Analytical strength assessments of austempered ductile iron components

Dedicated to Professor Dr.-Ing. Harald Zenner on the occasion of his eightieth birthday

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Article Information

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Austempered ductile iron (ADI) is a heat-treated ductile iron with improved tensile strength and toughness. Therefore, ADI is an interesting material for the construction of technical parts. However, for practical use, a strength assessment is necessary. An often-used option for an analytical strength assessment is the FKM-guideline. This guideline includes the strength assessment for steel, cast iron and aluminum materials, but it has not yet been especially investigated for ADI. In this work the use of the guideline for ADI is investigated. On the basis of experimental data, the accuracy of the guideline is examined and the limitations are discussed. Furthermore, the parameters that are used for the calculation in the guideline can be adjusted for the improvement of the accuracy of the strength assessment. In this way in particular, the forecast for shear stresses and the high strength materials can be improved.

Austempered ductile iron (ADI) is a heat-treated ductile iron in which tensile strength and toughness are improved compared to usual ductile iron. Its increased strength properties make it competitive with steel castings and forged components. For the industrial use of ADI components, a strength assessment is necessary. This can be done experimentally or analytically. The main advantage of an analytical strength assessment is that it can be done early in the design process, even if no fabricated part is available. For this reason, the possibility of an analytical strength assessment is a requirement for the economical use of ADI. One possibility for strength assessment is presented in the FKM-guideline [1]. It contains the strength assessments for steel, aluminum and cast iron as well. Thus, ADI, a ductile cast iron, is included in the guideline. However, the guideline has not yet been sufficiently investigated for the

calculation of ADI components. In this study, experimental results from our investigations as well as results from the literature [2-11] are compared with analytical results. By means of this comparison, the applicability of the guideline [1] can be examined. Furthermore, proposals for the improvement of accuracy are given.

Technical approach

The analytical strength assessment for ADI components should be examined experimentally. For this reason, a database with experimental fatigue data for the ADI material was established [2-11]. Several results regarding the fatigue strength of ADI have been presented in the literature. Less investigated are mean stress sensitivity and fatigue behavior under shear stress. Consequently, the database should be expanded to include our experimental investigations.

Experimental Investigation. Experimental investigation is the basis of the calculations intended for the verification of the FKM-guideline [1]. Experimental tests have been performed for the basic supplementation of the database. Two materials, GJS 800-8 and GJS 1400-1, are chosen to represent the strength range of ADI. For these investigations, standardized type-4 Y-samples are manufactured according to [11]. GJS 800-8 with a medium experimental tensile strength of $R_m = 892$ MPa has an elongation of $A_{5.65} = 8.2\%$. GJS 1400-1 with a tensile strength of $R_m = 1466$ MPa has an elongation of $A_{5.65} = 2.24\%$. For the investigation of the mean stress sensitivity, flat bending tests with stress ratios of $R = -1$ and $R = 0$ are performed. The tests are carried out on a resonance test bench with an approximate test frequency of $f = 30$ s⁻¹. After the flat bending tests, torsions tests

are performed to estimate the shear stress sensitivity. These tests are also carried out on a resonance test bench with an approximate test frequency of $f = 20 \text{ s}^{-1}$. For every fatigue test, approximately 15 test bars with diameters of 14 mm are tested according to the staircase method. The ultimate number of cycles is established as $N_G = 10^7$. Additional specimens with diameters of 4 mm are tested under push-pull loading. The results of the tests described above are given in Table 1. It can be seen that the fatigue strength of the GJS 1400-1 is less than that of the GJS 800-8. This result corresponds to results from the literature [2,3,6,11]. Hence, the assumption [1] that fatigue strength grows proportionally to the tensile strength, cannot be confirmed.

Comparison with the FKM-guideline. The FKM-guideline [1] includes static and fatigue strength assessments for components made of steel, cast iron and aluminum. In this investigation, only the fatigue strength assessment for cast iron is relevant because static examinations have not been carried out. In principle, the guideline is practicable for ADI materials because it is a GJS, and as such, included in the guideline. However, ADI is a special GJS, and the guideline has not been verified yet. For a comparison of the guideline with the experimental investigations, the safety factor in the calculations is set to $j_s = 1$. Furthermore, the tensile strength R_m , which is needed for the calculations, is taken from the tensile test data of the tested material. In this way, the test results for a default probability of 50 % are comparable to those of the calculations. This method is recommended in the guideline to retrace examinations of failures.

