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Fatigue strength and failure mechanisms in the VHCF-region for quenched and tempered steel 42CrMoS4 and consequences to fatigue design

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Abstract

Investigations on quenched and tempered steel 42CrMoS4 from two batches ($R_m = 1100$ MPa, $1350$ MPa) are presented. Fatigue tests with smooth ($K = 1$) and notched ($K = 1.75/1.55$) and partly shot peened specimens were conducted at $R = -1$ and $R = 0$ up to $N = 2 \times 10^9$ to determine fatigue strength behavior and failure mechanisms. A possibility for analysis of experimental data including VHCF-results is explained. From the comparison of the results with a S-N curve from a design code recommendations for design and assessment of components are derived.

Keywords: Fatigue strength; VHCF; quenched and tempered steel; 42CrMoS4; inclusions

1. Introduction

Many components in the field of mechanical engineering are subjected to cyclic loading. For their assessment design codes include S-N or Wöhler-curves at number of cycles greater than $N = 5 \times 10^7$ (LCF-region) which are represented by a straight line in a double logarithmic scale

$$N = N_k \cdot \left( \frac{\sigma_{na}}{\sigma_{NK}} \right)^{-k}$$

(1)

There are k slope, $\sigma_{na}$ nominal or local stress amplitude and $\sigma_{NK}$ stress amplitude at point of deflection $N_k$, for instance $10^6$ for steel and cast iron in [1] or $5 \times 10^6$ for steel in [2]. S-N curves are specified for probability of survival values $P_s$ of for instance 50% or 97.5%. From experimental data the scatter of stress has to be calculated

$$\frac{1}{T_s} \frac{\sigma_{na}(P = 10\%)}{\sigma_{na}(P = 90\%)}$$

(2)

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In some cases $\sigma_{nk}$ is also the fatigue limit which means that all stresses below that value can be sustained infinitely [1, 2]. Some codes as for instance the IIW-recommendation for welded joints [3] assume a further decrease of fatigue strength and describe it analogous to Eq. 1 but with a slope $k^* = 22$ for instance. The reason for that is that in the last years many investigations were done with fatigue tests in the very high cycle fatigue region (VHCF) up to $N > 10^7$ [4, 5, 6]. The results show failure for some materials and some up to now unknown failure mechanisms as internal failure.

The aim of the now described investigation [7] was to determine the fatigue strength and the failure mechanisms especially in the VHCF-region at number of cycles $10^7 < N < 10^9$ for the quenched and tempered steel 42CrMoS4 which is widely used in the two selected material states. Every construction has notches. Their influence on the fatigue behavior was important to investigate too. Shot peening as a possibility to increase fatigue strength had to be investigated selectively. Existing research results had to be reviewed from the perspective of designers and calculation engineers. Another question was whether design codes especially the FKM-Guideline Analytical strength assessment of components [1] gives a conservative estimation of fatigue strength in the VHCF-region.

Investigations on different quenched and tempered steels in the VHCF-region are described in [8, 9, 10, 11, 12]. In all cases failure at higher number of cycles occurs from inclusions inside. A significant reduction in fatigue strength could be found in JIS 435SCM (34CrMo4) for smooth specimens but is only 3% in 42CrMo4 ($R_m \approx 1500$ MPa) [8] at $10^7 < N < 10^9$ and $R=-1$. The influence of the direction of rolling on the fatigue strength is important. In [10, 11] 42CrMo4 with $R_m = 1530$ MPa shows failure at $10^9 < N < 10^{10}$ but not with $R_m = 1100$ MPa.

2. Material

The materials tested were quenched and tempered steel 42CrMoS4 from two different batches. Table 1 shows material properties and the chemical composition. For determination of cyclic material behavior incremental step tests were done. They show cyclic softening for both batches with a higher decrease of strength for the higher strength batch, see Fig. 1.

The microstructure of the steels shows a typical quenched and tempered structure with former austenite grain size of 12 µm. The residual austenite content is 3.3%. Examinations of the purity degree offer a mean sulfidic inclusion size of 32 µm but no oxidic inclusions of this size. However, after the failure of the specimens the fracture surfaces of both batches show an average oxide size of 80 µm with a maximum size of 130 µm when failure occurs from inclusions inside the specimen.

| Material   | $E$ [GPa] | $R_{po.2}$ [MPa] | $R_m$ [MPa] | $A$ [%] | $Z$ [%] | C  | Si  | Mn  | P   | S   | Cr  | Mo  | Ni  | Cu  |
|------------|-----------|------------------|-------------|--------|--------|----|----|----|-----|-----|-----|-----|-----|-----|
| 42CrMoS4   | 212       | 1000             | 1100        | 16     | 55     | 0.42| 0.30| 0.86| 0.015| 0.023| 1.15 | 0.25 | 0.22 | 0.26 |
| 42CrMoS4   | 208       | 1257             | 1350        | 13     | 53     | 0.41| 0.23| 0.79| 0.016| 0.010| 1.05 | 0.21 | 0.03 | 0.03 |

