Fundamental aspects of the effect of shot peening on the fatigue strength of metallic parts and structures

H.P. Lieurade, A. Bignonnet, IRSID 78105 St-Germain-en-Laye FRANCE.

1 - Introduction

Many factors can contribute to fatigue failure; however, the fatigue strength of a part is generally determined by the microstructure and mechanical properties of its surface layers.

It is for this reason that an improving method such as shot peening, which leads to the formation of surface compressive residual stresses, is widely used in mechanical industry and is beginning to be used for the construction of welded assemblies.

The purpose of this bibliographical overview is firstly to describe the role of this method and the effect of shot peening parameters, and secondly to discuss the effectiveness of this method according to loading conditions and environment.

2 - Rôle of residual stresses in fatigue crack initiation

2.1 - Macrostresses and microstrain

Residual stresses are generally considered to refer to the stresses existing in a part when the latter is not subjected to an external force. Several types of residual stresses can in fact be considered on the basis of the size of the volume of material in which they are present.

A distinction is made between first order stresses that produce strain in the part on a macroscopic scale, and between second or third order stresses that result in microstrain at intergranular level or in the crystalline structure respectively. These three types of stresses are interactive.

It is above all first order stresses (macrostresses) that affect fatigue strength; second and third order stresses (microstrain) affect the stability of residual stresses under fatigue loading conditions.

2.2 - Effet of mean stress

The macroscopic definition of residual stresses allows elasticity equations to be applied, particularly expressions of stress situations in which two stress components are superimposed.

When a part is simultaneaously subjected to residual stresses, characterized by σ_R, and stresses produced in service, characterized by σ_S, the real stress to which the part is subjected is defined by $\sigma_R + \sigma_S$ (figure 1).

Initially, the residual stresses may be considered to respond to fatigue loading in the same way as a mean or steady stress superimposed on an alternating stress.

Where shot peening is used as a surface treatment, thereby introducing compressive residual stresses, stress at the surface of the part is relaxed and consequently the fatigue limit is increased (figure 2).

In the high-cycle fatigue region (low amplitude levels for σ_a), this effect may be shown on a Goodman-Smith diagram where $\sigma_m \pm \sigma_a = f(\sigma_m)$. By way of an example, figure 3 shows the effect of a shot peening surface stress equal to -320 MPa on the fatigue limit of butt-welded assemblies (1).

Nevertheless the determination of the residual stress situation at the surface is not always an adequate basis on which to define the fatigue strength of a part; an identical surface residual stress σ_R may produce different fatigue strengths (2). In this particular case, the slope of the residual stress gradient below the surface must be taken into account (figure 4), since it can result in sub-surface crack initiation. Given that a crack may initiate at points where the fatigue limit has been exceeded locally, Starker et al. (3) propose the concept of local strength, taking into account the gradient of residual stresses :

$$[1] \quad \sigma_D(z) = \sigma_o - \alpha\, \sigma_R(z)$$

The relationship [1] allows σ_D to be plotted against z (figure 5); provided that the amplitude of the applied stress σ_a remains below $\sigma_D(z)$, there will be no crack initiation at z. This criterion has been observed to be true under various loading conditions.

3 - Effect of shot peening parameters

The effectiveness of a shot peening operation depends upon a number of parameters, particularly the type and energy of the incident jet, shot material and shot peening coverage.

3.1 - Almen strip measurements

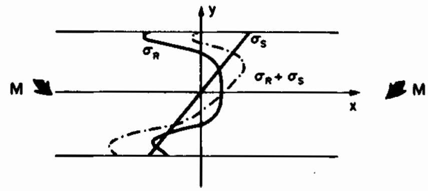
The existence of these many factors has made it necessary to develop a method for controllling the repeatability of a shot peening operation : measurement of the residual deformation of Almen strips.

Although the work of certain researchers has shown that there is a correlation between the severity of Almen strip deformation and the fatigue limit of parts, generally the optimum Almen intensity corresponding to the maximum fatigue limit depends upon the heat treatment to which the steel was subjected, and consequently upon the microstructure of the steel (figure 6) (3).

