EFFECTS OF GRINDING CONDITIONS ON FATIGUE BEHAVIOUR OF 42CD4 GRADE STEEL

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Fatigue tests carried out at CETIM on a NF 42 CD 4 grade steel (BS En 19 A or AISI 4140) have shown that grinding parameters such as down feed and the type of wheel had a very clear influence on residual stresses and fatigue limit under plane bending.
The stability in fatigue of residual stresses obtained by 3 grinding conditions were evaluated, using X ray diffraction methods, in order to inject stabilised values into a calculation procedure developed for determining fatigue strength.
This analysis contributes to a better knowledge of grinding effects in fatigue and allows the distinction between the respective influences of surface roughness and residual stresses.
It has also been demonstrated the importance of the reduction of the residual stresses in fatigue, and the relationship between this reduction and the behaviour of the metal under cyclic loading.

INTRODUCTION

Grinding is a machining operation which can be used for the finishing of many parts which require close tolerances, or when the mechanical properties of the steel being used are high. If a poor choice of grinding wheel is made, or the grinding conditions are too severe, the operation generally results in the generation of sufficient heat to bring about residual stresses in the surface layers of the metal. The behaviour of ground parts in service is thus dependent not only on the surface roughness, but also on the residual stresses.

From the results of work quoted in the references (1), (2), (3) and from fatigue testing carried out at CETIM(4), on parts which have been turned or ground, a nomogram has been produced from which the coefficient of reduction in fatigue limit, as a function of the surface roughness and ultimate strength of the steel can be obtained.

This type of nomogram, of which there are many to be found in reference (4), takes into account both the influence of the surface roughness and the influence of the residual stresses on the reduction in fatigue strength. However, for fatigue calculations only its roughness parameter can be used.

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In addition, other tests carried out on 42 CD 4(5) steel have shown that the residual stresses due to grinding can change considerably as the grinding conditions change(ie type of grinding wheel, down-feed), and that it was not possible to correlate the surface roughness with the induced residual stresses

In order to try to estimate the influence of a machining method on the fatigue strength, it would thus appear to be necessary to separate the respective effects of roughness and residual stresses. For this reason, in this investigation, greater attention has been paid to the residual stresses, i.e. to their change with the machining parameters, to their reduction during fatigue tests, and to their incorporation in a method of calculation. From fatigue tests in repeated plane bending of 42 CD 4 steel, it has been possible to show that the initial residual stresses are partially reduced during fatigue testing, and that it was possible to introduce these residual stresses into fatigue criteria in order to predict the fatigue strength of the ground part. Finally, the results obtained allowed the respective influences of residual stresses and surface roughness on the fatigue limit to be separated from each other.

TEST PROGRAM

The 42CD4 steel chosen for this investigation is widely used in mechanical engineering. Its high mechanical properties and its operating conditions often require finishing by grinding.

The tables below give the chemical composition (in ωt, %) and the mechanical properties after quench and tempering treatment (30 minutes austenitizing at 850°C-30 minutes tempering at 520°C).

- Chemical composition

C	Si	Mn	S	P	Ni	Cr	Mo
0.43	0.30	1.02	0.021	0.015	0.19	0.94	0.20

- Mechanical properties after heat treatment

Elastic limit $\sigma_{0,02}$ stress (MPa)	Ultimate strength Rm (MPa)	Elongation A %	Reduction in area Σ(%)	Hardness (HRC)
1180	1250	7	33	40

Specimens manufacture

The test specimens were machined from flat rolled section. First their thickness was reduced to 6 mm by milling and they were then subjected to the heat treatment defined above. After heat treatment, all the test specimens were soft ground to a thickness of 5.5 mm $\pm$ 0.01. They were then machined to the final dimension of 5 mm $\pm$ 0.02, in accordance to the procedures defined in Table 1.

Table 1

Type of grinding	Process ref.	type of grinding wheel and Young's modulus(kN/mm²)	Finishing process	roughness Rt µm
Soft longitudinal 	AL	soft A46HV E = 33.3	- for 200 µm : 12.5µm/pass - for the last 50 microns 2 passes of 10 µm + 6 finish passes of 5 µm	7.4
Soft transverse 	AT			7.5
Medium longitudinal	CL	medium A48KV E = 41.4	16 passes of 15 µm, from 5.48 mm dimension.	8.7
hard longitudinal	DL	hard A3605V E = 57.8	8 passes of 30 µm from 5.48 mm dimension	11.9
hard transverse	DT			11.4

The final geometry of the test specimens is shown in figure 1.

