Influence of decarburization on the fatigue behaviour of shot peened spring steels

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ABSTRACT

The influence of decarburization on the high cycle fatigue behaviour of shot peened spring steel was investigated. The material studied was a quenched and tempered carbon steel (0.55C, 1.9Si and 0.9 Mn). The specimens were decarburized to depths of 0.40 and 0.50 mm. Shot peening with full coverage then took place, leading to a thickness of the compressed surface layer of about 0.25 mm. The specimens were tested in bending fatigue to fatigue lives in the range $N_f = 1{\cdot}10^5$ to $3{\cdot}10^6$ cycles. Following fatigue limits were then achieved: 655 – 675 MPa for the two decarburized levels and 880 MPa for the non-decarburized specimens. Crack nucleation generally took place in the very surface zone. Stress relaxation during fatigue loading and surface roughness of the specimens were measured and correlated to the fatigue behaviour.

KEY WORDS

Decarburization, fatigue strength, residual stresses, shot peening.

INTRODUCTION

The influence of surface decarburization on fatigue properties is an important practical problem for many vehicle components. Different mechanical surface treatment methods have been examined to improve the fatigue durability of surface decarburized steels. Shot peening is considered as one of the major methods to improve fatigue durability of spring steels.

Decarburization at the surface of a component corresponds to a layer of lower yield strength than the core material. The requirement on maximum depth of the decarburized layer is usually in the range 0.1 – 0.2 mm. However, it has been observed that 0.4-0.5 mm decarburization depths are not rare in actual production. The aim of the present study was therefore to evaluate how shot peening could improve the fatigue behaviour of components with such thick decarburized layers. To gain further insight into the factors controlling the fatigue life, the fatigue testing was complemented with investigations of the residual stress relaxation during fatigue loading, crack initiation location and surface roughness.

MATERIALS AND METHODS

Ovako steel 51SiCr7 (Table 1) was employed as the test material in the present study.

Table 1: Chemical composition of the material, 51SiCr7 Ovako steel.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	V
Weight percent	0.55	1.89	0.88	0.019	0.015	0.24	0.09	0.02	0.21	0.022	0.006

The fatigue specimen used is shown in fig. 1. This type of specimen is frequently used for bend fatigue testing in Volvo Company. The fatigue testing after heat treatment and shot peening of the specimens was performed under plane bending stress condition at $R_\sigma = -1$ in a Volvo built equipment.

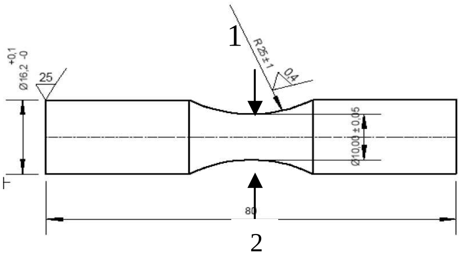
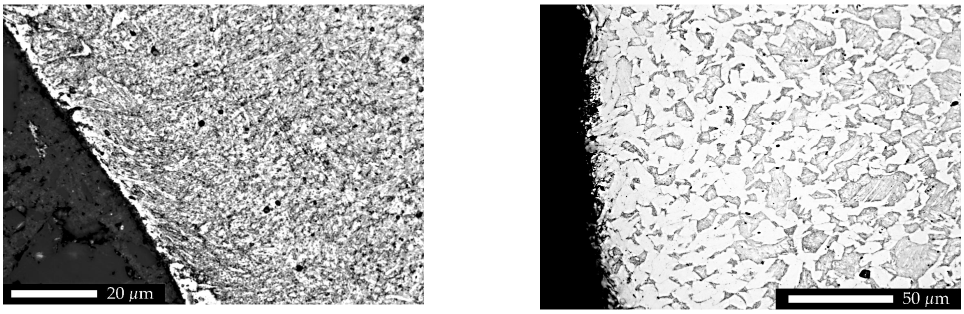


Fig. 1: Dimensions of the fatigue specimen. The arrows indicate the position where the residual stresses were measured. 1 refers to the side subjected to tensile load during the first half a cycle and 2 to the side loaded in compression during the first half a cycle.