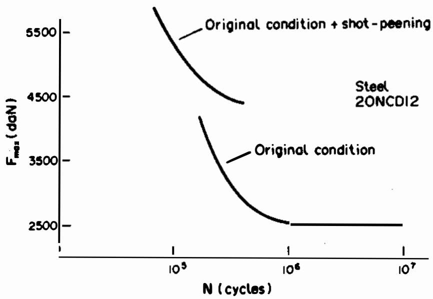
3.2 - Plastic strain mechanisms and formation of residual stresses

A double mechanism (figure 7) has been suggested by Wohlfhart (4) for the formation of residual stresses as a result of shot peening.

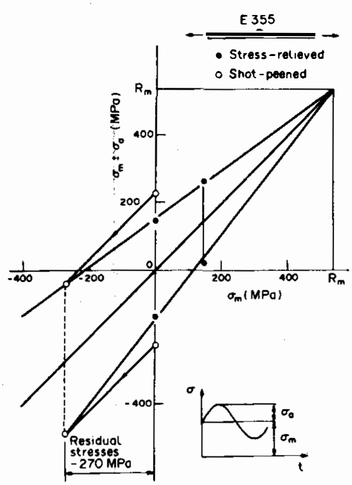
The first of these mechanisms consists of plastic elongation of the upper surface layers of the material; such elongation would be caused by the tangential forces generated by multiple shot indentations.



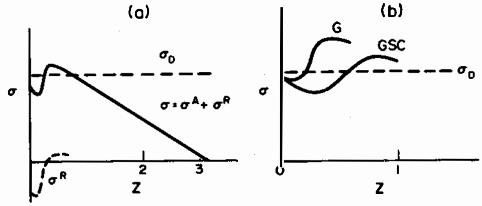
<u>Figure 1</u> - Superposition of applied and residual stresses.



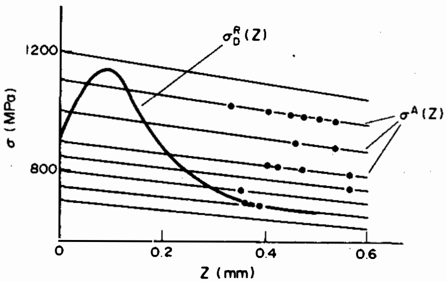
<u>Figure 2</u> - Improvement of the fatigue strength of lifting hooks by shot-peening.



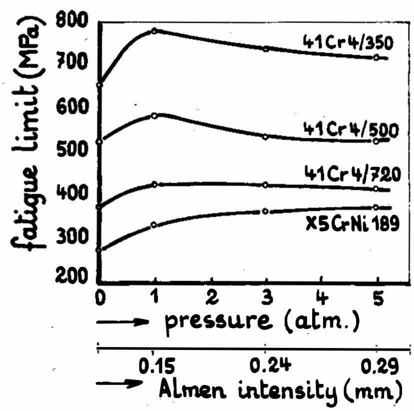
<u>Figure 3</u> - Influence of residual stresses on the fatigue limit : Goodman diagram for butt welded joints in E355 steel.



<u>Figure 4</u> - Stress distributions
a) residual and applied (bending)
b) applied and shot peening resual stresses (G) and stress peening stresses GSC.



<u>Figure 5</u> - Local fatigue limit curve σ_D^R (z) and applied stresses σ^A (z); . crack initiation location.



<u>Figure 6</u> - Influence of Almen intensity on fatigue limit.

This mechanism produces maximum plastic strain at the surface, which in turn results in distribution of the residual stresses with most of the stresses also remaining at the surface. The extent to which these stresses remain at the surface depends upon the intensity of the plastic deformation.

The second mechanism is superimposed upon the first and is linked to the Hertz pressure exerted by the shot at the moment of impact under the effect of forces normal to the surface of the material. The theoretical maximum shear resulting from this pressure is located below the surface at a depth of $z = 0.47a$, where a is the radius of the contact area between the shot and the surface.

This model helps to explain the variations in residual stress distribution that have been observed.

The interaction of these two mechanisms will mainly depend upon the relationship between the hardness of the shot and the material being peened, shot diameter, and the kinetic energy of the incident jet.

3.4 - Effect of the mechanical properties of the material

3.4.1 - Role of strain-hardening

Increased hardness generally has a beneficial effect on fatigue strength. Legus et al. (5) have observed a linear relationship (figure 8) between permissible stress amplitude at 10^6 cycles and Brinell hardness ($100 < HB < 500$).