Fig. 1. Static and cyclic stress-strain behaviour for both batches of 42CrMoS4
3. Experimental procedure and analysis

Fatigue tests were conducted in air at room temperature under constant tension or rotating bending amplitude at R = -1 and 0.1 with smooth (K_t = 1) and notched specimens (K_t = 1.75 for tension and K_t = 1.55 for bending). The maximum number of cycles was N = 2 \times 10^9 when using a servohydraulic testing machine (VHF) with f ≈ 200 to 400 Hz, a high frequency resonant machine (HFP) with f = 150 Hz and rotating bending machines (RBM) with f = 50 Hz. Additional tests were conducted with an ultrasonic test system (USP) with f = 20 kHz up to N = 2 \times 10^9 (University BOKU, Vienna). All together 180 specimens were tested.

Examples of the shape of the specimens are given in Fig. 2. For the smooth specimens the diameter in the minimum cross section was 5 mm at VHF, HFP and RBM. At the USP it was 3 mm. For the notched specimens the minimum diameter was 6 mm in every case. All specimens were manually turned and ground. Smooth specimens were mechanically polished. Single measurements of residual stresses at the surface of smooth and notched specimens show that there are already compressive residual stresses of about 200 to 300 MPa. Some specimens of the lower strength batch were shot peened.

The failure mechanisms were studied by scanning electron microscope investigation of the fracture surface. All together the initiation sites of 105 broken specimens were analysed concerning position and type of inhomogeneities. Three different types of crack initiation sites were distinguished—surface, subsurface when it was very close to the surface and internal.

The statistical evaluation of the fatigue strength can be done in different ways for instance with the staircase method, the arcsin√p-method, a polynomial regression or the maximum likelihood method. They are used for the analysis of different regions of the S-N curve. Up to now there is no special method for the VHCF-region. Because of the large scatter of data according to microstructural effects and the few experimental results an adoption or extrapolation of named methods is difficult and the results differ strongly. Here at first the results were compared with the FKM-Guideline [1] where a fatigue limit is assumed from N = 10^6 and the slope of the S-N curve k is 5 for components. For smooth specimens k = 15 is realistic [13].

Then the results were analysed whether failure at N > 10^7 or a change from surface to subsurface or internal failure occurred. If this was the case a decrease of fatigue strength in the VHCF-region was assumed. A recommendation with N_k = 5 \times 10^5, k^* = 45 and 1/T_e = 1.4 from [14] was used which was derived from a literature study of several materials and fits the here achieved results very well. But there still another curve can be fitted as well. The experimental results in the LCF-region to 5 \times 10^5 were analysed by a regression with Eq. 1. If there was no failure in the VHCF-region or no change in failure mechanism a fatigue limit is assumed in the VHCF-region. It was calculated by the arcsin√p-method [15] as well as the S-N curve.

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*a, b, c* Examples of specimens, a) smooth specimen for VHF/RBM; b) notched specimen for VHF/RBM; c) smooth specimen for USP
4. Fatigue strength and failure mechanisms

4.1. Fatigue strength

The experimental results of the fatigue tests of smooth and notched specimens of 42CrMoS4 ($R_m = 1100$ MPa) at $R = -1$ under tension loading are shown in Fig. 3, for rotating bending in Fig. 4 and for $R = 0$ under tension loading in Fig. 5. Included are the S-N curves, Eq. 1 and 2. For smooth specimens and $R = -1$ there is a marginal decrease of fatigue strength in the VHCF-region which is more distinctive at $R = 0$. There is a large scatter in lifetime in the VHCF-region which shows that the effect of microstructure is increasing with increasing number of cycles and that the influence of surface finish is decreasing. The lower fatigue strength of specimens tested at 20 kHz in comparison with the results at 185 Hz at $R = 0$ is noticeable, Fig. 5. Normally this is not the case. A reason for that could not be found yet.

Notched specimens have a fatigue limit in the investigated lifetime region. Shot peening, as expected, increases the fatigue strength.

