Relaxation of Shot Peening Induced Compressive Stress During Fatigue of Notched Steel Samples

Jens Bergström and Torsten Ericsson

Department of Mechanical Engineering
Linköping Institute of Technology
S-581 83 Linköping, Sweden

Abstract

This paper presents an experimental investigation on the surface residual stress relaxation behaviour of a shot peened 0.4% carbon low alloyed steel at fatigue load. A round specimen with a circumferential notch and a notch factor K_t=1.75 has been used in both shot peened and ground conditions. The loading conditions included here are axial fatigue load with R=-1, R=0, R=-1 plus peak load at 10^6 cycles, and also fatigue of smooth shot peened specimens at R=-1 load. It is shown how the relaxation is load level dependent, how peak load changes the surface residual stress state and that relaxation of the smooth and notched condition is similar.

Introduction

The importance of surface residual stresses in fatigue has long been recognized, and their behaviour during fatigue has also taken the interest of many researchers. Concerning shot peening applications, where the beneficial effects are to a large degree attributed to the compressive surface residual stress, it is, of course, of primary interest to know whether these stresses are stable or not. Several investigations have been carried out showing that they may change, and in what way, for some specific material and load combinations. Still greater knowledge is required in order to understand the mechanisms of relaxation and to acquire materials data, so that one can take it into account in design and calculation models.

Taira and Coworkers have in a series of articles investigated residual stress and X-ray line broadening changes in fatigued annealed steel specimen. Esquivel and Evans (1968) found some relaxation in shot peened AISI 4130 steel specimens in fatigue with R=0.06 and a load level around the endurance limit, and they tried to find a correlation between the residual stress gradient and amount of relaxation. McClinton and Cohen (1982) presented a work on normalized and shot peened SAE 1040 steel fatigued with R=0 demonstrating that compressive residual stresses could develop to tensile at higher load levels. Donati, et al. (1981), carried out a study on hardened 12% Cr steel showing some relaxation at the surface for both R=-1 and R=0 loads. Wolfhart (1973) showed that a low-carbon steel with initially tensile or compressive residual stress both relaxed towards zero when fatigued at R=-1 load. Kuo and Cohen (1983) investigated a normalized and cold-worked AISI 1008 steel at R=-1 load presenting data on residual stress and work-hardening, parameters such as domain size and microstrain, behaviour. James (1982) presented a short review on stress relaxation work and presented a restricted model on relaxation.

In this paper we focus the interest on notched specimens of a 0.4% carbon steel of medium hardness at different R=-1 and R=0 fatigue loading conditions.

Experimentals

The specimen material was a 0.40%C steel according to Swedish SS-142244-05 standard, equivalent to AISI 4140, quenched and tempered to 940 MPa tensile strength and 815 MPa yield strength. Cylindrical specimens were used with 16 mm diameter and a circumferential notch with notch radius 2.5 mm and notch factor $K_t=1.75$. The specimens were ground to surface roughness $R_a=1\mu m$ and then shot peened to Almen-intensity 30-35A(mm/100) with 100% coverage using steel shot of S 330 standard. Some specimens were left in the ground condition for comparison purposes.

Fatigue testing for determining Wöhler-curves for a shot peened and a ground condition were performed with axial constant load amplitude and R=-1 where 27 specimens per each surface condition were used. From these result three different load amplitudes were picked out, 283, 303 and 373 MPa, corresponding to fatigue lives of 10^5, 10^6 and 10^7 cycles. The resulting Wöhler-curves are shown in Fig 1.

