Influence of Shot Peening on the Bending Fatigue Behaviour of Notched Specimens of Ck 45

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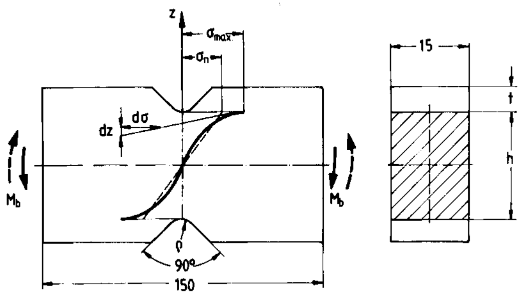
1. Introduction

As a consequence of shot peening of steel parts, the surface topography will be changed and at and below the surface characteristic residual stress states and workhardening states will be produced (1, 2). It is well established that these quantities influence the bending fatigue behaviour of smooth specimens. In most cases, considerable improvements of the bending fatigue strengths are observed (2 - 5). In two recent investigations it was shown that shot peened notched specimens reveal a stronger increase in bending fatigue strength compared with smooth specimens peened under the same conditions (6, 7). However, the material states near the notch root were unknown (7) and different surface states existed at smooth and notched specimens, respectively (6). Of course, to assess the increase of fatigue strength due to shot peening the precise knowledge of the material state at and below the notch root surface should be known. In particular, quantitative data of the residual stresses at and near the very surface of the notches are necessary. In this respect only X-ray diffraction procedures promise definite results. In the following, shot peened material states at and below the notch root surface of quenched and quenched and tempered bending specimens of a medium carbon steel (German grade Ck 45, SAE 1045) are analyzed. The results of bending fatigue tests with several stress amplitudes on smooth and notched specimens are shown. Finally, the results obtained from shot peened and ground specimens are compared and discussed applying the local fatigue strength concept.



stress concentration factor $\alpha_k = \sigma_{max}/\sigma_n$

relative stress gradient $\eta = d\sigma/dz \times 1/\sigma_{max}$

specimen	h [mm]	ρ [mm]	t [mm]	α_k	η [mm^{-1}]
notched	5.5	1.0	1.85	1.7	2.1
smooth	5.5	-	-	1.0	0.36

Fig. 1: Shape and dimensions of specimens used

2. Experimental details

The chemical composition of the steel investigated was 0.49 C, 0.26 Si, 0.66 Mn, 0.07 Cr, 0.01 Mo, 0.14 Cu, 0.07 Ni, 0.011 P, 0.018 S, 0.007 Al, 0.001 V, and 0.003 Nb (weight-%). Shape and dimensions of the specimens used with their stress concentration factors α_k and their relative stress gradients η are summarized in fig. 1. All specimens were produced with an oversize of 0.15 mm. After manufacturing, the specimens were austenitized 1 h at 830 °C, and then quenched in oil of 20 °C. One batch of these specimens was tempered for two hours at 600 °C in an argon atmosphere. After these heat treatments, the oxidized and decarburized skins of the specimens were removed by grinding. Finally, the quenched specimens were shot peened with shot S 230 in a compressed-air plant, using a pressure of 4.7 bar and shots of 46 - 50 HRC and 54 - 58 HRC, respectively. In the case of quenched and tempered specimens, the shot hardness was 46 - 50 HRC and the peening pressure 1.5 bar. In all cases, the peening time was $3 \times t_{98}$. t_{98} is the time to get a coverage of 98 % at smooth specimens.

Residual stress determinations were carried out with a ψ-diffractometer using the $\sin^2\psi$-method. In all cases {211}-interference lines were measured. In notched specimens the stresses in the notch root parallel to the longitudinal direction of the specimens were determined.

Since in respect to curved surfaces, contradictory statements about the applicability of the $\sin^2\psi$-method exist (10 - 12), a quantitative treatment of this problem was performed. It has been shown, that the stress in a notch root of cylindrical shape can correctly be evaluated according to the conventional $\sin^2\psi$-method from the slope of the $2\theta_{\phi,\psi}$, $\sin^2\psi$-distribution, if the width of the X-ray beam is small when compared with the notch radius (13). In the present investigation, a primary X-ray beam with a diameter of 0.3 mm was used to fulfil this condition.

The workhardening state produced by shot peening was evaluated by measurements of micro-hardness and half-width of interference lines at $\psi = 0^{\circ}$. The surface topography was characterized by average surface roughness values measured in the longitudinal direction of the specimens. The distributions of residual stresses, half-width and micro-hardness values below the very surface of the material were determined by step-wise removing of surface layers by electro-polishing. The residual stress values obtained have not been corrected.

