$$N_i = A + B(-\sigma_R)^{an + b}$$

Where Ni is the fatigue initiation life and A, B, a and b are constants depending on experimental and material conditions like yield strength, surface roughness etc. In low strength materials, the residual compressive stresses may get relaxed when the material yields in highly loaded zone (i.e. notch) which is especially true in random loading cycle. Therefore, the maximum gain may be achieved from residual compressive stresses in the high cycle region of S-N curve of a high strength material and minimum gain in case of low strength material in finite life region of S-N curve.

A comparison of three materials i.e. Al-alloy (500 Mpa yield strength), Ti alloy (1150 MPa) and maraging steel (2150 MPa) when subjected to equivalent stress level (σ_{max} applied/ tensile strength = 0.9), showed that for optimum peening intensity, the maximum fatigue life improvement factor was greater than 10 for the last two alloys, whereas it was only 2.5 in case of Al-alloy. This is explained by presence of large and stable residual compressive stresses in Ti alloy and maraging steel as compared to a rapidly relaxing one in

Al-alloy. The high compressive residual stress may enhance the crack propagation life by decreasing the effective stress intensity range.

Optimization of Peening Parameters for Repair/Fatigue Life Extension:

All peening treatments improve the fatigue life of components, but when rework (repeening) on a damaged component is to be done for life extension, optimizing of the peening parameters is a must. Poor control of peening procedure, or unnecessary 'overpeening can result in a relatively poor fatigue life[8].

Overpeening may result in introduction of surface damage in the form of laps / folds due to impact extrusion of the material parallel to surface. There may be an apparent improvement in the surface finish of a repeened component, but reduction in fatigue life may occur due to surface defects originating from the preceding peening i.e. deeper laps / folds being hammered deeper[9].

In general lighter peening media like hard plastics, glass or ceramic beads, may dramatically improve the fatigue performance as compared to steel shots and thereby reduce the scatter. Especially in the case of aluminium alloys, steel shot peening can be quite detrimental to the fatigue performance and needs optimizing and monitoring of the shot peening parameters due to relative softness. Uncontrolled peening/repeening may introduce surface damage, which can ***promote*** fatigue cracking[10,11].

The maximum improvement in the fatigue life can be achieved through a rework process involving removal of original peening by polishing, followed by inspection for cracks and then repeening with ceramic beads.

Prediction of Fatigue Crack Propagation Life in Shot Peened Components

Mechanism

A synergy exists between fatigue life (initiation / propagation), crack closure and degree of shot peening [12,13]. Shot peening, when conducted along the length of a crack of through thickness configuration produces plastic deformation on the free side surfaces of the crack, resulting in severe compression on the crack wake. Such changes induced in the crack wake according to Zhu et al. [14], enhance the crack closure effect in the wake and reduce the crack growth rate.

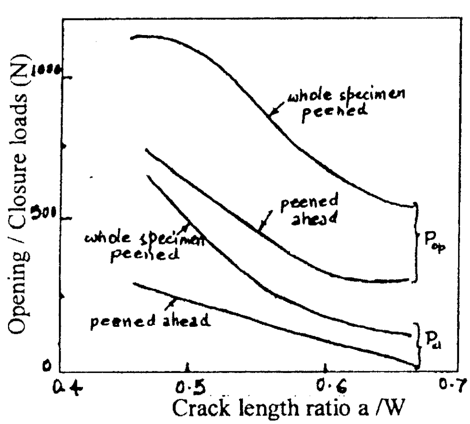

Fig.5a. Crack opening / closure levels at different peening different locations

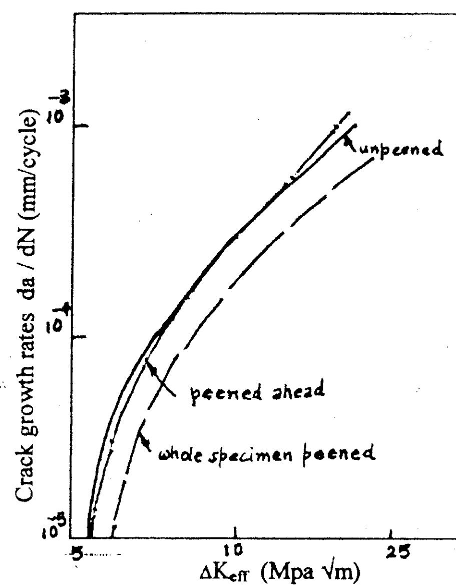

Fig.5 b. Crack growth rate behaviour of specimen peened at locations.

