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# Stability of residual stresses created by shot peening of pearlitic steel and their influence on fatigue behaviour

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**Abstract**

In this study the effect of shot peening on the fatigue lifetime of a near pearlitic microalloyed steel was investigated. The fatigue tests were run in strain control with parallel recording of stress relaxation and recovery of the work hardened surface zone at different total strain amplitudes exerted to the test specimens. These relaxation processes were followed versus cycle number up to half of the fatigue life time ($N=N_f/2$). Provided that the global plastic strain amplitude is lower than about 0.08 % a noticeable increase in life time is seen. Lower plastic strain amplitude increases the life time. At small plastic strain amplitudes it was found that the fatigue life time could be increased more than tenfold by the shot peening process.



*Keywords*: Fatigue; Strain control; Residual stress; Relaxation; Work hardening; Micro alloyed steel.

## 1. Introduction

The fatigue properties of components are generally much influenced by the behaviour of the surface zones. Different techniques such as shot peening have been developed to introduce compressive stresses close to the surface, thereby delaying failure of components exposed to fatigue loading. In shot peening the specimen is bombarded by small hard shots leading to plastic deformation of the surface zone. The plastic deformation changes the density of dislocations and interplanar spacing of the crystal lattice. We can express this as development of compressive residual stresses and a change in the work hardening state ([1-4]). The increase in density of dislocations can be verified by micro hardness measurements in the surface zone, and higher surface hardness of shot peened specimens has also been reported in the literature ([4,5]).

The compressive residual stresses may improve the fatigue properties by increasing the surface resistance to crack initiation as well as reducing the crack propagation rate ([6-8]).However the surface roughness inevitably increases due to the peening process which may have detrimental effects on the fatigue properties ([9-12]).

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The compressive residual stresses can be beneficial for fatigue durability provided that they are stable. However residual stresses may get relaxed during life time and this may depend on many different factors: the actual material and its microstructure, the strength properties, the peening state and temperature, the loading conditions, etc. [13]. The main relaxation of residual stresses normally takes place in the first cycle, followed by further gradual relaxation during the life time ([14-16]). The relaxation during the first cycle ("quasi static loading") [13] depends on the monotonic yield strength of the material in tension and compression, while relaxation during successive cycles is related to the cyclic yield strength. Since the relaxation is associated with dislocation movement, it is then correlated to the plastic strain amplitude and number of repeats of such cycles [17].

The present study is a part of a larger project on the influence of residual stresses on durability of components subjected to variable amplitude loading. The material selected for the present research was a microalloyed near pearlitic steel, commonly used in safety components in trucks. The objectives of the first stage of the project which was done under constant strain amplitude conditions were (i) to investigate the influence of shot peening on the fatigue properties (ii) to study the influence of plastic strain amplitude and number of strain cycles on the relaxation of residual stresses and recovery of the dislocation structure. Thorough investigation was done in two stages: the first cycle and successive cycles. As the progression during the very first cycle is of major importance also for later cycles, the results from the first cycle are presented in a separate paper [18]. From detailed analysis of stress-strain hysteresis loops during the whole fatigue life time, a deeper understanding of the relaxation processes occurring during fatigue of shot peened components is obtained.

## *2.* Experimental

### *2.1. Material and microstructure*

The actual component, from which the fatigue samples used in the present study are taken, is made of micro alloyed steel with chemical composition 0.39 w/o C and 1.39 w/o Mn with 0.08 w/o V, 0.017 w/o N and 0.026 w/o Ti as minority elements. The components are produced from cylindrical bar stock of diameter 50-85 mm via hot forging at 1300 °C followed by air cooling to room temperature, corresponding to a typical cooling rate of 0.5 °C $s^{-1}$. A hardness close to 270 HV10 was found through the whole thickness confirming a constant cooling rate through the entire component. Mechanical testing showed yield ($R_{p0.2}$) and ultimate tensile ($R_m$) stresses of 590 and 950 MPa respectively. The microstructure was essentially pearlitic with 5-10% of free ferrite.

### *2.2. Specimen preparation and experimental details*

The components were randomly picked out from the production line and all from the same batch of material. The fatigue cylindrical specimens (6 mm diameter and 15 mm gage length) were machined out from the components in the longitudinal direction. The specimens then were divided into two series. One series was untreated with grinding and final polishing with diamond paste of grain sizes down to 1 µm. The second series of specimens was peened with steel shots of size 0.9 mm with process data 0.25 mmA and 200% coverage.

