Investigation on the Effect of Shot Peening on the Elevated Temperature Fatigue Behavior of Superalloy

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Introduction

Before the sixties, the shot peening was ordinarily used only for the machinary parts working at ambient temperature but at high temperature. Since the sixties it had been used to improve elevated fatigue behavior of different superalloys in our country. A lot of elevated parts and components of turbine engine rupture due to the elevated fatigue. Therefore, the research for the influence of shot peening on the elevated fatigue behavior of machinary parts and components has an important significance. The influence of shot peening on the elevated fatigue behavior of the specimens with different stress concentration factors has been investigated in the present article.

Material and experiments

The material used is iron base austenitic superalloy GH132, equivaleut to **A286** , mechanical properties of which are listed in Table 1. The geometry and size of rotating bending fatigue specimens are shown in Fig. 1. The peened intensity of different specimen is: 0.22 Amm (for smooth specimen), 0.17 Amm (for $K_t=2,3$), 0.13 Amm (for $K_t=4$).

Table 1 Mechanical properties of GH132

Test temperature °C	Tensile Strength MPa	Elongation %	Hardness HB
25	1100 - 1120	28.5 - 29	3.5
650	800 - 840	21 - 24	-

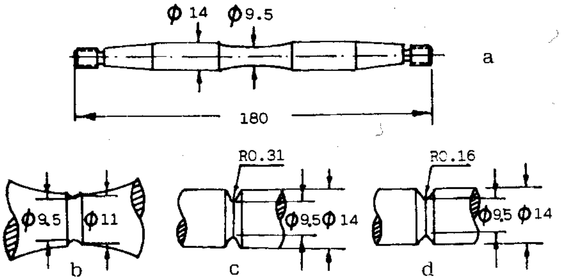


Fig. 1. Geometry and size of specimens with different stress concentration factors: a-$K_t=1$; b-$K_t=2$; c-$K_t=3$; d-$K_t=4$ (K_t-elastic stress concentrantion factor)

The rotating bending fatigue tests were conducted in PWC510WG fatigue testing machine with frenquency 82.6 Hz at 650°C.

Experimental results and discussion

The residual stress distribution with the depth after shot peening are shown in Fig.2. The depth of compressive residual stress is about 0.15 mm for different peened intesities. The depth of the surface strain layer is about 0.1 mm which is less than that of compressive residual stress. After elevated fatigue tests, the surface residual stresses relax alomst. In this case the microstructure strengthening factor has a major effect on the elevated fatigue strength. The elevated fatigue S-N curves of specimens with different K_t are shown in Fig.3 and Fig.4 respectively. According to the calcuation by means of the increament method, the fatigue limit of unpeened and peened specimens are obtained (Fig. 5).

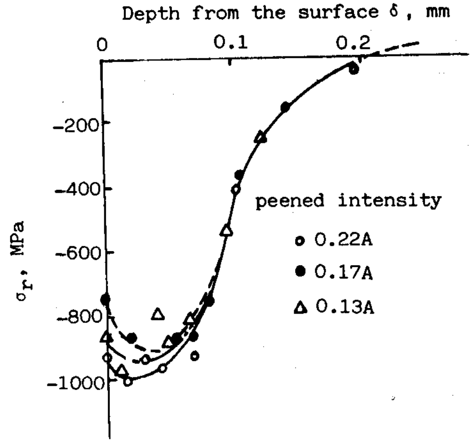


Fig. 2. Residual stress distribution induced by shot peening with the depth for different peened intensities A.

The test results show that for the smooth specimens shot peening decreases slightly the elevated fatigue behavior of iron base superalloy (see Fig.3). However, shot peening has a pronounced influence on the elevated fatigue strength for all notched specimens. It can be seen from Fig.5 that the microstructure strengthening factor exhibits more pronounced effect for improved fatigue properties of the specimens with high K_t value. Therefore, the higher the K_t value, the higher the increament fatigue limit of peened specimen.

