Multiaxial fatigue of cast aluminium EN AC-42000 T6 (G-AlSi7Mg0.3 T6) for automotive safety components under constant and variable amplitude loading

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ABSTRACT. Regarding the fatigue behaviour of EN AC-42000 T6 (A 356 T6), which is the most frequently used cast aluminium alloy for automotive safety components, especially under non-proportional constant and variable normal and shear stress amplitudes with changing principal stress directions, a poor level of knowledge was available. The reported investigations show that, under non-proportional normal and shear stresses, fatigue life is increased in contrast to ductile steels where life is reduced due to changing principal stress directions. This behaviour caused by the low ductility of this alloy (e < 10%) compared to quenched and tempered steels suggests the application of the Normal (Principal) Stress Hypothesis (NSH). For all of the investigated stress states under multiaxial constant and variable (Gaussian spectrum) amplitudes without and with mean stresses, the NSH was able to depict the life increase by the non-proportionality and delivered, for most cases, conservative but non-exaggerated results.

KEYWORDS. Cast aluminium; Multiaxial fatigue; Spectrum loading.

INTRODUCTION

Since the 1970s, cast aluminum has found increasing access into automotive applications, especially for safety parts, such as wheels, steering knuckles, brake brackets, axles, and engine carriers [1-4]. Fig. 1 shows an example of prominent automotive safety components, i.e. the multiaxial loading of a car wheel and its appertaining steering knuckle with acting reaction forces, which cause a combined non-proportional bending and torque on the shaft.
Because of missing necessary knowledge on the multiaxial fatigue behaviour of cast aluminium for the design of such safety parts a large investigation was initiated focusing on the mostly used cast aluminium alloy EN AC-42000 T6 [5]. The present paper will report the results and the applicability of the NSH.

MATERIAL PROPERTIES, SPECIMENS AND TESTING PROGRAMME

Material Properties and specimens

The precipitation hardened alloy EN AC-42000 T6 with the heat treatment T6 contains mainly 7 % Si and 0.38 % Mg. The porosity state, according to ASTM E 155 [6], is P ≈ 0, i.e. pore diameters d ≤ 0.3 mm. The investigated alloy is a cyclic hardening material, revealing monotonic and cyclic yield stresses $R_{p0.2}$ = 253 MPa and $R'_{p0.2}$ = 307

MPa, respectively. The ultimate tensile stress R_m = 310 MPa, the Young's modulus E = 71 GPa, the elongation e = 5.9 % and the hardness HB5/250 = 103 are the further characteristic mechanical properties.
The notched specimens with the stress concentration factors K_{tB} = 1.89 and K_{tT} = 1.37 for the uni- and multiaxial testing, were first cast and then, after the T6 treatment, the outer contour was machined. The geometry of the specimens is displayed in following figures.

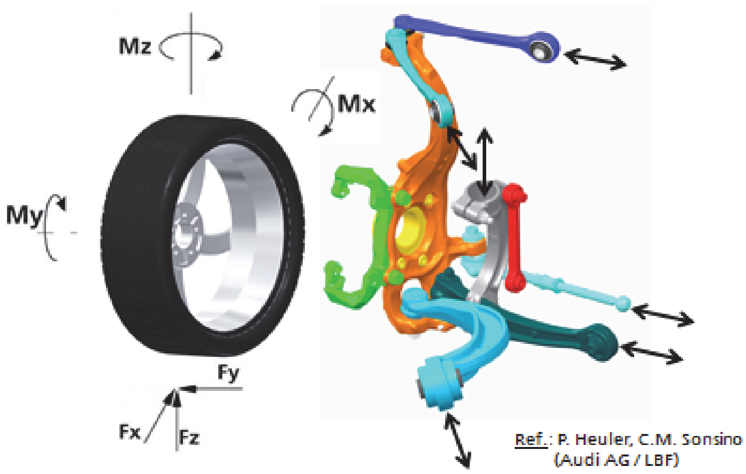

Figure 1: Acting multiaxial wheel-loads and reaction forces on a steering knuckle