Measurement of residual stresses took place with an X-ray diffraction technique, using an Xstress 3000 X-ray equipment and $\sin^2\psi$ method with Cr Kα- radiation on {211} planes in the ferrite phase. The ψ angle was varied between -40° and +40° with ±5° oscillations (12 angles in total). The corresponding full width at half maximum (FWHM) of the X-ray peak was also measured for all stress measurements.

Both series of specimens were fatigue tested in a fully reversed push-pull total strain control condition with saw-tooth wave shape and a strain rate of $1\cdot10^{-2}$ $s^{-1}$. The tests were conducted at total strain amplitudes ($\Delta\varepsilon_t/2$) of 0.25, 0.3, 0.4, 0.6, and 1 % respectively until final failure. All fatigue tests were run in a computer controlled Instron 8501 Servo Hydraulic testing machine with later shape analysis of the recorded stress-strain loops.

The relaxation during the first and successive strain cycles was investigated. One series of shot peened specimens was deformed up to predefined numbers of cycles until half of the number of cycles to failure, $N_f/2$. All fatigue tests started in tension and finished at the end of the full cycle by returning to zero stress. The residual stresses and

FWHM of the X-ray peak were obtained at the surface before and after the tests. These tests were done at the same total strain amplitudes as for the fatigue tests.

## 3. Results

### *3.1. Residual stresses before fatigue testing*

The distribution of residual stresses in depth for peened specimens prior to fatigue testing are presented in Fig. 1, indicating a minor but seemingly systematic stress difference in the two principal directions. Despite this, residual stresses shown later in the paper all refer to surface residual stresses in longitudinal direction.

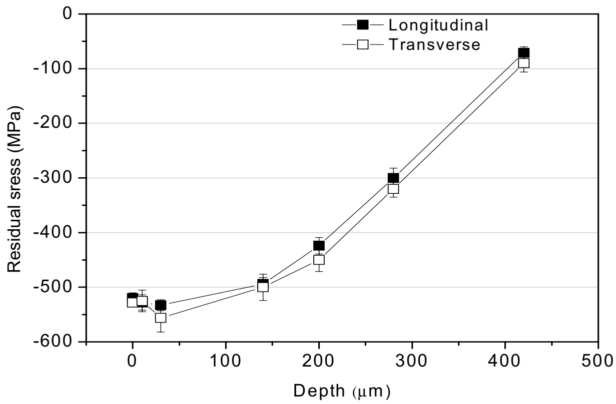


Fig. 1. The distribution of residual stresses in depth as recorded for peened, unstrained specimens.

### *3.2. Life times and stress amplitude development*

Fig. 2 shows the life times for different imposed strain amplitudes $\Delta\varepsilon_t/2$ in a Coffin-Manson type diagram. The peened and unpeened specimens show very similar life times at larger strain amplitudes. However at small plastic strain amplitudes there is a considerable difference between the life times of peened and unpeened specimens; thus at 0.3 % total strain amplitude, corresponding to a plastic strain amplitude of about 0.034 %, the shot peened specimens lasted about five times longer than the unpeened ones. Such increase in life time is even more pronounced at 0.25% total strain amplitude corresponding to 0.008 % plastic strain amplitude, where the shot peened specimens survived 1.5 million cycles with no failure, meaning that shot peening created an increase of fatigue life time of more than a factor 15. No significant difference between the global plastic strain amplitudes of peened and un-peened specimens was observed.

Fig. 3 demonstrates the development of stress amplitude during life time. Both shot peened and un-peened specimens showed a very slight hardening during the first 10 cycles at the largest strain amplitudes. This initial hardening decreases at lower strain amplitudes and is replaced by a pronounced softening during the first few cycles at 0.3% strain amplitude. It is also evident from Fig. 3 that shot peened specimens show larger stress amplitudes at smaller cycle numbers. The difference diminishes to zero after a couple of cycles at all strain amplitudes but 0.25% where the stress amplitude for shot peened specimens remains higher all through life time.