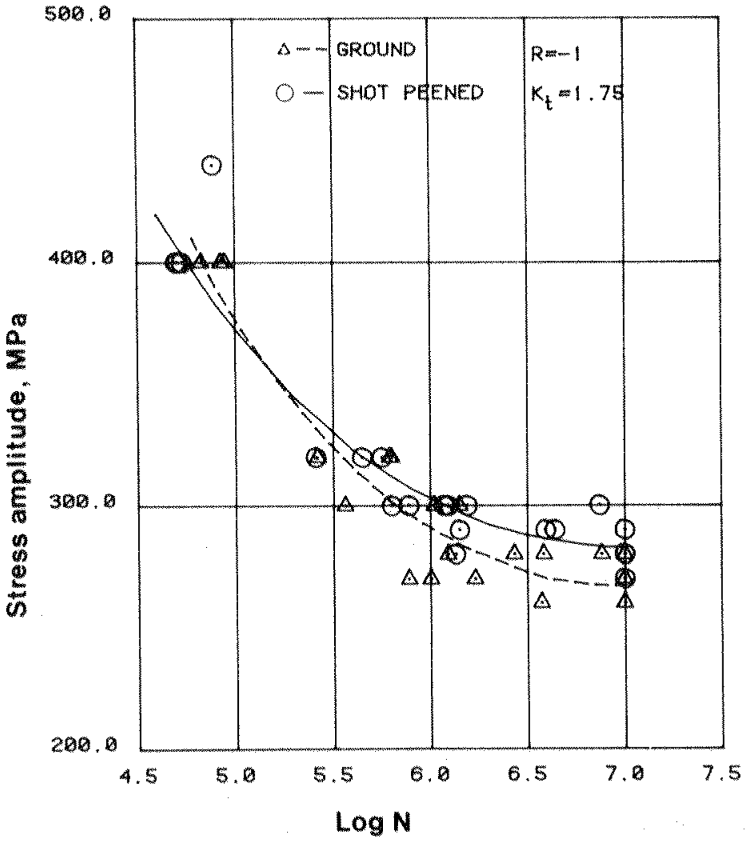

Fig 1 Wöhler-curves for the notched shot peened and ground conditions at R=-1 load. The data points at 10^7 cycles consists of 10 and 9 runouts for the ground respectively the shot peened condition

Fatigue testing was then performed with residual stress measurement at intervals, where the specimens were transported back and forth between the fatigue machine and the X-ray diffractometer. The loading and specimen conditions were as follows, where the R value expresses the ratio of minimum stress to maximum stress.

1) Axial constant load amplitude, R=-1.

   Two shot peened specimens at each of the three load amplitudes evaluated from the Wöhler-curve were used, plus one ground specimen at maximum and one at minimum amplitude.

2) Axial constant load amplitude, R=0.

   Two shot peened and one ground specimen at each of the two higher load amplitudes were used at R=-1 and at 80% of lowest load amplitude used at R=-1.

3) Axial constant load amplitude, R=-1, with +100% or -100% peak load at 10^6 cycles, which means (+283+283 MPa) or (-283-283 MPa) as peak loads.

   Two shot peened specimens at each +100% or -100% were used at the lowest load amplitude from the R=-1 series.

4) Axial constant load amplitude, R=-1.

   Two specimens were turned and ground to the notch bottom diameter and then shot peened to 30-35A(mm/100) intensity so as to obtain smooth specimen data. The same nominal load as the lowest of the notched R=-1 series was used up to 10^6 cycles, whereafter the load was increased by multiplying the nominal load by the notch factor.

Note that all load sequences, except at peak loads, began with a tensile and ended with a compressive load cycle.

Residual stress measurement was made by X-ray diffraction of CrK_α-radiation using a JEOL-diffractometer equipped with a position sensitive detector sampling from the (211) plane in the ferrite phase. Stresses were calculated by the $\sin^2\psi$-method using an X-ray elastic constant $(1+\nu)/E$ of $5.73\cdot10^{-6}$ MPa^{-1} and three to five ψ-angles. ψ varied between -40° to $+40^\circ$ and -45° to $+45^\circ$ for axial respectively tangential measurements. The peak determination of the diffraction intensity curve was done by the parabola method.

In order to measure in the bottom of the notch a pin-hole collimator was used which resulted in a well concentrated X-ray spot of 0.5 mm diameter in the notch. The specimen was rotated during measurement so as to give an average residual stress value around the specimen periphery.

The error in the measured residual stress value is estimated to ±30 MPa as derived from the linear fit to the $\sin^2\psi$-curve and from repeated measurements Though, for the ground conditions the error of the linear fit could be bigger typically ±60 MPa, due to ψ-splitting in the $\sin^2\psi$-curve.

A stress profile curve for both axial and tangential residual stress was recorded, Fig 2, by removing surface layers with an etching technique. No corrections for removal of the surface layers were made due to the specimen geometry, and neither for stress gradients.

