FATIGUE STRENGTH PREDICTION OF A SHOT PEENED 42CRMO4 STEEL USING MULTIAXIAL FATIGUE CRITERION AND SURFACE ROUGHNESS CORRECTION

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Abstract: High cycle multiaxial fatigue tests were carried out in fully reversed plane bending on smooth specimens made of 42CrMo4 steel. These specimens were machined and shot peened under different operating conditions. The experimental endurance limits were compared with the predictions of a multiaxial fatigue strength model for shot peened components. This model is based on the Crossland multiaxial fatigue criterion. It is able to take into account the effect, on the endurance limit, of the biaxial residual stresses due to both the shot peening and the machining process. The roughness effect is considered by using a correction factor. A good estimation of the fatigue strength improvement due to shot peening is predicted by the proposed model. Some evolutions are needed for instance to consider the effect of surface defects such as indents burrs and folds. The influence of such factors on the fatigue strength can not be included in a single roughness parameter.

1. Introduction

For weight light design purpose, the fatigue strength of some components (crankshaft, suspension arm, etc...) needs sometime to be increased compared to the intrinsic fatigue limit of the material. Shot peening is one of the possible strengthening treatments. The aim of this paper is to compare the fatigue strength of smooth specimens treated under different shot peening conditions (with steel or glass balls and different Almen intensities) and the fatigue resistance of untreated specimens (ground or turned). The material investigated is the 42CrMo4 steel. The different endurance limits under fully reversed plane bending are compared and a simple fatigue strength prediction model based on the Crossland multiaxial fatigue criterion is proposed. The multiaxial residual stresses due to both the machining process and the shot peening are considered, together with the roughness effect.

2. Material and experimental conditions

Material

The studied material is the quenched and tempered 42CrMo4 steel. Its chemical composition is indicated in Table 1 and its mechanical characteristics (after heat treatment) are: $Rp_{0,2\%} = 905$ MPa, Rm = 1040 MPa, A% = 19%, Z% = 53% and HB = 302.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu
Rate (%)	0,415	0,200	0,710	0,016	0,030	1,020	0,070	0,200	0,012	0,150

Table 1 : Chemical composition of the 42CrMo4 steel.

Specimen geometry and manufacturing

All the fatigue tests were carried out on smooth specimens (Figure 1) with a theoretical stress concentration factor in bending Kt(bend)=1.03 [1]. Five different manufacturing processes were investigated: turned specimens, turned and ground specimens, turned and shoot peened specimens with 3 different shot peening conditions SP1, SP2 and SP3 (Table 2). The specimen manufacturing conditions are the following. The turning process was done by CETIM Senlis with the following machining parameters for the median torus (diameter 16±0.02): cutting speed Vc=150m/mn, for sketching out: cut depth 0.2 mm (tool PDNN σ=35°, radius 0.8 mm) and for finishing: cut depth 0.1 mm (tool PDNN σ=35°, radius 0.4 mm). The grinding was done with the following conditions: the sketch out was the same than in turning, the finishing conditions of the median torus are:

rotation speed of the specimen: 1000 rpm, cutting speed: 30 m/s. A cylindrical grinding of the median torus was done, the last 0.01 mm was machined with a longitudinal grinding for having a low roughness and longitudinal striations. The shot peening was carried out by MIC France with the conditions summarized in Table 2.

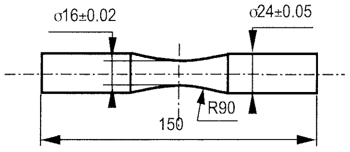

Figure 1: Specimen geometry (dimensions in mm).

Code	Shot type [2]	Almen intensity	Covering rate (%)
SP1	cast steel Ø 600 µm	F 30 – F 35 A	125
SP2	cast steel Ø 400 µm	F 20 – F 25 A	125
SP3	glass beads Ø 300 - 355 µm	F 20 – F 25 N	125

Table 2: Shot peening conditions.

Fatigue tests

The fatigue tests were carried out at ENSAM-LAMEFIP with a resonant electrodynamic fatigue testing machine under fully reversed pure plane bending, with load control, at room temperature and in air. The operating frequency was 52 Hz. The detection of fatigue crack initiation was done by monitoring the resonance frequency drop. Between 18 and 22 specimens were tested in each configuration.