For each case (fixed grinding wheel and finishing conditions), twenty test specimens were ground under the same conditions.

For a given grinding wheel, it was possible to adjust the down-feed only. The other machining parameters were as follows :

- speed of the grinding wheel : 30 m/sec
- speed of the table : 13 m/min
- transverse speed of the grinding wheel (continuous) : 7,7 mm/sec
- length between edges : 200 mm
- lubricant : Labo-Industrie SPARCO 2159

In our tests, movements of the grinding wheel and the part were opposed.

. Dressing conditions for the grinding wheel :

- the grinding wheel was dressed before each face of the test specimen was machined
- dressing was carried out in both directions
- down feed : 0.03 mm
- dressing speed : for 2850 r.p.m., V_d = 285 mm/min, f_d = 0.1 mm/rev.

FATIGUE TESTING

The fatigue tests were carried out on a Schenk electrohydraulic machine, usually used for torsion fatigue tests. A special fixture allowed alternating or repeated bending tests to be carried out on the flat tests specimens.

Test results

The fatigue limit (5 x 10^6 cycles) in repeated plane bending at was determined by the standard staircase method. The results obtained in terms of maximum stresses, are given in Table 2.

Table 2

Reference of the grinding procedure	fatigue limit and mean square deviation $\sigma max._f \pm s$ [MPa]		Roughness R_t (µm)
AL	762	112	7.4
AT	690	105	7.5
CL	751	8	8.7
DL	564	13	11,9
DT	520	41	11.4

A very distinct reduction in the fatigue limit (- 26 %) is noted for hard grinding compared with soft grinding. The soft and medium machining conditions gave a similar fatigue limit. The orientation of the grinding marks in relation to the axis of the applied stress also affected fatigue life. As might be expected, transverse grinding gives always a lower fatigue life than longitudinal grinding.

VARIATION OF THE RESIDUAL STRESSES WITH MACHINING CONDITIONS AND FATIGUE TEST LOADING

Variation of the stresses with changes in machining conditions

For the different grinding conditions chosen, distinctly different distribution curves of the residual stresses were obtained with X-ray diffraction method (figure 2).

It was hard-grinding, either longitudinal (reference DL) or transverse (reference DT), which particularly resulted in high residual stresses. No significant difference was observed between the two types of grinding longitudinal or transverse. In both cases, the peak of residual stresses transverse to grinding direction is lower by 10 to 15 % to the peak of residual longitudinal stresses.

For soft (reference A) and medium (reference C) grinding conditions, only a very low level of residual stresses was observed.

Relaxation of residual stresses after fatigue testing

The relaxation of residual stresses by fatigue testing was checked by measuring them by X-ray diffraction. Measurement of the residual stresses was carried out on parts which had not failed in fatigue, and which were tested close to the fatigue limit. The reduction in residual stresses observed is that corresponding to a loading close to the fatigue limit of the part.

The measurements were made on the face of the test specimen plane subjected to tensile stressing during repeated bending. The material is thus subjected to the minimum fatigue load at residual stress σ_R and to the maximum fatigue load at $\sigma_{max} + \sigma_R$

The values found before and after the fatigue test are given in Table 3.

The following observations may be made :

- hard longitudinal grinding (reference DL)

  . the longitudinal residual stress in the direction of applied load is reduced by 52 %, compared with 43 % in the transverse residual stress
  . the prestressed layer depth does not vary (figure 3)
  . the stress relaxation occurs principally in the area of the peak stress (figure 3). It is in this area that the maximum stress is reached during fatigue cycling, and that plastic micro-strains occur, which are probably due to the elastic limit of the material being exceeded locally and are the origin of the stress relaxation.
  . the distribution of the stresses after fatigue tends to be more regular. The peak stress tends to diminish to the value of the residual stress at the surface, resulting in a reduction in the stress gradient (figure 3).

- hard transverse grinding (reference DT)

In this case, it is the transverse stress (σ_{Rt}) which is reduced the most, since it is parallel to the direction of the applied load (fig.4).

