A new approach for the analytical hcf strength assessment of components from nickel-base alloys

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Abstract

Based on the requirement of common guidelines for the assessment of the fatigue strength of structural components, this paper presents an approach to create an assessment workflow for components made of nickel-base alloys, based on the basic workflow of an existing guideline. Material-related parameters of the guideline that are considered to require adjustment when used for nickel-base alloys are modified, covering recent publications and available material studies. Besides the analytical determination of the materials fatigue strength, the approach especially deals with the influence of mean stress and notch sensitivity. The new approach is verified using component-like specimens which are designed based on typical pump-components. Staircase tests are performed to retrieve the specimen’s high cycle fatigue strength experimentally. A finite element model of the specimen including the test environment provides realistic local stress values for the computational process. The evaluated attempts to calculate the main influences are compared to the test results. Further selection is made regarding the usability of the presented approach.

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1. Introduction

The fatigue behaviour of engineering components made of various steel or aluminium materials has been investigated for several decades and can today be assessed in great detail. Thus it is possible to design and assess even critical components based on numerical strength assessment. However there are still particular cases where
components face challenging conditions that bring even special steel materials to their limits. Being exposed to rather aggressive media such as saltwater, gases like H₂S and abrasive particles even at the same time, pump components do not only face high cycle fatigue conditions but they are also weakened by constant corrosive damage and wear. As such cases require the use of nonferrous materials with equivalent mechanical strength, nickel-base alloys have come to the spotlight for the use in pumps.

While nickel-base alloys have extensively been used in jet engines or gas turbines due to their excellent heat and creep resistance, investigations on the fatigue behaviour have not yet lead to a fully developed strength assessment guideline. Although available publications cover a variety of influences on low as well as high cycle fatigue, most experiments lack of comparable conditions such as stress ratio or temperature (e.g. Kobayashi (2009)), or focus on rather special influences e.g. the loading frequency (Belan (2015), Yan et al. (2010)) or the specimen size (Kashaev et al. (2013)). This leads to a quite unstructured picture of the detailed fatigue behaviour of this material and retards a precise strength assessment of engineering parts in a general manner. The aim of the present research is to develop an assessment workflow for engineering components made of nickel-base alloy, to be used in a general and applied manner.

This paper presents an approach for the assessment workflow for engineering components made of nickel-base alloy, focused on a specimen with a specific geometry and loading situation, according to an actual engineering component. A series of attempts to quantify important influences on the high cycle fatigue strength based on material parameters (e.g. yield or tensile strength) were investigated and valued at performed fatigue tests. As most types of nickel-base alloys show mainly γ-phase (Belan (2015), Kobayashi et al. (2004)), which leads to a similar structure as found in austenitic chromium-nickel-steels, most available studies also show a comparable basic fatigue behaviour, including the fact that there is no endurance limit above the usual threshold (Kobayashi et al. (2004), Ma et al. (2010), Belan (2015)). Thus, the assessed attempts were mostly taken from investigations regarding iron-base materials. Fatigue strength, in further reference, is determined as the value of stress at which failure occurs after more than 10⁶ cycles.

2. Fatigue strength assessment

For the Fatigue strength assessment of engineering components made of iron-base materials, several guidelines are available to provide a general process as well as detailed information to calculate specific influences on the components fatigue strength analytically (eg. EuroCode, ASME-Code…). One example is the FKM-Guideline “analytical strength assessment” (FKM (2012)) which is well-established among mechanical engineers especially in Europe. Parts of this guideline were adapted for the basic assessment workflow.

The assessment in the FKM-guideline is carried out by comparing the characteristic service stresses σₐ occurring in the component, with the component’s strength values σₐK derived from the mechanical material properties and relevant design parameters. Including the desired safety factors jD a components degree of utilization aD is calculated

![Fig. 1: Procedure of the fatigue strength assessment according to the FKM-guideline](image-url)

\[ a_D = \frac{\sigma_A}{\sigma_{AK} / j_D} \]
The assessment can be stated as successful, if the degree of utilization is less or equal to one. The complete guideline provides assessment algorithms for static and fatigue strength, each available for the use of either nominal or local stresses. The calculation process of the guideline works with several material, design and loading related parameters.

The here presented approach covers effects of notches, mean stress and multiaxial stress, since these aspects control the fatigue strength of the regarded specimen. The component fatigue strength for constant stress amplitudes \( \sigma_{AK} \) is calculated based on the materials fatigue strength for fully reversed push-pull loading \( \sigma_w \) (equates to \( S_f \)), which is modified by a support-factor \( n_\sigma \) to cover notch effects and a mean-stress-factor \( K_{AK} \). The full assessment process is carried out for each stress component resulting in three individual degrees of utilization \( a_{\sigma I}, a_{\sigma II}, a_{\sigma III} \).

