Fatigue Behaviour of Shot Peened Steel

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Introduction :

Some 4135 steel automobile parts are subjected to mechanical fatigue, and in such cases prestressing shot peening often appreciably increases working performance [1] [2]. For Wohlfarht [1] the contribution of shot peening to fatigue resistance stems from two phenomena : work hardening of the surface layer, and the residual compressive stress resulting from the elastic return emanating from the core of the part following surface plastification under the impact of the shot. The increased lifetime of ductile materials such as mild steel is mainly due to work hardening, while that of resistant materials such as hard steel mainly depends on residual compressive stress. The mentioned steel has intermediate characteristics, and is therefore sensitive to the two effects.

An elastoplastic model allows us to estimate the strain and the residual stresses distribution in a shot peened material, knowing the main parameters of the shot peening (nature, diameter and speed of the shots, cyclic behaviour law of the material) [3].

In contrast to thermochemical types of surface hardening (case hardening, nitruration, etc) any residual compressive stress due to shot peening may attenuate with operating time and extent of loading. For Kodama [2], residual stress changes in two phases : the first brings elastic shakedown of the peened surface, followed by relaxation of the residual stresses which is linear versus the logarithm of the number of cycles. In order to better understand the phenomena we studied the variation of the surface stresses and plastic deformation for three degrees of applied stresses including fracture between 10^5 and10^8 cycles (fatigue limit).

The values of the residual stresses were determined by X-ray diffraction.

Test data :

Material :

Chemical analysis gave the following results for elements other than iron :

element :	C	Si	Mn	S	P	Cr	Ni	Mo
wt % :	0.36	0.38	0.69	0.004	0.01	1.1	0.13	0.24

Table 1 : chemical analysis of SAE 4135 steel

The 4135 steel was subjected to oil quenching after austenizing during 35 mn at 850 C and annealing at 610 C during 2 h followed by air cooling, giving a microstructure of annealed martensite.

The mechanical properties appear below :
- Elastic limit at 0.2% : Re = 760 MPa , - Breaking point : Rm = 920 MPa ,
- Elongation to yield : A = 17.5 % , - Vickers hardness : 310 HV ± 10 / 30 kg,
- Cyclic elastic limit : after 1 cycle : 735 MPa , 4 cycles : 720 MPa , 10 cycles : 700 MPa .

This steel becomes milder with the degree of stressing.

Fatigue specimens :

The rotating bending specimens (ø 6.74 mm) underwent turning on an automatic lathe with a carbide tipped tool.

The specimens were shot peened in an air blast machine having three nozzles arranged at 120° around the workpiece. The nozzles tilted to sweep the entire width of the throat while the specimen was rotated about its axis of revolution. The treatment, of 4/6 A Almen intensity, was performed with cast steel shot S110 (tough steel shot) with a 150% coverage rate.

Fatigue stressing was performed with rotating bending machines driving the specimens at 100 Hz. In test at 1 and 10 cycles the rotation was manual hence frequency was low.
In the following, the term "applied stress" means the amplitude of the external stress applied to the specimen.

S-N curves show the following endurance limits in rotating bending :

- machined material : 400 MPa
- shot peened material : 500 MPa

Thus peening is of advantage for fatigue performance.

X-ray diffraction :

On each specimen identified by an applied stress and number of fatigue cycles, circumferential stress and axial stress were determined with some uncertainty. In fact the computer coupled to a goniometer computes the complete tensor by the multiple regression method on the ellipsoid of the strain, by assuming that the stress normal to the surface is zero [4]. The uncertainty is set for a 95% confidence interval according to the Fisher-Student law, which is approximately twice the typical deviation for a normal law.
To analyse the X-ray diffraction on the cylindric samples, we built an apparatus put on a goniometer Siemens D500. This apparatus allows the φ rotation and adjust the axe of the cylinder on the X-ray beam. It is drived by a computer DEC PDP11-23.