In respect of shot peening, it is possible to differentiate between the improvement due to strain-hardening (microscopic effects) and the improvement due to the formation of macroscopic residual stresses (6). The lower curve on the diagram in figure 9 corresponds to purely microscopic effects, and shows that for hardness values above 57 R_C the improvement is only due to macrostresses.

3.4.2 - Depth to which shot peening is effective

The depth to which shot peening is effective is also closely related to the mechanical properties of the material; increased material strength results in a decreased depth of effectiveness.

The depth generally varies from 0.1 to 1 mm. This parameter has a significant effect on fatigue strength (cf. 2.3) and increases according to the kinetic energy of the shot jet, E (and therefore velocity, v), and above all shot diameter, d, as expressed by the following relation :

$$[2] \quad E = \frac{\pi}{12} \rho \cdot d^3 \cdot v^2$$

where ρ is the mass volume of the material from which the shot is made.

3.4.3 - Shot peening conditions

The effect of shot peening parameters therefore depends very much upon the mechanical properties of the material.

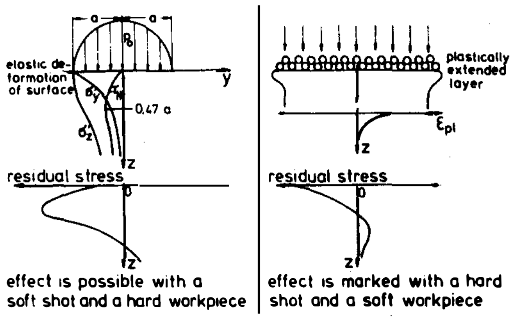


Figure 7 - Formation of residual stresses in shot peening.
Left : Hertzian pressure
Right : Stretching of the surface layer.

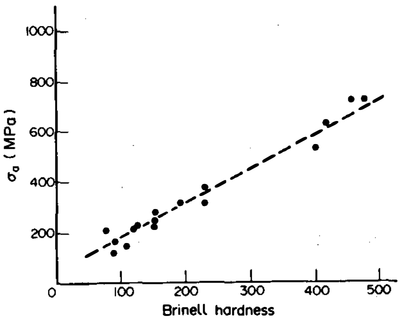


Figure 8 - Evolution of the fatigue limit with the Brinell hardness of steels.

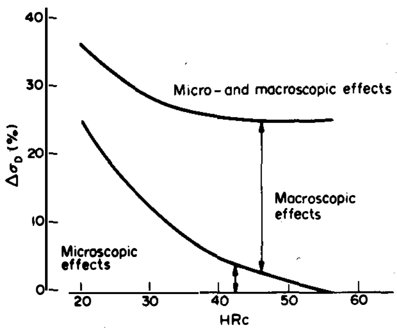


Figure 9 - Influence of macroscopic stresses and microscopic effects on the fatigue limit with respect to the hardness of the material.

. Materials with low hardness (HV < 300)

The significant parameter is the depth to which shot peening is effective. In order to increase this depth, significant strain-hardening is obtained (7, 8) by using large-sized shot (SAE 660) and by achieving an Almen intensity of at least 0.010" C. The maximum residual stress is approximately 0.8 σ_{ys}.

. Materials of medium hardness (300 < HV < 600)

With these materials, maximum stress concentration is generally in the sub-surface. The two mechanisms suggested by Wohlfahrt are therefore combined.

When the blasting velocity is increased, there is interaction between the increased force of shot impact (increase in the maximum stress produced in the sub-surface) and the increased area of contact (increase in surface stress).

The optimum results would seem to be obtained through use of relatively small shot (SAE 110, 170 or 230) and an Almen intensity of approximately 0.003" C (7). A higher Almen rating would have adverse effects (increase surface roughness, formation of microcracks).

. Materials with high hardness (HV > 600)

Shot of the usual hardness should be used (45 to 55 HR_C); in which case surface deformation is limited, the material is only affected to a depth of approximately 0.1 to 0.3 mm, and maximum stresses in the sub-surface may be extremely high.