![Fig. 3. Experimental results and S-N curves for 42CrMoS4 ($R_m = 1100$ MPa) for smooth and notched specimens under tension loading at $R = -1$](image1)

![Fig. 4. Experimental results and S-N-curves for 42CrMoS4 ($R_m = 1100$ MPa) for smooth, notched and notched and shot-peened specimens under rotating bending at $R = -1$](image2)
The experimental results of the fatigue tests of smooth specimens of 42CrMoS4 (Rm = 1350 MPa) under tension loading at R = -1 and R = 0 are shown in Fig. 6. Here especially for R = -1 a decrease of fatigue strength in the VHCF-region is observed.

4.2. Failure Mechanism

In the LCF-region crack initiation sites are at the surface. There is usually more than one crack initiation site at higher stresses but only one at lower values.

In the VHCF-region the crack initiation sites of smooth specimens of 42CrMoS4 (Rm = 1110 MPa) are direct at the surface, Fig. 7 (R = 0), or at globular oxides at or close to the surface, Fig. 8 (R = -1). Internal crack initiation sites from oxides are very seldom, Fig. 9 (R = -1) and 10 (R = 0), but even occur under rotating bending, Fig. 11.

For the 42CrMoS4 (Rm = 1350 MPa) the crack initiation sites at R = -1 are globular oxides inside the specimen. A typical fracture surface is shown in Fig. 12 and in Fig. 13 in detail. It has 6 different crack growth regions. In region 1 the fracture surface is very plane because of low crack growth rate. Region 2 has a radial structure with a...
higher crack growth rate as a comparison of striations shows. In region 3 and 4 the surface gets rougher. Region 5 results from static fracture with a shearing surface in 6. This is also found in rotating bending. Specimens with large oxides have a short lifetime of course, Fig. 14. At $R = 0$ surface and internal failure from globular oxides occurs, Fig. 15 and 16.

The crack initiation site of the notched specimens is always at the surface because of stress concentration. Oxides are not important there. They are intrinsic notches which have a strong influence on fatigue behavior only for smooth specimens in the VHCF-region. Whether surface or subsurface failure occurs also depends on the diameter of the specimen and the then different probability of having oxides at the surface or in the volume of the specimen. It seems that the steel with the higher strength ($R_m = 1350$ MPa) is more susceptible to failure in the VHCF-region than the lower strength steel although ductility and microstructure are comparable.

For the estimation of fatigue strength including inclusion sizes the $\delta$-area-method by Murakami [16] is often used but in this case not satisfying. A calculation of fatigue strength is also complicated because metallographic analyses do not give the correct average or maximum inclusion size which is found at the fracture surfaces, Chapter 4. Therefore much more metallographic or other analyses would have been necessary to give information about inclusion size and distribution in the specimen volume.

Fig. 7. Fracture surface with surface crack initiation site for smooth specimen of 42CrMoS4 ($R_m = 1100$ MPa), $\sigma_s = 285$ MPa, $N = 9.62 \times 10^8$, $R = 0$, a) overview, b), c) detail of crack initiation site

Fig. 8. Fracture surface with surface crack initiation site for smooth specimen of 42CrMoS4 ($R_m = 1100$ MPa), $\sigma_s = 610$ MPa, $N = 4.92 \times 10^7$, $R = -1$, a) overview, b) detail of crack initiation site with c) globular oxide 30 $\mu$m

Fig. 9. Fracture surface with internal crack initiation site for smooth specimen of 42CrMoS4 ($R_m = 1100$ MPa), $\sigma_s = 600$ MPa, $N = 1.06 \times 10^6$, $R = -1$, a) overview, b) detail of crack initiation site with c) globular oxide 79 $\mu$m
Fig. 10. Fracture surface with internal crack initiation site for smooth specimen of 42CrMoS4 ($R_m = 1100$ MPa), $\sigma_s = 450$ MPa, $N = 1.04 \times 10^6$, $R = 0$, a) overview, b) detail of crack initiation site with c) former place of globular oxide 52 $\mu$m.

Fig. 11. Fracture surface with internal crack initiation site for smooth specimen of 42CrMoS4 ($R_m = 1100$ MPa), $\sigma_s = 600$ MPa, $N = 9.63 \times 10^5$, $R = -1$ (rotating bending), a) overview, b) detail of crack initiation site with c) globular oxide 68 $\mu$m.

Fig. 12. Fracture surface with internal crack initiation site for smooth specimen of 42CrMoS4 ($R_m = 1350$ MPa), $\sigma_s = 480$ MPa, $N = 2.0 \times 10^6$ (no failure), $\sigma_s = 620$ MPa, $N = 9.01 \times 10^7$, $R = -1$, a) overview, b) detail of crack initiation site with c) globular oxide 52 $\mu$m.