According to the results of fatigue limit ($N=10^7$) for unpeened specimens obtained from both present and previous tests, the relationship between fatigue limit of smooth specimen and notched specimens with various K_t exists following experienced equation:

$$\sigma_{wn} = \sigma_w K_t^b \qquad (1)$$

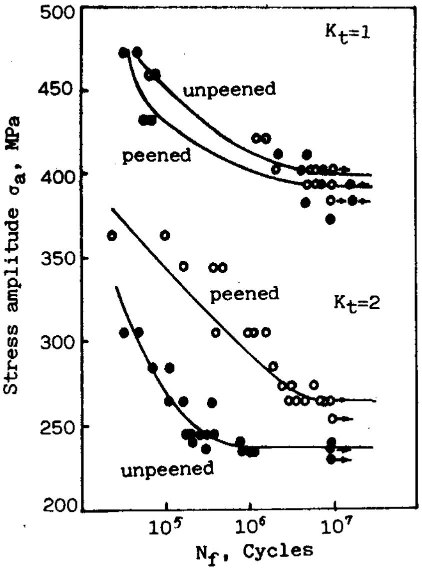
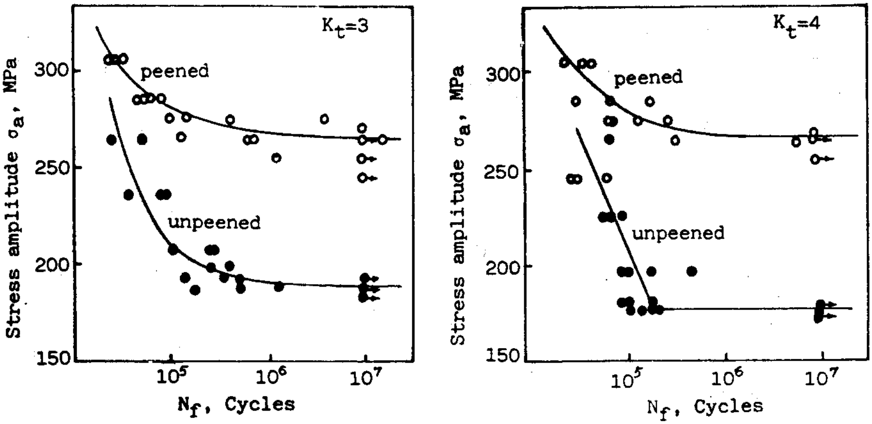


Fig. 3. Elevated fatigue S-N curves of smooth (K_t=1) and notched (K_t=2) specimens before and after shot peening.



(a)

(b)

Fig. 4. Elevated fatigue S-N curves of notched specimens before and after shot peening; a-K_t=3; b-K_t=4.

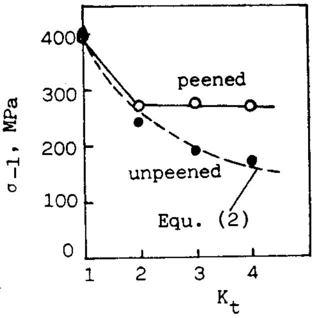


Fig. 5. Elevated fatigue limit, σ_{-1}, (650°C) of unpeened and peened specimens with different K_t.

where σ_{wn} and σ_w - fatigue limit for both notched and smooth specimens, b-constant. In the case of present test, the equation can be written:

$$\sigma_{wn} = 400\ K_t^{-0.607}\ \text{MPa}$$

Conclusion

1. Shot peening can be effectively used to improve the elevated fatigue properties of iron base superalloy specimen with different stress concentrations.

2. The higher the stress concentration factor, the higher the microstructure strengthening effect for improved elevated fatigue properties of superalloy.

Fatigue Strength of shot-peened grade 35 NCD 16 steel. Variation of residual stresses introduced by shot peening according to type of loading

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1 - Introduction

Shot peening is a method that is widely used to improve the fatigue strength of mechanical parts subjected to high levels of stress loading. The work presented in this paper concerns a grade 35 NCD 16 steel with a tensile strength of 1,100 MPa. A comparison was made of the results obtained through two methods of surface treatment : fine grinding and shot peening. The investigation mainly addressed the variation in fatigue strength with residual stresses introduced by shot peening under four types of alternating load : rotating-bending, tension-compression, alternating-torsion and alternating torsion-bending in which the bending component is $\sqrt{3}$ times the torsion component. This investigation falls within the scope of the Fatigue Committee of the Société Française de Métallurgie and was able to be completed as a result of assistance provided by nine laboratories.

2 - Experimental procedures

The material studied was a 4 Ni-Cr (35 NCD 16) steel that had been heat treated to obtain a tensile strength of 1,100 MPa. The mechanical properties of the bars used in the investigation are given in table 1.