The interaction between the two mechanisms suggested by Wohlfahrt are above all apparent in the ratio between shot hardness and the hardness of the material : if shot hardness is significantly lower than that of the material treated, residual stresses vary neither with shot hardness nor with shot blasting velocity.

In contrast, if shot hardness and the hardness of the target material are equivalent, an increase in shot hardness or in shot blasting velocity will significantly increase surface residual stresses. Almen intensity should generally be medium to low.

3.5 - Shot peening coverage

Coverage of more than 100 % is necessary to ensure uniform distribution of residual stresses. Figure 10 shows that coverage of more than 200 % will generally only produce a slight improvement in residual stress levels and fatigue strength.

3.6 - Surface roughness

The surface roughness obtained after shot peening mainly depends upon the relationship between the hardness of the shot and the hardness of the material that is peened; surface roughness increases with blasting velocity and shot diameter.

Occasionally the double-peening technique is used in order to avoid the adverse effects of increased surface roughness on fatigue strength. This technique

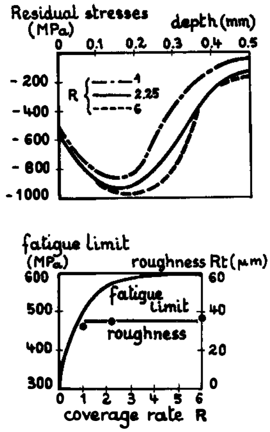


Figure 10 - Effect of coverage rate (8).

consists of high-velocity peening using large shot (high-level stressing) following by low-intensity peening using small shot (low surface roughness).

3.7 - Welded assemblies

In order to obtain optimum fatigue performance, Bignonnet et al (9) suggest that the shot-peening operation should be double : the first operation uses small shot capable of reaching even the smallest weld defects, the second peening operation uses large shot in order to achieve a high intensity.

4 - Relaxation of residual stresses

Compressive residual stresses introduced by shot peening can only improve fatigue strength provided that there is no rapid relaxation of these stresses in service.

In practice, an evolution is frequently observed during the first loading cycles due to changes in residual stress distribution. Stress stability (10) is affected by a number of factors.

4.1 - Effect due to type of material

The relaxation of residual stresses depends first and foremost on the structure of the material treated. If the structure of the material is such that it tends to vary in time under the effect of loading conditions or temperature, residual stresses will vary.

An example of this is given by Starker et al. (2) who noted no changes in residual stress in tempered material (800 HV), irrespective of the amplitude of applied stresses, whereas residual stresses were relaxed in annealed and tempered material (600 HV) in direct proportion to stress applied (figure 11).

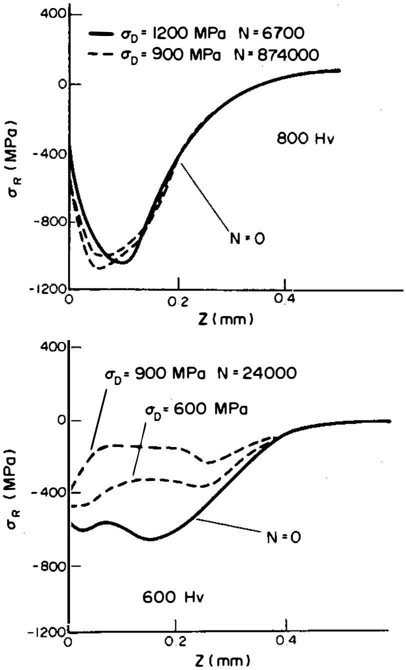


Figure 11 - Variation of the residual stresses due to shot peening with alternating bending.

The mechanism for relaxation of residual stresses may be expressed as follows :

- during the initial fatigue cycles, residual stresses vary in accordance with the response of the material to the yield strength being exceeded on a macroscopic scale or to local exceeding of the yield strength of grains or crystals on a microscopic scale;
- the relaxation that follows this initial response varies according to the load applied, but also depends upon the type of material.

4.2 - Effect of mechanical loads

4.2.1 - Pre-loading

Preliminary application of tensile or compressive loads can have a significant effect on the effective residual stress field during the subsequent service life of a part under fatigue loading.