In the FKM Guideline [1], the fatigue strength of the components is calculated starting with the tensile strength of the selected material. The first step in this calculation is an estimation of the material fatigue strength for completely reserved axial stress $\sigma_{W,zd}$. It is calculated using the fatigue strength factor according to Equation (1). The factor is given as $f_{W,\sigma} = 0.34$ which depends on the material group. Experimental results and results from the literature [2,3,6,11] show that the fatigue strength of ADI, especially high strength ADI, does not increase with increasing tensile strength. Therefore, the approach of the guideline for the estimation of material fatigue strength is not suitable for ADI.

$$\sigma_{W,zd} = f_{W,\sigma} \cdot R_m \quad (1)$$

The influence of the geometry of the component is taken into account by the design factor. Because of the constitution of the samples, this is unambiguously determined by the K_t - K_f ratio. Here, the material-mechanical K_t - K_f ratio is used, which is composed of the statistical-, the deformation-mechanical and the fracture mechanical K_t - K_f ratio. In contrast to the K_t - K_f ratio developed by Stieler, the material-mechanical K_t - K_f ratio is physically justified, in particular because it considers the size of the tested component. For the estimation of the statistical K_t - K_f ratio n_{st} , the highly stressed volume $V_{\sigma,st}$ is taken into account. This is relevant for the calculation because of the occurrence of internal cracks in the experimental tests. As shown in Equation (2), n_{st} is calculated as the ratio between $V_{\sigma,st}$ and a reference volume $V_{ref,st}$, and it depends on the Weibull exponent, which is rendered in [1] as $k_{st} = 10$. The highly stressed volume is calculated by the "SPIEL" method which is a stress integral determination based on unit load cases as published by Diemar in [12]. The deformation-mechanical K_t - K_f ratio is presented in [1] as $n_{vm} = 1$ for cast iron and thus for GJS as well. The fracture mechanical K_t - K_f ratio only exists for notched parts due to the geometry of the samples, hence, $n_{bm} = 1$. Consequently, according to [1], the difference in the fatigue strength of the bending and axial specimens must be ex-

plained by the statistical effect. For Figure 1, the fatigue strengths are normalized by the statistical K_t - K_f ratio. Nevertheless, the fatigue strength of the bending test bars is higher than that of the axial test bars. This is either an indication of a greater statistical effect or of the existence of another strength-supporting effect.

$$n_{st} = \left(\frac{V_{ref,st}}{V_{\sigma,st}} \right)^{\frac{1}{k_{st}}} \quad (2)$$

Subsequent to the bending and axial tests, torsion tests were performed in the course of which the resistance of ADI against shear stress were tested. In [1], the fatigue strength for shear stress is calculated using fatigue strength for normal stress conditions and the fatigue strength factor for shear stress conditions, as shown in Equation (3). The fatigue strength factor is given as $f_{W,\tau} = 0.65$ in [1]. Figure 2 shows the experimentally determined fatigue strength factors for shear stress. The calculation is made by means of the material-mechanical K_t - K_f ratio as given in [1]. It can be seen that the experimental shear stress sensitivity is less than that given in the guideline.

$$\tau_{W,s} = f_{W,\tau} \cdot \sigma_{W,zd} \quad (3)$$

In general, the load of a component is not totally reserved. The guideline takes this into account by mean stress sensitivity

Figure 1: Material fatigue strength calculated from the experimental data considering the K_t - K_f ratio (*data from Khalil [2])

Material	R_m (MPa)	$A_{5,65}$ (%)	Load type	$S_{A,R=-1}$ (MPa)	$S_{A,R=0}$ (MPa)
GJS 800-8	892	8,20	Flat bending	417	300
			Rotating bending	367	
			Torsion	355	249
			Axial	359	
GJS 1400-1	1466	2,20	Flat bending	389	247
			Torsion	334	204
			Axial	327	