Table 1 - Mechanical properties of the grade 35 NCD 16 steel used in the study.

σ_{ys} (MPa)	UTS (MPa)	Elongation (%)	Reduction in area (%)
1,000	1,110	17.5	64

Low cycle fatigue tests were performed to determine the cyclic yield strength (σ'_{ys}) of the material. The results revealed significant softening of the material. The variation of the cyclic yield strength may be expressed by :

$$\sigma'_{ys} \text{ (MPa)} = 920 - 55.14 \log N$$

Half of the test specimens for each loading category were shot-peened under identical conditions. Shot peening parameters are given in table 2 below.

Table 2 - Parameters for shot peening of test specimens

Shot peening		Deformation of Almen strips	Coverage
Standard	mean diameter		
S230	0.57 mm	0.30 to 0.35 mm A	200 %

The residual stress introduced by grinding and shot peening was measured by X-ray diffraction analysis (1-2). The stress tensors measured at the surface of each type of test specimen are given in table 3.

Table 3 - Surface residual stress tensors on the different specimen types

	rotating-bending	tension-compression	alternate-torsion	bending-torsion
. Grinding	$\begin{array}{c}\begin{array}{ccc}\theta & \underline{z} & r\end{array}\\ \begin{pmatrix}-180 & 0 & 0\\ 0 & -50 & 40\\ 0 & -40 & 0\end{pmatrix}\end{array}$	$\begin{array}{c}\begin{array}{ccc}\theta & \underline{z} & r\end{array}\\ \begin{pmatrix}-170 & 0 & 0\\ 0 & 50 & 40\\ 0 & -40 & 0\end{pmatrix}\end{array}$	$\begin{array}{c}\begin{array}{ccc}\underline{\theta} & z & r\end{array}\\ \begin{pmatrix}-100 & 0 & 20\\ 0 & -300 & 0\\ -20 & 0 & 0\end{pmatrix}\end{array}$	$\begin{array}{c}\begin{array}{ccc}\theta & \underline{z} & r\end{array}\\ \begin{pmatrix}-210 & 10 & 0\\ 10 & 0 & 50\\ 0 & -50 & 0\end{pmatrix}\end{array}$
. Shot peening	$\begin{array}{c}\begin{array}{ccc}\theta & \underline{z} & r\end{array}\\ \begin{pmatrix}-380 & 0 & 0\\ 0 & -600 & 0\\ 0 & 0 & 0\end{pmatrix}\end{array}$	$\begin{array}{c}\begin{array}{ccc}\theta & \underline{z} & r\end{array}\\ \begin{pmatrix}-450 & 0 & 0\\ 0 & -570 & 0\\ 0 & 0 & 0\end{pmatrix}\end{array}$	$\begin{array}{c}\begin{array}{ccc}\underline{\theta} & z & r\end{array}\\ \begin{pmatrix}-400 & 0 & 0\\ 0 & -580 & 0\\ 0 & 0 & 0\end{pmatrix}\end{array}$	$\begin{array}{c}\begin{array}{ccc}\theta & \underline{z} & r\end{array}\\ \begin{pmatrix}-360 & 0 & 0\\ 0 & -600 & 0\\ 0 & 0 & 0\end{pmatrix}\end{array}$

N.B. All values are given in MPa. The underlined coordinate corresponds to the direction of grinding.

θ : tangential stresses - z : axial stresses - r : radial stresses.

An example of the distribution of these stresses in depth is given in figures 1 and 2.

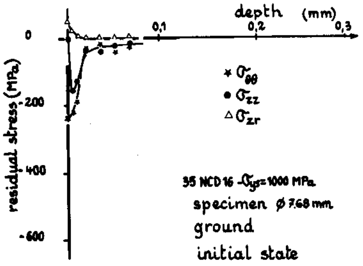

Figure 1 - Residual stress field introduced by grinding.

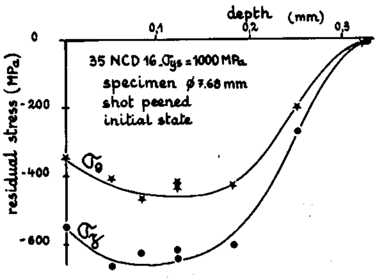

Figure 2 - Residual stress field introduced by shot peening.