Three series of specimens (R, D1 and D2) with geometry as in fig.1 were used in the study. Series R was the base material in its virgin, undisturbed state, while series D1 and D2 were decarburized at 985 °C for 45 min and 85 min respectively in a furnace kept at a constant carbon potential of 0.10 wt-% in order to achieve different degrees of decarburization. Directly after decarburization the specimens were quenched in oil and tempered at 450 °C. Owing to the relatively slow cooling rate during quenching, the microstructure in the decarburized specimens contained considerable amounts of free ferrite with intermixed tempered martensite regions close to the surface; cf. figs. 2a and b. The virgin material underwent a identical Q&T treatment.



a.

b.

Fig. 2: The tempered martensitic microstructure in the reference, virgin specimen R (fig. a), and the maximum decarburized specimen D2 (fig. b)

The heat treatments used lead to the yield strength 1540 MPa, the tensile strength 1650 MPa and elongation 10 % in the bulk of the specimens. The decarburization was determined by hardness recordings (HV1), where the depth of carburization was defined as the distance from the surface, where the core hardness had decreased by 50 units. By the hardness criterion used, there is fairly small difference in the decarburized depths between specimens D1 and D2, 0.4 and 0.5 mm respectively. The three series of specimens were then shot peened with the same peening data, Table 2.

Table 2: The shot peening data employed for all three series of specimens.

Almen intensity	Coverage	Shots	Shot hardness (HRC)
0.45 mmA	100%	Cut wire	55-62

The surface roughness of randomly chosen shot peened specimens in series R and D2 was determined with an interference microscope, WYKO RST plus, from Vecco Instrument Inc. USA. A field of 0.5 mm x 0.6 mm in size was used. The reference specimen R then showed a R_a value of 3.6 μm, while R_a = 5.3 μm was found for the decarburized specimen D2 with its softer surface. Some inclined surface cracks of depth typically 10 μm were found in all three specimen series.

Measurement of residual stresses took place by X ray measurements, using an AST Xstress 3000 equipment. In the evaluation, (211) peaks were used; in martensite for the reference R specimens and in ferrite for the decarburized D2 specimens. Complete stress profiles in depth were recorded on all test series before fatigue testing. Recording of the stresses on the specimen surfaces was then performed on specimens from all series run to different numbers of cycles during the fatigue tests.

RESULTS

The residual stress profiles for untested specimens are presented in fig. 3. The compressive profiles for the two decarburized series D1 and D2 are identical with a flat stress level apart from the region in the very surface. The reference specimen R, on the other hand, exhibits larger compressive stresses but with similar depth of the compressive zone.

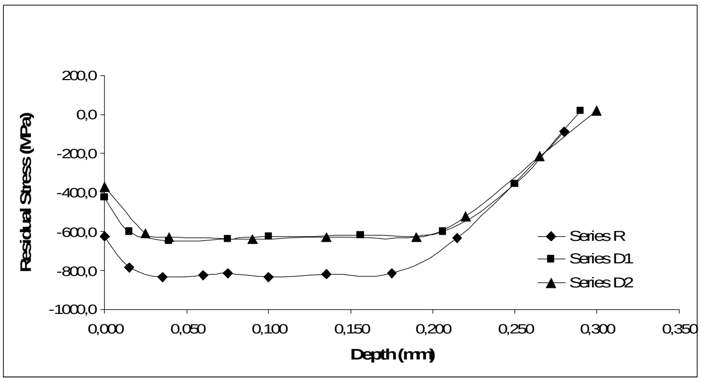


Fig. 3: The residual stress profiles after shot peening for the three series of specimens.

Fig. 4 shows a Wöhler diagram, summarising the results of the fatigue tests for all three series of specimens. The cycle number 10^6 is here considered as the life time close to the threshold and the samples with longer life time than 10^6 cycles as survivors. The fatigue limit estimated at 10^7 cycles is given in Table 3. The fatigue limit of the reference specimens is obviously higher than that of the decarburized ones. There is a relatively small difference between the two series of decarburized specimens (D1 and D2).