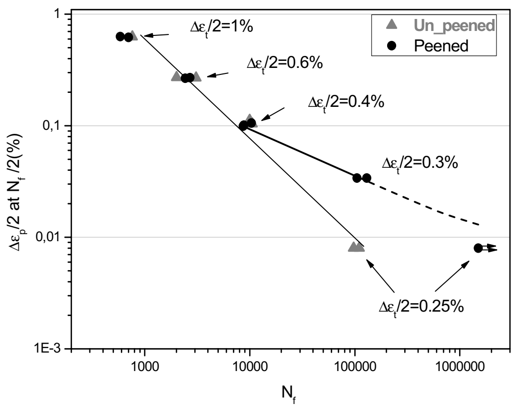


Fig. 2. Plastic strain amplitude vs. number of cycles to failure. Arrow on symbol indicates a survived (peened) specimen.

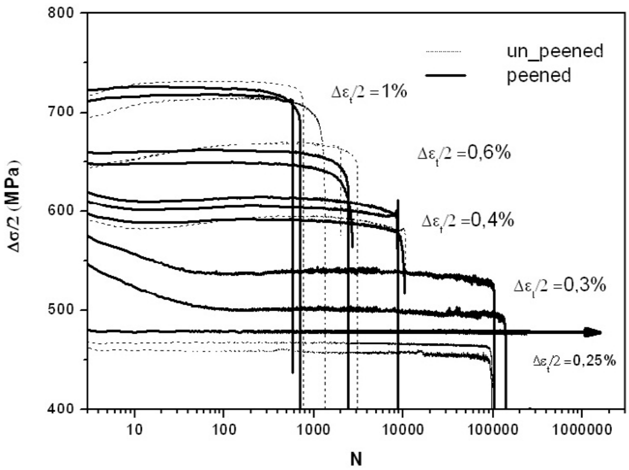


Fig. 3. Stress amplitude vs. number of cycles

### *3.3. The relaxation of residual stresses*

The residual stresses at the surface were obtained after different number of cycles. The tests were done at 0.25, 0.3, 0.4, 0.6 and 1 % total strain amplitudes. The residual stress measurement took place at the end of a full strain cycle; however, due to unloading (going to zero load to take the specimens out) some plastic strain remained in specimens. Fig. 4a shows the loading condition for cycle number one, however the same condition is applied for all tests performed at different cycle numbers.

The relaxation of surface residual stresses for different strain amplitudes is displayed in Fig. 5. At 1% strain amplitude the residual stresses were almost totally relaxed after the first cycle. For 0.6% and smaller total strain amplitudes, however, the relaxation is successively lower and mainly takes place during the first cycle followed by incrementally reduced changes during further cyclic loading. The remaining residual stresses at $N_f/2$ become more compressive by decreasing the strain amplitude. For the lowest total strain amplitude (0.25%), the relaxation is very limited and the change in absolute value of residual stress is less than 100 MPa after 1.5 million cycles.

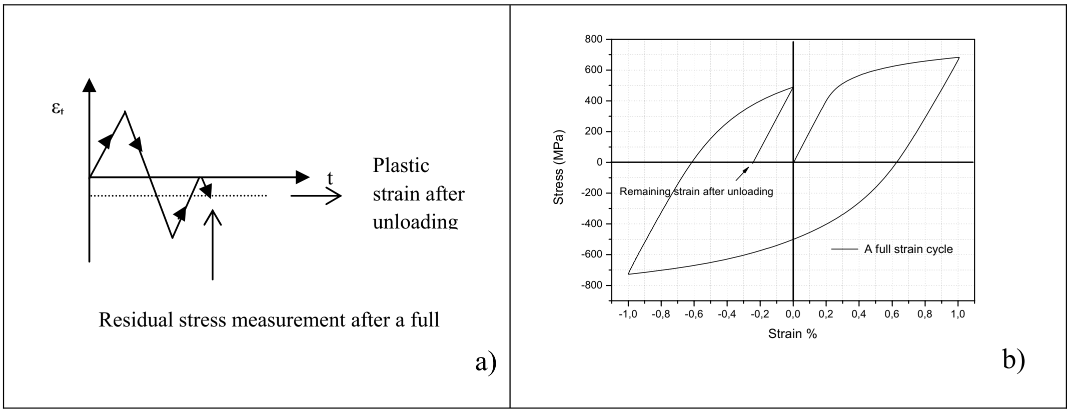


Fig. 4. a) A scheme of strain vs. time, b) stress-strain curve for one full cycle tested at 1% total strain amplitude