Alternating bending fatigue tests were carried out with sinusoidal loading, a cyclic stress ratio $\sigma_{min}/\sigma_{max} = -1$, and a frequency of 25 Hz. For each material state 30 fatigue tests were performed. From the data obtained, Wöhler-curves with a fracture probability of P = 50 % were determined applying the arc sin $\sqrt{P}$- transformation (14).

3. Experimental Results

3.1 Material states after shot peening

Fig. 2 shows longitudinal residual stresses, half-width values, and micro-hardness as a function of the distance from the surface for quenched specimens at the left-hand side and for quenched and tempered specimens at the right-hand side. Data are included for notched and smooth specimens for distances up to 0.5 mm from the notch root surface and from the smooth surface, respectively.

With respect to the quenched state, the smooth and one part of the notched specimens were peened with shot of 54 - 58 HRC. The other part of the notched specimens was peened with shot of a reduced hardness of 46 - 50 HRC. After the first mentioned treatment the notched specimens show enhanced compressive surface residual stresses, and below the surface much larger magnitudes of residual stresses than the smooth specimens. However, with shot of reduced hardness similar depth distributions of residual stresses in notched and smooth specimens can be achieved. Independent of the shape of the specimens and the hardness of the applied shot, similar depth distributions of half-width values

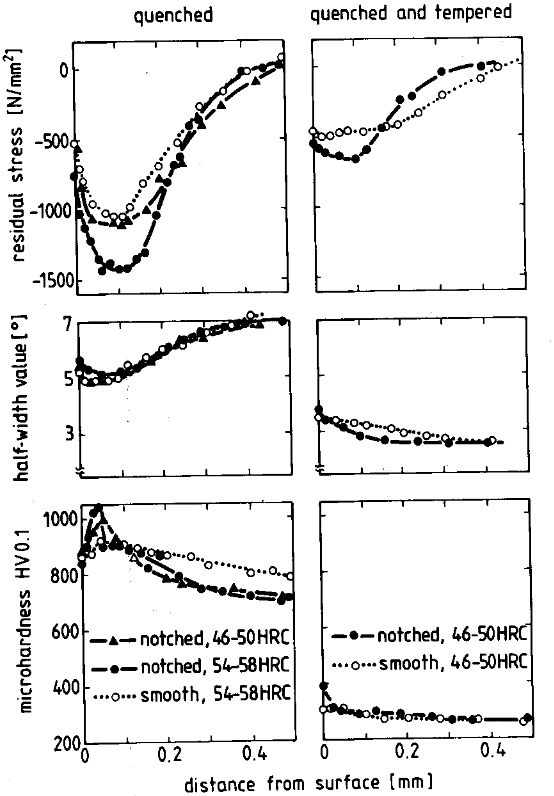


Fig. 2: Residual stresses, half-widths and micro-hardness values due to shot peening vs. distance from surface for shot peened, quenched and quenched and tempered specimens with and without notches. The Rockwell hardness numbers of the shots used are indicated.

are observed. Minimum values occur approximately 0.03 mm below the surface. With increasing distance from the surface, the half-width values increase up to about 7°, which is characteristic of the only heat-treated material. The micro-hardnesses at the surface of all quenched and shot peened specimens are smaller than the HRC-values in a distance 0.03 mm below the surface. The largest values of micro-hardness are revealed by notched specimens after peening with the harder shot. However, the HRC-maximum appears below the surface and with another distance from the surface than the maximum of the compressive residual stresses. As can be seen in the lower left part of fig. 2, at larger distances from the surface the micro-hardness of smooth specimen is about 100 HV larger than that of notched ones. It seems worth mentioning that the mean surface roughness values of quenched and peened smooth specimens are with 4.8 μm higher than those of similarly treated notched specimens with 3.0 μm. Quenched and notched specimens peened with shot of 46 – 50 HRC reveal a mean surface roughness of about 2.5 μm.

The right part of fig. 2 summarizes results obtained from quenched and tempered notched and smooth specimens after peening treatments of the same kind. As in the case of quenched specimens, the residual stress distributions are different in notched and smooth specimens. A weak maximum of compressive residual stresses occurs below the surface of notched specimens. Half-width values and micro-hardness values of notched specimens are somewhat greater at the surface than those of smooth specimens. The decrease of these quantities with increasing distance from the surface is nearly the same for both types of specimens. However, large mean values of surface roughness are produced differing by a factor of two for notched (18 μm) and smooth (36 μm) specimens, respectively.