- for soft and medium grinding

After fatigue testing, a change in the stresses was observed, resulting in a reduction of the initial stresses. Despite the low stress levels measured before and after fatigue testing, a change of stresses may be evidenced. Due to the scatter in the stress measurements in the layers very close to the surface, these results must be considered as reasonable orders of magnitude. It will be noted that for soft and medium grinding, a tensile longitudinal residual stress and a compressive transverse stress were obtained.

- Measurements were also made on the compression side of the fatigue specimens. No relaxation was observed (fig.5)

The values obtained after fatigue testing are given in Table 4.

Table 3

Ref. of machining conditions	test specimen No	Max applied σ (5.10^6 cycles) MPa	Max $\sigma R1$ MPa	Max $\sigma R1$ MPa mean value	Max σRt MPa	Max σRt MPa mean value	$\frac{\Delta\sigma R1}{\sigma R1}$ Relaxation in %	$\frac{\Delta\sigma Rt}{\sigma Rt}$
AL	A5	0	118		- 178		4	12
	A13	762	113	-	- 157	-		
AT	-	0	-	-	-	-		
	A16	690	125	-	- 200	-		
CL	C5	0	307	-	- 31	-	23	
	C22 C31	751	233 241	237	- 122 - 13	-		
DL	D10 D20	0	640 630 620 630	630	603 570 540 550	566	52	43
	D47 D8	564	337 250 309	300	376 272 311	320		
DT	D73	0	600 620	610	550 550	550	43	48
	D58 D92	520	361 350 340	350	260 285 308	284		

Table 4

	σ_1.max.f MPa	σ_2.max.f MPa	σ_{R_1} parallel to loading MPa	σ_{R_2} perpendicular to loading MPa	$\sigma_1 = \sigma_{1 max\ f} + \sigma_{R_1}$ MPa	$\sigma_2 = \sigma_{2 max\ f} + \sigma_{R_2}$ MPa	σ_{eq} Mises crit. MPa
DL tension side	564	169	300	320	864	469	751 ≃ Rev decreased
DL compression side	- 564	- 169	523	501	- 41	332	354 << Rev no decrease
DT tension side	520	156	284	350	804	506	704 ≃ Rev decreased

These results would thus seem to confirm the hypothesis adopted earlier :

- there is a relaxation of the stress when the true elastic limit Rev of the metal is reached (Rev = 760 MPa for 42 CD4 steel at 40 RC hardness)
- the value of the stabilised residual stress (σ_{R_S}) should be related approximately to the true elastic limit Rev of the metal (cyclic loading) and to the maximum stress ($\sigma_{max.f}$) due to fatigue loading such as

$$\sigma_{eq\ Mises}\ (\sigma_{RS},\ \sigma_{max.\ f}) = Rev \qquad (1)$$

In the case of cracks initiating at the surface (bi-axial stress condition) and for a bi-axial fatigue stress, the equation will be written :

$$\left[(\sigma_{1_{max.f}} + \sigma_{1_{RS}})^2 + (\sigma_{2_{max.f}} + \sigma_{2_{RS}})^2 - (\sigma_{1_{max.f}} + \sigma_{1_{RS}})(\sigma_{2_{max.f}} + \sigma_{2_{RS}})\right]^{1/2} = Rev \qquad (2)$$

where σ_{1RS} and σ_{2RS} are the stabilised residual stresses and $\sigma_{1\ max.f}$ and $\sigma_{2\ max.f}$ the maximum applied fatigue stresses.

In an attempt to obtain a better prediction of residual stress releaving, use was made of a simplified method for the resolution of problems of cyclic plasticity, proposed by J. Zarka and J. Casier (6), from which we developed a computer program using plane finite elements, valid for materials subjected to kinematic work-hardening, assuming small displacements and small strains. Up till now, only the case of elastic shake-down due to radial loading has been treated in its entirety (determination of the condition of shake-down at each point by a limited number of elastic calculations).

The program tested for the purpose of our investigation into the relaxation by fatigue of residual grinding stresses has given satisfactory results. Figure 6 shows the results obtained for hard longitudinal grinding. The predicted reduction agrees fairly well with the experimental results in the case of hard grinding, for which the distribution curve of the residual stresses can be measured with fair accuracy. Agreement between the model and the experimental results is worse for soft and medium grinding, for which the determination of the stress gradient before and after fatigue is more inaccurate. On the other hand, the model of the cyclic behaviour of the layer very close to the surface cannot be represented by the macroscopic cyclic work-hardening curve of a test specimen. This might reflect the limits of modellization of a microscopic localized phenomenon using the rules of macroscopic behaviour and calculation.

