# RESIDUAL STRESS SENSITIVITY OF CASE-HARDENED NOTCHED SPECIMEN



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## ABSTRACT

Case-hardened gear wheels e.g. in vehicle transmissions are very high cyclically stressed components. Their lifetime is determined by the interaction of loading, tooth flank load-capacity and tooth foot load-capacity. The latter is influenced by a multitude of parameters. One of them is the residual stress state which appears during operation. In this contribution results from the investigation of case-hardened notched specimen with different residual stress states under a cyclic bending loading without and with mean loading are reported. The load capacity of the specimens are analysed using a local concept and an additional consideration of a fracture mechanical approach. The different residual stress states arose from the case-hardening treatment on the one hand and were produced by different shot peening treatments on the other hand.

The different specimen variants exhibit strongly different fatigue strengths and different dependencies of the fatigue strength on the mean loading. With the local concept it was possible to determine the crack initiation site which was partly at the surface and partly below the surface. The fracture mechanical approach was necessary to understand the crack stop behaviour e.g. of surface cracks which develop especially at shot peened specimens. Using a local concept a uniform description of all notched specimen variants could be achieved by a modified Haigh diagram which takes into account the local stress condition at the failure critical site.

## SUBJECT INDEX

Fatigue, Case-Hardening, Residual Stress Sensitivity, Mean Stress Sensitivity, Local Concept

## INTRODUCTION

The lifetime of case-hardened gear wheels is determined by the interaction of a complex loading and the load capacity of the gear wheel. Especially the tooth foot load-capacity is influenced by a multitude of parameters. One of them is the residual stress state which is effective during operation. Case hardened gear wheels exhibit after a heat treatment according to the level of technology compressive residual stresses in the hardened surface layer in the unloaded condition. These residual stresses are induced primarily by the heat treatment and may be changed significantly by a shot peening process especially in the area of the tooth foot. It is well known that compressive residual stresses reduce the harmful effect of the tensile loading stresses. Therefore, an increase of the fatigue strength is ascribed to them generally. Also in the case of gear wheels the tooth foot load-capacity is determined by the interaction load stresses, residual stresses and material strength. Despite the beneficial effect of residual stresses on the lifetime behaviour of gear wheels up to now it is not allowed to consider compressive residual stresses in the standardized dimensioning of the tooth foot according to German standards [1]. One of the reasons for this situation is that the mode of action of residual stresses at inhomogeneous microstructures which arise during case-hardening, are not definitively cleared. Particularly it is still unclear whether residual stresses and load mean stresses have different effects on the fatigue strength or act uniformly at case-hardened components. The investigations on hand to this topic usually refer to homogeneous material conditions [2]. Therefore, in this paper it shall be checked whether the known relations to describe the influence of residual stresses are valid for case-hardened specimens.

## SPECIMENS / EXPERIMENTAL PROCEDURE

Specimens with notches on both sides made of the steel 16MnCr5 were used for the examinations. The notches were milled using a tooth shape cutter. Therefore, the notches had similar geometry conditions as it appears at gear wheels with a module of 3. The notch factor amounts $k_t \approx 1.57$ and the related stress gradient which describes the stress distribution near the surface is $\chi^* = 0.81$ MPa/mm. At the outer edges of the specimens chamfers were worked in to reduce the danger of a too high carbon content at the edges during the heat treatment (edge effect). After mechanical processing the specimens were case hardened industrially by ZF-Friedrichshafen, Germany.

For the experimental determination of the mean stress sensitivity and the residual stress sensitivity eight specimen variants were defined to indicate the used load ratio $R = \sigma_{bend,min} / \sigma_{bend,max}$ and the respective shot peening condition. Load ratios between R = -1 and 0.8 were realized. Two shot peening procedures were carried out at the institute using a Baiker air blast facility. One with a high peening intensity (blasting pressure 3 bar resulting in an Almen intensity of 0.54 mmA) and one with a medium peening intensity (blasting pressure 2 bar resulting in an Almen intensity of 0.45 mmA). The respective variants were marked as variant A to J.