Testing programme and local stress ratios

The testing programme comprised uni- and biaxial test series under constant and variable amplitudes without and with mean stresses, i.e. fully reversed loading $R = \sigma_{min} / \sigma_{max} = \tau_{min} / \tau_{max} = -1$ and pulsating loading R = 0. For the tests under variable amplitudes [7], a standard Gaussian distribution with a sequence length of $L_s = 1 \cdot 10^5$ cycles and an irregularity factor of I = 0.99 was used. Under uniaxial plane bending, a local biaxial normal stress state occurs in the notch with longitudinal and tangential normal stress components σ_x and σ_y , which are related to each other by $\sigma_y = 0.25 \cdot \sigma_x$. The local stress state under pure torsion is also biaxial with the shear stress component τ_{xy}. For combined plane bending and torsion between the local longitudinal and shear stress amplitudes, a ratio of $\tau_{a,xy} / \sigma_{a,x} = 0.72$ and the phase angles δ = 0 and 90° were chosen; this ratio lies in the range of ratios, i.e. 0.5 to 1.0, applied in different investigations [4].
For constant amplitude loading, about 10 tests per Woehler-line and, for variable amplitude loading, about 5 tests per Gassner-line were carried out [7]. The test frequency depended on the load level and varied between f = 10 to 12 s^{-1}. The failure criterion, for which the results are presented later, was total failure. However, the technically detectable first surface cracks with l = 1 mm were also registered using video cameras. For the investigated specimens, the ratio between the fatigue lives to crack initiation and total rupture was on average $N_{cr} / N_f \approx 0.50$, and the fatigue lines for the failure criteria technical crack and total failure revealed overlapping scatter bands [5]. The following evaluations will be performed using the fatigue lines for the criterion of total rupture, but, because of the aforementioned overlapping, they are also valid for the criterion of a technical crack with l = 1 to 2 mm surface length, which is required in the design of automotive safety components [8].

EXPERIMENTAL RESULTS AND DISCUSSION

Presentation of experimental results

Figs. 2 and 3 present the fatigue lines for total failure with a probability of survival P_s = 50%. The Gassner-lines, obtained under variable amplitude loading, are presented by the maximum stress amplitude of the spectrum and all lie, as expected, above the Woehler-lines due to the lower damage under spectrum loading [7].

Discussion of experimental results

The stress amplitudes are local values, i.e. notch stresses which are, with the exception only of the highest levels for pure bending under spectrum loading, below the cyclic yield stress $R'_{p0.2}$ = 307 MPa. This means that the evaluation of the multiaxial stress states can be carried out without considering any plasticity effects.

The outliers in brackets in Figs. 2 and 3 were not considered because they did not fit into the expected course of the Woehler-lines, based on past experience [9-11]. Microshrinkages, acting as crack-starters on the surfaces, were responsible for these premature failures [5].

