Influence of shot peening on fatigue durability of decarburized spring steels

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ABSTRACT

The influence of shot peening on high cycle fatigue behaviour of spring steel was investigated. The material studied was a quenched and tempered carbon steel 51SiCr7 (0.55 C, 1.9 Si and 0.9 Mn). Three series of fatigue specimens with zero, 0.15 and 0.50 mm depth of decarburization were produced. Half of the specimens from each series were shot peened, leading to a thickness of the compressed surface layer of about 0.25 mm. The specimens were tested in bending fatigue. A 45% improvement in fatigue limit of the decarburized series was achieved after shot peening. The detail of relaxation of the residual stresses was followed and compared for different series of specimens.

KEY WORDS

Decarburization, fatigue strength, residual stresses, shot peening.

INTRODUCTION

The fatigue life of components is to a large degree controlled by the behavior of the surface zones. Mechanical surface treatments methods such as shot peening have been developed to introduce compressive stresses close to the surface, thereby delaying failure of components exposed to fatigue loading [1].

Surface decarburization during heat treatment is a common practical problem for many truck components. The requirement on maximum depth of the decarburized layer is usually in the range of 0.1 – 0.2 mm. However, up to 0.5 mm decarburization depths has been observed in actual production. The aim of the present study was to evaluate the influence of shot peening on fatigue durability of decarburized components. The relaxation of the residual stresses during cyclic loading was followed and correlated with the fatigue life times.

MATERIALS AND METHODS

Ovako steel 51SiCr7 was employed as the test material in the present study. The chemical composition (in wt.-%) is 0.55 C, 1.9 S, 0.88 Mn, 0.24 Cr, 0.022 Al and 0.006 V. Three series of specimens (U, D1 and D2) with geometry as in fig.1 were used in the study. This type of specimen is frequently used for bend fatigue testing in Volvo Company. Series U denotes the base material with tempered martensite microstructure and no surface decarburization as presented in fig. 2a. Series D1 and D2 were made from the same batch of material and with the same microstructure as the series U but with 0.15 and 0.45 mm decarburization at the surface, fig. 2b and 2c respectively.

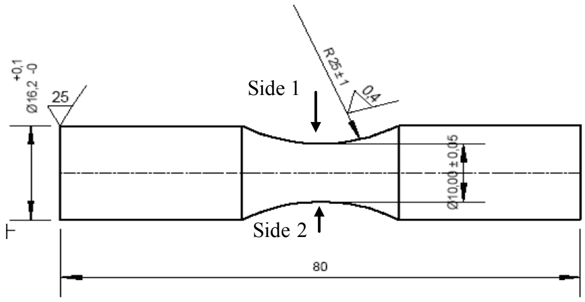
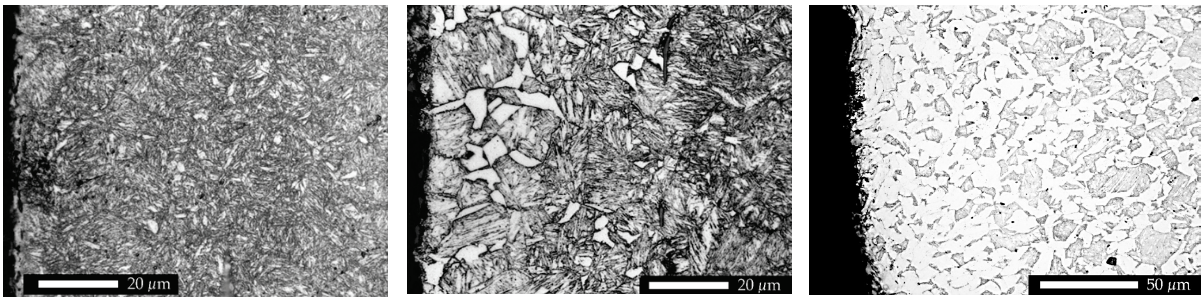


Fig. 1: Dimensions of the fatigue specimen. The vertical arrows indicate the positions where the residual stresses were measured. 1 refers to the side subjected to tensile stress during the first half a cycle and 2 to the side with compression during the first half a cycle.