According to the FKM-guideline an entire degree of utilization \( a_\sigma \) is calculated from \( a_i \) to consider the multiaxial stress state.

\[
\sigma_{AK} = \sigma_w \cdot n_\sigma \cdot K_{AK}
\]  

Finally the calculation of the fatigue strength in the present case is deduced to three basic influencing values. In the following, several attempts for the calculation of the named parameters are presented:

- The calculation of the materials fatigue strength at zero mean stress \( \sigma_w \) (unnotched specimen, zero mean stress).
- The increase of the components fatigue strength due to notch support effects using the support-factor \( n_\sigma \).
- The computation of the materials sensitivity to mean stress for the calculation of the mean-stress-factor \( K_{AK} \).

### 2.1. Materials fatigue strength at zero mean stress \( \sigma_w \)

The materials fatigue limit for unnotched specimen at zero mean stress is used as the basic strength value in most fatigue strength assessment algorithms. It is deemed to be a material immanent value and often computed from static material strength parameters. The most popular attempt is to scale the materials ultimate tensile strength \( R_m \) by a defined factor:

\[
\sigma_w = f_{w,\sigma} \cdot R_m
\]  

In case of the FKM-guideline the corresponding factor \( f_{w,\sigma} \) would be 0.4 for corrosion-resistant steel. Another chosen attempt that uses the ultimate tensile strength is provided by Hück et al. (1981):

\[
\sigma_w = 0.385 \cdot R_m + 30 \text{MPa}
\]  

As nickel-base alloys usually are of remarkably high strength, in some cases (including the present) combined with a high ductility, it is appropriate to include attempts that use other material parameters than the ultimate tensile strength. Therefore a method by Hück and Bergmann (1992) has been implicated in the present investigation:

\[
\sigma_w = 0.44 \cdot R_{p0.2} + 100 \text{MPa}
\]  

Where \( R_{p0.2} \) is the materials yield strength. Additional to the above attempts that are originally designed for ferrous materials, different publications regarding the fatigue behavior of nickel-base alloys were investigated. Although no general attempt in the above described manner was found, analysis of the data (e.g. S-N curves) in the available publications yielded factors for the general attempt in (2) between 0.314 and 0.51 and for the attempt in (4) between 0.32 and 0.59. Tien (1972) concludes for nickel-base alloys (5):

\[
\sigma_w = 0.25 \cdot R_{p0.2}
\]
2.2. Support-factor \( n_\sigma \)

Local service stress values around notches often exceed the expected strength values without causing failure. This behaviour can be traced back to macro and micro supporting effects in the local material. There are several approaches to quantify the resulting influence on the fatigue limit of notched specimen(s) respectively components in comparison to unnotched specimen(s). One that is used in several guidelines and has caused a variety of attempts to predict notch influence uses the “relative” stress gradient at the root of the notch \( G_\sigma \) as the determining factor.

Three different attempts are included in this study, all using the above approach. The FKM guideline offers a split calculation method, again using the ultimate tensile strength as the corresponding material property:

\[
 n_\sigma = \begin{cases} 
 1 + G_\sigma \cdot mm \cdot 10 \left( a_G - 0.5 \frac{R_\sigma}{b_G \cdot MPa} \right) & \text{for } G_\sigma \leq 0.1 \text{mm}^{-1} \\
 1 + \sqrt{G_\sigma \cdot mm} \cdot 10 \left( a_G + \frac{R_\sigma}{b_G \cdot MPa} \right) & \text{for } 0.1 \text{mm}^{-1} < G_\sigma \leq 1 \text{mm}^{-1} \\
 1 + 4 \sqrt{G_\sigma \cdot mm} \cdot 10 \left( a_G + \frac{R_\sigma}{b_G \cdot MPa} \right) & \text{for } 1 \text{mm}^{-1} < G_\sigma \leq 100 \text{mm}^{-1} 
\end{cases} 
\]  

(6)

With \( a_G = 0.4 \) and \( b_G = 2400 \) for corrosion-resistant steel. The second attempt uses the materials yield strength as the reference parameter and is originated from a strength assessment guideline of the former German Democratic Republic, TGL (1983):

\[
 n_\sigma = 1 + \sqrt{G_\sigma \cdot mm} \cdot 10 \left( 0.333 \frac{R_{pl,2}}{712 MPa} \right) 
\]

(7)

Hück et al. (1981) proposed an attempt as a result from an analysis of a great number of S-N curves, which is independent of any material parameters and valid for steels with an ultimate tensile strength between 250 MPa and 1200 MPa:

\[
 n_\sigma = 1 + 0.45 \cdot (G_\sigma \cdot mm)^{0.3} 
\]

(8)

The fatigue notch-factor is calculated for each principal stress with the corresponding stress gradient. Since normally for one stress component no gradient at the notch root can be calculated, the notch-factor in this case would be set to one. For further details on the relative stress gradient or fatigue notch behavior please refer to special literature.