The residual stress relaxation phenomenon has been explained here by means of a purely mechanical model (stressing beyond the cyclic elastic limit). It should be born in mind, however, that the residual stresses can also be reduced by means of loadings which do not always imply the true macroscopic elastic limit. This reduction can, for example, be obtained by vibration, where the loading levels are well below the true elastic limit (7). Heat treatment, can also be used to reduce residual stresses (fig.7).

It can be seen that a purely macroscopic mechanical explanation cannot by itself take into account all the phenomena involved in the reduction of residual stresses. On the other hand, if this mechanical explanation is applied to stresses of the second or third order (residual stresses concerning the grain or the crystal), it would appear to be possible to explain the reduction in the residual stresses for loadings which are below the true elastic limit. In the case of stress relief by vibration with a low macroscopic stress level, it is possible to imagine for those grains most adversely aligned in relation to the loading, that the elastic limit is exceeded locally and that the residual stresses within such grains are altered. This alteration will lead to a change in the macroscopic stresses 1st order stresses), which are just the sum of the 2nd and 3rd order residual stresses.

CALCULATED PREDICTION OF THE FATIGUE STRENGTH WHEN RESIDUAL STRESSES ARE PRESENT

In order to take the residual stresses into account in a calculated prediction of fatigue, a fatigue criterion must be available which can be used for multiaxial stress conditions. Recent work has shown that the Dang Van and Crossland criteria would seem to take a good account of the fatigue behaviour when residual stresses (3) and multiaxial loading (5) are present. It is these criteria that we shall use first of all in attempting to analyse the results obtained during this investigation.

Dang Van criterion (8)

According to this criterion : the fatigue strength is a function of two parameters :

- the maximum local shear stress τ in the least favourably orientated plane. For the stressing in plane bending used here $\tau = \tau_a = \sigma_a/2$ (τ_a and σ_a being the levels of the shear stress and the alternate tensile stress at the fatigue limit respectively).

- If σ_1 , σ_2 , σ_3 are the maximum values of the principal stresses, the maximum hydrostatic pressure is

$$P_{max} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

In order to prevent fatigue failure, the Dang Van criterion specifies that in work conditions τ_a stressing, P_{max} must lie within a range bounded by two straight lines located symmetrically about the axis of P_{max} calculated.

$$\tau_a \pm \alpha \, P_{max} = \pm \beta \qquad (3)$$

The equation for the limit straight line may be approximated to using the results of fatigue tests (in tension compression and alternate torsion, for example, let σ_D and τ_D be the respective fatigue limits).

$$\tau_a + 3 . \frac{2\tau_D - \sigma_D}{2\,\sigma_D} . P\,max = \tau_D \qquad (3\ bis)$$

CROSSLAND criterion (9)

In the Crossland criterion, the fatigue strength is also a function of the maximum hydrostatic pressure, but unlike the Dang Van criterion, the second parameter is the amplitude of octahedral shear stress. This octahedral shear stress is that which acts on a particular plane equally inclined with respect to the three principal directions. With respect to the thre principal stresses σ_1 , σ_2 , σ_3 , this shear stress is expressed by the relationship :

$$\tau_{oct} = \sqrt{\frac{2}{3} . J_2} = \frac{1}{3} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \qquad (4)$$

and for a biaxial stress state ($\sigma_3 = 0$).

$$\tau_{oct} = \frac{\sqrt{2}}{3} . \left(|\sigma_1^2 + \sigma_2^2 - \sigma_1 . \sigma_2| \right)^{1/2} \qquad (5)$$

In order to prevent fatigue failure, the Crossland criterion specifies that the point representing loading in the τ_{octa} chart (amplitude of the octahedral shear stress), pmax must lie within the zone bounded by the abscissa and the straight line defined by the equation.

$$\tau_{octa} + \alpha \, P_{max} = \beta \qquad (6)$$

Comparing equation (3) with equation (6), it can be seen that in the case of the flat specimens used in bending fatigue, the Dang Van and Crossland criteria are not very different. For both criteria, the maximum hydrostatic pressure is identical, but the amplitude of the shear stress as a function of the amplitude of the bending stress σ_a is different :

$\tau_a = 0{,}5\ \sigma_a$ for Dan Van

$\tau_{octa} = 0{,}42\ \sigma_a$ for Crossland

Results obtained

These two criteria have been used in assessing the fatigue test results obtained with different grinding conditions.