To determine the fatigue strength of the respective specimen variants deflection controlled cyclic bending experiments were carried out. With 20-25 specimens each per variant the fatigue strength for a failure probability of 50 % was determined using the stair case method [3,4]. The single tests were run until macroscopic crack initiation or up to the ultimate number of cycles $N_u = 10^7$.

## RESULTS

### Microstructure

After case-hardening in the notch root of the specimen the microstructure consists of martensite with about 20 % retained austenite. At the surface an oxidized zone reaching 5 – 10 µm into the depth was observed. In the core of the specimens a martenisitic / bainitic microstructure was found. The case hardening depth was about 0.6 mm.

**Residual Stresses**

Characteristic depth distributions of the residual stresses were determined from X-ray measurements using the $\sin^2\psi$-method. For the unpeened specimen variants an unloaded as well as a run-out specimen from each test series was investigated. The residual stress state produced during the heat treatment was not changed during tests with R = -1, 0.1 and 0.5 (variants A, D and E, see Fig. 1a)). The maximum of the residual stresses lies at the surface and amounts to about –230 MPa. With increasing depth the compressive residual stresses decrease continuously. Caused by load induced retained austenite transformation the run-out specimen of the variant J (R = 0.8) exhibits a residual stress depth distribution with a maximum about 40 µm below the surface and a value of about –580 MPa. In Fig. 1b) and 1c) the depth distribution of the residual stresses of the variants shot peened variants is represented. As can be seen, the residual stress state produced by the shot peening with high intensity remains stable during the fatigue tests under the chosen loading conditions. For these variants a residual stress distribution with a maximum of about –1170 MPa in depth of about 45 µm can be regarded as characteristic (Fig 1b)). Another situation exists at the variant C which was shot peened at a medium intensity (Fig. 1c)). After shot peening a depth distribution with a maximum of about –990 MPa about 20 µm below the surface is observed. A fatigue loading in the transition lifetime range increases the maximum of the compressive residual stress to about –1180 MPa and moves it deeper into the material to a depth of about 50 µm. Loading induced retained austenite transformation are responsible for this effect.

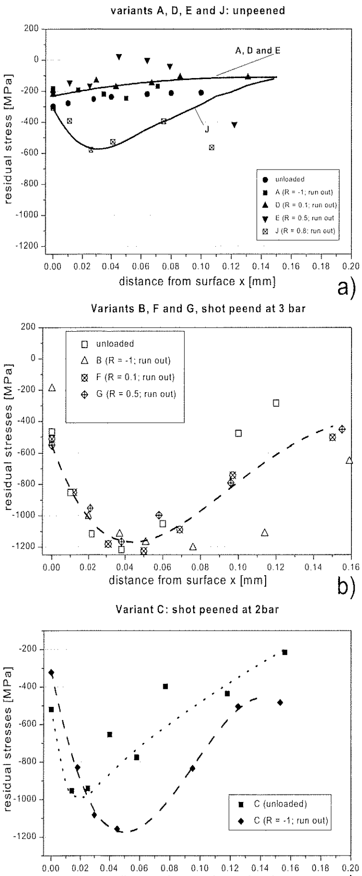


Fig. 1: Characteristic depth distribution of the residual stresses in the different variants of specimens

**Fatigue Tests**

Fig. 2 summarizes the results of the fatigue tests with shot peened and unpeened specimen variants in a Haigh diagram in which the nominal fatigue strength is plotted over the nominal mean loading. The marked values correspond to the 50 % failure