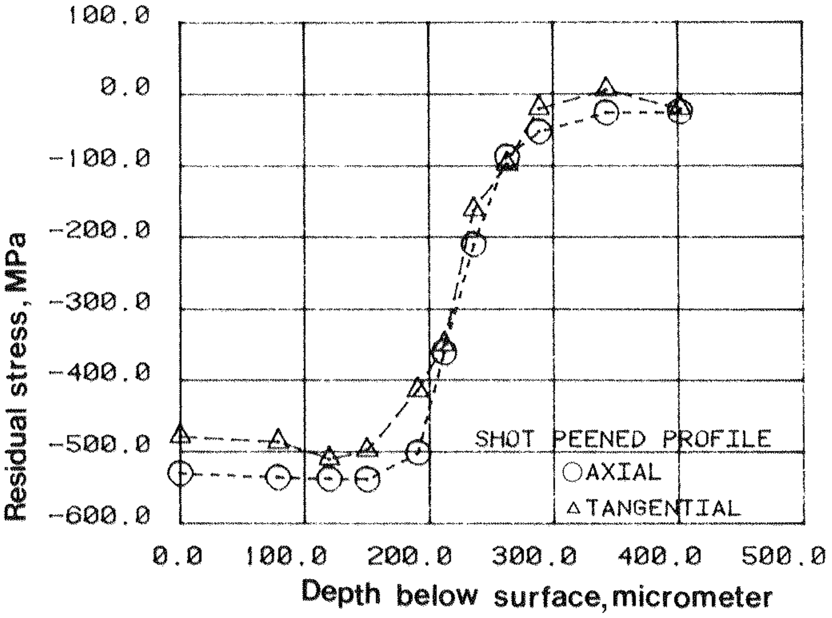

Fig 2 Residual stress profile for axial and tangential directions at the bottom of the notch.

Results and discussion

At R=-1 load it can be seen, Fig 3,4, that both axial and tangential surface residual stress relax due to the fatigue load. The first cycle causes an immediate decrease of compressive stress and thereafter relaxation continues throughout the specimen life. The amount of relaxation depends on the load range and there is more relaxation in the axial than in the tangential direction.

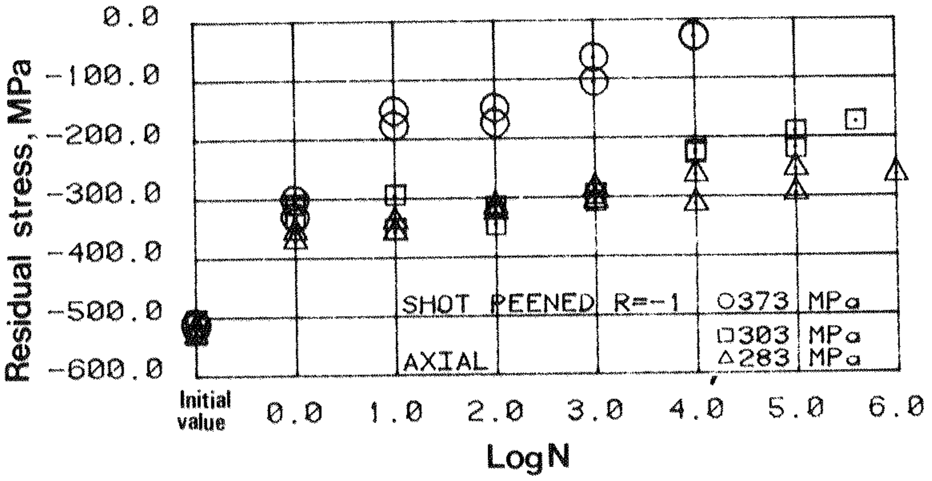

Fig 3 Axial residual surface stress as function of number of load cycles, N, and nominal stress amplitude at R=-1 load.