Due to the inaccuracy of the fatigue crack initiation zone, the values of residual stresses used for the calculation are the maximum stabilised stresses, i.e. measured after fatigue testing. The results are shown on figures 8 and 9. In these figures, the reference fatigue limit in rotating bending has been plotted.

In figures 8 and 9, the residual stresses have been taken into account in the calculation of the hydrostatic pressure. The upper lines represent the intrinsic fatigue strength of the steel, since in longitudinal grinding, the roughness has no influence. The lower lines, on the other hand, show the influence of surface roughness.

In order to check the applicability of any of the criteria studied, a greater number of experimental results concerning the reference fatigue limit of the steel are required. The torsional fatigue limit of the steel would, for example, have allowed the lines drawn through the middle of the experimental points to be cHecked.

INFLUENCE OF THE SURFACE ROUGHNESS

It is usual to quantify the influence of the surface roughness by the surface finish factor Ks, defined as :

$$Ks = \frac{\text{Fatigue limit for a given machining condition}}{\text{Fatigue limit for the reference machining condition}}$$

If the soft longitudinal grinding (AL) is used as the reference, the following results are obtained ;

reference	roughness Rt µm	fatigue limit MPa	overall Ks	% reduction in fatigue limit = 1 - Ks	% reduction due to residual stresses	% reduction due to surface finish
AL	7.5	762	1	-	-	-
AT		690	0.91	9	-	9
DL	11.5	564	0.74	26	26	-
DT		520	0.68	32	24	8

For the roughness values considered (7.5 to 11.5 µm Rt), it may be said that the influence of the direction of the grinding marks is of the order of 10 %. Residual stresses decrease the fatigue limit by about 25 %. It is normal to have a similar fall due to the residual stresses alone for cases DL and DT, since the transverse stresses are broadly equal to the longitudinal stresses for these two conditions of machining . Only the direction of the grinding marks can bring about a difference in the fatigue strength. In the light of these results, and considering figures 8 and 9, it would seem that, as the severity of the grinding increases, it is mainly the residual stresses which cause the fatigue strength to decrease.

The roughness values considered here are in fact very close (7.5 and 11.5 µm Rt), and thus it was not possible to analyse the influence of roughness when it varies considerably.

However, by using the Dang Van or Crossland criteria, it has been possible to separate the respective influences of residual stresses and roughness.

Charts using either one of these criteria could be plotted for different values of the surface roughness as shown in figure 10.

It should be noted, however, that with this approach it is difficult to take the influence of the surface roughness correctly into account, for loadings as differing as torsion or tension. It is known, in fact, that machining marks perpendicular to the axis of a test specimen do not, themselves, influence the fatigue limit in tension or in torsion.

CONCLUSIONS

In this investigation, on a ground 42CD4 steel, a definite decrease in fatigue strength has been evidenced when the severity of grinding increases.

X-rays diffraction has been applied in tracking the relaxation of the residual stresses. When steel was subjected to a load corresponding to its fatigue limit, a reduction in residual stresses of the order of 40 to 50 % was noted. This decrease seems to be linked to the true elastic limit of the metal being locally exceeded. To establish a model of this relaxation taking into account the cyclic behaviour of the metal, a simplified method for calculating the stabilised residual stresses, using a limited number of elastic calculations by finite elements, has been used. Calculations and experimental results agree satisfactorily in the hard-grinding case but this has to be confirmed by applying the model to other materials and other residual stress conditions.

Dang Van or the Crossland criteria, which make use of the hydrostatic pressure, allow the respective influences of the surface roughness and the residual stresses on the fatigue strength to be separated. The use of Dang Van or Crossland fatigue charts plotted for different values of roughness, should help design engineers in better quantifying the factors which affect the fatigue strength of a mechanical engineering part ; namely they are :

- mechanical properties and microstructure of the material
- surface roughness
- residual stresses.