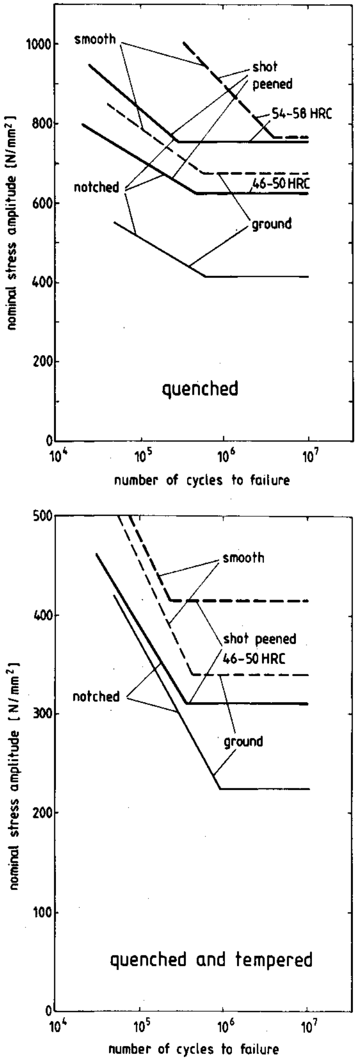


Fig. 3: Wöhler-curves of quenched (upper part) and quenched and tempered (lower part) batches of differently treated specimens with and without notches. In each case, ground as well as shot peened specimens are compared. The Rockwell hardness numbers of the shots used are indicated.

3.2 Wöhler-curves

In fig. 3 the Wöhler-curves of shot peened, quenched and quenched and tempered specimens are summarized. Additionally, Wöhler-curves of notched and smooth specimens nearly free of residual stresses, which were finally manufactured by grinding, are given by thin lines.

As can be seen from the upper part of fig. 3, in the case of quenched specimens, shot peening results in a considerable improvement of the bending fatigue behaviour. Although the bending fatigue strength of smooth specimens will only be enhanced about 14 % by shot peening, peening of notched specimens with shot of low hardness (46 - 50 HRC) and high hardness (54 - 58 HRC) yields an increase of 51 % and 82 % in the bending fatigue strength, respectively. It seems to be important that the bending fatigue strength of notched and smooth specimens peened with shot of 54 - 58 HRC do nearly coincide, if number of cycles to fracture larger than 5×10^6 are considered. In all notched specimens crack initiation occurred at the surface of the notch root. In smooth specimens, cracks initiated about 0.5 mm below the surface.

Also, in the case of quenched and tempered specimens with and without notches as shown in the lower part of fig. 3, improvements of bending fatigue strengths by shot peening can be achieved. Using a shot with 46 - 50 HRC notched and smooth specimens reveal an increase in the fatigue strengths of 38 % and 22 %, respectively. These values are considerably smaller than those for quenched specimens. From fig. 3 it can also be seen that the Wöhler-curves of peened and ground specimens run close together at low numbers of cycles to fracture. Consequently, shot peening has no large influence on the bending fatigue life of specimens loaded with relatively high stress amplitudes. In all cases, crack initiation occurred at the surface of the specimens.

4. Discussion

The experimental results presented above showed the following important aspects:

- In the quenched state shot peening improves the bending fatigue behaviour of Ck 45 specimens with and without notches.
- The improvement of the fatigue strength of notched specimens which increases with increasing hardness of the shot is remarkable.
- In comparison with notched specimens, the enhancement of high cycle fatigue strength of smooth specimens is rather small.
- In the quenched and tempered state shot peening also improves the bending fatigue behaviour of notched and smooth specimens.
- The improvement of the bending fatigue behaviour is almost entirely restricted to small loading amplitudes leading to high number of cycles to fracture.
- The increase in bending fatigue strength due to shot peening is distinctly smaller than in the case of quenched specimens.