Table 1: Experimental fatigue strength for an ultimate number of cycles of $N_G = 10^7$

which can be calculated using Equations (4) and (5). The constants are given as $a_M = 0.35$ and $b_M = 0.08$ for GJS in [1]. Figure 3 shows a comparison of experimental mean stress sensitivity and mean stress sensitivity according to [1]. With respect to the normal stress fatigue tests conducted, the results correspond quite well with the guideline; with respect to data acquired from literature however, there are deviations. Specifically, the connection between tensile strength and mean stress sensitivity is not confirmed because shear stress and mean stress sensitivity are underestimated by [1]. This can be partially compensated for by an adjustment of the fatigue strength factor for shear stress according to the investigations above.

$$M_\sigma = a_M \cdot 10^{-3} \cdot \frac{R_m}{\text{MPa}} + b_M \quad (4)$$

$$M_\tau = f_{W,\tau} \cdot M_\sigma \quad (5)$$

A comparison of experimental and calculated fatigue strength is given in Figure 4. Test series for which the quality and the ADI microstructure is uncertain due to information given in the literature [6-8] are marked in gray. It can be seen that for high strength ADI materials, fatigue strength is overestimated in the guideline while shear stress fatigue strength is commonly underestimated. Up to a tensile strength of approximately 1000 MPa the guideline can be used for the strength assessment of ADI.

In this region, strength assessment is commonly on the safe side. However, for shear stresses in particular, the full capability of ADI materials cannot be evaluated by [1]. Thus, the parameters of the guideline should be adjusted for ADI. Further information regarding the parameters and their determination can be found in research papers [13] and [14].

Adjusting the parameters of the guideline. For the improvement of the accuracy of the guideline, a deformation-mechanical K_t - K_f ratio is calculated. The calculation of the material fatigue strength from the test results shows that the material fatigue strength calculated for bending test specimens is higher than that for axial test specimens. This could be explained by the existence of a deformation-mechanical K_t - K_f ratio which can be calculated by the Liu's approach [15], shown in Equation (6), which is also the basis of the procedure in [1]. Here, the linear elastic stress ($K_t \sigma_{na}$) calculated is referred to as the local elastic plastic stress (σ_a). This stress is minor if there are any local plastic deformations. For the determination of elastic plastic stress, a cyclic stress-strain curve is used in the FE calculation which can be determined by strain-controlled fatigue tests or estimated using literature data.

$$n_{vm} = \frac{K_t \cdot \sigma_{na}}{\sigma_a} \quad (6)$$

Furthermore, the parameters supplied in the guideline can be adjusted. The basis for this adaptation has been garnered from the experimental test data in tests performed at our Institute and in data from [2]. This database is chosen because of the investigation of varied mean stress and shear stress in the studies. Moreover, the experimental data is comprehensively documented. The adjustment of the calculation, according to the guideline, is performed by parameter variation. In this way, the fatigue strength factor for shear stress, the Weibull exponent for the estimation of the statistical K_t - K_f ratio and the constant b_M for the estimation of mean stress sensitivity are diversified. The fatigue strength factor for normal stress is not considered for these calculations because of experimental results, which have shown that fatigue strength is not proportional to tensile strength. Consequently, the linear approach of the guideline is not valid.

The area in which the variation of the parameters is carried out is chosen by consid-

Figure 2: Fatigue strength factor estimated from the experimental data (*data from Khalil [2])

Figure 3: Comparison of mean stress sensitivity estimated from the experimental data and estimated according to the FKM Guideline [1] (*data from Khalil [2])

Figure 4: Comparison of fatigue strength according to the FKM-guideline [1] and experimental data [2-11]

Figure 5: Experimental material fatigue strength dependence on tensile strength (data from own investigations and Khalil [2])

ering the test results and the values given in the guideline [1]. In the next step, material fatigue strength is calculated for every combination of the parameters given and for each test series. Deviations in calculated fatigue strength for the different materials are computed for the valuation of a large number of parameter combinations. The combination of the parameters for which material fatigue strength has the least scatter fits best to the material. The next step requires determining the parameters that best fit all investigated materials. Considering the number of test series for each material, the parameter combination with the slightest total deviation is chosen. This combination leads to the best agreement with the calculation of material fatigue strength and best represents experimental results. The combination selected is: $f_{w,\tau} = 0.84$; $k_{st} = 18$; and $b_M = 0.06$. Shear stress sensitivity is less than given, as is expected by virtue of the tests above. Moreover, the Weibull exponent is higher than that provisionally given in the guideline. However, the constant for the estimation of mean stress sensitivity is almost the same as that in [1].