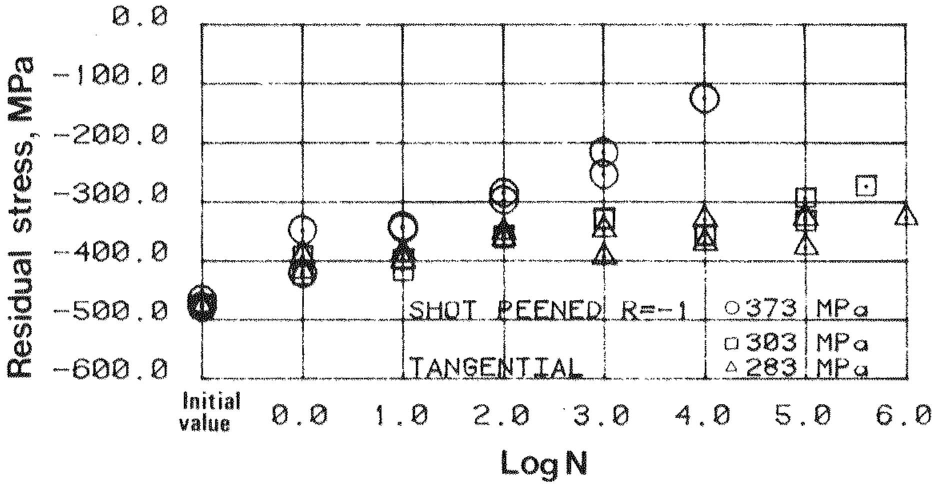

Fig 4 Tangential residual surface stress as a function of number of load cycles, N, and nominal stress amplitude at R=-1 load.

When the specimens were subjected to R=0 fatigue a different pattern emerges, Fig 5,6. The axial residual stress will not relax at all until shortly before failure, but it will, on the contrary, increase somewhat. The tangential stress, though, relaxes in the same manner as with the R=-1 load.

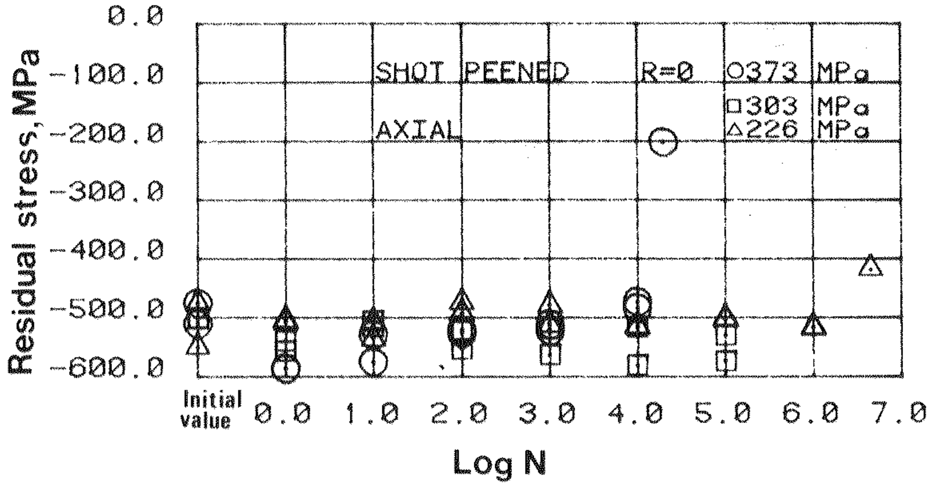

Fig 5 Axial residual surface stress as a function of number of load cycles, N, and nominal stress amplitude at R=0 load.

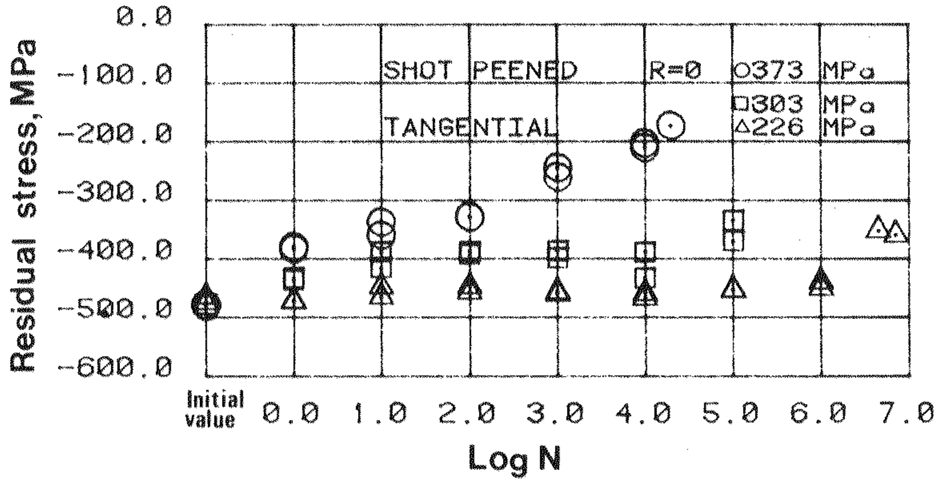

Fig 6 Tangential residual surface stress as a function of number of load cycles, N, and nominal stress amplitude at R=0 load.