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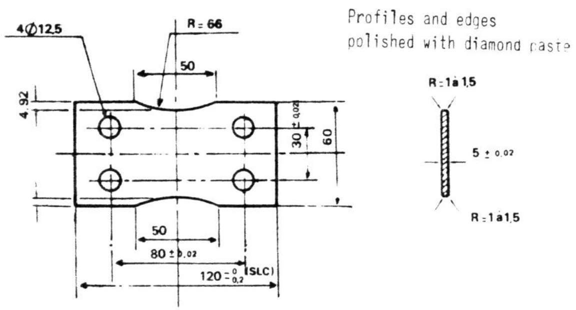

Figure 1 : Geometry of test specimen for repeated plane bending tests

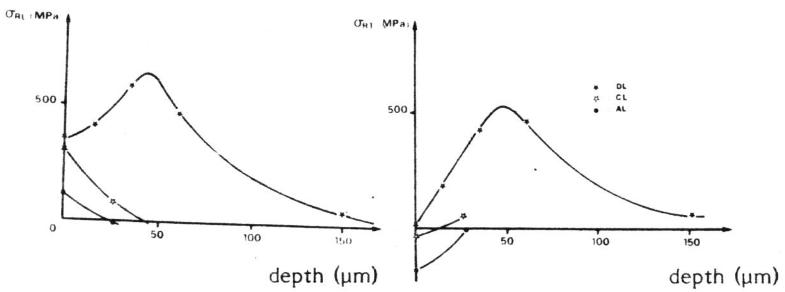

Figure 2 : Distribution curves of residual stresses for different grinding conditions

σ_{RL} : residual stresses parallel to the grinding marks

σ_{RT} : residual stresses perpendicular to the grinding marks

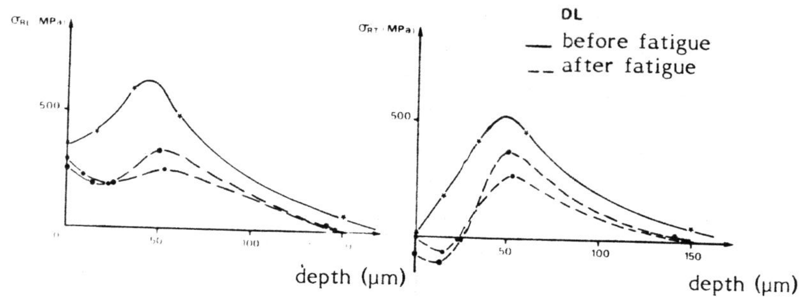

Figure 3 : Residual stresses before and after fatigue testing in the case of hard-grinding (reference DL)

For the measurements after fatigue testing the curves shown were obtained from 2 specimens.

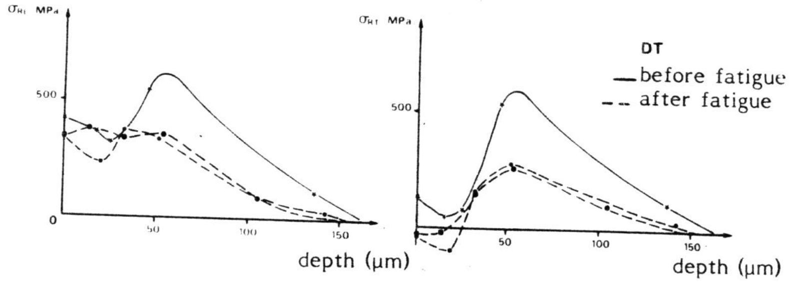

Figure 4 : Residual stresses before and after fatigue testing in the case of hard-grinding (reference DT) (Results after fatigue testing from two test specimens).

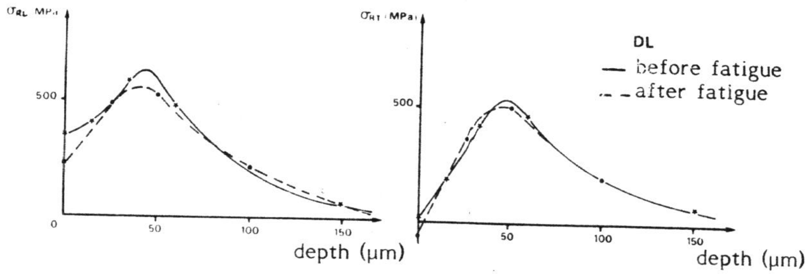

Figure 5 : Residual stresses, before and after fatigue testing, on the compression side of test specimens (hard grinding DL)