According to the observations of these investigators if peening is done ***ahead*** of the crack tip in a CT specimen, the wake remains unaltered as a result there is no increase inthe crack closure effect, consequently reduction in crack growth rate is not significant. On the other hand peening over ***whole*** of the existing crack results in the plastic deformation and work hardening of the crack edge material, which in turn results in large interference zone in the crack wake(Fig.5a,b) [14]. This suggests that crack closure plays a major role in inducing fatigue crack retardation.

In a further observation, crack growth rate was found to reduce markedly when the specimen is shot peened under load (Fig.6a,b). This is because of the beneficial increase in plastic deformation along the free side surfaces of the crack, which enhanced the crack closure and in turn reduced the effective stress intensity factor range 'ΔK_{eff}' during fatigue cycles.

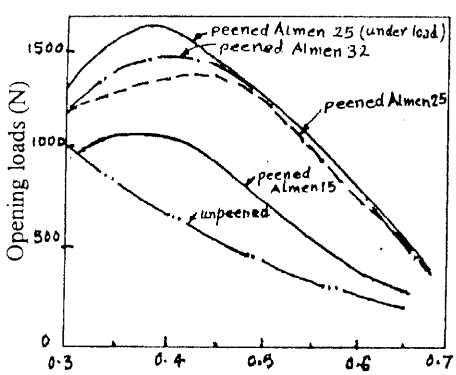

Fig.6 a. Crack opening levels at various peening conditions different peening conditions

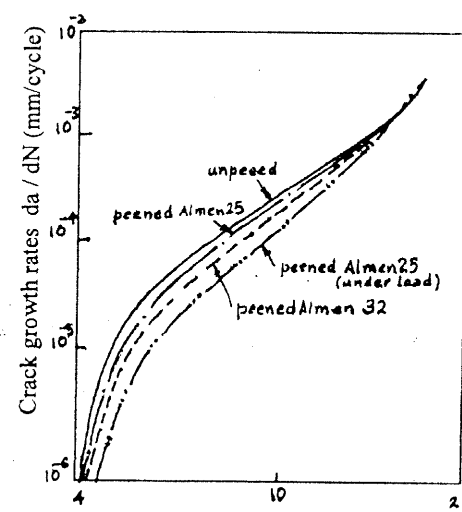

Fig.6 b. Crack growth rate behaviour of specimen for Life prediction

Life prediction

The Paris equation describes the stage II crack growth behaviour during fatigue in metallic materials, and can be used for evaluation of crack propagation life.

$$da / dN = C(\Delta K)^n$$

Where 'da / dN' is the crack growth rate. 'ΔK' is the range of stress intensity factor ($\Delta K = K_{max} - K_{min}$) and C and n are the Paris constants.

Since the establishment of the concept of crack closure by Elber[15], there is a commonly accepted modification inthe Paris law i.e. using ΔK_{eff} in place of ΔK.

It appears to be certain that the changing behaviour of the crack growth rate in the peened components is due to the higher crack opening levels, resulting in lower ΔK_{eff} , where ΔK_{eff} is expressed as,

$$\Delta K_{eff} = K_{max} - K_{op}$$

K_{op} being the crack opening stress intensity factor after shot peening. This results in a lower crack growth rate after shot peening '$(da / dN)_p$' and a modified Paris law $(da / dN)_p = C(\Delta K_{eff})^n$

It is reported that the maximum closure phenomenon with higher opening levels (Fig.6a), occurs in the region of a/W = 0.34 - 0.38, where a and W are the crack depth specimen width respectively. The extra constraint on the crack surface decays linearly with further crack advance. A similar decay is reported with the increasing number of cycles[16,17]. This can be attributed to stress redistribution in the crack wake after shot peening.

