Shot-peened induced residual stresses relaxation on steel DIN 34CrNiMo6 under different axial loading

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Abstract
Shot-peening treatment (I_{SP}: 8A & C:200%) was applied to improve the R: -1 axial fatigue strength of DIN 34CrNiMo6 (Q+T) steel specimens, due to the introduction of a compressive residual stress field in the near-surface area. However, this residual stress field tends to reduce or relax when an external stress, quasi-static or cyclic, is applied. Quasi-static tests were conducted to evaluate the role of tensile or compressive applied stress. Results showed that tensile applied stress induced lower relaxation and compressive applied stress required lower magnitude to initiate the stress relaxation. Cyclic tests, with R: -1, were developed to evaluate the influence of the cyclic applied stress magnitude on the surface stress relaxation. In addition, cyclic tests with load ratio R ≠ -1 (-0.5 < R < -0.25), including tensile mean stress, were performed to assess the influence of the tensile mean stresses on the residual stress relaxation. Results showed that, in the range of R studied, higher tensile mean stresses reduce the amplitude of residual stress relaxation.

Keywords shot-peening, residual stress relaxation, axial applied stress, mean stress.

Introduction
Shot-peening is a mechanical treatment widely employed to increase fatigue resistance of the treated parts. This improvement is related with the introduced residual stress field, which reduces the crack growth rate, and the work-hardening, which enhances the mechanical properties of the treated material, due to the increase of dislocation densities, twinning, phase transformations or nano-crystallization [1]. This microstructure distortion is quantified by the parameter FWHM.
However, there are two main factors which reduce the fatigue improvement caused by shot-peening. Surface plastic deformations increase the surface roughness and surface micro-defects or micro-cracks, which facilitate the crack nucleation. In addition, compressive residual stress field tends to reduce when an external stress, quasi-static or cyclic, is applied. If the external applied stress is high enough to overcome the yield point, the onset of plastics strains will produce residual stress relaxation [2]. So, higher applied stress produces higher relaxation rates. When the applied stress is cyclic, cyclic mechanical properties of the treated material should be considered, especially when the material tends to cyclic-softening.

Experimental Methods
Hourglass specimens were manufactured according to ASTM E466-15 with DIN 34CrNiMo6 (Q+T) steel, whose monotonic mechanical properties are presented in Table 1. This material presents cyclic-softening behaviour and the cyclic yield point was set at 825 MPa.

Table 1. Monotonic mechanical properties of DIN 34CrNiMo6.

σ_{yp}	σ_{ut}	ε_{ut}	Z
1,084 MPa	1,209 MPa	12.18 %	60.17 %

Surface roughness of the shot-peened samples were measured according to ISO 4287, obtaining R_a 1.93 µm and R_z 11.3 µm. Surface hardness and the in-depth microhardness according to ISO 4545-1:2018 were measured for shot-peened samples. Shot-peening produced a slight hardness increment, from 38 HRC to 39.8 HRC for a depth of 0.15-0.20 mm. In addition, FWHM and residual stress field in-depth were measured with X-Ray diffraction technique [3] and the correction for layer removal is performed following [4]. Results are shown in Figure 1.

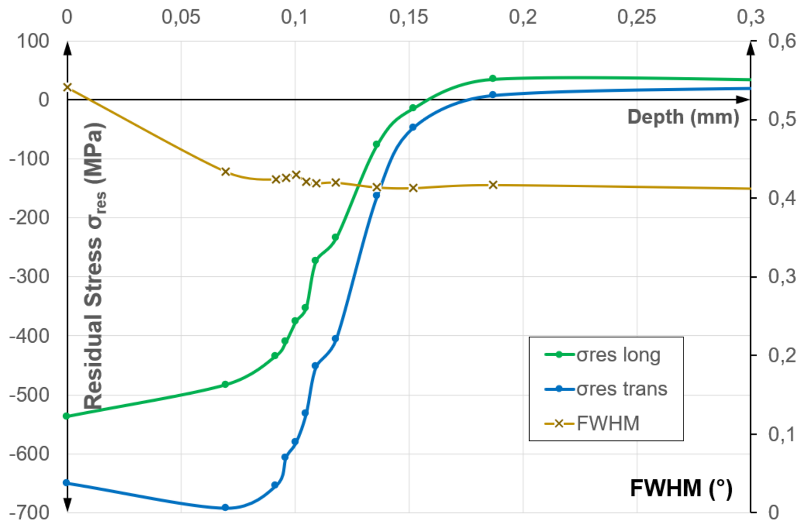

Figure 1. Shot-peened surface properties.