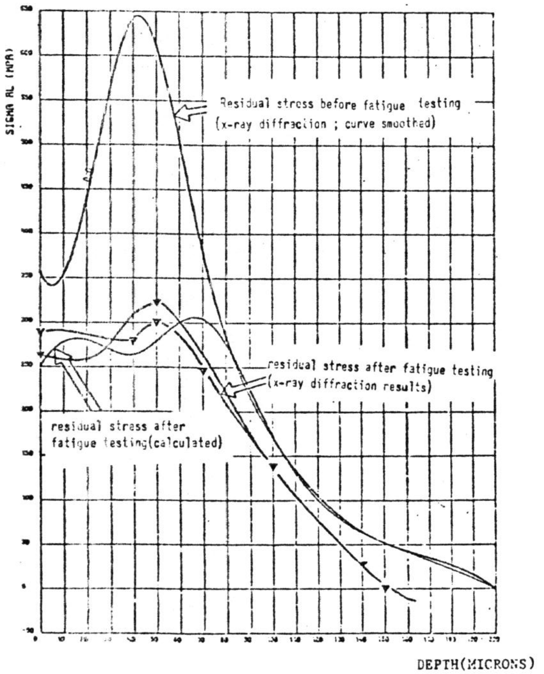

Figure 6 :
Predicted reduction of the residual stresses by calculation. Hard longitudinal grinding case.
X-ray diffraction measurements made on two test specimens after fatigue testing.

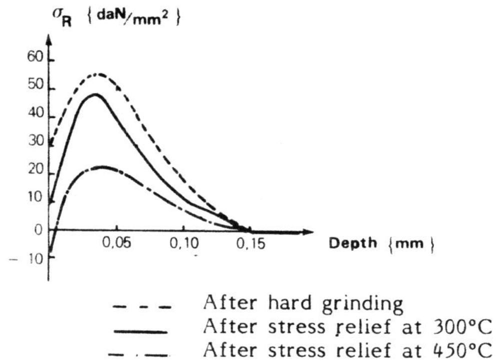

Figure 7 : Reduction of the residual stresses σ_{RL} related to the stress relief temperature (1 hour), for the hard grinding case.

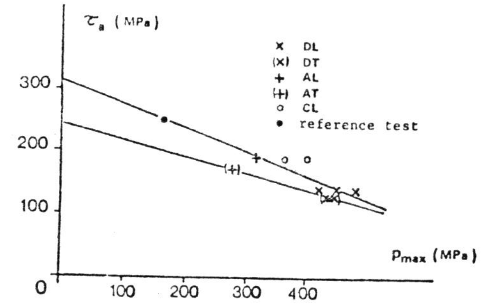

Figure 8 : Variation of the maximum alternating shear stress at the fatigue limit with respect to the hydrostatic pressure for the various experimental results. (Dang Van criterion).

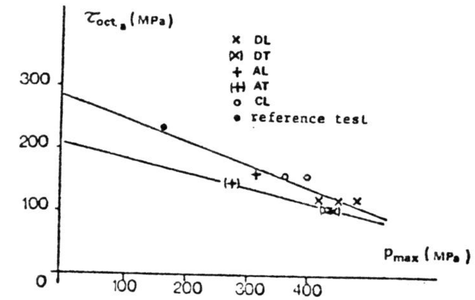

Figure 9 : Variation of the alternating octahedral shear stress at the fatigue limit with respect to the hydrostatic pressure for the various experimental results. (Crossland criterion).

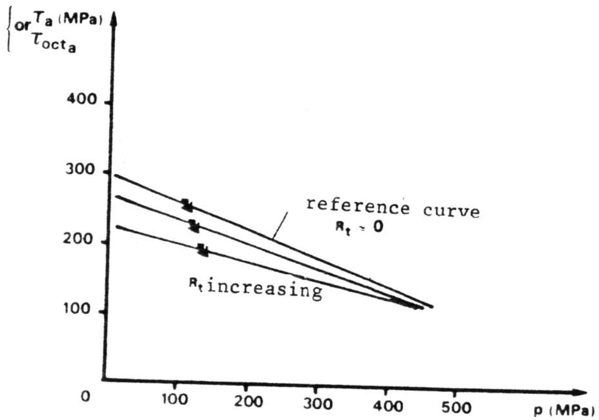

Fig. 10 : Plotting of the Dang Van or Crossland chart for for different values of roughness