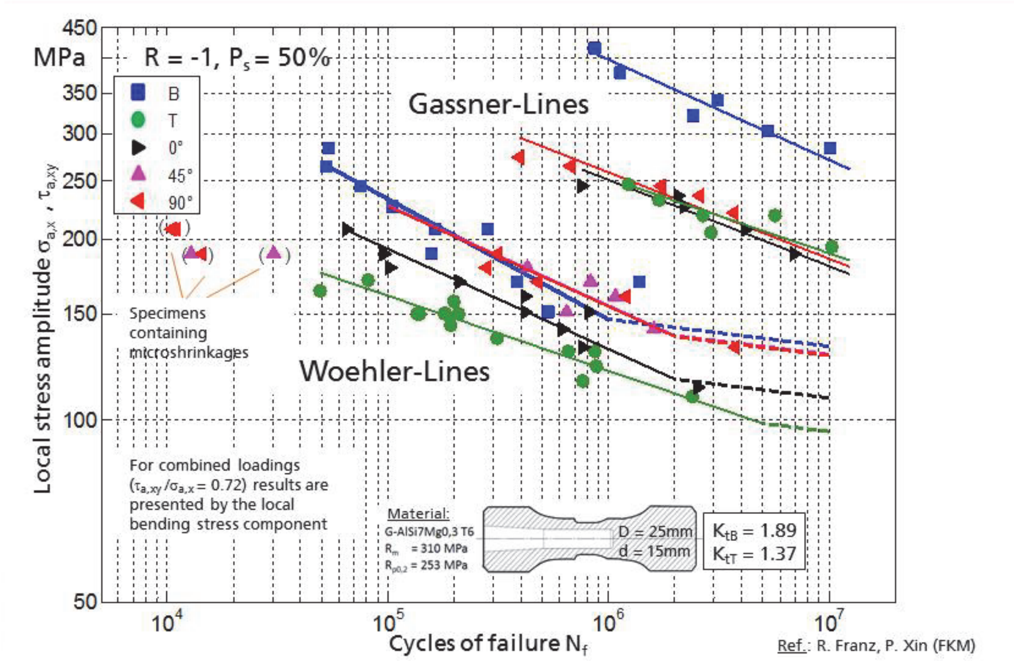

Figure 2: Fatigue behaviour of cast aluminium G-AlSi7Mg0.3 T6 (EN AC-42000 T6) under fully reversed uniaxial (B = pure bending, T = pure torsion) and combined loadings (δ = 0, 45 and 90°).

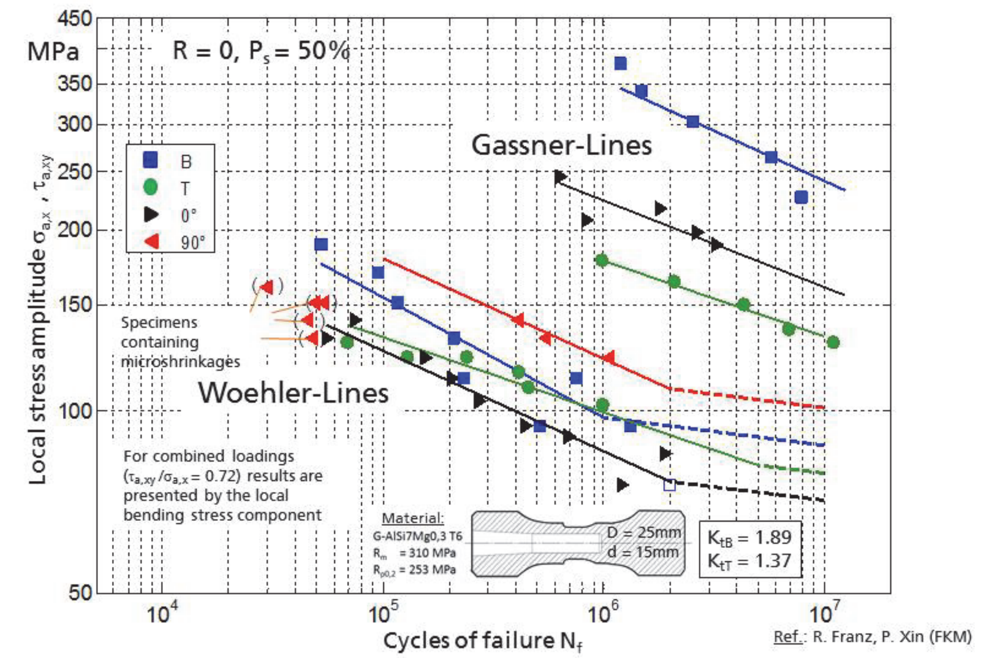

Figure 3: Fatigue behaviour of cast aluminium G-AlSi7Mg0.3 T6 (EN AC-42000 T6) under pulsating uniaxial (B = pure bending, T = pure torsion) and combined loadings (δ = 0, 45 and 90°).

The evaluation by regression analyses also considered slopes, i.e. inverse Basquin exponents, $k = \Delta \log N_f / \Delta \log \sigma_{a,x}$, up to the knee points N_k of the Woehler-lines, known from various investigations with cast aluminium alloys [9, 10]. Under constant amplitude loading, the values k = 5 for pure bending, 8 for pure torsion and 6 for combined loadings described the results very well, as did the values $k = 6$ for pure bending and 7 for combined loading under variable amplitudes. The position of the knee points $N_k = 1 \cdot 10^6$ to $5 \cdot 10^6$ cycles and the slopes $k^* = 22$ after them were based on experience and recommendations given in [9, 11] as tests in the high cycle regime were not carried out. The determined scatters of the stress amplitudes $T_\sigma = \{1 : [\sigma_a(P_s=10\%) \ / \ \sigma_a(P_s=90\%)]\}$ were not higher than 1 : 1.26, i.e. they were much lower than scatters known from other investigations [1-3, 9, 11].