From the above we deduce that relaxation in the axial direction is caused during compressive loads, as expected, and in the tangential direction we will observe relaxation during the tensile load cycle which causes negative tangential strain.

It is worth noting that the magnitude of tangential relaxation is the same for both R=-1 and R=0 load, even though the tensile load is the double in the R=0 case compared to that in R=-1.

The peak load specimens were all run continuously to 10^6 cycles with R=-1 after which the residual stresses had dropped to the same level as the previous R=-1 series, Fig 7. The two specimens, which were subsequently subjected to -100% load, dropped further to near zero axial stresses and these turned somewhat more compressive with continued cycling. The +100% overload resulted in increased axial residual stresses but faded with continued cycling to the level prior to the overload.

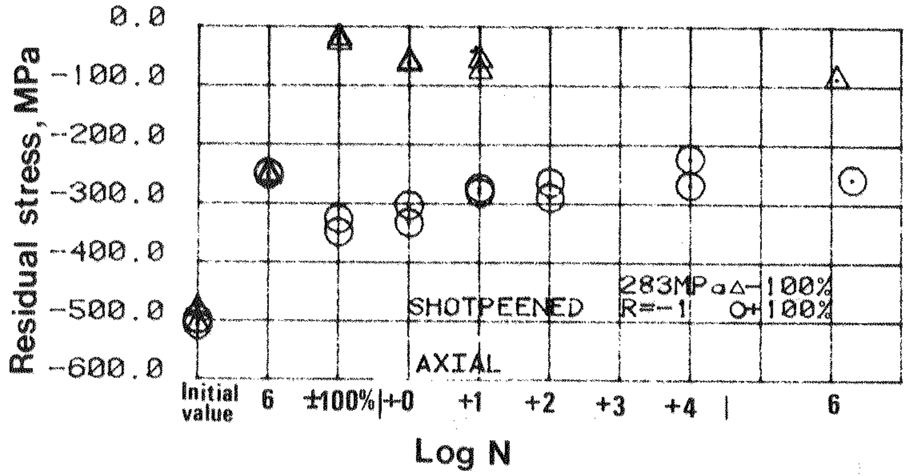

Fig 7 Axial residual surface stress of shot peened specimens subjected to +100% or -100% peak load at $N=10^6$ cycles.

The tangential residual stress was shifted to a somewhat lower compressive value due to both the + and -100% peak load. The -100% caused a larger compressive decrease than did the +100% load.

Two smooth shot peened specimens were run at R=-1 and lowest nominal load in order to investigate the constraining effect of the notch on the relaxation behaviour, Fig 8. Only a small amount of relaxation could be observed up to 10^6 cycles, whereafter the load was increased with the notch factor on one of the specimens. The subsequent relaxation showed to be equivalent to that of a notched specimen at the same axial surface load stress. This implies that this notch will not reduce the ability of the material to relax.

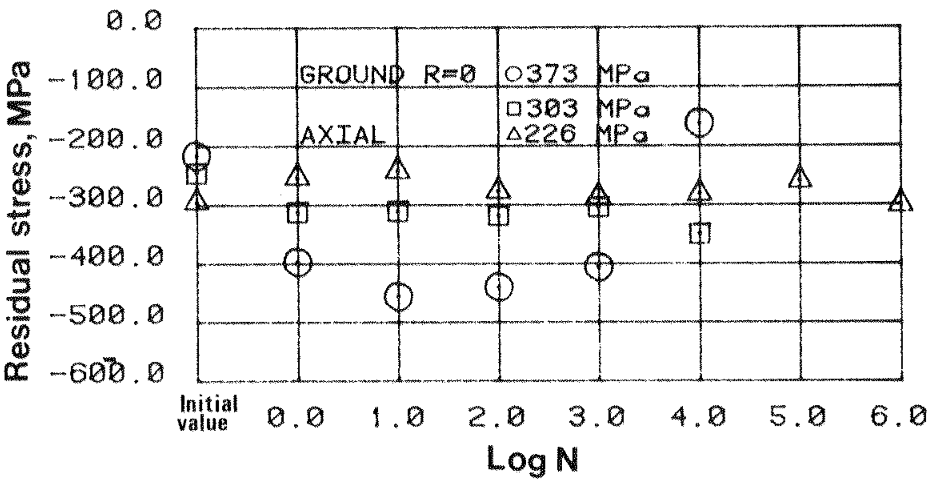

Fig 8 Axial residual surface stress as a function of number of load cycles, N, and nominal stress amplitude at R=-1 load of smooth shot peened specimens.