The main test parameters were as follows :

- Chromium Kα ray (30 KV and 30 mA),
- Rear vanadium filter in front of P.S.D.,
- 6φ angles ,
- Typical omega goniometer, automatic in ψ and φ,
- 25 seconds acquisition per peak,
- 7 ψ angles with ±1° oscillations,
- Collimator giving a spot of 1mm dia. on specimens,
- Family of diffraction planes {211} of $2\theta = 156°$ Bragg angle.

Modelling :

The prediction of residual shot peening stresses is essential for better utilisation of material. By treating shot peening as a cycling loading of the surface, a theoretical model has been developped to evaluate the distribution over depth of residual shot peening stresses .
The model is based on Zarka simplified method [5]. It consists in determining the residual stresses field from the elastic stresses field as given by the Hertzian theory .
We set up a system of cylindrical coordinates (O, r, θ, z). Where O is the center of impact, (O, r, θ) is the plane bounding the body and Oz is normal to the surface of the body (with z>0 towards the interior).
The Hertzian elastic stresses tensor has the following form [6] :

$$\underline{\Sigma} = \begin{vmatrix} \Sigma_{rr} & 0 & 0 \\ 0 & \Sigma_{\theta\theta} & 0 \\ 0 & 0 & \Sigma_{zz} \end{vmatrix} \quad , \text{ with } \Sigma_{rr} = \Sigma_{\theta\theta}$$

The residual stresses generated by shot peening are independant of co-ordinates r and θ, and remain constant in any plane parallel to that bounding of body. The residual stresses should verify both equations of equilibrium and boundary conditions, the residual stress tensor has the following form:

$$\underline{\rho} = \begin{vmatrix} \rho & 0 & 0 \\ 0 & \rho & 0 \\ 0 & 0 & 0 \end{vmatrix}$$

The inelastic residual strain $\underline{E}(x,t)$ is composed into an elastic part associated with the residual stress $\underline{\rho}(x,t)$ by the laws of elasticity and an irreversible strain $\underline{E}^p(x,t)$ as following : $\underline{E}^{ine}(x,t) = \underline{M}\,\underline{\rho}(x,t) + \underline{E}^p(x,t)$ [5][7], where $\underline{M}$ is the compliance matrix.
For a semi-infinite body the inelastic strain tensor has the following form :

$$\underline{E}^{ine} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & E^{ine} \end{vmatrix}$$

Taking into acount the plastic incomressibility, the plastic strain tensor has the form [3] :

$$\underline{E}^p = \begin{vmatrix} E^p & 0 & 0 \\ 0 & E^p & 0 \\ 0 & 0 & -2E^p \end{vmatrix}$$

We introduce internal variable y ,which is related to the plastic strain. Transformed variable Y is deduced from the residual stress and the plastic strain by : Y=y - devρ [7] where devρ is the deviatoric part of the stresses tensor. The tensor of transformed variables has the form [3] :

$$\underline{Y} = \begin{vmatrix} Y & 0 & 0 \\ 0 & Y & 0 \\ 0 & 0 & -2Y \end{vmatrix}$$

Therefore to arrive to the residual stresses field, we must determine by Zarka method the variable Y through a geometrical design [7].

The elastic domains centred on the minimal and the maximal elastic loadings can be designed in the space of transformed variable. As the loading is considered as a radial one and its minimal value is zero, the distance between minimal and maximal states is equal to S_{eq}^{el} (equivalent elastic stress deviator).

Two cases are distinguished (fig. 1) :
- elastic shakedown: the two elastic domains have a common part then $Y = S_{eq}^{el} - R$,
- plastic shakedown : the two elastic domains have an empty intersection then Y=R ,

where R is Von Mises radius :

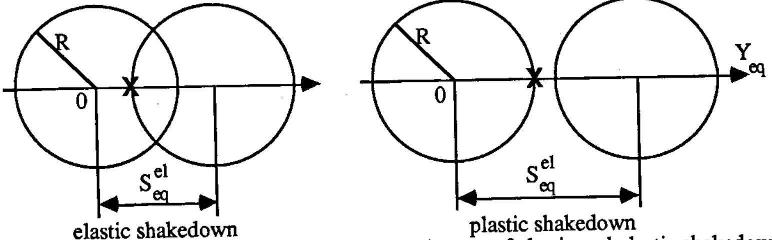


Fig. 1 : equivalent transformed parameter in case of elastic and plastic shakedown

The model shows the influence of the main parameters of shot peening, it provides a good estimate of the Almen deflexion, the figure 2 shows that we found good agreement between the (residual stresses versus depth) curve yielded by the model and experimental results obtained by X-ray diffraction for SAE 4135 on flat piece.