The decarburized surface contained some free ferrite with intermixed tempered martensite regions close to the surface (figs. 2b and c). The details of the decarburization as well as the heat treatment procedures to produce such specimens are presented elsewhere [2]. The decarburization was determined by hardness recordings (HV1), where the depth of carburisation was defined as the distance from the surface, where the core hardness had decreased by 50 units. Yield and tensile strengths of 1540 and 1650 MPa respectively with an elongation of 10 % were obtained for the undecarburized specimens.

Half of the specimens from each series were then shot peened to 100% coverage and 0.45 mmA intensity with cut wire shots of 55-62 HRC. The residual stresses were obtained using X-ray diffraction. An Xstress 3000 equipment and the $\sin^2\psi$ method with Cr K_α-radiation on {211} planes in martensite for the reference U specimens and in ferrite for the decarburized D1 and D2 specimens were employed.

All six series of specimens (U, D1 and D2 with and without shot peening) were fatigue tested under plane bending stress condition at R_σ = -1 in a Volvo built equipment. The relaxation of the residual stresses was followed at different stress amplitudes and number of cycles.



a. **b.** **c.**

Fig. 2: Microstructure of tempered martensite in specimens a) U, without decarburization, b) D1, with 0.15 mm and c) D2, with 0.45 mm depth of decarburization.

RESULTS

The compressive residual stress profiles for the different conditions after shot peening but before fatigue testing are presented in fig. 3. The stress profiles for the two decarburized series D1 and D2 are quite similar (slightly higher for D1 series), while the undecarburized specimen U exhibits larger stress magnitudes. The depth of compressive zone, however, seems to be quite similar for all three series.

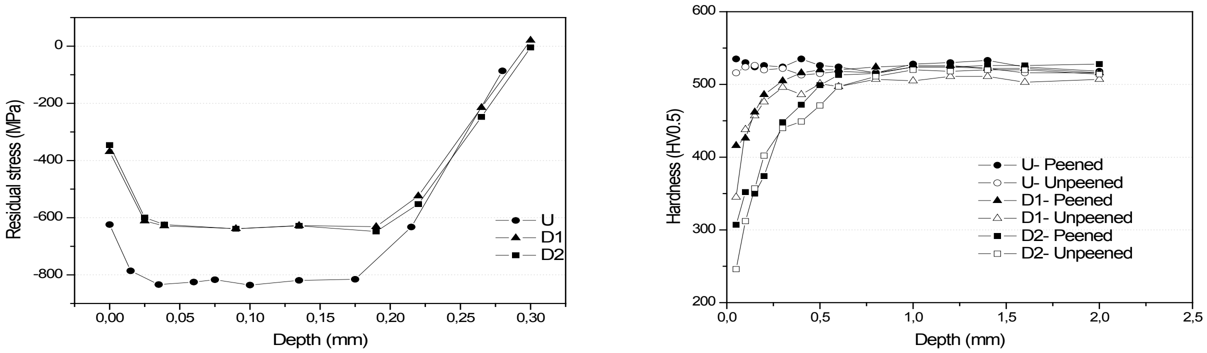


Fig. 3: In depth profiles of a) Residual stress; peened condition, b) Micro hardness; peened and unpeened conditions.

Vickers micro hardness profiles (0.5 kg load) were recorded for all series of specimens in both peened and unpeened conditions (fig. 3b). Although in all series shot peening contributes to an increase in hardness, the influence is markedly larger for the decarburized specimens D1 and D2.

Fig. 4 shows a Wöhler diagram summarising the results of the fatigue tests for all six series of specimens. The samples with longer life time than 10^6 cycles are considered as survivors. The fatigue limits estimated at 10^7 cycles are given in table 1. The negative influence of larger decarburization depth as well as the positive influence of shot peening on fatigue limits is evident from table 1 and fig. 4. It can be observed that the D1 series after shot peening shows quite similar life times as the U series before shot peening. In all but one specimen the crack initiation point was observed at the very surface. Crack initiation underneath the surface emanating from an inclusion only occurred in one undecarburized specimen, subjected to very low amplitude loading for 10^7 cycles.