Zhu et.al.[14] have also reported a significant increase in the reinitiation life Ni(cycles for crack growth of 0.1mm from a value of a/W = 0.3) when peened at intensities above 15 of Almen scale(Fig.7). There is a surface hardening and thus an increase in the opening load) P_{op} resulting in a delayed crack initiation. A quadratic relationship has been proposed(Fig.8) as follows.

$$N_i = A_0 + A_1(P_{op}) + A_2(P_{op})^2$$

Where A_0, A_1 and A_2 are material constants and can be experimentally determined.

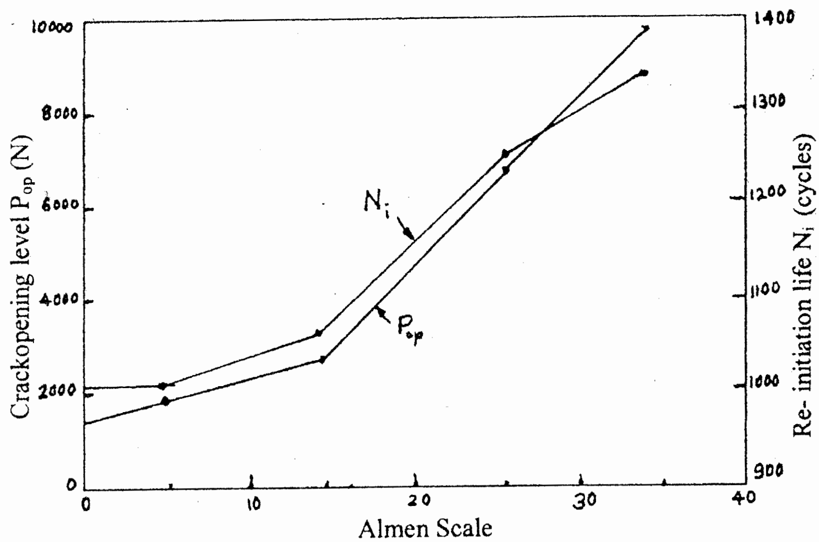

Fig.7 Correlation of Almen scale with crack opening level / reinitiation life.

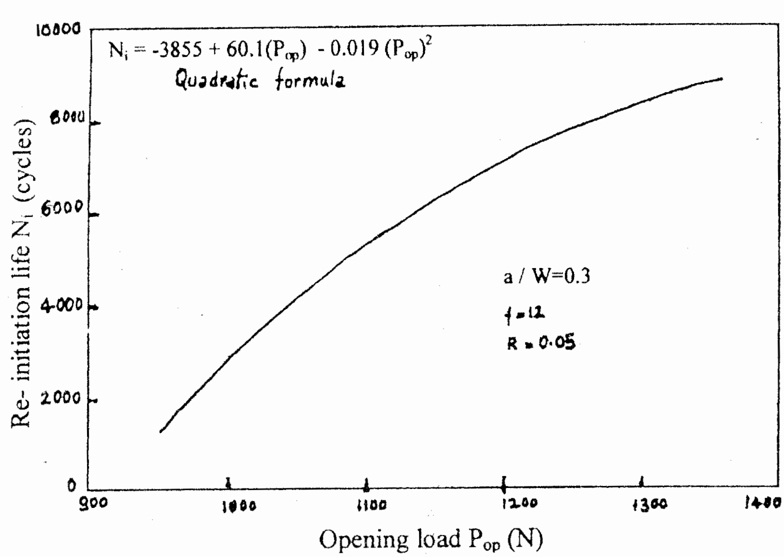

Fig.8 Reinitiation life as a function of crack opening load. Effect on Precipitation Hardenable Alloys