In all cases, the depth to which shot peening produced an effect was appxoximately 0.3 mm, and 0.025 mm for grinding.

3 - Fatigue tests

Wöhler curves were plotted using a limited number of test specimens (ten in each case) in order to determine the behaviour of the material between 10^5 and 3×10^7 cycles. These endurance tests were performed using ground specimens and shot-peened specimens for tension compression, rotating-bending, alternating-torsion and alternating bending-torsion where $\sigma_{\text{bending}} = \sqrt{3}.\tau$. The resultats obtained are given in figure 3.

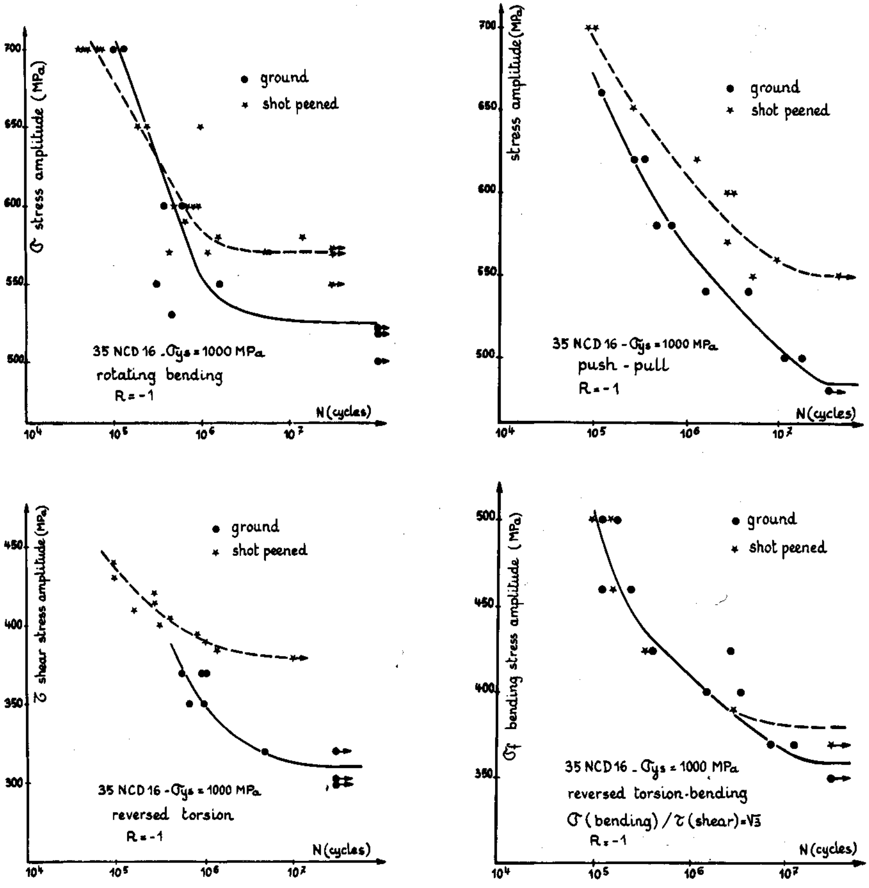

Figure 3 - Wölher curves for grade 35 NCD 16 steel in both ground and shot-peened condition when subjected to four types of loading.

On the basis of these results, the gain in the endurance limit as a result of shot peening may be estimated at 10 to 20 % in the case of alternating fatigue loads (table 4).

Table 4 - Estimate of endurance limits for R = -1 with grade 35 NCD 16 steel (σ_{ys} = 1,000 MPa) after grinding and shot peening (0.30 to 0.35 mA).

Loading		Grinding	Shot peening	Gain
Rotating-bending	σ_D (MPa)	525	570	7 %
Tension compression	σ_D (MPa)	490	550	12 %
Alternating torsion	τ_D (MPa)	310	380	23 %
Alternarting torsion-bending	σ_{fD} (MPa) τ_D	360 208	380 220	6 %

4 - Variation of stresses introduced by shot peening with fatigue

In order to analyze the behaviour of shot-peened parts in greater detail, interrupted fatigue tests (see ref. 2) were carried out in order to measure changes in the stresses produced by shot peening.

4.1 - At the surface

The variations in axial and circumferential residual stresses have been plotted in figure 4 according to the number of cycles for various levels of applied stress.