The most important result of this investigation is the fatigue life increase under non-proportional biaxial loading caused by the phase difference between the local normal and shear stresses. Under fully reversed loading, Fig. 2, this is more pronounced for variable amplitude than for constant amplitude loading. However, under pulsating constant amplitude loading, the life increase is most pronounced, compare Figs. 2 and 3. Unfortunately, multiaxial pulsating spectrum loading was not investigated.

Furthermore, from stand-point of hypothesis selection and application this result is very important, because a fatigue life increase under out-of-phase loading indicates the major role of normal stresses, which are mainly responsible for the crack initiation.

SELECTION AND APPLICATION OF THE APPROPRIATE STRENGTH HYPOTHESIS

Selection of the appropriate strength hypothesis

There are several indications for selection of the Normal (Principal) Stress Hypothesis (NHS) for the evaluation of the results, i.e. the low ductility of the investigated material, e = 5.9 %, the crack plane for pure torsion under 45° [5], the high mean-stress sensitivity, the prolongation of fatigue life under non-proportional loading, see Figs. 2 and 3, and, last but not least, the cleavages on the fracture surfaces after rupture, which confirm the sensitivity of the material against normal stresses [2].

Application of the Normal Stress Hypothesis for constant and variable amplitude loading

For low-ductility (up to brittle) materials, the critical plane φ on a surface element is the one where the normal stress $\sigma_n(\varphi) = \{[(\sigma_x + \sigma_y) + (\sigma_x - \sigma_y)\cdot\cos 2\varphi] \ / \ 2 + \tau_{xy}\cdot\sin 2\varphi\}$ or the cumulative damage of its spectrum becomes at maximum [2, 4]. When mean normal stresses are involved, then the normal stress amplitudes must be transformed to R = -1 or 0 by the mean-stress-sensitivity of the particular material [14] $M = \{[\sigma_a(R=-1) \ / \ \sigma_a(R=0)] - 1\}$ which is the inclination of the Haigh-line in the mean-stress-amplitude diagram [12-14]. After determining the maximum mean-stress-compensated normal stress amplitude (or the maximum cumulative damage in the case of spectrum loading), which is the equivalent stress amplitude (or its spectrum) according to the NSH, the next step is its evaluation, i.e. the calculation of the appertaining fatigue life. For this, depending on the stress ratio for which the amplitude transformation is carried out, Woehler-lines with R = -1 or 0, obtained under uniaxial loading, are needed. Here, amplitudes were transformed to the ratio R = -1.

In this context, the cumulative damage must also be addressed for the evaluation of the results determined under multiaxial spectrum loading. In this case, the critical plane is the one with the highest damage sum $D = \sum(N_i/n_i)$. The appertaining mean-stress-compensated normal stress spectrum is then the equivalent stress spectrum. Fatigue life is then estimated according to the Palmgren-Miner hypothesis and its frequently applied modification, where, in the high-cycle fatigue area, the inclination k of the Woehler-curve is reduced according to [13] with $k' = 2k-i$ depending on the material [7, 9, 12, 13], in order to account for the damaging influence of small load cycles. For cast materials, i = 2 is suggested [7, 9, 12, 13]. The spectrum results from the amplitude transformation of the rainflow-matrix to the stress ratio R of the Woehler-curve using the particular mean-stress sensitivity of the material. Because of the well-known fact that the theoretical damage sum $D_{th} = 1.0$ results in an unsafe estimate for 90 % of all published results [7, 12, 13], the life calculations are carried out using $D_{al} = 0.3$ as the allowable damage sum, as recommended for cast aluminium parts in [10].

Evaluation according to the Normal Stress Hypothesis

For the assessment of fatigue life, the calculated maximum normal local stress amplitude or its spectrum must be allocated to a Woehler-curve determined for the local stress system under pure bending or pure torsion and for the stress ratio R for which the amplitudes were transferred. Theoretically, for materials obeying the NSH, the Wöhler-lines (or curves) for pure bending or pure torsion should be identical because, under pure bending the local normal stress amplitude $\sigma_{a,x}$ is, at same time, the principal stress amplitude and the equivalent stress $\sigma_{a,eq} = \sigma_{a,1} = \sigma_{a,x}$ and, under pure torsion, the local shear stress amplitude $\tau_{a,xy}$ is, at same time, the principal stress amplitude and the equivalent stress amplitude has the value $\sigma_{a,eq} = \sigma_{a,1} = \tau_{a,xy}$.