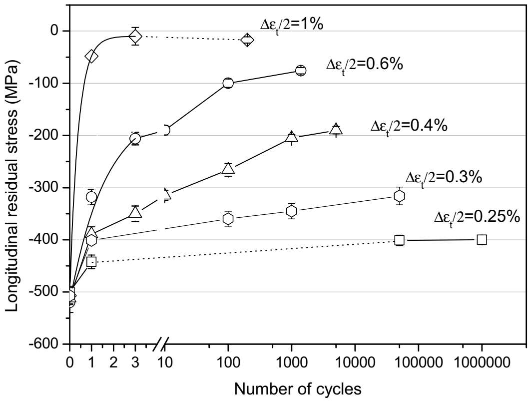


Fig. 5. Relaxation of the surface residual stresses at different strain amplitudes until cycle number $N_f/2$

### 3.4. Recovery of dislocation structure

The full width half maximum (FWHM) of the X-ray peaks was also measured before and after the cyclic straining. FWHM corresponds to appearing microstrains in material which are mainly built up by increased dislocation density in this case. Relaxation of residual stresses corresponds to redistribution and annihilation of the dislocations which could also be related to dislocation density. In the present study the work hardening – or actual flow stress – has been used as a representation of the dislocation density. Fig. 6 demonstrates the development of FWHM at the surface versus number of cycles at different strain amplitudes. At 1 % strain amplitude the FWHM decreased by 30% in first few cycles. Corresponding decrease is around 12% for $\Delta\varepsilon_t/2$=0.6% and less than 9% for

$\Delta\varepsilon_t/2$=0.4 %. For $\Delta\varepsilon_t/2$=0.25 % the FWHM was virtually unchanged during most of the life time with a decrease of only about 4% after $1.5*10^6$ cycles.

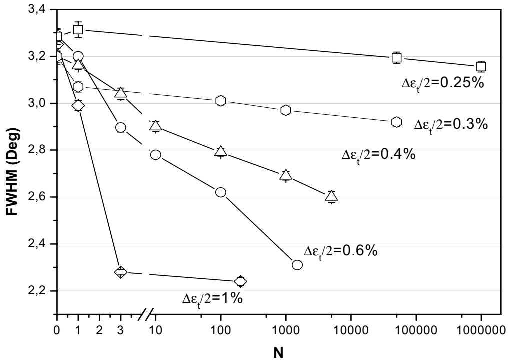


Fig. 6. FWHM at the surface vs. number of cycles at different total strain amplitudes.

## 4. Discussion

Shot peening as a method of surface treatment was employed to improve the material durability under fatigue loading conditions. The tests were all done at total strain amplitudes larger than 0.25 % corresponding to peak stresses equal to or exceeding the global monotonic yield strength. Despite global plastic deformation, considerable improvement in fatigue life times of shot peened specimens tested at lower strain amplitudes was observed. The life time improvement coincides with the more stable residual stresses and less relaxation. Due to the fact that this study is a part of a larger project on variable amplitude loading fatigue, the influence of plastic deformation on onset of relaxation during the first cycle and the rate of relaxation during continued cyclic loading are of special interest.

### *4.1. Relaxation*

The relaxation of residual stresses may be looked upon in two stages: the first cycle and successive cycles. During the first quarter of the first cycle, the loading condition is close to monotonic loading and the specimen yields once the global monotonic yield point is met. Therefore global, monotonic yielding in the first quarter of a strain cycle can be considered as the point when relaxation of residual stresses can start. Later on in the first cycle and during following cycles there is a gradual approach to cyclic loading conditions and further relaxation of residual stresses can take place when the cyclic yield strength ($\sigma_{cycl,N}$) is exceeded [13, 14].

### *4.2. Stability of residual stresses in the first cycle*

As it has been shown in Fig. 1, the compressive residual stresses as well as the work hardening state vary within the surface zone. As a result of such variation a gradient of yield strength is created within the surface zone. However in the simplest case one yield strength corresponding to mean or maximum residual stress may be considered for the surface zone. Therefore straining of such a specimen would be built up by at least two different stress-strain responses, one for the surface zone and one for the core [19-21]. However the global stress-strain curve obtained during fatigue test is different from the surface and core stress-strain responses.

Due to the very limited relaxation at 0.25% strain (Fig. 5), this strain level may be considered as the critical strain for onset of relaxation during the first cycle. However since the residual stresses larger than -300 MPa are kept for tests at strain amplitudes up to 0.6% (corresponding to 0.27% plastic strain amplitude) it can be looked upon as a threshold strain amplitude value above which the relaxation is high in the first cycle and almost no benefit from the residual stresses can be achieved.