Picouet et al. (11) have shown (figure 12) that the pre-loading of fillet welds shot peened through application of tensile nominal stresses up to the yield strength of the base metal has no effect on the service life under fatigue loading conditions, and also that preliminary application of compressive nominal stresses of less than -250 MPa were required to produce a significant reduction in the beneficial effect of shot peening, taking into account the high local stresses (yield strength exceeded) at the weld toe.

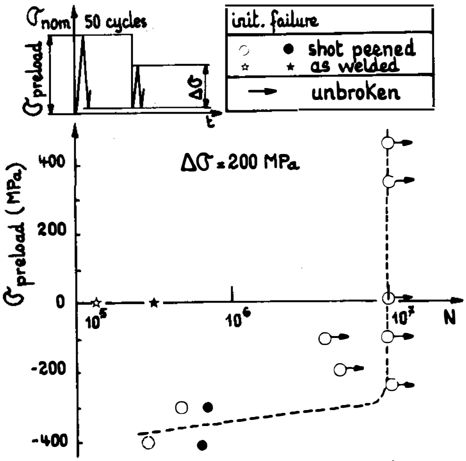


Figure 12 - Influence of high stress peaks (tensile or compressive pre-loading) on the fatigue life of shot peened welded joints (E460 steel).

4.2.2 - Type of loading

A study of the variation during testing of residual stresses introduced by shot peening in grade 35 NCD 16 steel (UTS = 1100 MPa) has shown that any such variation depends upon the mode of loading (12).

Where the loading exhibits a gradient (rotary-bending, alternating torsion) residual stresses will relax progressively, whereas they will be relaxed during the first cycles of an axial loading test.

4.2.3 - Direction of cyclic loading

Residual stresses tend to be relaxed to a greater extent if they are oriented in the direction in which the cyclic stress is applied. Figure 13 shows that the relaxation of longitudinal residual stresses oriented parallel to the bending stress is greater than that of transverse stresses.

4.2.4 - Level of cyclic loading

Since the relaxation of residual stresses is subject to the extent to which the yield strength is exceeded overall (macrostresses) or locally (microstrain), such relaxation will increase the closer the sum of the stresses (maximum fatigue loading stress + residual stress) is to the yield strength of the material. In view of the results described in the literature, the cyclic yield strength of the material should be considered.

With particular reference to tests performed under alternating stress loading conditions (R = -1), since the stress applied is added to the internal stresses, in the portion of the cycle in compression, if the amplitude of the load is high enough the shot-peened layer will be subject to plastic deformation.

Residual stresses that were initially compressive will vary with the cyclic softening or hardening of the material; stabilization will therefore depend upon their initial condition, the applied stress and the cyclic yield strength of the material (figure 13).

The diagram in figure 14 proposed by Bignonnet (12) shows the variation in residual stresses observed in the case of a steel exhibiting significant softening.

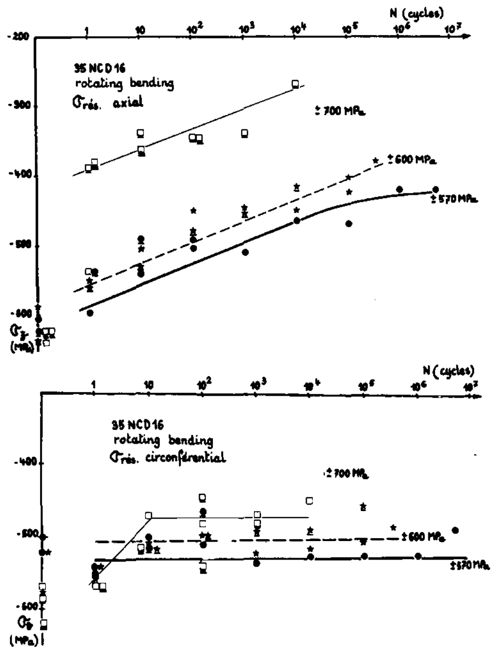


Figure 13 - Evolution of axial and tangential residual peening stresses at the surface of rotating bending specimens.