It was noted that the higher the level of applied stress, the higher and faster the relaxation of surface stresses. Relaxation at the surface was higher in the direction in which loads were applied, i.e, σ_z for rotating bending and tension-compression. Whith alternating torsion, stress relaxation was noted in two directions (axial and circumferential).

In respect of loading mode resulting in a stress gradient (torsion and bending), whatever the level of loading applied, stress relaxation was progressive. With rotating bending, there was practically no change in circumferential stresses following their relaxation during the first ten cycles; in contrast, axial stresses relaxed progressively.

Under tension loads, a significant relaxation of axial and circumferential stresses was noted in the first cycle at the highest loading level.

4.2 - In depth

The evolution of in depth residual stress field may be determined through destructive testing.

The variation in axial and circumferential stresses after 10^2, 10^5 and 10^7 cycles under alternating torsion loading is represented in figure 5a and 5b for a shear stress amplitude of τ = 430 MPa and τ = 380 MPa respectively. It may be noted that although the depth affected (0.3 mm) remains unchanged, there is an overall drop in the residual stress field at depth. The values of σ_θ and σ_z are therefore relatively close.

Figures 6a and 6b represent the variation in axial and circumferential stresses under rotating-bending loading after 100 fatigue cycles for stress amplitudes of 550, 600 and 700 MPa.

Figures 7a and 7b represent the case of tention-compression loading after 1,000 fatigue cycles with $\sigma = \pm 500$ MPa and $\sigma = \pm 600$ MPa, and after 100 cycles with $\sigma = \pm 700$ MPa.

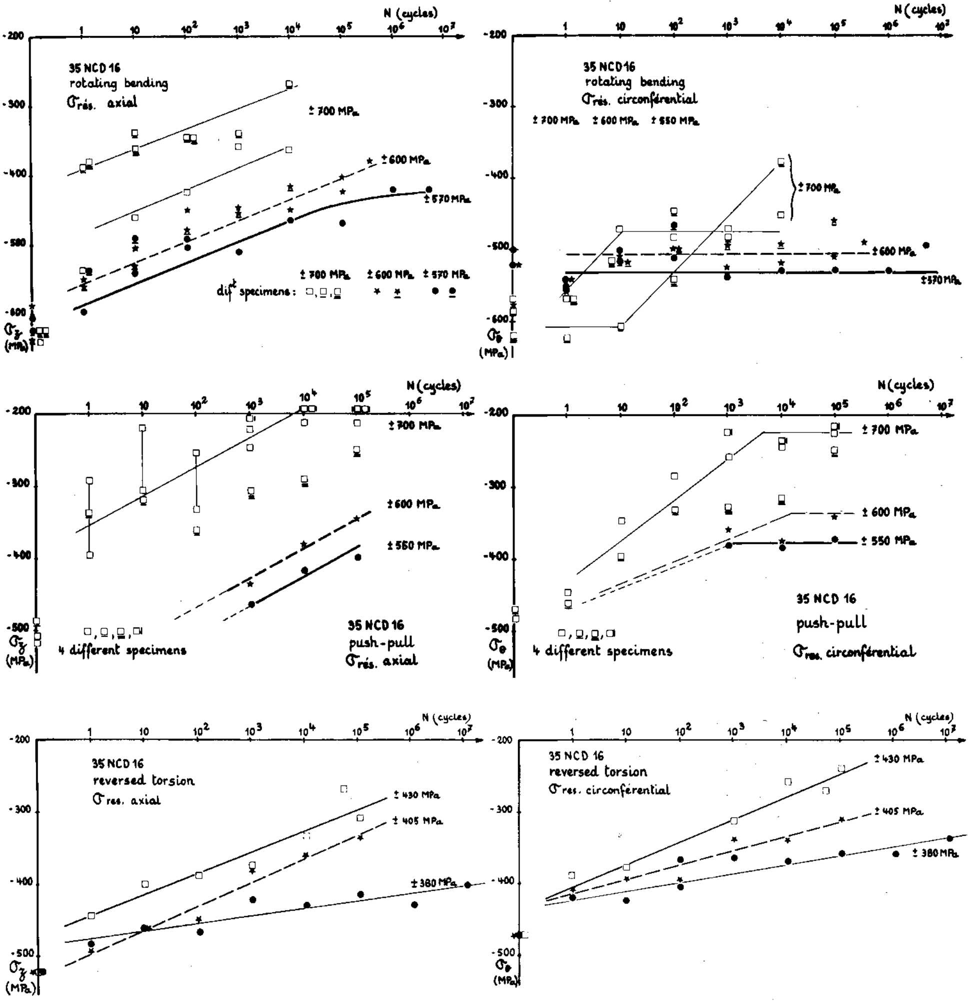

Figure 4 - Variation of axial and circumferential residual stresses at the surface under three types of loading conditions.