3. Experimental results and analysis

S-N curves

The S-N curves of the 5 different specimen types were identified from experimental data, between 5.10^4 cycles and 5.10^6 cycles, by using ESOPE software [3] and the linear model: N=A/(S-E). The median curves (failure probability = 0.5) are illustrated in Figure 2. The highest median endurance limit is for the ground specimens with the following decreasing order SP2, SP3, SP1 and turned specimens. But, if the scatter of the fatigue data is considered, as it has to be done for design purpose, this order is modified as illustrated in Figure 3 for a failure probability Pf=0.1. The SP3 shot peening conditions lead to a higher endurance limit than SP2 and the S-N curve for SP1 with Pf=0.1 is really lower than the corresponding median S-N curve because of a very large scatter in this case. One can think that this order is modified because the SP3 shot peening was done with the lower Almen intensity (Table 2). It creates smaller surface defects (indents, burrs and folds) than the other shot peening conditions. The higher surface roughness produced by SP2 conditions explains the larger scatter of the SP2 fatigue results compared to the SP3 ones for the same residual stresses (see the next part).

SEM observations and roughness

In all cases the fatigue crack initiation areas were observed at the specimen surface. For the turned specimens, the fatigue crack initiates on a machining striation (Figure 4a) or a machining defect due to the tool wear. A striation is also the location of fatigue crack initiation for the ground specimens (Figure 4b). For the shot peened specimens with cast steel shots (SP1 and SP2), the crack initiation areas are both material fold due to shot peening (Figure 5a) or shot indents (Figure 5b). The specimens treated with glass beads have two types of crack initiation sites: material fold due to shot peening (Figure 6a) or striation from turning (Figure 6b), because the Almen intensity is smaller for SP3 conditions than for SP1 and SP2. These observations prove that the shot peening conditions used in this study are too damaging for this mild steel. The ground specimens have the highest fatigue strength because the surface roughness is better in this condition than for all the others

(Table 3). Furthermore, the grinding process introduces compressive residual stresses in the material surface layer below the surface (Figure 7).

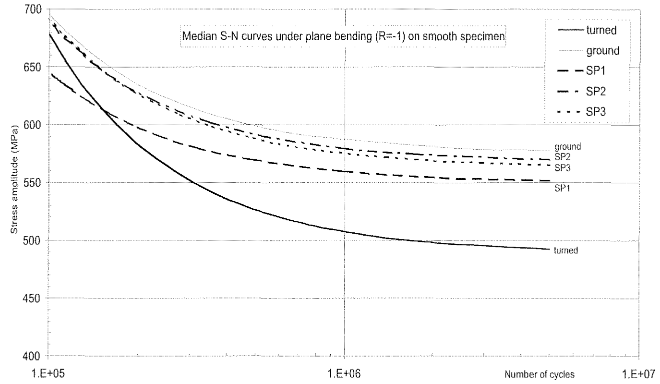

Figure 2: Median S-N curves for the different manufacturing conditions under fully reversed plane bending.

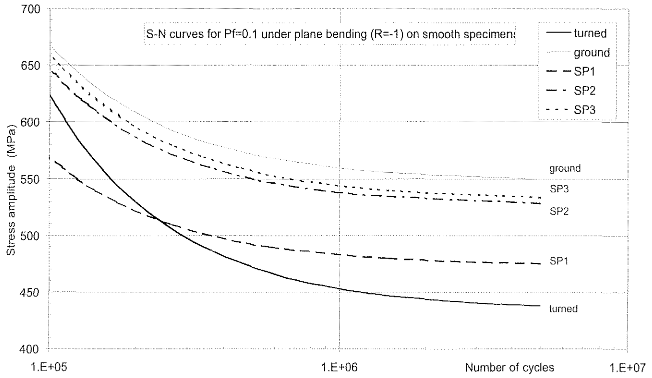

Figure 3: S-N curves for Pf=0.1 for the different manufacturing conditions under fully reversed plane bending.

	Turned	Ground	SP1	SP2	SP3
Ra (µm)	0.95	~0*	2.75	3.13	1.1
Rt (µm)	6	~0*	16.6	23.3	10.3

*Table 3: Roughness of the different specimen types. * the ground striations are parallel to the specimen longitudianl axis (perpendicular to the normal stress due to bending).*

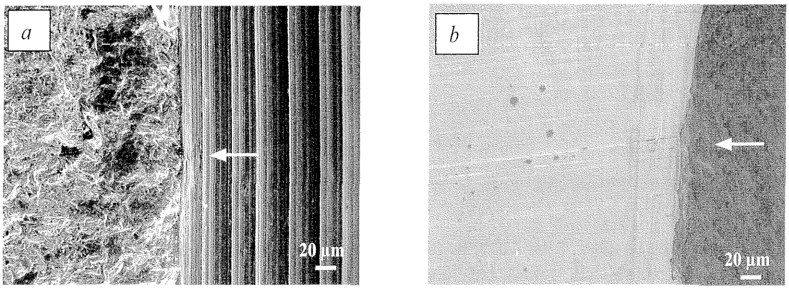

Figure 4: Crack initiation area on (a) on a striation due to turning for a turned specimen, (b) multiple crack initiation on a grinding striation.