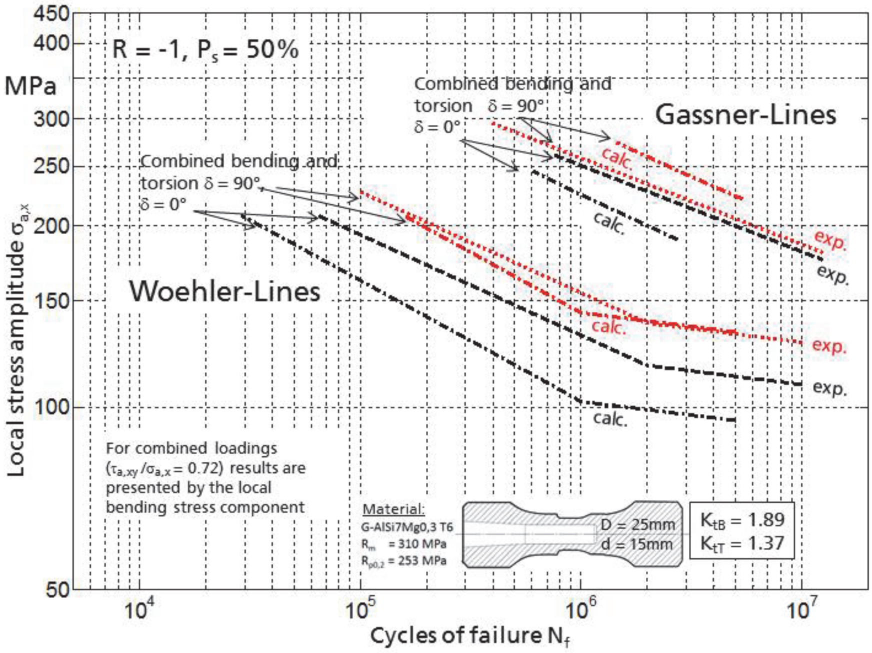

Figure 4: Comparison of experimental and calculated results for combined fully reversed loadings according to the Normal Stress Hypothesis

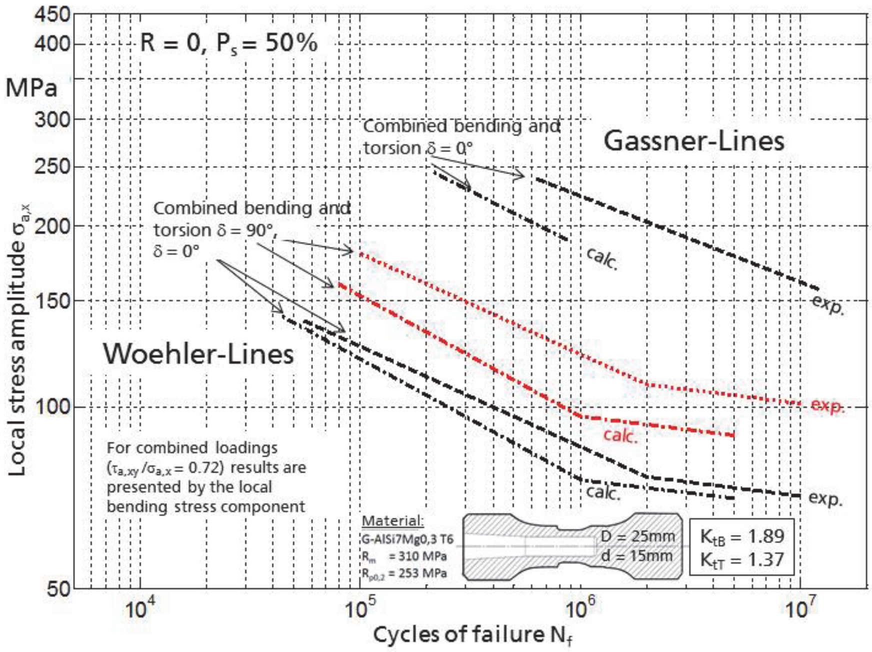

Figure 5: Comparison of experimental and calculated results for combined pulsating loadings according to the Normal Stress Hypothesis