5 - Discussion

This study of a grade 35 NCD 16 steel has shown that shot peening increases the endurance limit by 10 to 20 %, depending upon the type of loading. In the low-cycle region ($<10^6$ cycles), the gain is lower, and even non-existent for higher levels of applied stresses. Although this increase may seem small given the high initial values of these stresses, an explanation may be found firstly in the fact that alternating stresses were used for loading, and secondly in that

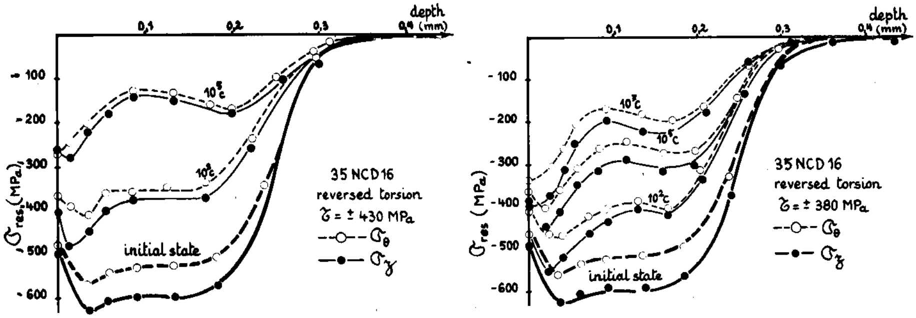

Figure 5 - Variation of the residual stress field in depth at two levels of alternating stress under torsion loading.

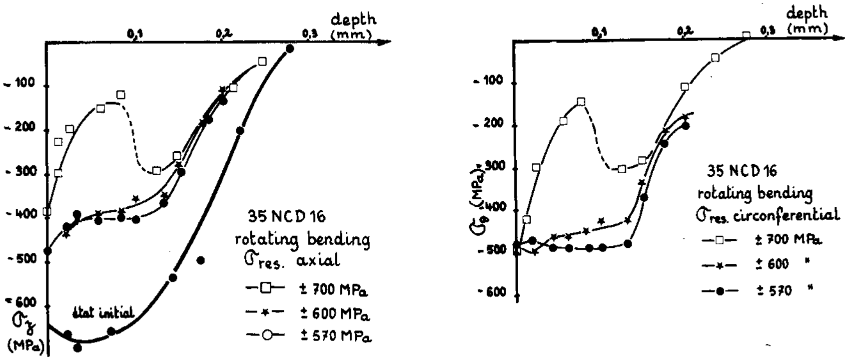

Figure 6 - Variation of axial and circumferential residual stresses in depth under rotating bending loading.

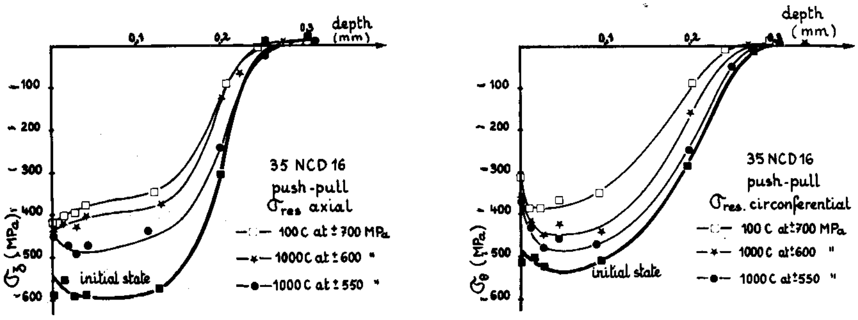

Figure 7 - Variation of axial and circumferential residual stresses under tension-compression loading.

the material studied is subject to considerable softening when it sustains fatigue loading. Since applied stresses will be added to the internal stresses when applying compression, if the amplitude of the load is high enough the shot-peened layer will be subject to plastic deformation. The initial residual stresses, which were compressive stresses, will then be redistributed and their absolute value will fall. In this case, the residual stresses will relieve during subsequent cycles to the level where their algebraic sum together with the applied stress are such that plastic deformation is precluded (figure 8). Consequently, the residual stresses should stabilize at a level determined by their initial level, the applied stress and the cyclic yield strength of the material.