New approach to the fatigue strength factor. The linear approach for the estimation of fatigue strength from tensile strength is not applicable because of decreasing fatigue strength in high strength ADI materials. In Figure 5, material fatigue strength calculated from the tests is given alongside tensile strength. It can be seen that fatigue strength can be approximated via a square function; this correlation is

given in Equation (6). In this way, the material fatigue strength of ADI can also be calculated from tensile strength.

$$\sigma_{w,zd} = 0.704 \cdot R_m - 2.99 \cdot 10^{-4} \cdot R_m^2 \quad (7)$$

Results

Verification of the adjusted guideline.

For the verification of the estimated parameters, calculated and experimental fatigue strength are compared in Figure 6. The calculated fatigue strength of the high strength ADI in particular better matches the experimental results and is no longer overestimated. Additionally, the accuracy of low strength ADI also improves. The strength reserves of ADI under shear stress can be exploited more efficiently too. Even the scattering of the calculation can be reduced. Despite all the improvements, it can be seen that for some materials fatigue strength is overestimated. Presumably, the structure of these materials differs from a real ADI structure. The test results marked in gray are from [6-8], where the influence of heat treatment and the alloy constituents are investigated for which reason the microstructure may not be as perfect as required. In other references, such as in [5], deviations in the microstructure are found which potentially reduce fatigue strength. Overall, analytical strength assessment for ADI is possible if the required microstructure can be ensured. It should be noted that erroneous heat treatment can often not be detected by tensile tests.

Figure 6: Comparison of fatigue strength according to the FKM-guideline [1] with adjusted parameters and experimental data [2-11]

Conclusions

The results show that the FKM-guideline [1] can be used for ADI up to a tensile strength of 1000 MPa. For materials with higher tensile strengths, fatigue strength decreases, so that the guideline leads to uncertain results. To improve the guideline, both the parameters and the approach used for the estimation of material fatigue strength need to be adjusted. Using the square approach, the fatigue strength of high strength ADI can be estimated. The adjustment of the parameters especially improves the estimation of shear stress fatigue strength. Additionally, a higher Weibull exponent reduces the scatter of the calculation. The adjustment of the mean stress sensitivity is low and only has a small effect on the calculation.

The results also show that in many investigations ADI structure is not attained for the complete cross-section of the sample [5]. Imperfect ADI structure leads to lower fatigue strength, even if tensile strength often reaches the targeted value. Thus, an investigation of microstructure is necessary.

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Abstract

Rechnerischer Festigkeitsnachweis von ADI Gussbauteilen. Austempered Ductile Iron (ADI) ist ein wärmebehandeltes Gusseisen mit Kugelgraphit, dessen Festigkeits- und Dehnungseigenschaften gesteigert sind. Damit wird es interessant für technische Anwendungen. Für den praktischen Einsatz von Bauteilen aus ADI ist jedoch ein Festigkeitsnachweis erforderlich. Die FKM-Richtlinie stellt eine Möglichkeit zur Erbringung eines rechnerischen Festigkeitsnachweises dar. Die Richtlinie enthält den Nachweis für Bauteile aus Stahl, Eisenguss und Aluminiumwerkstoffen. Die Anwendung auf ADI Bauteile ist jedoch noch nicht untersucht. In dieser Arbeit wird auf der Basis von experimentellen Versuchsdaten die Anwendbarkeit der Richtlinie und ihre Grenzen untersucht. Weiterhin werden die für die Berechnung genutzten Parameter angepasst, um die Treffsicherheit der Richtlinie zu erhöhen. Dadurch können insbesondere hochfeste ADI Werkstoffe und Schub beanspruchte Bauteile besser bewertet werden.

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