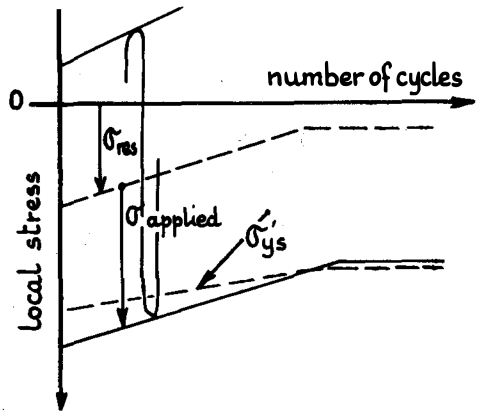


Figure 14 - Schematic representation of alternating loading resulting in fatigue releiving of residual stresses.

On the other hand, in the case of cracks intitiated at the surface (biaxial stress situation) with a uniaxial cyclic stress amplitude, Skalli (13) observed relaxation as soon as the equivalent stress, as defined by Von Mises and determined under maximum loading, together with residual stresses exceeded the cyclic yield strength σ'_{ys} :

$$[3]\quad [(\sigma_{1max} + \sigma_{1RS})^2 - 2\,(\sigma_{1max} + \sigma_{1RS})\,\sigma_{2RS} + \sigma_{2RS}^2\,]^{\frac{1}{2}} \geq \sigma'_{ys}$$

4.2.5 - Loading ratio - R

The shot peening operation produces an initial dissymetry between the elastic domains in tension and in compression. Since the residual stresses are relaxed as soon as the load applied results in the yield strength being exceeded, either in tension (σ_{ysT}) or in compression (σ_{ysC}), the level of R that produces the lowest relaxation is equal to the ratio between the yield strengths in tension and in compression of the shot-peened layers.

This result confirms the results given in the literature which indicate a smaller relaxation for R = 0 than for R = -1 or R = 0.5.

4.2.6 - Number of loading cycles

The relaxation of residual stresses increases with the number of cyclic loading cycles (figure 13). Most authors suggest a relationship for this variation whereby stress is logarithmically proportional to the number of cycles (12).

Morrow et al.(21) suggests the following expression :

$$[4] \quad \frac{\sigma_m(N)}{\sigma_{m_o}} = \frac{\sigma_{ys} - \sigma_a}{\sigma_{m_o}} - \left(\frac{\sigma_a}{\sigma_{ys}} \right)^b \quad . \log N$$

where $\sigma_m(N)$ représents mean stress (including residual stresses) at N cycles;

σ_{mo} is the mean stress prior to fatigue;

σ_{ys} is the yield strength of the material;

σ_a is the amplitude of the fatigue stress.

4.3 - Effect of the gradient of the residual stresses

The steeper the gradient of residual stresses, the greater the relaxation (see 2.4.2.3).

In respect of a type 60SC7 spring steel (UTS = 1900 MPa) subjected to shot peening of different intensities, Farrahi and Lebrun (14) observed that the stability of residual stress concentration increased in accordance with the depth to which the material was subject to plastic deformation, and was directly related to the size of the region of compressive residual stresses. Under given cyclic loading conditions, they demonstrated an increase in service life in relation to the depth of plastic deformation (figure 15).

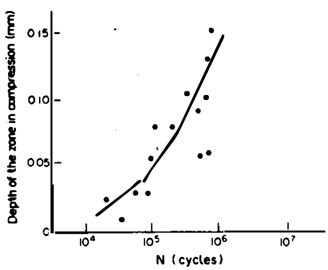


Figure 15 - Evolution of the number of cycles to failure with respect to the depth affected by shot peening (steel 60SC7, UTS 1900 MPa, $\sigma = \pm 750$ MPa).

4.4 - Effect of temperature

An increase in temperature can provide an input of energy favourable to microstructural rearrangement and result in a material evolution to a more stable structure.

It is for this reason that certain temperatures applied during subsequent treatments or during service, if exceeded, will nullify the beneficial effect of shot peening. Critical temperatures vary according to the type of material (10) :

- aluminium alloys : 100-120°C
- carbone steels : 250°C
- tool steels : 450°C
- titanium alloys : 450-500°C
- austenitic stainless steels : 500°C
- nickel-based allloys : 700°C.

The relationships suggested for expression of the relaxation of residual stresses, σ_R, in accordance with temperature T (°K) and time t, are generally as follows (15) :

$$[5] \quad \sigma_R\,(t) = \sigma_{R_o} - \frac{RT}{\beta}\,\text{Log}\,\left(\frac{t}{t_o} + 1\right)$$

where t_o and β are constants determined according to material.