A number of specimens from U, D1 and D2 series were fatigue tested at two specific stress amplitudes while the relaxation of the residual stresses were followed at different cycle numbers. The tests were performed at stress amplitudes corresponding to the fatigue limits as well as at 100 MPa higher levels, in each case at three successive stages during the fatigue process. In the first stage the specimens were statically bent to the intended stress amplitude and unloaded to zero stress so that while one side of the specimens was in tension (side 1 in fig. 1) the opposite side was in compression (side 2 in fig. 1). Afterward the specimens were fatigue tested for 1200 cycles, consisting of a ramp of 1000 cycles with gradually increased stress amplitude from zero to the final stress amplitude followed by 200 cycles at this level. Following this the specimens were cycled for 10^4-10^5 cycles (roughly half life time) at the intended stress amplitude. The stress measurements took place at each stage and on the two sides of the specimens (sides 1 and 2), distinguished by the directions of the initial applied stress.

Table 1: Fatigue limits of the different series of specimens [MPa].

Specimen series	U	D1	D2
Unpeened	785	520	440
Peened	855	755	640

As it can be observed from fig. 5, after the first stage and for all series of specimens, the relaxation is much more pronounced in side 2 (subjected to initial compression) than in side 1 (subjected to initial tension). During the second and the third stages of loading, however, the relaxation was gradually increased in side 1 while side 2 remained quite stable. The slope of the relaxation curve for side 1 seems to be increasing by increasing the stress amplitude as well as the depth of decarburization. It should be noted that for some series the residual stresses in side 1 remained larger in magnitude than on side 2 even after the second and third stages of the tests.

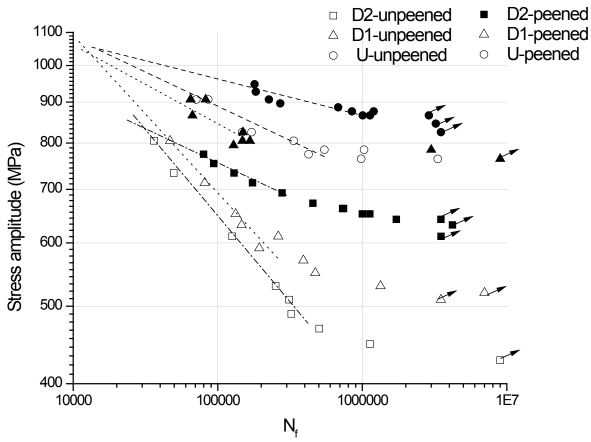


Fig. 4: Wöhler curves for the three series of specimens (U, D1 and D2) in both peened and unpeened conditions. The arrows indicate specimen survivors.