The material under investigation softens gradually, and the cyclic yield strength falls continuously the higher the number of cycles. Under these conditions, the stabilization of residual stresses during the fatigue cycle will be delayed. If the amplitude of the alternating stress loading is high enough to reach the level of the cyclic yield strength, the residual stresses will be relieved to complete elimination.

In respect of the material studied in this paper, the cyclic yield strength is stabilized at around 660 MPa, any applied stress greater than 660 MPa will eventually result in total releiving of residual stresses. In all such cases, it is difficult to predict the endurance strength of a shot-peened part.

However, on the basis of the stress loadings investigated we have been able to plot Dang Van's endurance diagram (3) (amplitude of maximum shear stress τ versus hydrostatic pressure p) for grade 35 NCD 16 steel treated by grinding and shot peening. This diagram (figure 9) can then be used to estimate the endurance limit for any type of multiaxial loading for both of the surface conditions studied. Dang Van's straight line equations are as follows :

τ (MPa) = $-0.38\,p + 310$ in ground condition
τ (MPa) = $-0.53\,p + 380$ in shot-peened condition.

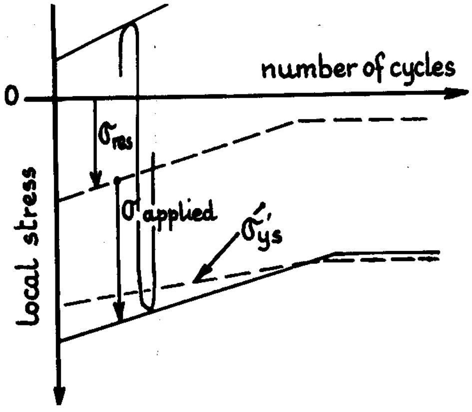

Figure 8 - Schematic representation of alternating loading resulting in fatigue releiving of residual stresses.

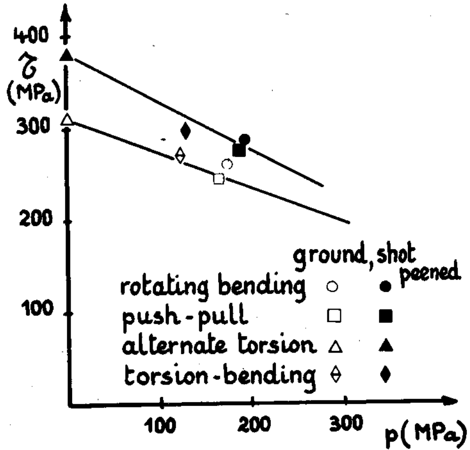

Figure 9 - Dang-Van diagram for 35 NCD 16 steel subjected to grinding and shot peening.

6 - Conclusion

The effect of shot peening on the endurance limit of a grade 35 NCD 16 steel was studied under four types of stress loading : rotating-bending, tension-compression, alternating torsion and alternating torsion-bending ($\sigma_{bending} = \sqrt{3}.\tau$). Depending upon the type of stress loading, shot peening increases the endurance limit by 10 to 20 %. The releiving of surface residual stresses is increased by a higher amplitude of applied stresses and a greater number of cycles. Stress relaxation is greater for residual stresses oriented in the direction in which the load is applied.

The redistribution of residual stresses in depth does not change the depth affected, but will result in an overall fall in stress levels.

Since applied stresses will be added to the internal stresses, when applying compression if the amplitude of the load is high enough the shot-peened layer will be subject to plastic deformation. The initial residual stresses, which were compressive stresses, will then be redistributed and their absolute value will fall. In the event of this happening, the residual stresses will releive during subsequent cycles to a level where their algebraic sum together with the applied stress are such that plastic deformation is precluded. Consequently, the residual stresses should stabilize at a level determined by their initial level, the applied stress and the cyclic behavior of the material.

References

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