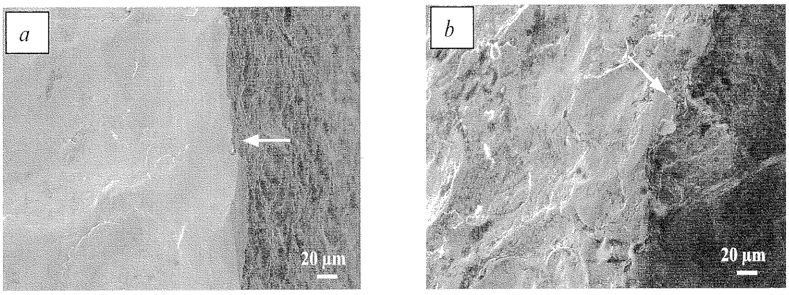

Figure 5: Crack initiation for shot peened specimens, (a) SP1, (b) SP2.

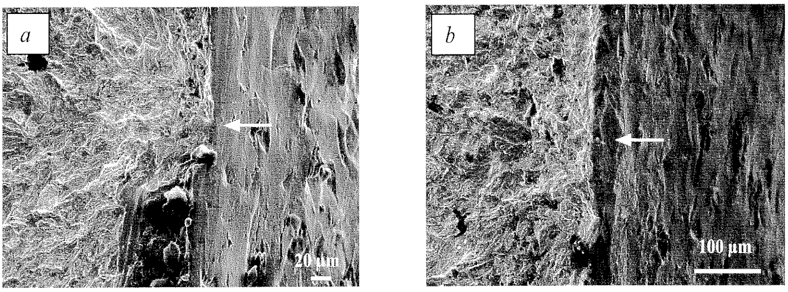

Figure 6: SP3 shot peened specimen, (a) crack initiation on material fold due to shot peening, (b) crack initiation on a striation due to turning.

Residual stresses analysis

The analysis of the residual stresses was carried out by X ray diffraction at CETIM [5] on several specimens of each type. The longitudinal and circumferencial residual stresses were analysed on each specimen at different depths from the specimen surface to the core (Figure 7).

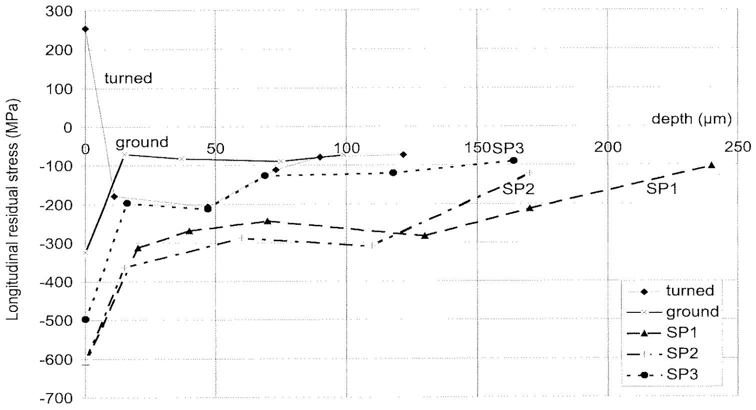

Figure 7: Longitudinal residual stress versus the depth for the different specimen types before cyclic loading.

A tensile longitudinal residual stress has to be noticed at the surface of the turned specimens (this is the same for the circumferencial stress, not illustrated) while the other processes introduce residual stresses in compression. That is a reason why the fatigue strength of the turned specimens is the lowest. For all the shot peening conditions a high residual stress in compression is observed at the surface with a plateau around –300 MPa for SP1 and SP2 up to 125 µm approximatively and a plateau around –200 MPa for SP3 up to 50 µm. This is coherent since the SP3 has the lowest Almen intensity. But, the high compressive residual stresses at the specimen surface (between –500 and –600 MPa from 0 to 25 µm) for all the shot peened specimens should be the consequence of a high material hardening in the surface layers due to the mechanical treatment. This was confirmed by analysing the width of the diffraction peaks.

The residual stresses were also analysed before and after cyclic loading on specimens loaded during 5.10^6 cycles around their endurance limit without fatigue crack. A low relaxation (compared with the measurement uncertainty) of the residual stresses is observed due to the fatigue loading. But, because of the scatter of the residual stresses from one specimen to another one, no conclusion is available for the material behaviour with regard to stress relaxation.