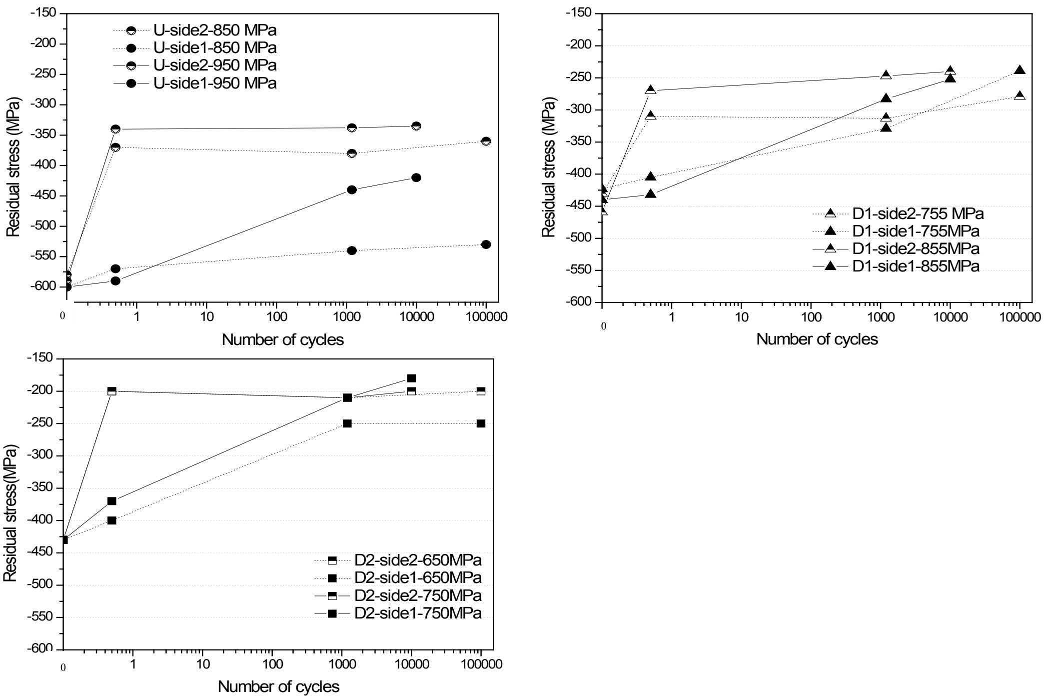


Fig. 5: Relaxation of residual stress at sides 1 and 2 for series U (top left), D1 (top right) and D2 (bottom).

DISCUSSION

Shot peening induced plastic deformation creates compressive residual stresses and changes the work hardening state at the surface zone [3]. Higher surface hardness for some shot peened materials has been reported in the literature [4]. Both compressive residual stresses and higher work hardening may improve the fatigue properties by increasing the surface resistance to crack initiation as well as reducing the crack propagation rate. However, the residual stresses are influential only if they are stable during cyclic loading [5].

As can be seen from fig. 4, the fatigue durability of all series of specimens was improved by shot peening. The increase in fatigue limit for the two decarburized and the undecarburized series was about 45 % and 9 % respectively (table 1). It should be noted that the Wöhler curves obtained for series D1 after shot peening and series U before shot peening are reasonably close with only 4 % difference in fatigue limit (fig. 4 and table 1). In other words, shot peening compensates the negative influence on fatigue caused by a slight surface decarburization. The improvement for the D2 series is also pronounced and the fatigue limit in this case reached 80 % of the U series before shot peening.

Once the superposition of the residual stresses and the loading stresses reaches the stress required for plastic deformation, the relaxation starts [6]. The amount and the rate of relaxation, however, are controlled by the magnitude of the plastic deformation. Therefore, at higher stress amplitudes corresponding to larger plastic strains the residual stresses will be washed away already from the beginning [1] and cannot contribute to the fatigue durability. As can be observed in fig. 4, there exist some critical stress amplitudes above which shot peening does not have a beneficial influence on fatigue life time. These critical stress amplitudes can be estimated as 820 MPa for the D2 series, 1020 MPa for D1 and 1050 MPa for the U series. Above these critical stress amplitudes (corresponding to $N_f \approx 10^4$ or slightly more) there is a rapid shrinkage of the residual stresses and possibly also a fairly rapid crack nucleation, making the effect of shot peening neglible.

As presented in fig. 5, residual stress relaxation for each series of specimens was followed at two stress amplitudes both smaller than the critical stress amplitudes. Due to surface plastic deformation during the first stage of the test, very pronounced relaxation was observed on side 2 (initially compressed). Being in elastic condition, side 1 with its residual stresses remained unchanged. During the second stage of the test and as a result of the first stage relaxations, the residual stresses in side 2 remained quite stable while the side 1 underwent a gradual relaxation. Depending on the surface yield strength and the imposed stress amplitude, the residual stresses on the two sides can approach each other at different cycle numbers. This condition appears at larger cycle numbers, the higher the surface yield strength and the lower the stress amplitude are. For the U series with its large surface yield strength this might be the reason that even after 10^5 cycles the residual stresses on both sides did not coincide.