The details of the experiments with straining for one full cycle starting in positive and negative strain directions respectively as well as the residual stress development in each quarter of a cycle will be presented in a dedicated paper [18].

*4.3. Stability of residual stresses during cyclic loading*

It is evident that the relaxation of residual stresses increases by increasing number of cycles (Fig. 5). The most pronounced relaxation takes place during the first strain cycle, followed by gradually decreased release rate upon further cycling. As indicated in the literature [14, 22, 23] the residual stresses $\sigma_{rs}$ at cycle number N decreases linearly with the logarithm of the number of cycles, or

$$|\sigma_{rs}| = |\sigma_{(rs,\ N=1)}| - m \, Log \, N \qquad (1)$$

with $\sigma_{(rs,\ N=1)}$ answering to corresponding residual stress after cycle number one. The data in Fig. 5 reasonably well follow this relationship but with larger m-values at higher strain amplitudes. Knowing the value of residual stresses after one cycle and at $N_f/2$ as well as assuming linear approximations of the curves in Fig. 5, the m-value for each amplitude could be plotted against the stabilised flow stresses at $N=N_f/2$ ( Fig. 3). The result is shown in Fig. 7 indicating a simple linear relation.

As dislocation movement is conditional for stress relaxation it is evident that the cyclic yield strength ($\sigma_{cycl,N}$ ) during fatigue loading rather than the monotonic yield strength is determining whether relaxation takes place or not. The cyclic yield strength of the surface zone and the core are of course different, but the global (stable) cyclic yield strength can be defined as the stress under which no relaxation of residual stresses occurs ([13], [5]). The stress corresponding to m=0 thus represents the global cyclic yield point in the sense that no relaxation ("softening") comes about. From Fig. 7 this global cyclic yield point is found to be 460 MPa.

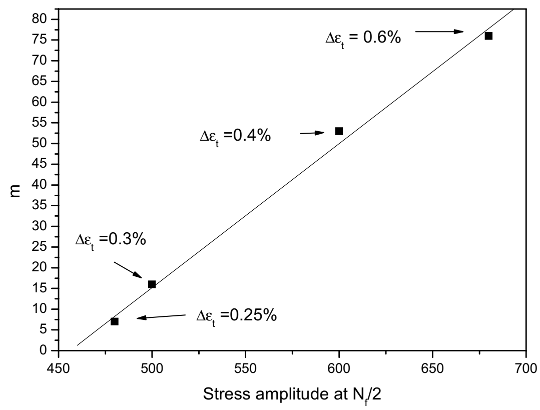


Fig. 7. Calculation of global cyclic yield strength based on m

In all tests the stabilised stress amplitude has been above the cyclic yield strength of the compound. The rate of relaxation however highly depends on the amount of plastic deformation as presented in Fig. 5 . Comparing the relaxation curves in Fig. 5 and m vs. stress amplitude relation in Fig. 7,with the life time curves in Fig. 3it can be concluded that m-values smaller than about 40 leads to some life time improvement. Yet, the m-value has to fall below 20 to strongly retard relaxation and thereby to markedly increase the fatigue life time The information about the slopes of the relaxation curves are specially instructive for block tests and variable amplitude testing giving some estimate of influence of number of cycles at certain strain amplitude.

Fig. 8 compares the relaxation after one and $N_f/2$ cycles for different estimated plastic strain amplitudes. The influence of number of cycles can be clearly observed. The specimens tested for one cycle at all total strain amplitudes smaller than or equal to 0.6%, kept below -300 MPa compressive residual stresses at the surface. However only the specimens tested for $N_f/2$ cycles at smaller than or equal to 0.3% total strain amplitude, remained with residual stresses lower than -300 MPa at the surface.

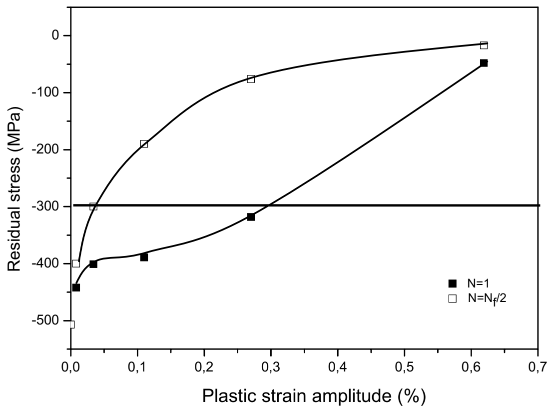


Fig. 8. Relaxation of residual stresses after the first cycle and $N_f/2$, recorded at the very surface region.