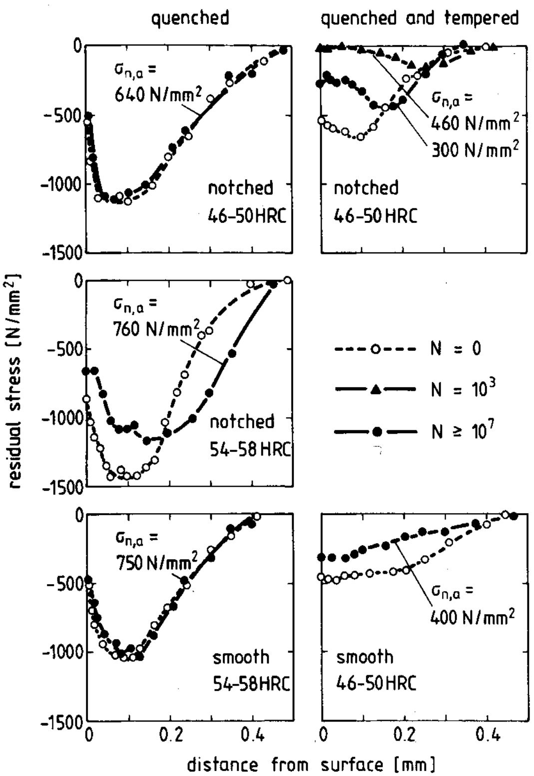


Fig. 4: Residual stresses in unloaded (N = 0) and cyclically loaded ($N = 10^3$ and $N = 10^7$) specimens with and without notches vs. distance from the surface. In every case, the cyclic nominal stress amplitudes applied and the Rockwell hardness numbers of the shots used are indicated.

To assess these findings, first of all it seems necessary to discuss the stability of the shot peening residual stresses during the bending fatigue tests. Typical examples of the residual stress distributions below the surface of not loaded (open circles) and cyclically loaded (dots and triangles) bending specimens are shown in fig. 4. At the left part of the figure, results of quenched specimens with a lifetime larger than 10^7 (solid lines) are compared with those of uncycled specimens (dashed lines). The appertaining cyclic nominal stress amplitudes $\sigma_{n,a}$ are indicated. The local stress amplitudes in the notch root of the notched specimens are approximately given by α_k $\sigma_{n,a}$ equal to 1088 N/mm^2 and 1275 N/mm^2, respectively. These values considerably exceed the cyclic nominal stress amplitude $\sigma_{n,a}$ = 750 N/mm^2 of the smooth specimens considered. As can be seen, only in notched specimens peened with shot of high hardness the residual stress distributions change. As a consequence of locally high compressive residual stresses and of high stress amplitudes, the peening residual stresses relax during cyclic loading at the very surface and in a thin zone below the surface and the locus of the maximum residual stresses shifts to a larger distance from the surface. Nevertheless, even after 10^7 cycles there are still compressive residual stresses exceeding 1100 N/mm^2 below the surface. Obviously, the high stability of the peening residual stresses in quenched specimens with notches accounts for the considerable improvement of the bending fatigue strength due to shot peening. However, the comparatively small increase in bending fatigue strength of smooth specimens cannot be explained on this basis and will be discussed later on.

The right-hand side of fig. 4 shows for quenched and tempered specimens with and without notches, characteristic examples of residual stress distributions due to shot peening and after subsequent cycling up to 10^7 cycles. For peened notched specimens, also the residual stress distribution after 10^3 cycles with $\sigma_{n,a}$ = 460 N/mm^2 is shown. In this particular case, according to fig. 3 approximately 5×10^4 cycles to failure have been expected. Notched specimens loaded with $\sigma_{n,a}$ = 300 N/mm^2 as well as smooth ones fatigued with $\sigma_{n,a}$ = 400 N/mm^2 show a considerable decrease of compressive residual stresses. In distances up to 0.1 mm below the surface, the residual stress relaxation in the notched specimens is twice that in the smooth one. On the other hand, 10^3 cycles with $\sigma_{n,a}$ = 460 N/mm^2 completely remove the compressive residual stresses at the notch ground and almost entirely below the surface of notched specimens. Thus, such and similar loading conditions do not let expect beneficial effects of peening compressive residual stresses on the bending fatigue behaviour. The still occurring small increase in the fatigue life of shot peened notched specimens cycled with $\sigma_{n,a} > 310$ N/mm^2, which is documented by the results in fig. 3 may be caused rather by the increased workhardening state than by the peening residual stresses. The moderate increase in the bending fatigue strength of the shot peened notched specimens in comparison with the unpeened ones for lifetimes > 5×10^5 can be contributed to incomplete stress relaxation during the bending fatigue tests.