4. Fatigue strength prediction and comparison with experiments

Based on the Crossland multiaxial fatigue criterion [6], a simple software ("Prefagre") was developed by ENSAM-LAMEFIP to predict the endurance limit of shoot peened components. Any other multiaxial fatigue criterion (Dang Van, Papadopoulos…) could be used if it is hydrostatic stress dependent. The Crossland criterion is: $\tau_{oct,a}+\tau\,.\tau_{Hmax}\tau\tau$, where $\tau_{oct,a}$ is the amplitude of the octoedral shear stress and σ_{Hmax} the maximum over the load cycle of the hydrostatic stress. To identify the material parameters σ, σ, two endurance limits on smooth specimens are needed. If the user does not know them, they can be approximated by the empirical relationship proposed by CETIM [4] depending on the maximum tensile strength, Rm, of the steel. These endurance limits are modified by the surface roughness. This is modeled by the empirical coefficient, Ks, proposed by CETIM [4] depending on the maximum tensile strength, Rm, of the steel. The total roughness Rt was chosen in this work but the Ks coefficient with the Rt parameter was proposed for machined components (not shot peened). It is known that the roughness effect in shot peening has a lower importance on the fatigue strength than in machining because of the great residual stresses importance. At the moment the roughness correction on the endurance limits is done with the same Ks coefficient in torsion and in tension (or bending). This is a safety approach. Indeed, the roughness effect is known to be load type dependent because of the striation orientation effect with regard to the loading. If the Rt parameter is unknown its value can be estimated with the Iida model [8]: $Rt=\frac{100}{T_r}\sqrt{\frac{\rho}{6Re}}\,d\,V\cos\rho$, where Rt is the total roughness, T_r is the coverage rate, σ the volumetric mass of the balls, Re the shot peened material yield stress, d the ball diameter, V the shot velocity, σ the projection angle between the normal of the shot peened surface and the projection direction. Finally, the stabilised residual stresses (after relaxation if any) are considered as mean stresses and sum with the cyclic stresses (due to the mechanical loading) [7]. The results of the software is a Crossland diagram with: (i) the reference threshold of the material (polished surface with Rt~0 µm), (ii) the component threshold with its roughness, (iii) the point corresponding to the studied cyclic stress state with and without residual stresses, (iv) the safety factor.

Treatment	σ^D(MPa)	Ks	Safety factor with surface residual stresses	Safety factor with reasonable residual stresses
Turned	493	0.9	0.74 – 0.82	
Ground	577	0.96	0.98 - 1	
SP1	552	0.83	1.01 – 1.05	0.89
SP2	570	0.79	0.92 – 0.96	0.83
SP3	565	0.88	1.01 – 1.06	0.89

Table 4: Experimental endurance limit in plane bending (R=-1), safety factors predicted by the proposed model for the different specimen types and the Ks factor

For the different specimen types, table 4 illustrates the Ks value (determined from the measured Rt roughness, not from the Iida model), the experimental endurance limits, σ^D, and the safety factor corresponding to the experimental data. If this factor is greater than 1, the predicted fatigue strength is greater than reality. For the shot peened specimens, this factor was computed in two cases: (i) by considering the residual stresses analysed by X ray diffraction at the specimen surface and (ii) by considering "reasonable residual stresses", i.e. the mean value of the residual stress below the surface in depth (125 μm for SP1 and 110 μm for SP2 and 50 μm for SP3). This was to avoid the anormal very high compressive peak at the surface and to take into account the plateau (see paragraph 4). For the surface stresses (i), the safety factor is given with an interval corresponding to the different residual stresses analysed on several specimen.

Except for the turned specimens, the predictions are in very good agreement with the experiments (the safety factor is between 0.9 and 1), especially for the shot peened specimens, when the surface residual stresses are considered. If the "reasonnable residual stresses" are used, the predictions are conservative (safe); but using the surface residual stresses is easier than their mean value in depth because of experimental simplicity for analysing such stresses. For the turned specimens the endurance limit is not well predicted. This shows that some progress has to be done to take into account in a correct manner both the residual stresses, the surface roughness, and especially, the material stress-strain hardening in the surface layer due to the manufacturing process.

5. Conclusion and prospects

A simple multiaxial fatigue strength prediction model and software were developed for shot peened components. The Crossland multiaxial fatigue criterion is used with an empirical roughness correction based on the total roughness Rt and the Ks factor proposed by CETIM. Despide the simplicity of this approach, if the surface residual stresses are considered, the predictions, under fully reversed plane bending, are in good agreement with the experiments carried out on shot peened smooth specimens (with three different shot peening conditions) made in 42CrMo4 quenched and tempered steel. This steel is too ductile to obtain a good efficiency of the shot peening with regard to the possible fatigue strength increasing. The software validation has to be done with an other steel with higher mechanical characteristics and with non proportional multiaxial loadings. The roughness effect on the endurance limit has to be more investigated to find an efficient roughness parameter for both shot peened components and machined ones.

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