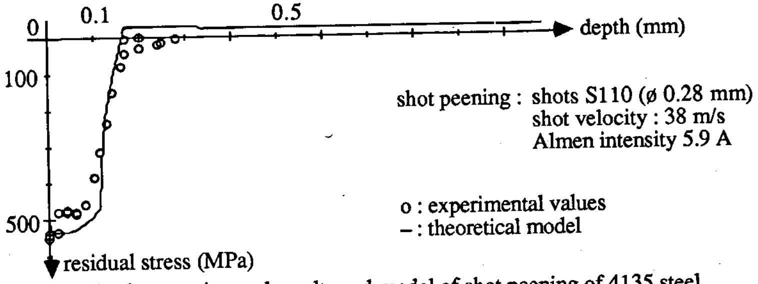


Fig. 2 : experimental results and model of shot peening of 4135 steel

Following peening and before stressing, the residual circumferential and axial stresses (mean values and standard deviations for normal typical distribution) on the surface of some twenty cylindrical specimens were as follows :
- circumferential stress : - 621 ± 23 MPa
- axial stress : - 524 ± 20 MPa

It is usual for the stress not to be isotropic with this type of specimen [8].

The in-depth study shows that the maximum number of residual compressive stresses are on the surface and that the plastified film is 0.15 mm thick.

Fatigue study :

The analysis of the decrease of the residual stresses versus the number of cycles shows two stages : during the first cycles the elastic shakedown of the shot peened surface and during all the other cycles the relaxation.

Elastic shakedown :

The points shown on figure 3 indicate the circumferential and axial stresses depending on the number of cycles, versus various applied stresses. The residual stresses decrease during the initial cycle, and this phenomenon increases with the intensity of the load (Kodama [2]).

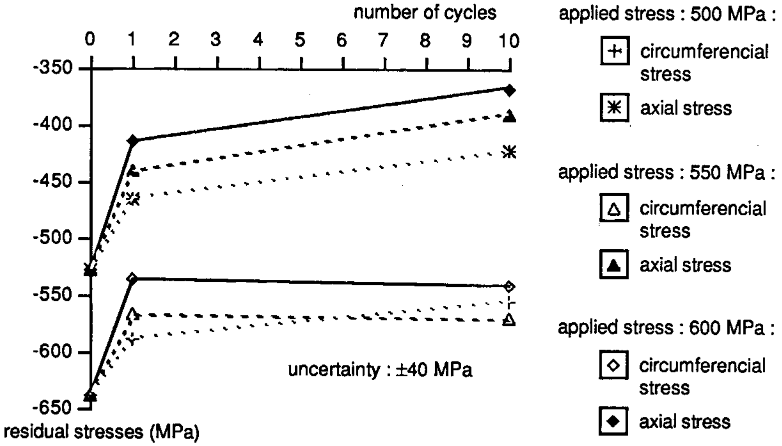


Fig. 3 : Fluctuating residual stresses during initial cycles

Under the first compressive stresses (Fig. 3) the peening stresses decrease sharply. The peened surface plastifies, and the workpiece then settles down into its range of elasticity after the first cycles : that is elastic shakedown.