2.3. Mean-stress-factor \( K_{AK} \)

To value the effect of mean stress on the allowed stress amplitude, several attempts (e.g. Goodman relation, Gerber parabola) are available resulting in different lines in the Haigh-diagram. The FKM-guideline uses a linear approach...
with four sections depending on the stress ratio, also presented by Haibach (2002). The slope of the curve is defined as the materials mean stress sensitivity $M_\sigma$. The FKM-guideline calculates the mean-stress-factor $K_{AK}$ depending on the expected overload-behaviour and the stress Ratio. These calculations are completely adapted for the presented assessment workflow. The factor for section III (0<R<0.5) of the second overload-case (constant stress ratio) corresponds to the specimens load characteristic in this study and is calculated as follows:

$$K_{AK} = \frac{3 + M_\sigma}{(1 + M_\sigma) \cdot (3 + M_\sigma \cdot \sigma_m / \sigma_a)}$$  \hspace{1cm} (9)

With $\sigma_m$=mean stress and $\sigma_a$=stress amplitude. The materials fatigue sensitivity to mean stress however is known to be a material parameter in the range of zero to one, where one would describe fatigue behaviour with the maximum stress instead of the stress amplitude as the critical value. In the FKM-guideline $M_\sigma$ is calculated depending on the ultimate tensile strength with the constants $a_M=0.35$ and $b_M=-0.1$ for steel:

$$M_\sigma = a_M \cdot 10^{-3} \cdot R_m / \text{MPa} + b_M \hspace{1cm} (10)$$

This approach is compared to another attempt that can be concluded from a fatigue-model by Murakami et al. (2002) with the Vickers-hardness (HV) as the corresponding material parameter:

$$M_\sigma = e^{(0.0693 \cdot (HV/1000)^0.157)} - 1 \hspace{1cm} (11)$$

2.4. Component fatigue strength and degree of utilization

The components fatigue strength amplitude at an actual mean stress in the (reduced) form that is presented here, is calculated as shown in equation (1). Each of the three factors is calculated by using one of the presented attempts. The degree of utilisation for each (principal) stress component $a_{\sigma_i}$ is calculated according to fig. (1) with $\sigma_i$ as the component service stress amplitudes and $j_0=1$. The entire degree of utilization for ductile materials according to the FKM-guideline is calculated by equation (12):

$$a_{\sigma,v} = \sqrt[2]{\frac{1}{2} \left[ (a_{\sigma_1} - a_{\sigma_2})^2 + (a_{\sigma_2} - a_{\sigma_3})^2 + (a_{\sigma_3} - a_{\sigma_1})^2 \right]}$$ \hspace{1cm} (12)

3. Experimental

To verify the investigated assessment approaches, high-cycle fatigue tests were carried out to determine the component fatigue strength at $10^6$ cycles. To ensure an applied perspective, specimens with a component-like geometry were developed for the fatigue testing. The core component of a special pump type was analysed, regarding geometric and loading parameters. Based on the components stress condition, a stress equivalent specimen was designed, meeting the requirements of applicability in fatigue testing on the one hand and a loading situation close to the operating component on the other hand. Besides the distribution of the three nominal stresses, the stress gradient at the specimen radius is expected to match the actual component, which offers a component near investigation especially of the effects of notches and multiaxial stresses. The specimens are made of annealed nickel-base alloy 625 (Nicrofer 6020 hMo) with an ultimate tensile strength of $R_m=950\text{MPa}$, an offset yield strength of $R_{p0.2}=552\text{MPa}$ and a Brinell hardness of 230HB at room temperature. The specimen and its loading situation are illustrated in fig. 3a) and 3b). The disk-shaped specimen [1] is stacked on an axis [2] and the shaft is pre-loaded mechanically in axial direction. The whole specimen is loaded with sinusoidal hydraulic pressure $p_L$ on one side, and constant atmospheric pressure $p_0$ on the other.
The pressurization is enabled by a special rubber seal membrane [3] having minimum influence on the specimen’s stress state. The specimen’s outer diameter is 40mm and the notch radius between the shaft and the disk is 0.2mm. A cracked specimen is shown in fig. 3c).