However, from Figs. 2 and 3, it can be seen that the lines for pure torsion are inferior to those lines for pure bending, revealing differences in the slopes ($k_\sigma = 5$ and $k_\tau = 8$), knee points ($N_{k,\sigma} = 1 \cdot 10^6$ and $N_{k,\tau} = 5 \cdot 10^6$) and stress levels up to factor of 1.5. The differences in the slopes of these lines, determined under load control for the failure criterion of total rupture, cannot be attributed to different crack propagations under pure bending and pure torsion, because deformation-controlled tests for the failure criterion of crack initiation also reveal the same tendency for pure axial strain and pure shear strain [5]. The significantly different stress levels under fully reversed bending are caused by the different highly stressed material volumes in the notches due to the particular stress concentrations. Under pulsating loading, as the mean-stress effect for bending is more pronounced than for torsion, the stress levels are quite close to each other. These differences make choosing the appropriate Woehler-line for the assessment of fatigue life difficult. However, as the local normal stresses under combined loading are more dominant than the local shear stresses, the lines for pure bending are taken as starting Woehler-lines for fatigue lifing:

- $R = -1$, $\sigma_{ak} = 147$ MPa, $N_k = 1 \cdot 10^6$, $k = 5$, $k^* = 22$
- $R = 0$, $\sigma_{ak} = 97.5$ MPa, $N_k = 1 \cdot 10^6$, $k = 5$, $k^* = 22$

The mean-stress sensitivity, which is needed for amplitude transformations for $R = -1$ when mean stresses vary, is $M = 0.51$ resulting from the strength values at the knee points. Fatigue lifing is carried out for the applied Gaussian amplitude distribution with the sequence length $L_s = 1 \cdot 10^5$ according to the modified Palmgren-Miner hypothesis with $k' = 8$ against the allowable damage sum $D_{al} = 0.3$ using the Woehler-line for pure bending with $R = -1$.
The experimental and calculated fatigue-life lines for fully reversed and pulsating constant and variable amplitude loadings are displayed in Figs. 4 and 5.
The application of the NSH reflects the life increase due to the non-proportional combined loading. Except in one case, all results are on the safe side, by up to a factor of about 3 in life. The unsafe result for fully reversed out-of-phase spectrum loading differs by a factor of about 2 from the experimental outcome. Regarding the stresses, the calculated values are up to a factor of about 1.25 on the safe side and, in the unsafe case, by a factor of about 1.10.
In addition to this outcome, it can be observed that neither the slopes nor the knee points of the calculated fatigue-lines are in accordance with the experimental ones. The calculated results are driven by the properties of the starting Woehler-lines and the experimental results by the combination of local normal and shear stresses. Also, the comparison of the Woehler-lines for pure bending and pure torsion indicated the problem by their different slopes and knee points. This was also observed in other investigations [15] and particular modified Woehler-lines for overcoming these different influences on these properties were derived for the assessment. However, because of space limitations this will not be presented here.

SUMMARY AND CONCLUSIONS

The investigations carried out with component-like specimens of the cast aluminium alloy EN AC-42000 T6 (A 356 T6, G-AlSi7Mg0.3 T6), show that, under non-proportional normal and shear stresses fatigue life is increased in contrast to ductile steels where life is reduced due to changing principal stress directions. Because of the low ductility of this cast alloy ($e < 10\%$) compared to ductile quenched and tempered and structural steels, normal stresses are considered to be the main damage driving property, suggesting the application of the NSH. Fatigue lives under uni- and multiaxial spectrum loadings were estimated by the modified Palmgren-Miner-Rule using the allowable damage sum $D_{al} = 0.3$.
For all investigated stress states under multiaxial constant and variable (Gaussian spectrum) amplitudes without and with mean stresses, the NSH was able to depict the life increase by the non-proportionality and, for most cases, delivered conservative but non-exaggerated results. Except for one case, all results were on the safe side by up to a factor of approximately 3 in life. The one unsafe result, for fully reversed out-of-phase spectrum loading, differed by a factor of approximately 2 from the experimental outcome. Regarding the appertaining stresses, the calculated ones are up to a factor of about 1.25 on the safe side and, in the unsafe case, by a factor of about 1.10. In design practice safety factors j_σ for safety components of vehicles are in the range of about 1.7 to 2.2 [8] and cover the mentioned under- or overestimation of supportable stresses by the NSH.
If, in final durability proof tests, the fatigue life should be insufficient, then the required duration can be adjusted by simple geometrical modifications, e. g. by lowering local stresses by the use of larger radii, if this is not possible, by increasing thickness. As, for most safety components, the dominant loading partition is bending rather than torque or axial loading, to compensate the above mentioned factor of 1.10 resulting from the unsafe calculation, an increase of thickness by the square root of this factor, i.e. 1.05, 5 % only, would be sufficient. In the case of the conservative factor of 1.25 under predominantly bending loading, thickness could be reduced by factor of 1.12. Because of the advantage of the