Fatigue tests were carried out with a servo hydraulic test rig to assess the fatigue improvement provided by the shot-peening treatment. With the same set-up, quasi-static and cyclic axial tests were performed to assess the surface residual stress relaxation. Quasi-static tests were applied in tensile or compressive direction and six different stress applied magnitudes were selected. Test data can be seen in Table 2. Surface residual stresses were measured before and after the tests.

Table 2. Quasi-static tests definition.

	Stress applied magnitude (MPa)					
Stress applied direction	Nº 1	Nº 2	Nº 3	Nº 4	Nº 5	Nº 6
Tensile (T)	630	850	978	1,084	1,119	1,154
Compressive (C)	-630	-850	-978	-1,084	-1,119	-1,154

Cyclic applied stress tests with no mean stress (R: -1) were conducted with four different magnitudes of σ_a; A_1: ± 849 MPa, A_2: ±776 MPa, A_3: ± 703 MPa and A_4: ± 630 MPa. After applying a determinate set of cycles, the samples were removed from the test rig and the surface residual stresses were measured. In addition, cyclic tests including mean tensile stress ($-0.5 < R < -0.25$) were performed with three different stress ratio R. Selected stress cases can be seen in Table 3.

Table 3. R≠ -1 cyclic tests definition.

Case	MT_1	MT_2	MT_3
σ_a	733.7	607.5	611.4
σ_m	244.6	244.6	366.8
R	-0.50	-0.426	-0.25

Experimental Results

Axial Fatigue Tests

S-N curves for machined and shot-peened variants were calculated according to ASTM E739-10-2015. Their S-N curves are presented in Figure 2. Shot-peening treatment provides an improvement of 31% for the fatigue limit compared to non-peened condition (machined variant surface condition: R_a 0.8 μm and R_z 4.5 μm)

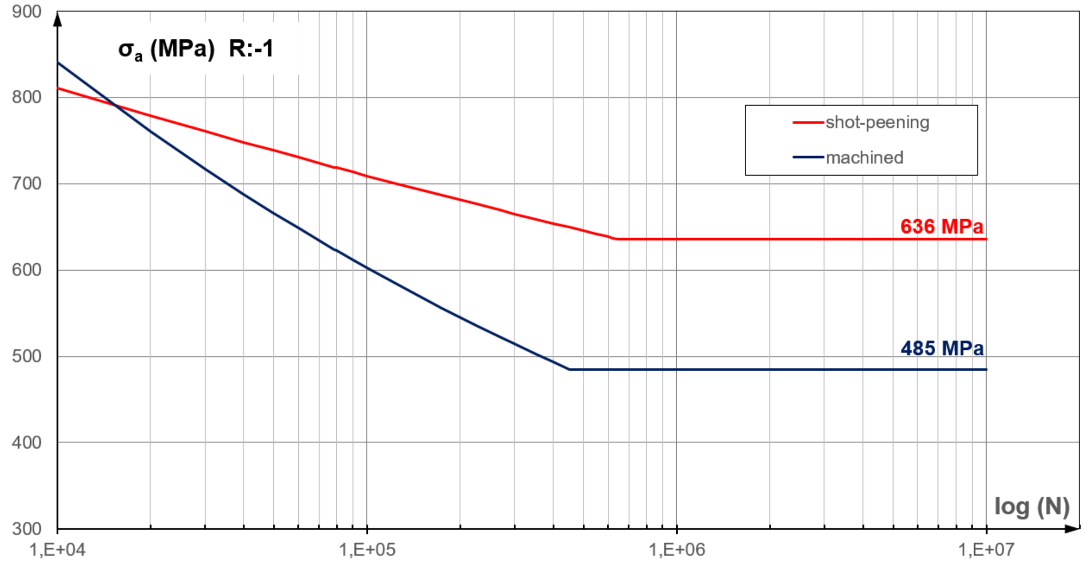

Figure 2. S-N curves for machined and shot-peened variants.