4.5 - Notched parts

With respect to notched parts, the relaxation of stresses at the root of the notch is a more complex phenomenon in that a nominal load in the elastic domain can produce plastic strain at the notch root.

For notched specimens subjected to a bending load, Peiffer (16) has demonstrated by means of X-ray stress measurements and strain gage measurements that the relaxation at the notch root varies according to whether the load applied is a tensile load (R = 0) or a compressive load (R = -∞) (figure 16). With R = 0 he observed significant relaxation during the first cycles followed by stabilization; in contrast, with R = -∞ he noted significant but progressive relaxation.

5 - Crack initiation criteria

The integration of residual stresses into a calculation based on Goodman or Haigh type diagrams only permits combination of uniaxial stresses. However, the residual stress field produced by shot peening is either biaxial (crack initiation at the surface) or triaxial (crack initiation in the sub-surface).

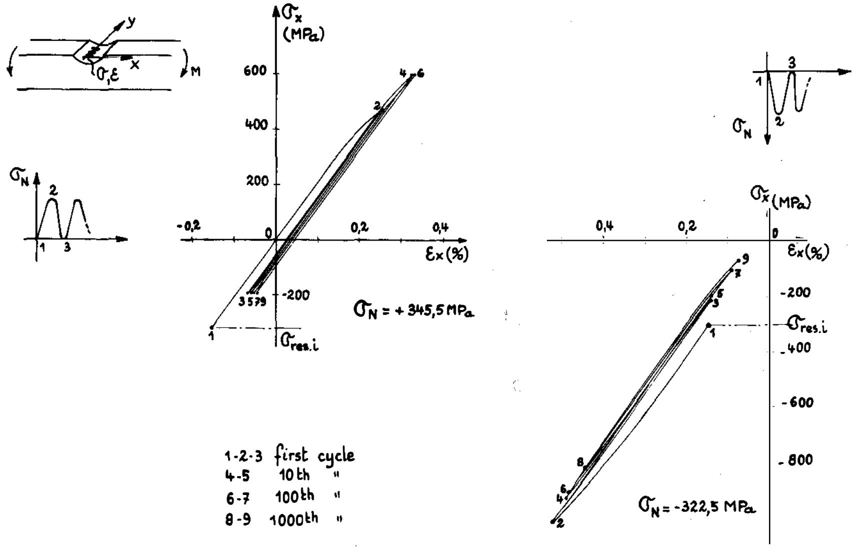


Figure 16 - Evolution of σ-ϵ for tensile or compressive loading cycles.

5.1 - Choice of criteria

Experience shows (17) that the criteria of Von Mises and Tresca cannot be used if significant mean or residual stresses are present. In such cases, it is preferable to use criteria that account for octahedral shear stress amplitude, τ_{oct_a}, or maximum shearing stress, $\tau_{a_{max}}$, and maximum hydrostatic pressure, p_{max}, and in particular :

- Crossland's criterion : $\tau_{oct_a} + \alpha\, p_{max} = \beta$
- Dang Van's criterion : $\tau_{a_{max}} + \alpha\, p_{max} = \beta$

Where fatigue cracks are initiated at the surface, the stress situation to be taken into account is biaxial, and the following may be written :

$$\tau_{oct_a} = \frac{\sqrt{2}}{3}\left(\sigma_{1a}^2 + \sigma_{2a}^2 - \sigma_{1a} \cdot \sigma_{2a}\right)^{1/2}$$

$$\tau_a = \sigma_{1a}/2$$

$$p_{max} = \frac{1}{3}\left(\sigma_{1a} + \sigma_{2a} + \sigma_{1m} + \sigma_{2m} + \sigma_{1R} + \sigma_{2R}\right)$$

where σ_{1a} and σ_{2a} represent the amplitude of the principal stresses ($\sigma_{1a} > \sigma_{2a}$)

σ_{1m} and σ_{2m} are the mean value of the principal stresses

σ_{1R} and σ_{2R} are the value of residual stresses measure in these two directions (stabilized values).

Details concerning application of these criteria are given in (17).