Despite some global softening at 0.3% and some global hardening at large (1%) strain amplitudes which take place during the first few cycles, the shot peened specimens showed rather stable stress amplitudes in the first 80% of life time. It should be noticed that since at 1% total strain amplitude complete relaxation of residual stresses occurs during the first cycle further investigation during cyclic loading is not of interest. However for specimens tested at low strain amplitudes, cyclic softening does not seem to influence the relaxation of residual stresses (Fig. 3 and Fig. 5). It is, however, important to consider the simultaneous events taking place in the surface zone, namely stress relaxation and softening (dislocation annihilation). While the first factor shifts the pre stress toward zero from the negative side, softening diminishes the internal flow stress. Therefore these events counteract each other leading to less pronounced effects on the global peak stress curves (Fig. 3).

*4.4. Maximum values of global strain and stress amplitudes to benefit from shot peening*

Considering the life times (

Fig. 2) it is possible to identify an approximate threshold in strain amplitude below which the residual stresses are beneficial. However not only the amount of the surface residual stresses but also the depth of them should be taken into account. In this study $\Delta\varepsilon_t/2$= 0.3% corresponding to 0.034% plastic strain amplitude and a depth of 20 μm of appreciable compressive stresses at $N_f/2$ cycles could represent such threshold conditions [18].

Fig. 9 summarises how the magnitude of the initial residual stress related to the stress amplitude improves the fatigue life time after shot peening. As long as the absolute value of the surface residual stresses is higher than about 50 % of the stress amplitude at half of the life time, a pronounced improvement in fatigue life time can be expected.

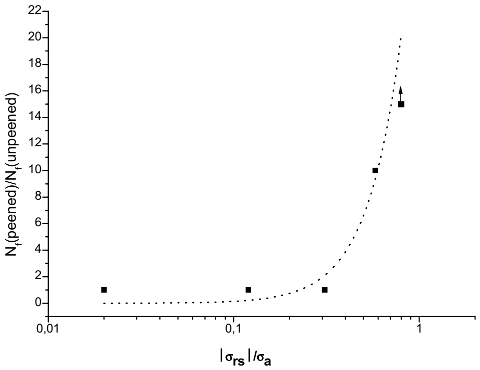


Fig. 9. The influence of surface residual stresses and the stress amplitude at $N_f/2$ on the life time.

## 5. Conclusions

The present investigation concerned the stability of residual stresses created by shot peening of a near pearlitic steel with composition 0.39 w/o C and 1.39 w/o Mn with 0.08 w/o V, 0.017 w/o N and 0.026 w/o Ti as micro alloying additions. Different strain amplitudes and number of cycles were followed during fatigue loading, and the effect on the fatigue life time was recorded. To allow easier physical interpretation of the behaviour of the surface zone compared to the core of specimens, the fatigue tests were run in strain control with a range of amplitudes from essentially elastic up to large plastic parts of the strain range. Besides, accompanying recovery of work hardening effects (FWHM of X-ray peak) was also investigated. The fatigue behaviour of the shot peened material was related to that of the material in its virgin state. The results can be summarised in the following way:

- The shot peened material exhibits longer fatigue life time compared to that in unpeened condition as long as the residual stresses introduced by shot peening are reasonably stable. The residual stresses can be kept even at the presence of global plastic deformation provided that the plastic strains are small enough. This stability is governed by both plastic strain amplitude and number of cycles during the fatigue loading. At small plastic strain amplitudes the fatigue life times is increased by more than one order of magnitude compared with similarly loaded unpeened specimens.

- With increased plastic strain amplitude the improvement in fatigue life time by peening gradually lessens. At global plastic amplitudes larger than about 0.08 %, relaxation proceeds relatively fast and no benefit in fatigue life time is gained.

- Parallel to stress relaxation during fatigue loading there is also a relaxation of the work hardening effects as determined by the X-ray peak width (FWHM). There is a linear relation between the residual stresses and the FWHM at any depth and total strain amplitude.

- When calculating stress amplitudes from the recorded data from strain controlled tests it is found that shot peening leads to an increase in fatigue life time provided that the amount of residual stress is larger than about 50 % of the stress amplitude.

## Acknowledgment

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