Quasi-static tests

Relaxed surface residual stresses after the quasi-static tests are presented in Figure 3. Compressive applied stresses produce higher residual stress relaxation than tensile applied stresses. Applied stresses with higher magnitude produces higher relaxation.

The onset of residual stress relaxation with tensile applied stress is set at 997 MPa, which is the *effective tensile yield point* for surface residual stress relaxation. In this case, residual stress relaxation is produced by the plastic strains generated in the core of the sample.

The onset of residual stress relaxation with a compressive applied stress can be set at -444,7 MPa, which is an amplitude wide lower than tensile loading. Considering the average longitudinal residual stress after shot-peening treatment is -535.5 MPa, the *effective compressive yield point* can be set as the sum of both stresses in compressive direction, 980.2 MPa, which is quite similar to tensile case. In this case, plastic strains are developed in the external ring, the area where the residual stress field is generated by shot-peening process.

R: -1 cyclic tests

Cyclic relaxation presents higher relaxation rate if the applied stress has higher magnitude, as can be observed in the Figure 4. Higher applied stress magnitudes generate higher plastic strains according to Ramberg-Osgood equation for cyclic loading [5]. In this research, the two highest applied stress levels (A_1: 849 MPa & A_2: 776 MPa) produce residual stress relaxation until the last failure cycle. This is related with the important plastic strain level and the cyclic-softening tendency of the material. In addition, the value of the FWHM gradually tends to reduce until achieve its reference value 0,41º. This reduction is related with the movement and reduction of dislocation densities.

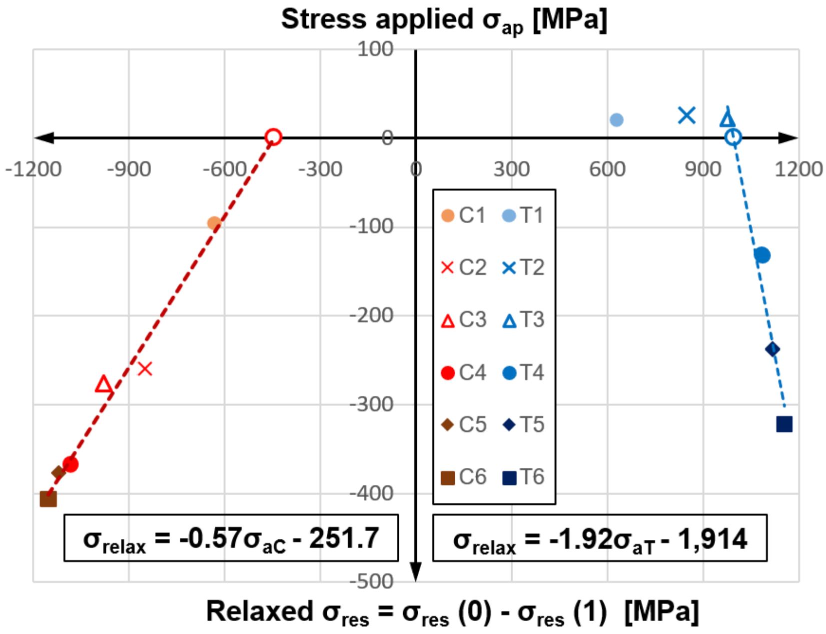

Figure 3. Quasi-static residual stress relaxation.

Logarithmic equation (1) predicts the surface residual stress evolution for the number of cycles of different applied stress magnitudes, where $\alpha = \sigma_a/\sigma'_{yp}$, $\sigma'_{res\,(0)}$ can be considered the average measured value of longitudinal stresses (-535.5 MPa) and N can be calculated from S-N curve.

$$\sigma_{res}(n) = \sigma^0_{res} + ([\alpha \cdot \sigma_a] - \sigma^0_{res} - \sigma'_{yp}) \frac{\ln(n+1)}{\ln(N+1)} \qquad (1)$$