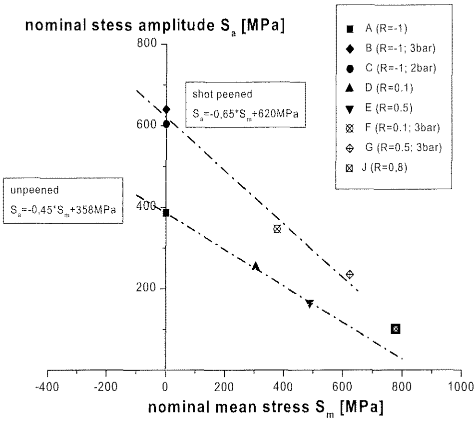


Fig. 2: Haigh diagram for the different variants

probability of the nominal fatigue strengths which were determined at the different loading conditions from the respective series of experiments. As expected, in comparison with the shot peened specimens for the unpeened specimens variants considerably lower nominal fatigue strengths are observed. However, for the unpeened variants A, D, E and J the evaluated best fit straight line satisfactorily describes the results only for the three lowest load ratios. This regression straight line yields to a fatigue strength of about 385 MPa for zero mean stress and a mean stress sensitivity M = -0,45. But for a load ratio R = 0.8 a considerably higher fatigue strength appears. For the shot peened specimen variants B, C, G and F a best fit straight line arises from which formally a nominal fatigue strength of about 620 Mpa at zero mean stress and a mean stress sensitivity M = -0.65 could be setimated. Thus, the consideration of the nominal loading stresses results in different mean stress sensitivities for the shot peened and the unpeened specimen variants.

## DISCUSSION AND CONCLOSIONS

This is a further indication that the consideration of the nominal stresses is not satisfactory for the life time estimation of cyclically loaded components. An alternative is the local concept. This is based on the comparison of the local loadings appearing at failure critical sections of a component and the local material resistance at this sections and, therefore, in principle offers the possibility of taking into account consequences of loading gradients, mean stresses and local residual stresses at the assessment of the fatigue strength behaviour. In the following the application of the local concept is discussed under bend loading of case-hardened notched specimens. Prerequisite for it shall be that a simple model is valid for the estimation of the fatigue strength and that the required characteristic values can be found out experimentally or assessed empirically in a way as simple as possible. Details to this may be found in [5], for example.

A consideration of the durability of a component according to the local concept is either based on the depth distribution of the local strength or on the depth distribution of fracture mechanical characteristic values. Since the transition from the short crack behaviour to the long crack behaviour is not well-known especially for high-strength martensitic material conditions both a consideration of the local fatigue strength as well as fracture mechanical consideration is necessary. The consideration of the local fatigue strength results in the estimation of the crack initiation site. The fracture mechanical approach assesses the crack growth behaviour. In the following only the consideration of the local fatigue strength is reported. Information concerning the fracture mechanical concept are included in [6].

The estimation of prospective crack initiation sites results from the comparison of the depth distribution of the load stresses and the depth distribution of the local fatigue strength. For the case-hardened surface areas which reach a depth of approx. 100 –200 µm the material properties are regarded as homogeneous. Therefore, in this area the local fatigue strength depends only on the distribution of the residual stresses.
To calculate the local loading stress distribution of the notched specimens a related stress gradient $\chi^*$ was used for the surface near area:

$$\chi^* = \left| \frac{1}{\sigma_{\max}} \cdot \frac{d\sigma(x)}{dx} \right| = 0.81. \qquad (1)$$

The maximum stress $\sigma_{max}$ in the notch root is given by the product of the maximum of the nominal stress $S_{max}$ and the notch factor $k_t$. The depth distribution of the loading stresses as a function of the distance from the surface x is calculated as

$$\sigma(x) = \sigma(x=0) \cdot (1 - \chi^* \cdot x). \qquad (2)$$

Thus, the depth distribution of the permitted loading amplitude $\sigma_D^{load}$ as the local fatigue strength arises as

$$\sigma_D^{load}(x) = \sigma_a(x) - M \cdot \sigma_m(x) - m \cdot \sigma^{RS}(x) \qquad (3)$$