The ground specimen conditions all had initial compressive residual surface stresses in both axial and tangential directions ranging between -180 and -300 MPa. In the axial direction and R=-1 load, relaxation occurred but in an oscillating manner. The behaviour of the axial residual surface stress at R=0 load can be seen in Fig 9. A strikingly large increase in compressive stress is noted at the highest load level, but it drops shortly before failure. The tangential directions showed a load dependent stress relaxation, as in the shot peened state, for both the R=-1 and R=0 loads.

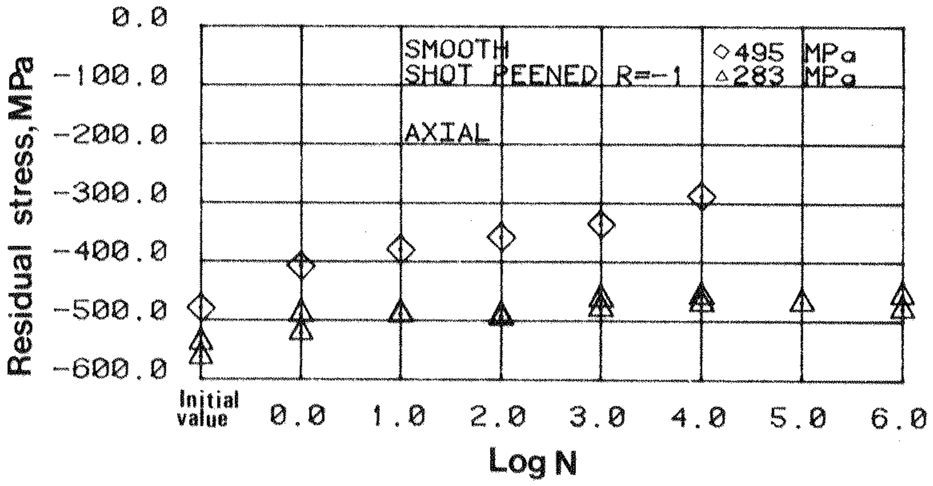

Fig 9 Axial residual surface stress as a function of number of load cycles, N, and nominal stress amplitude at R=-1 load of ground specimens.

The residual stress data versus load demonstrates clearly the relaxation behaviour. All compressive loads will lead to relaxation, an instantaneous part from the first load cycle originating from exceeding the yield limit on the compressive side. As the fatigue process progresses a kind of cyclic creep will occur, the magnitude of which depends on the load range. Tensile load will increase the residual stresses, one part from the first cycle if the yield limit is exceeded, and another cyclic part.

Summary

From the data presented in this article some conclusions can be deduced, refering to the material, specimen and load conditions used here.

1) Relaxation of compressive residual stresses occurs at fatigue loads which include compressive stresses and/or strains, depending on load and residual stress level.
2) At tensile fatigue loads the compressive residual stresses may increase during the fatigue history depending on load and residual stress level.
3) Negative peak loads are detrimental to the compressive residual stress state. Positive peak loads may cause increased compressive residual stresses, but will soon relax to the residual stress level previous to the peak load.
4) Smooth and notched specimens relax at the same rate at the same local stress.
5) In none of the specimens has a change from compressive to tensile residual stress been observed.

References

Donati, J.R., Grattier. J., Masson, S.H. and Ternon, F., (1981), First Intern. Conf. on Shot Peening, Paris 1981, 663-673, Pergamon Press

Esquivel, A.L. and Evans, K.R., (1968), Experimental Mechanics, Nov. 1968, 496-503

James, M.R., (1982), Residual Stress and Stress Relaxation, 297-314, Plenum Press

Kuo, H.K. and Cohen, J.B., (1983), Techn. Rep. No 9, Northwestern University, Evanston

McClinton, M. and Cohen, J.B., (1982), Materials Science and Engineering, 56 (1982) 259-263

Wohlfahrt, H., (1973), Härterei-Technische Mitteilungen, 28 (1973) Nov. 288-293

Acknowledgement

The authors acknowledge the support of the private companies ASEA AB, Atlas Copco MCT AB and Saab-Scania AB for furnishing testing, test material and shot peening.