Table 3: The fatigue limits of three different series of specimens.

Specimen series	R: Non decarburized	D1: 0.4 mm decarburization	D2: 0.5 mm decarburization
Fatigue limit (MPa)	880	675	655

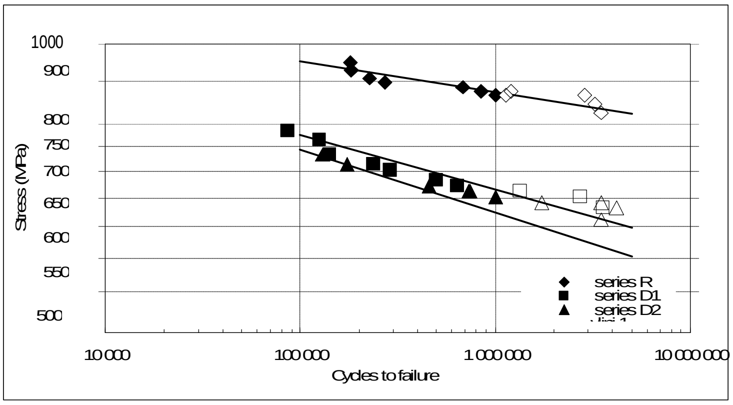
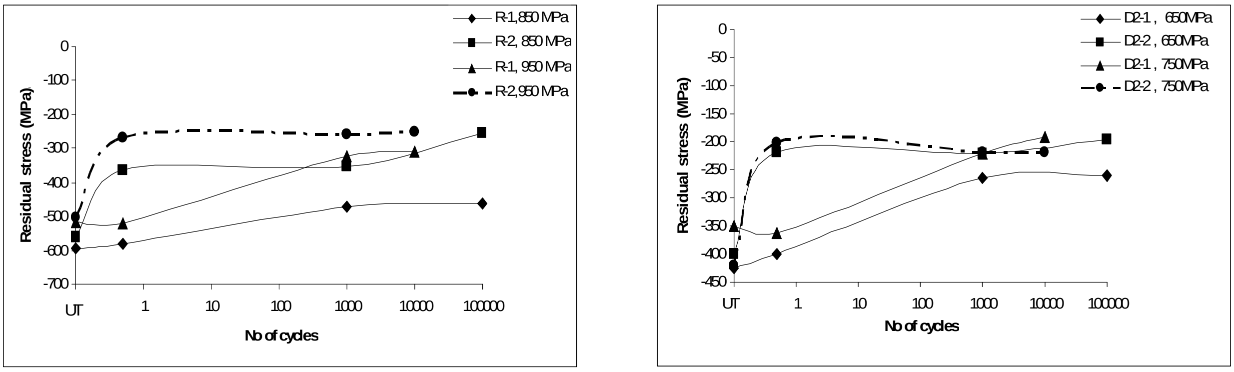


Fig. 4: Wöhler curves for the three series of specimens (R, D1 and D2). The unfilled symbols indicate specimens judged as survivors.

The relaxation of the residual stresses at the surface was compared between series R and D2 specimens after different number of cycles (sites 1 and 2 in fig. 1), fig. 5. Sites 1 and 2 correspond to the tension and compression sides of the specimens in the first half a cycle, respectively. The specimens were here fatigued at two different stress amplitudes. The first group corresponds to a stress amplitude equal to the corresponding fatigue limits (850 MPa and 650 MPa respectively for series R and D2). The second group of tests for the two materials was performed at stress amplitudes 100 MPa higher than the first series, corresponding to fatigue life times ten times shorter or $N_f = 10^5$ for both R and D2 series. All data points refer to unbroken specimens.

The relaxation of the residual stresses follows a clear pattern: In compressive mode during the first quarter of the stress-strain cycle (site 1 in fig. 1), relaxation of the stresses to roughly half of its initial value takes place in both the reference (series R) and decarburized (series D2) specimens. Corresponding relaxation for site 2 with initial tensile loading is more gradual, reaching the same stationary level as for site 1 after about 1 % of the life time corresponding to about 1000 – 10000 cycles. Comparing figs. 5a and 5b tells that the recovery is faster at the higher stress amplitudes, yet with not so pronounced differences.