casting technology to perform local dimensional modifications, the mentioned thickness changes do not hinder the realisation of lightweight designs, even if axial loads would be predominant and therefore a local thickness increase or reduction would be linear to the factors 1.10 and 1.25 respectively.
These results underline that the Normal (Principal) Stress Hypothesis (NSH) can be applied in its original form without any modifications for "fitting" the obtained experimental results, despite the not very significant limitations. Under- or overestimation of required fatigue lives or local stresses are, in any case, revealed by the durability proof tests, which are mandatory for vehicle safety components [7-9].

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REFERENCES

[1] Sonsino, C. M., Ziese, J., Fatigue Strength and Applications of Cast Aluminium Alloys with Different Degrees of Porosity, Int. J. Fatigue, 15(2) (1993) 75-84.
[2] Sonsino, C. M., Grubisic, V., Mechanics of Fatigue Failures of Cast and Sintered Structural Materials under Multiaxial Stresses, Konstruktion, 37(72) (1985) 7261–269, in German.
[3] Sonsino, C. M., Structural Durability of Cast Aluminium Gearbox Housings of Underground Railway Vehicles under Variable Amplitude Loading, Int. J. Fatigue, 27(8) (2005) 944-953.
[4] Sonsino, C. M., Influence of Material's Ductility and Local Deformation Mode on Multiaxial Fatigue Response, Int. J. Fatigue, 33(8) (2011) 930-947.
[5] Franz, R., Xin, P., Improvement of Fatigue Life Estimation for Multiaxial Loaded Safety Components of Forged Steel and Cast Aluminium by Selection of Appropriate Calculation Algorithms, Final Report – FKM/AiF No. 16059 N/1 (2013), VDMA, Frankfurt/Germany, in German.
[6] ANSI/ASTM-E 155-79, Standard Reference Radiographs for Inspection of Aluminium and Magnesium Castings, American Society for Testing and Materials, (1979).
[7] Sonsino, C. M., Principles of Variable Amplitude Fatigue Design and Testing, Fatigue Testing and Analysis under Variable Amplitude Loading Conditions, In: McKeighan, P. C. and Ranganathan, N., Editors, ASTM STP, 1439 (2005) 3–23.
[8] Grubisic, V., Criteria and Methodology for Lightweight Design of Vehicle Components Subjected to Random Loads, SAE-Paper No. 850367 (1985), Warrendale, PA/USA
[9] Sonsino, C. M., Berg, A., Grubisic, V., Structural Durability Proof of Automotive Safety Components – Present State of the Art, SAE-Paper No. 2005-01-0800 (2005), Warrendale, PA/USA
[10] Hänel, B., Haibach, E., Seeger, T., Wirthgen, G., Zenner, H., FKM-Guideline – Analytical Strength Assessment of Components in Mech. Eng., VDMA, Frankfurt/Germany, 5th extended Ed., (2007).
[11] Sonsino, C. M., Course of SN-Curves Especially in the High-Cycle Fatigue Regime with Regard to Component Design and Safety, Int. J. Fatigue, 29 (2007) 2246-2258.
[12] Buxbaum, O., Structural Durability - Safe and Economic Design of Fatigue Components, 2nd Edition, Verlag Stahleisen, Düsseldorf (1992).
[13] Haibach, E., Structural Durability – Methods and Data for Calculation, 3rd Ed., VDI-Verlag, Düsseldorf, (2003), in German.
[14] Sonsino, C. M., Leightweight Design Chances Using High-Strength Steels, Mat.wiss. u. Werkstofftech. 38(1) (2007) 9-22.
[15] Susmel, L., Sonsino, C. M., Tovo, R., Accuracy of the Modified Wöhler Curve Method Applied Along with the r_{ref} = 1 mm Concept in Estimating Lifetime of Welded Joints Subjected to Multiaxial Fatigue Loading, Int. J. Fatigue 33 (2011) 1075-10.