The residual stresses obtained after 10^4 to 10^5 cycles are about -200, -250 and -350 MPa for D2, D1 and U series respectively. Although the residual stresses remaining in the specimen at half of fatigue life time are higher in series U, the improvement in fatigue limit is smaller than what is case for the decarburized specimens D1 and D2. Fig. 3b, on the other hand, demonstrates a hardness increase of 70 HV in the surface for the two decarburized series after shot peening, while the change for the U series remained marginal. This argues for the positive influence of the higher surface work hardening on fatigue durability. An entangled dislocation structure corresponding to a higher flow stress/hardness is a result of the high strain rate during the plastic deformation in the shot peening process [7]. However, the strain hardening in the surface zone taking place during shot peening is a function of the initial microstructure. For materials with already high density of dislocations such as tempered martensite, the shot peening process induces only slight work hardening. Even the opposite development with decreasing dislocation density during shot peening can sometimes occur [8]. In the present case, however, the ferrite patches in the decarburized specimens D1 and D2 work harden during peening owing to their low initial dislocation density. In contrast, the tempered martensite microstructure with its high initial dislocation density may be unstable during peening, resisting further work hardening or even leading to some softening. Therefore, a pronounced work hardening effect due to shot peening is expected in the decarburized specimens while no such effect is seen in the, undecarburized specimens.

CONCLUSIONS

The influence of shot peening on the fatigue behaviour of quenched and tempered carbon steels with different depth of surface decarburization has been studied. Following general statements can be made:

1. In all series of specimens (with and without surface decarburization) the fatigue durability was improved by shot peening. The relative improvement was more pronounced for the decarburized specimens. Thus the decrease of the fatigue limit in moderately decarburized specimens could be fully compensated by the positive effect of shot peening.
2. The positive influence of shot peening on the fatigue life time is limited to stress amplitudes below a level typically 20-30 % above the fatigue limit. At larger stress amplitudes – corresponding to a lcf situation - no benefit from shot peening is seen, because relaxation of the residual stresses takes place within a few cycles.
3. The importance of the first loading cycle was observed. The side experiencing a large compressive stress in the first loading stage has a more pronounced relaxation throughout life time provided that the surface yield strength is high.

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REFERENCES

[1] K.Dalaei, B. Karlsson and L.-E. Svensson, *Stability of shot peening induced residual stresses and their influence on fatigue life time*, Materials Science and Engineering A, http://dx.doi.org/10.1016/j.msea.2010.09.050.
[2] K. Dalaei, J. Höijer, G. Åkerström, B. Karlsson & L.-E. Svensson, *Influence of decarburization on the fatigue behaviour of shot peened spring steels*, The 10th International Conference on Shot peening, Tokyo (2008), pp 274-279.
[3] H. F. Moor, Shot peening and the fatigue of metals, American foundry equipment CO., Mishkawa, Indiana, USA, 1944.
[4] U. Martin, I. Altenberger, B. Scholtes, K. Kremmer, H. Oettel, *Cyclic deformation and near surface microstructures of normalized shot peened steel SAE 1045*, Materials Science and Engineering, A246 (1997) 69-80.
[5] M.A.S. Torres and H.J.C. Woorvard, *An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel*, International Journal of Fatigue 24 (2002), pp 877–886.
[6] D. Löhe and O. Vöhringer, *Stability of Residual Stresses,* Handbook of Residual Stress and Deformation of Steel, (2003),pp 54-69.
[7] V. Schulze, Modern *Mechanical Surface Treatment, State, Stability, Effecs*,first ed.,Weinheim, 2006.
[8] H. Holzapfel, V. Schulze, O. Vöhringer, E. Macherauch, *Residual stress relaxation in an AISI 4140 steel due to quasistatic and cyclic loading at higher temperatures*, Mater. Sci.Eng., A 248 (1998) 9-18.