with M as mean stress sensitivity and m as residual stress sensitivity. The distribution of the residual stresses $\sigma^{ES}(x)$ is estimated from the characteristic stress distribution of the respective variant (see Fig. 1). For the first calculations as fatigue strength at the surface the estimated fatigue strength for 50% failure probability from the respective test series was used. As initial values plausible values of M = m = 0.4 for the mean stress and the residual stress sensitivity were assumed.
From the comparison of the local loading stress distribution with the local fatigue strength distribution the crack initiation site could be determined. Everywhere where loading stresses are higher than the local fatigue strength cracks which are able to propagate could be initiated. These sites represent the critical areas. The local fatigue strengths and the local mean loadings as the sum of the local mean stress and residual stress arising from these considerations are registered in a modified Haigh diagram. In this representation a first-order approximation arises for the actual valid values of residual stress free fatigue strength and the mean stress as well as residual stress sensitivity of the respective variants. With these values the depth distribution of the local fatigue strength is calculated newly and compared with the distribution of the local acting stresses. After few iteration steps stable values arise. Figure 3 exemplarily shows the result of the last iteration for the variant A (Fig. 3a)) and the variant J (Fig. 3b)).
It turns out that the surface represents the critical areas at the variant A. Therefore, the values of the local fatigue strength and the local loading conditions relevant for this variant are in the depth 10 µm which is the depth of the surface layer oxidation. At the variant J two critical sites arise. These are at the surface and in a depth of about 80 µm where the local loading stresses are higher than the local fatigue strength. Thus, both sites are potential crack initiation sites. With a fracture mechanical approach it can be shown that the crack initiating at the surface has not the potential to grow. Therefore only the crack initiating in a depth of 80 µm below the surface is relevant for failure. The values arising for all variants investigated are represented together in a modified Haigh

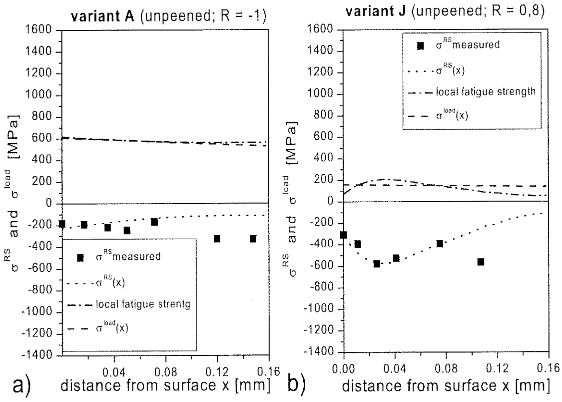


Fig. 3: Comparison between local fatigue strength an load stress distribution for variant A (a)) and variant J (b)).

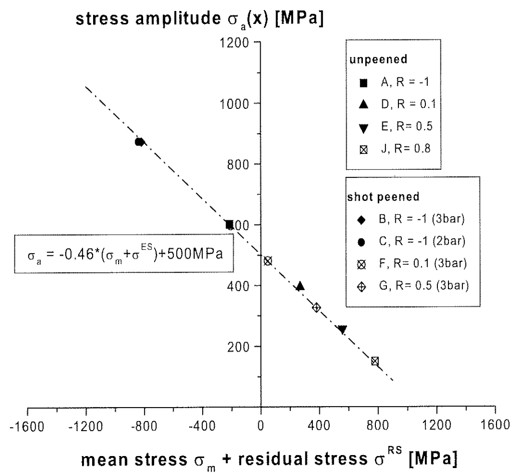


Fig. 4: Modified Haigh diagram for the different variants.

diagram in Figure 4. This Figure points out that the results for all specimen variants lies on one common best fit straight line. As residual stress free fatigue strength a value of about 500 Mpa is obtained and both the mean stress and the residual stress sensitivity amount to 0.46, values which finds itself frequent in the literature. But this also means, that for the investigated material state there is no difference between mean stress sensitivity and residual stress sensitivity.

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