The reference curve for the material considered is needed in order to use these criteria, as in the case of Goodman or Haigh diagrams.

An example of application of this criterion to grade 35 NCD 16 steel (σ_{ys} = 1100 MPa) (12) is given in figure 17, for soft ground specimens or shot peened.

The lines thereby determined can then be used to estimate the fatigue limit for any loading path.

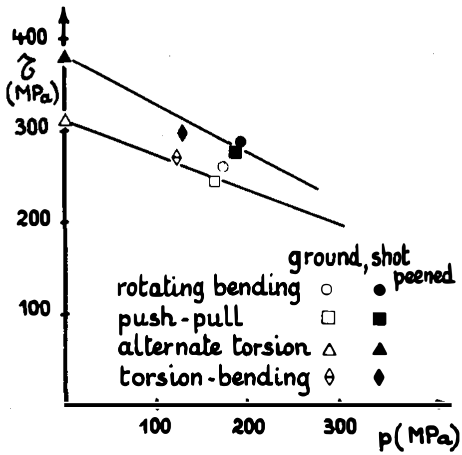


Figure 17 - Comparison of fatigue limit for ground and shot peened condition of a 35 NCD 16 steel, in a Dang Van Diagram.

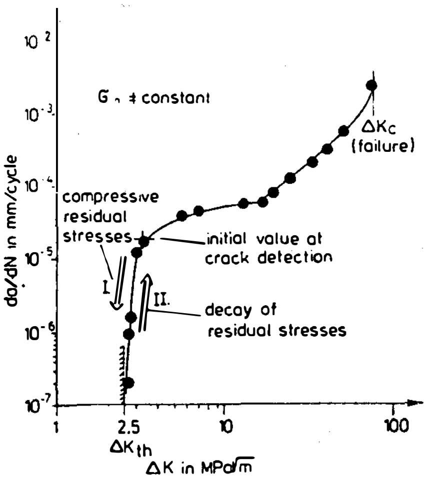


Figure 18 - Crack growth rate from a shot peened surface.

5.2 - Definition of residual stress levels

Correct application of a crack-initation criterion requires determination of the values of residual stress levels to be used in the calculation. The following points should be taken into consideration :

- measurement methods or calculations must be available for evaluation of residual stresses in the critical zone (at the surface or in the sub-surface);

- calculation methods used must take into account the gradients of residual stresses in the surface layer and should consider a cross section of material that is thick enough to be representative of the unit volume in which fatigue damage occurs (18);

- the value of stabilized residual stresses must also be included in the calculation; they should be determined either by measurement in a part previously subjected to cyclic loading, or through estimating the relaxation on the basis of experience or models;

- others facts must also be taken into account in the calculation, particularly surface roughness and strain-hardening of surface layers.

6 - Role of residual stresses in fatigue cracking

Given affected depth by shot peening the effect of shot peening on fatigue crack propagation is limited to the "short crack" domain.

In this respect, shot peening results in partial closure of the crack, which is minor, if not non-existent, if there are non compressive residual stresses.

This domain is very large in the case of mechanical parts, since it corresponds to the largest part of the lifetime of such components.

Gray et al. (19) have studied such an effect in the case of a titanium alloy. They shows the beneficial effect of shot peening for surface cracks up to 2 mm in length.

Berns et al. (20) have schematically represented (figure 18) the behaviour of a crack in a residual stress field produced by shot peening. Initially crack growth rate decreases (I), whereas compressive residual stress increases; crack may either stop in the event that ΔK decreases to the threshold of non-propagation, or have its propagation delayed. Due to redistribution of stresses at the root of the notch, a relaxation of residual stresses will result in resumed increase in ΔK and therefore a renewed increase in crack growth rate.

Conclusion

The amount of resarch that has been undertaken into the behaviour of shot-peened parts is such that today we can have a clear idea of the parameters to be taken into account in order to optimize the shot peening operation.

The results obtained by research workers show that in each case preliminary tests must be carried out in order to determine accurate values for these parameters.

In addition, in view of the high levels of permissible stress that may be reached, industrial application of a shot peening treatment is subject to strict verification of the reproducibility of operating parameters.

Provided that the above two comments are taken into account, the application of a shot peening treatment to parts subject to cyclic loading conditions should become more widespread in the future.

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