As a consequence of the local differences of hardness and residual stresses at and near the surface of shot peened specimens, local fatigue strength distributions

$$R_D(z) = R_W(z)\left(1 - m\frac{\sigma^{RS}(z)}{R_{W(z)}}\right)$$

can be defined (4,15). $R_D(z)$ is the local fatigue strength, $R_W(z)$ the fatigue strength of specimens free of residual stresses, $\sigma^{RS}(z)$ the residual stress, and m is the residual stress sensitivity with m = 0.4 for quenched and m = 0.3 for quenched and tempered smooth specimens of Ck 45 (16). This equation is similiar to the Goodman-relationship which describes the influence of mean stresses on the fatigue strength. Appropriate R_W-values can be taken from fig. 3, which reveals fatigue strengths of ground smooth specimens free of residual stresses. R_W = 675 N/mm^2 for quenched specimens and R_W = 340 N/mm^2 for the quenched and tempered specimens are obtained. Neglecting the shot peening induced variations of hardness and surface roughness, the full lines in fig. 5 are computed as the local fatigue strength distributions of the material states of interest. The dashed lines describe the loading stress distributions for amplitudes which yield a fracture cycle number > 10^7. In both quenched specimens with notches, the loading stresses exceed the local fatigue strengths only at and near the surface. Hence, cracks are expected to initiate at the notch root surface and to propagate through material zones subjected to high residual compressive stresses. As a consequence, the bending fatigue strengths should increase with increasing peening compressive residual stresses. According to fig. 2, the magnitude of the peening residual stresses can be enhanced with the hardness of the shot used.

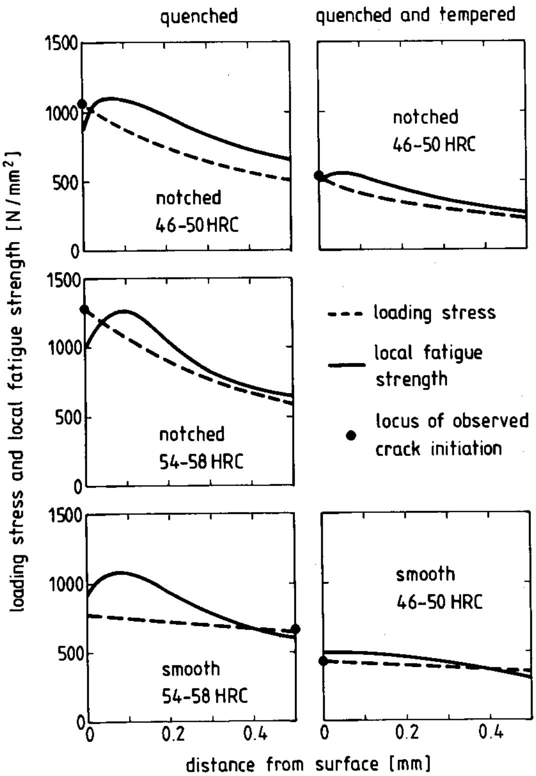


Fig. 5: Loading stress amplitudes for fatigue life > 10^7 cycles and local fatigue strengths of quenched (left) and quenched and tempered (right) specimens with and without notches vs. distance from the surface. The Rockwell hardness numbers of the shots used are indicated.

In contrast to this, in the smooth specimens considered, the loading stress amplitudes exceed the local fatigue strength in a distance of approximately 0.4 mm from the surface, because the stress gradient in smooth specimens is much smaller than in notched ones. Consequently, only a small increase in bending fatigue strength by shot peening is expected which corresponds to the difference in the loading stress amplitudes at the surface and at the locus of crack initiation. With increasing nominal stress amplitudes $\sigma_{n,a}$, that is with decreasing number of cycles to fracture, the stress gradients inrease, and the appertaining loci of crack initiation shift towards the surface into zones which bear higher compressive residual stresses. Consequently, the increase in bending fatigue strength by shot peening is much more pronounced at lower than at higher numbers of cycles to fracture. All conclusions drawn are in full agreement with the results presented in fig. 3.

Due to shot peening in quenched and tempered specimens with and without notches, only small increases in the local fatigue strengths at and near the surfaces of interest arise. This is a consequence of the relatively small amounts of compressive residual stresses produced by shot peening. Furthermore, the relaxation of these stresses during cyclic bending reduces the local fatigue strengths. Altogether, in notched specimens crack initiation is expected at the notch root. As can be seen in the upper part at the right side of fig. 5, this conclusion agrees with the experimental observations. On the other hand, the smooth specimens considered should reveal crack initiation below the surface, which, however, is not observed experimentally. This discrepancy may be caused by the already mentioned stress relaxations during the bending fatigue tests (see fig. 4).

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