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 non-decarburized specimen, subjected to very low amplitude loading for 10^7 cycles.



a **b**

Fig. 5: The relaxation of residual stress at sides the surface of series R (fig. a) and D2 (fig. b) specimens. The stresses were measured in sides 1 and 2. UT represents the stress levels before fatigue testing.

DISCUSSION

It is generally known that shot peening changes the surface hardness, residual stress state and surface texture of the treated component. Alteration in the material state may also affect the fatigue strength of the component (Kaiser, 1987). However, the stability of the residual stresses determines whether they are influential on the fatigue properties of the component. In the present study it has been demonstrated that the compressive stresses caused by shot peening survive to about half of their initial values for both virgin and decarburized states of the Q&T steel studied. This applies for stress ranges at the fatigue threshold or 100 MPa higher stress range. The partial stress relaxation typically takes place within some per cent of the total lifetime. The maintained compressive stresses at larger cycle numbers (fig. 5) was further proved by measurements on specimens run up to stress cycle numbers of 400,000. The pronounced influence of initial load direction in the first cycle on the rate of stress recovery has to do with the maximum imposed stress level related to local yield stress (compression or tension). It is believed that more complete stress recovery would take place at higher stress amplitudes, thereby eliminating any beneficial effect of the shot peening on the fatigue strength.

The residual stress levels before fatigue testing (Fig. 3) are obviously different for the virgin and decarburized materials. The lower yield strength of decarburized layer compared to the virgin material is the main reason for these lower compressive residual stresses (Hirsch et al., 1982). However, the situation is more complicated in the present case since compressive stresses in the ferritic phases are likely to develop as a result of swelling caused by the formation of martensite.

The depth of the residual stresses is almost the same for all three series of specimens. Keeping the shot peening parameters constant, however, the depth of penetration is determined by the hardness of material (Holzapfel et al., 1998; Martin, 1980). Referring to fig. 3, the depth of residual stresses is in the order of 0.2 mm, which is less than the decarburization depth for both D1 and D2 series of specimens. The maximum hardness of the decarburized specimens at 0.2 mm depth is 410-420 HV (1Kgf) which is about 100 units less than the core hardness (or surface hardness of virgin material). It seems that such a difference in hardness does not have a pronounced effect on the depth of the residual stress profiles.

According to fig. 4 a large difference in fatigue limits is observed between the virgin and the decarburized series of specimens. However the difference between the two series of decarburized specimens is negligible. Therefore it seems that a slight change in decarburization depth (from 0.4 to 0.5 mm) does not change the fatigue limit.

Slight changes in surface roughness between the virgin and decarburized specimens have no marked effect on the recovery conditions. Likewise the fatigue thresholds of the two types of materials seem not to be influenced by the relatively small difference in surface roughness.

CONCLUSIONS

The influence of shot peening on the fatigue behaviour of quenched and tempered carbon steels has been studied for both virgin and decarburized states. Following general statements can be made:

1. There is a marked difference in fatigue strength between the virgin and the decarburized materials. In both cases shot peening improves the fatigue strength.
2. Identical shot peening parameters create somewhat larger compressive residual stresses in the virgin material compared to the decarburized condition. The depth of the compressive zone is however the same in both cases.
3. At fatigue loading at stress amplitudes close to or somewhat higher than the fatigue threshold, the residual stresses recover to roughly 50 % of their initial value. This recovery occurs within typically 1 % of the fatigue life time; thereafter no further recovery takes place.
4. There is little dependence of the fatigue behaviour on the exact decarburization depth, provided the decarburized depth extends the depth of the initial residual stress zone.

ACKNOWLEDGMENTS

The authors wish to acknowledge Anna-Karin Johansson and Ida Fritzon for parts of the fatigue testing. Sincere thanks are directed to Mirsattar Hejazifar for providing residual stress measurements. This paper is published with the permission of Volvo Powertrain AB. Financial support was given by Swedish Agency for Innovation Systems (VINNOVA).

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