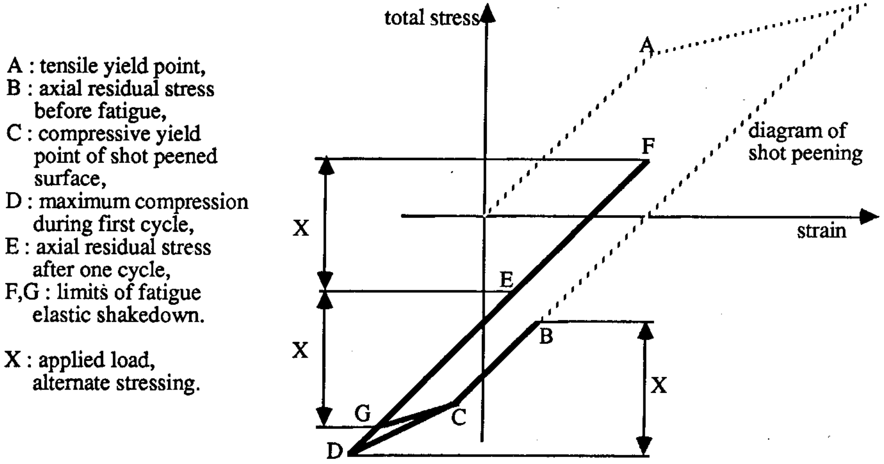


Fig. 4 : explanation of elastic shakedown of material during 1st cycle

Figure 4 suggests a diagrammatic representation of a single-axis path followed by the stresses and strains of a peened surface during the first fatigue cycle in rotating bending. Only the residual stresses of points B and E may be determined by X-ray diffraction ; the others are derived by computation .

Following peening, strain and residual axial stresses on the surface are shown at point B. Under the effects of applied stress X, the representative point should pass through D and exceed the compressive yield strength at point C. After this first cycle of strain, the representative point is at E, meaning that the following cycles will cluster between F and G in the elastic range. This decrease in residual stress - the stress at E being less intense than the stress at B - is explained by plastic strain between C and D which induces a rearrangement of defects in the microstructure. In fact this reorganization of the microstructure is continuous under loading, and the path followed by the stresses passes directly from C to G.

The plastic strains at points B and E on figure 4 are computed by continuous medium mechanics which furnishes the relationship binding the residual axial and circumferential stress with plastic strain [8]. This gives the following deformation for points B and E :

	before fatigue	one cycle 500 MPa	one cycle 550 MPa	one cycle 600 MPa
cir. plast. strain :	0.219%	0.213%	0.206%	0.196%
ax. plast. strain :	0.172%	0.145%	0.135%	0.126%
axial total strain :	0.011%	0.008%	0.007%	0.005%

table 2 : plastic strain before and after one cyle

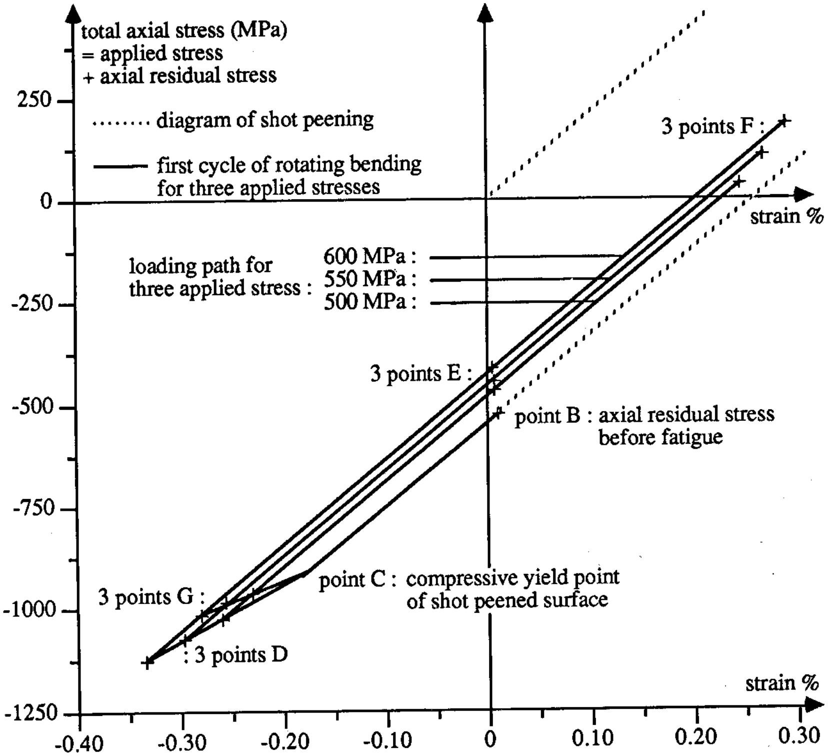
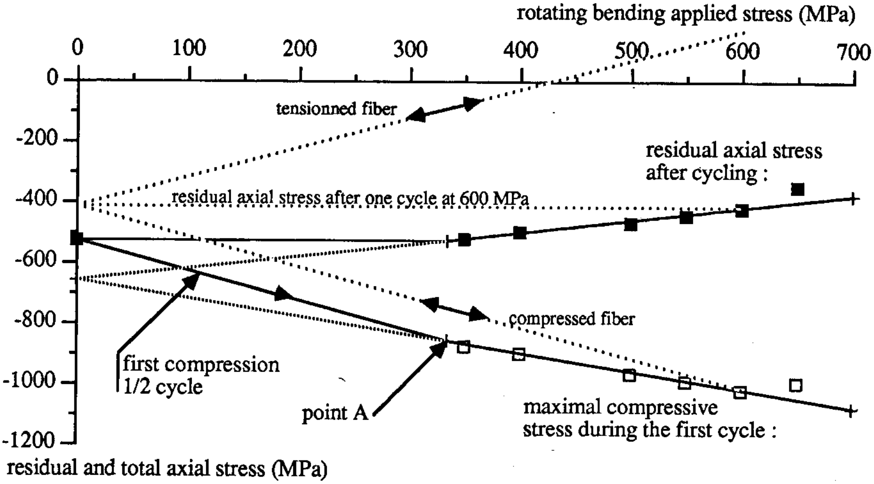