If the applied stress magnitude decreases, plastic strain level is also reduced. Then, the relaxation rate is lowered, especially after 0.4N cycles, when the relaxation rate is almost null. In this stage, the *stabilized residual stress* on the surface appears. In this study, the stabilized residual stress was set if the stress applied magnitude is lower than 720 MPa. The lack of important plastic strains can be appreciated with the value of FWHM for the two lower applied stress levels, which presents a steady value along the complete fatigue life, as can be seen in Figure 4. The equation (2) correspond to the stabilized value of the surface residual stresses. Due to the cyclic-softening of the material, cyclic yield point must be considered as a threshold for the onset of plastic strains.

$$\sigma_{res\ st} \approx \alpha \cdot \sigma_a - \sigma'_{yp} \qquad (2)$$

Stabilized values obtained after cyclic testing are presented in Table 4, where slight deviations between obtained and calculated stabilized residual stresses are obtained. Two more cases of *run-out* specimens are also included in this study.

Table 4. Stabilized residual stress tests results, values in MPa.

Applied stress	Obtained $\sigma_{res\ ST}$	Calculated $\sigma_{res\ ST}$	Difference
703	-233	-226	-7
645	-337	-321	-16
630	-343	-344	-1
630	-348	-344	-4

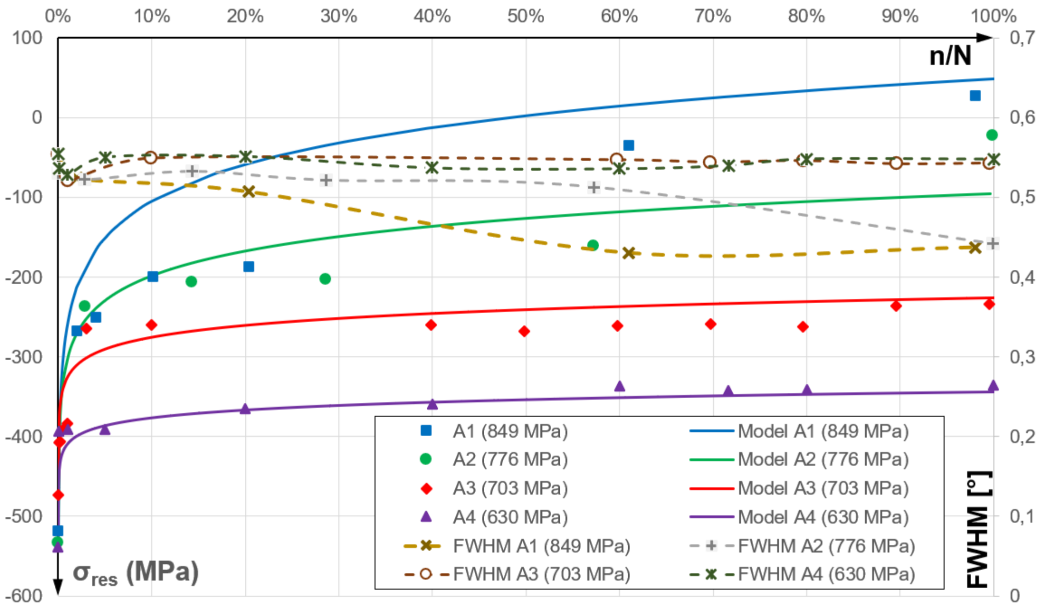

Figure 4. R: -1 cyclic tests results.

R≠ -1 cyclic tests

Test results show the influence of the tensile mean stress on the surface residual stress relaxation. When mean stress magnitude is high enough, it reduces the relaxation rate. The coefficient β is introduced to quantify the influence of the tensile mean stress. Thus, equation (1) can be generalized to equation (3):

$$\sigma_{res}(n) = \sigma^0_{res} + ([\alpha \cdot \sigma_a + \beta \cdot \sigma_m] - \sigma^0_{res} - \sigma'_{yp})\frac{\ln(n+1)}{\ln(N+1)} \quad (3)$$

The logarithmic prediction equation fits properly with the obtained data, as can be seen in Figure 5. In the Figure 5, the surface relaxation for σ_a 609 MPa, according to equation (1), is represented to better compare the influence of the tensile mean stress on the relaxation rate.