The plastic deformation behaviour of precipitate hardenable alloys may differ microscopically even if the amount of macroscopic plastic deformation is equal. In precipitation hardenable Fe-Ni-Cr-Ti alloys, the inhomogeneous distribution of plastic deformation is favoured by small precipitate particles(which can be easily cut / sheared by dislocations needing lower stress for subsequent dislocation motion), low stacking fault energy and large grain size. With increasing inhomogeneity of slip, the decreasing number of fatigue cycles are needed for crack nucleation at the high slip step. Larger precipitates, on the other hand, contribute to homogeneous slip as the dislocations have to by-pass them and lead to enhanced crack initiation life.

Another interesting aspect in this alloy is that the same microstructural conditions, which favour early crack formation, lead to a low crack propagation rate and vice versa. The optimum fatigue life can therefore, be obtained by enhancing the initiation life through a homogeneous slip distribution and improving the propagation life by inhomogeneously deforming microstructure. Both these effects canbe combined by shot peening of an underaged alloy, which possesses inhomogeneously deforming microstructure.

By shot peening, large number of sessile dislocations are generated in the plastically deformed layer. The piled up dislocations have to interact with the sessile dislocations in the deformed zone so that no sharp slip steps can be formed. This effect leads to a very homogeneously deforming surface zone and therefore, to a retardation of crack initiation. If a crack is initiated, it grows slowly through the compressive stress zone present in the subsurface region. Also the subsequent crack propagation in the matrix material is retarded due to the reversibility of slip at the crack tip.

SHOT PEENING AND CORROSION FATIGUE RESISTANCE

Corrosion fatigue (CF) life can be enhanced under pitting condition as because pit initiation and propagation are retarded by compressive residual stresses and thereby microcrack growth is lowered[18]. Under passive corrosion condition, the beneficial effect of shot peening can be explained by 'passive film rupture model'. In an unpeened state, slip steps produced by cyclic deformation may rupture the passive layer on the metal surface. During the following repassivation a certain amount of metal is dissolved. Repetition of this film rupture-repassivation mechanism leads to a small notch along the slip band, which leads to corrosion fatigue attack. In the peened state, the cyclic deformation of bulk material has to react with the deformed surface material. This interaction leads to a finer slip distribution and decreases the successive slip step height. The result is that much higher bulk deformation (or higher stress) are required to produce slip steps that are high enough to rupture the passive layer and cause corrosion fatigue cracking[19].

The corrosion fatigue resistance can be enhanced by choosing an environment, which is not so aggressive, by minimizing the localized attack and by using protectiv coating. For example, the corrosion fatigue resistance of highly alloyed stainless steel in a less aggressive environment canbe markedly improved by shot peening whereas a 12%Cr turbine blade material develops pits in oxygenated hot chloride solution and shot peening does not improve the CF resistance to any significant extent.

CONCLUDING REMARKS

i. The various parameters related to shot peening have been identified and their interaction with material parameters discussed.

ii. The plastic deformation induced due to shot peening is beneficial for both the hard as well as soft materials. In the former case, it develops a hard zone at the surface and somewhat softened layer beneath the surface, whereas in latter case it produces homogeneous type of deformation promoting hardening without tendency for crack nucleation.

iii. The fatigue life of both the high and low strength material canbe improved in the high and low cycle fatigue region of the S-N curve respectively by shot peening.

iv. The fatigue life can be enhanced due to shot peening through the increase in surface hardness(by strain hardening), by microstructural change, by improvement of surface condition and by an optimum distribution of residual stresses in the surface / subsurface layers.

v. The fatigue crack propagation life appears to be improved by shot peening mainly due to closure effect induced in the wake region of a crack. However, this needs further investigation.

vi. The CF resistance is improved by shot peening due to the retardation of pit initiation and its propagation by compressive residual stresses generated during peening. In case of passive film rupture mechanism the severity of CF is reduced by formation of finer slip steps.

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