Fig. 5 : change in axial stresses after the first cycle

Figure 5 shows the same points as figure 4, but computed from the previous table, do that the straight lines linking the three points D and the three points G intersect at C on the straight line of elastic deformation passing through point B. The figure 5 allows us to estimate the compressive yield point of shot peened surface about 900 MPa.

The circumferential plastic strains are superior to the axial one. We can explain this fact by the geometry of the specimens. During shot peening several shots touch lightly the side of the pieces and deform the surface in the circumferential axis.

To know this yield point with better precision, many rotating bending samples were stressed at 350, 400 or 650 MPa during one cycle.
Figure 6 shows black squares representing the residual axial stresses determined by X-ray diffraction after loading several specimens at one cycle for six applied stresses.
The white squares indicate the maximum value of axial compressive stresses during the first cycle :
Total stress = residual stress after one cycle - applied stress



applied stress :	0	350	400	500	550	600	650
residual stress :	-524	-518	-495	-464	-438	-414	-342

Fig. 6 : change in axial stress vs. amplitude of applied stress

The first rotating bending stress at 600 MPa is shown on figure 3. Starting from the initial residual axial stress (-524 MPa) the material remains in the elastic range during the application of external compressive forces up to point A (-860 MPa). After this the peened layer plastified as long as the 600 MPa of applied stress is not reached. During that strain the superficial residual stress decreases to -414 MPa. The following cycles will cluster around the new mean value without occasioning any notable plastification.
The compressive yield point of shot peened surface is about 860 MPa.

The linear regression on the various points give :

$\sigma_{\text{res. or total}} = a \cdot \sigma_{\text{applied}} + b$:

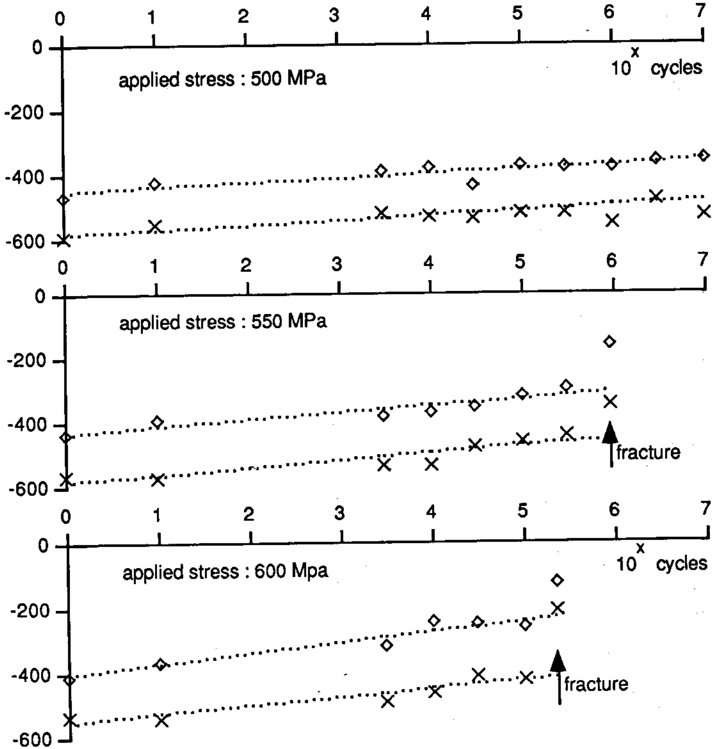
	a	b
residual stress :	0.403 ± 0.022	-659 ± 11
total stress :	-0.597 ± 0.022	-659 ± 11

table 3 : linear regression on the residual stresses and the total stresses

The samples stressed at 650 MPa are different of the others. At this applied stress all the shot peened layers are plastified during the compression, and 650 MPa being about the tensile yield point, the material not hardenned is plastified during the tensile loading.

Relaxation :

We study the shot peened specimens fatigued at 500 MPa, 550 MPa and 600 MPa. 500 MPa is the endurance limit, 550 and 600 MPa are respectively greater by 10 and 20 % than that limit.
Measurements of fractured specimens are by way of indication only, as the material was cracked and greatly plastified around the fracture zone, hence the risk of large error on the value of the stresses determined by X-ray diffraction.
Following elastic shakedown, the relaxation was the quicker as the applied stress was high. The residual stress decreases even with an applied stress of 500 MPa, close to the endurance limit.



◊ : residual axial stress in MPa
x : residual circumferential stress in MPa

applied stress	axial residual stress	circumferential residual stress
500 MPa :	= - 450 + 14 . Log N	= - 584 + 15 . Log N
550 MPa :	= - 433 + 21 . Log N	= - 585 + 22 . Log N
600 MPa :	= - 407 + 34 . Log N	= - 552 + 25 . Log N

Fig. 7 : peened specimens fatigued at 500 MPa, 550 MPa and 600 Mpa

Following the initial cycles the stresses decrease slowly and regularly (Fig.7). That is relaxation. The linear regression of the residual stresses versus the logarithm of the number of cycles shows that with

the maximum values of the applied stresses :
- the residual compressive stress at the origin decreases in absolute value (elastic shakedown),
- the slope of the relaxation straights increases.

This phenomenon is linked to a shift in the defects (especially dislocation) introduced in large numbers during work hardening due to shot peening.

Conclusion :

The study of shot peened SAE 4135 steel shows that we can find the residual stresses due to shot peening with a model using Zarka elastoplastic theory. There is a good agreement between the theoretical result given by the model and the experimental values of residual stresses obtained by a special triaxial apparatus.

The decrease of the residual stresses with the number of cycles and the applied stress sets out two stages. During the first cycles the shot peened layer platifies under the compressive loading induced by the the applied and the residual stress, this is the elastic shakedown. Then the residual stresses decrease slowly, this is the relaxation due to microplasticity of the material even at an applied stress close to the endurance limit.

The study of the residual stresses and the plastic strains during the elastic shakedown of the shot peened surface allows to estimate the compressive yield point about 860 MPa. During the initial cycles, the material shakes down if total compressive stress (applied stress + residual stress) induced in the material is greater than the compressive yield point of the shot peened surface. In this case the elastic limit is exceeded for an applied stress (of 335 MPa) below the endurance limit (of 500 MPa).

In spite of everything, the considered shot peening increases the endurance limit in rotating bending of this SAE 4135 steel of 25%.

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