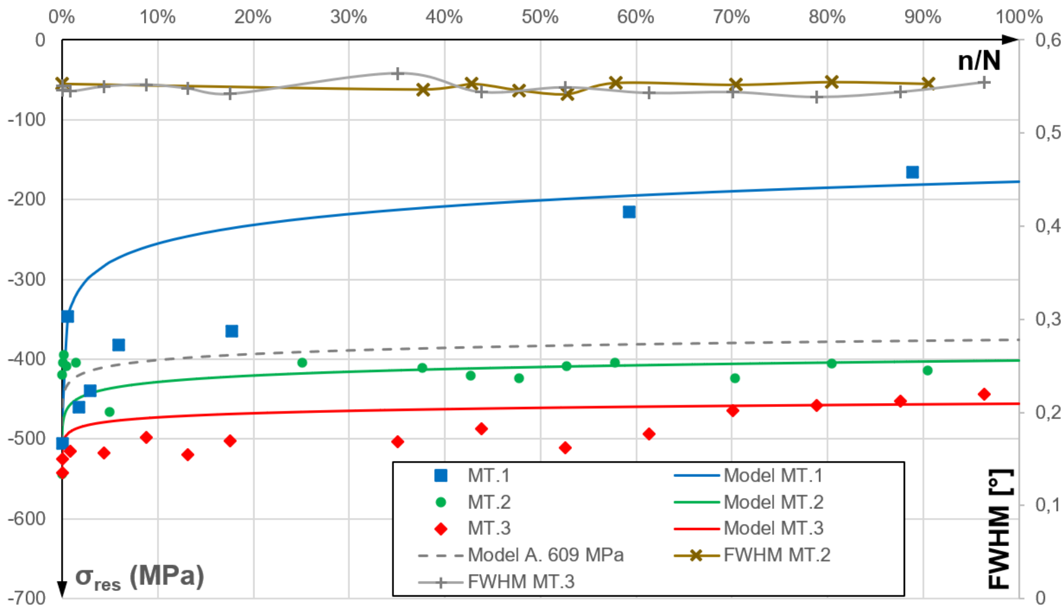

Figure 5. R≠ -1 cyclic tests results.

The relationship between the coefficient β and stress ratio R is presented in the Figure 6. In the studied range of R (-0.5<R<-0.25), higher stress ratio produces higher influence of the mean stress, which reduces the relaxation rate.

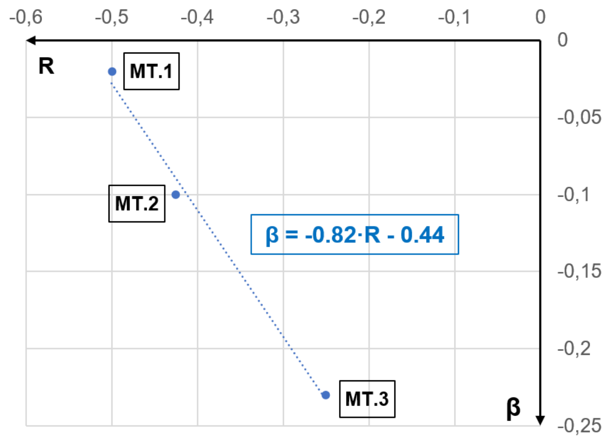

Figure 6. Relationship between β and R.

Discussion and Conclusions

Applied shot-peening increases the fatigue performance of DIN 34CrNiMo6 steel compared to the as machined variant. The residual stress field introduced by shot-peening relaxes when an external stress is applied. The relaxation is related to the onset of plastic strains on the treated material. So, higher stress magnitudes produce higher relaxation rates.

Quasistatic tests showed that the applied stress direction affects the relaxation rate. Tensile applied stresses produce lower relaxation. However, compressive applied stress, due to the compressive residual stress field, require lower magnitude to produce residual stress relaxation. The sum of both compressive stresses achieves a higher plastic strain level.

Cyclic tests with a high magnitude of applied stress showed the influence of plastic strains on the relaxation process, which can be easily identified by the variation of the value of FWHM. Lower applied stress magnitudes maintain FWHM steady and achieve the stabilized residual stress. The introduction of a tensile mean stress, within the stress ratio R range of (-0.5 < R < -0.25), produce lower relaxation rate compared with an R: -1 applied stress.

References

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