A staircase test according to Hück (1983) is used to gain the desired fatigue strength values at $10^6$ cycles. The load levels are defined with a constant logarithmic load step based on an assumed standard deviation for the fatigue strength of 5%. A load ratio of 0.1 is applied, causing a stress ratio (first principal stress) between 0.02 and 0.05 due to a scatter in the actual radius of the specimens. In order to gain a reliable value of the standard deviation of the fatigue strength, at least 17 specimens are tested. The staircase test is evaluated using the method proposed by Hück (1983). The fatigue limit ($10^6$ load cycles) is reached at load amplitude of 46 Bar with logarithmic standard deviation of 0.0294.

The stress values for the verification are obtained from a detailed finite element model, including not only the specimen itself but also other directly involved parts of its environment. The notch radius of each specimen was measured and all tests have been simulated with the actual loading state and geometry. The exact stress values for all specimens were used to gain mean values for each pressure load step. The pressure value for 50% probability of failure from the test evaluation was then converted in a value for the mean stress amplitude of the first principal stress. The value for a 2.5% probability of failure is calculated using a statistical factor. A corresponding multiaxial stress state is obtained by another simulation using the calculated pressure values and a mean value for the notch radius.

The stress gradient at notch root
4. Discussion

According to eq. (1) one attempt for each of the investigated factors as summarized in table 1 is used to calculate the components fatigue strength, which would be valid for a 2.5% probability of failure. The resulting values of all combinations of the different attempts are presented in fig. 6 along with the estimated specimens fatigue strength for $10^6$ cycles and with 2.5 % failure probability as well.

<table>
<thead>
<tr>
<th>Fatigue strength factor</th>
<th>Attempt 1</th>
<th>Attempt 2</th>
<th>Attempt 3</th>
<th>Attempt 4</th>
</tr>
</thead>
</table>

Fig. 6: Component fatigue strength amplitude - comparison of the different attempts – first principal stress

The first two discussed influences are presented by the x- and y-axis, while the two attempts to cover mean stress effects are represented by the two stacked surfaces in the plot. As the strength values for the first principal stress due to the ductile material behaviour cannot be referenced alone, the described assessment process is carried out for all three principal stress components and the entire degree of utilization as in eq. (12) is calculated for an adequate verification. In this case the test results are represented by a degree of utilization equal to one (fig. 7) and taken for

Fig. 7: Component degree of utilization – comparison of the different attempts
reference. Note that no safety factors are included in this calculation ($j_B=1$).

It is visible that Tien’s approach shows far too small values for the materials fatigue strength in case of this investigation, while the fatigue notch factor by Hück et al. overestimates the materials strength by far. The twelve remaining combinations however provide reasonably close predictions of the fatigue strength values approved by the testing. Comparing the components entire degree of utilization for all presented attempts (fig. 7) and analysing the remaining combinations, the materials fatigue strength calculation by Hück et al. is causing the biggest deviation from the test results with values between 0.8626 and 0.9192, while the best conformity is reached with the combination of [Hück and Bergmann; FKM; Murakami] ($\sigma_w$, $n_\sigma$, $M_\sigma$) with a value of 1.02. Using only the FKM-guideline (FKM (2012)) leads to a moderate consistency with an entire degree of utilization of 0.9343.

5. Conclusion

From nine attempts for three important factors in calculating the component fatigue strength, the resulting 24 combinations where compared to fatigue tests with special specimens in a component-like shape and with equivalent service stresses. Two attempts showed insufficient results, leaving 12 combinations with good conformity. The best match provided the materials fatigue strength at zero mean stress according to Hück and Bergmann (1992), combined with the fatigue notch factor from the FKM-Guideline and taking into account the materials mean stress sensitivity provided by a method by Murakami (2002). Regarding usability however, further selection can be made: As, in contrast to the ultimate tensile strength, the Vickers-hardness of a material is not always provided by the manufacturer, the attempt according to Murakami does not offer full applicability. Therefore the combination [Hück and Bergmann (1992); FKM (2012); FKM (2012)] is recommended for use with actual components, providing a slightly higher amount of safety due to an entire degree of utilisation of 1.035. The use of safety factors as provided in common assessment guidelines is strongly recommended to ensure a safe operation of the assessed components.

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References

Hück, M., Bergmann, J., 1992. Mikrolegierte Stähle, Bewertung der Schwingfestigkeit der mikrolegierten Stähle 27MnVS6 und 38MnVS5. FKM-Bericht 5, Frankfurt/M.
TGL 1983, Dauerfestigkeit der Maschinenbauteile, TGL19340/03