Fig. 13. Typical fracture surface with internal crack initiation from a globular oxide and 6 different crack growth regions, detail from Fig. 12.
5. Fatigue design and assessment of components

For assessment and construction of components design codes are used. The included S-N curves are based on extensive experimental investigations, which were done in the most cases with specimens, and practical experiences with components. Very often a fatigue limit is assumed at for instance $N = 10^6$ [1]. Furthermore a safety concept with safety factors for all input parameters as loading and material has to exist to prevent failure of components. Experimental investigations included fatigue tests in the LCF- and HCF- but not in the VHCF-region in the most cases. So possible decreasing fatigue strength in this region is only considered in the safety margin which will decrease too with number of cycles. The application area of design codes is also not explicitly limited to special materials strength. High strength materials are not excluded although their VHCF-behavior may be important and different from low-strength materials.
The results of the explained investigations in comparison with the design code FKM-Guideline *Analytical strength assessment of components* [1] are summarized in Table 3. Safety factors are not considered.

For the quenched and tempered steel 42CrMoS4 an assessment of notched specimens would have been safe in general and also in the VHCF-region. Only the results of the smooth specimens (Rm = 1100 MPa) at R = 0 and 20 kHz are not conservative in comparison with [1] whereas these results also do not fit the expected behavior in Fig. 5 as already mentioned in Chapter 4. For the smooth specimens (Rm = 1350 MPa) at R = -1 only the specimen in Fig. 14 with an unusually large inclusion would have been assessed as not safe by [1]. But taking into account usual safety factors in both cases the assessment of the smooth specimens would have been safe too.

Following recommendations for fatigue design and assessment of components are given as result of the investigations:

- The number of cycles which the component has to sustain has to be estimated. From this, from the known material behavior in the VHCF-region and the stress concentration in the component it has to be decided whether a decrease of fatigue strength at N > 10^6 has to be considered or not. Adequate safety factors have to be used.
- Although here notched specimens do not show a decrease of fatigue strength in the investigated number of cycles but only smooth specimens do components can have large volumes and small stress concentrations where failure at very high number of cycles can occur at material inhomogeneities. So care must be taken in these cases.
- If a decrease of fatigue strength in the VHCF-region has to be assumed a S-N curve with a point of deflection N_k = 5⋅10^5 and a slope k* = 45 can be used. The term fatigue limit should be carefully used and is possibly to substitute by fatigue strength at a definite number of cycles.
- Experimental investigation should include fatigue tests up to higher number of cycles for instance N > 10^7.
- Quality of material concerning the inhomogeneities as inclusions has to be observed carefully especially their homogeneous distribution in size and location.

| Tensile strength Rm [MPa] | Specimen K_t | Load ratio R | Decrease of fatigue strength at N>10^6 | Fatigue limit at N=10^6 [MPa] | PS=97.5% from [1] | Conservative fatigue design [1] at N>10^6 |
|--------------------------|--------------|--------------|----------------------------------------|-------------------------------|-------------------|-----------------------------------|
| 1110                     | 1            | -1           | marginal                               | 460                           | yes               |                                  |
| 1110                     | 1            | 0            | yes                                    | 366                           | (no)              |                                  |
| 1350                     | 1            | -1           | yes                                    | 559                           | (no)              |                                  |
| 1350                     | 1            | 0            | no                                     | 419                           | yes               |                                  |
| 1110                     | 1.75         | -1           | no                                     | 294                           | yes               |                                  |
| 1110                     | 1.75         | 0            | no                                     | 235                           | yes               |                                  |

6. Conclusions

The results of the fatigue investigations on quenched and tempered steel 42CrMoS4 with two different tensile strength (Rm = 1100 MPa, 1350 MPa) and nodular cast iron EN-GJS-900-2 at R = -1 and R = 0 can be summarized as follows:

- Notched specimens (K_t = 1.75) show a fatigue limit in the investigated lifetime region up to N = 2⋅10^9. Crack initiation site is always at the surface according to stress concentration.
- Smooth specimens have a slight decrease of fatigue strength in the VHCF-region.
There is a large scatter in lifetime in the VHCF-region which can only be correctly analysed by testing a high number of specimens. This was not possible. Therefore a recommendation \( N_k = 5 \times 10^5, k^* = 45 \) and \( 1/T_{10} = 1.4 \) [18] which is derived from literature study is used to describe the S-N curve. It fits the here achieved results.

In the LCF-region failure in smooth specimens always starts at the surface. In the VHCF-region subsurface or internal failure dominates. Typical crack initiation sites are material inhomogeneities as globular oxides.

A comparison of the results with the design code FKM-Guideline Analytical strength assessment of components [1] shows that in most cases an assessment would have been safe without considering safety factors.

Further investigations with variable amplitude loading are necessary for estimating the practical relevance of the here achieved results for component design and assessment.

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