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Overitev trajnosti aluminijastih sestavnih delov

Structural Durability Validation of Aluminium Components

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Zaradi povečane uporabe aluminijevih zlitin za sestavne dele vozil je treba povzeti najsodobnejša spoznanja o presoji trajnosti sestave v delovnih pogojih. V prispevku smo predstavili postopke za preizkusno in numerično vrednotenje delovne trdnosti vlitka, kovanih in varjenih sestavnih delov iz aluminijevih zlitin. Predstavili smo tudi rezultate raziskav vpliva korozije, prav tako pa tudi metode pospešenega odobravanja preizkusov. Ti so nato potrjeni in priporočeni za uporabo v praksi.

(Ključne besede: delovni pogoji, trdnost materialov, trajnost, vplivi korozije, utrujenost materialov)

The increasing trend to use aluminium alloys for vehicle components makes it necessary to summarize the state of the art related to the approval of their structural durability under operational conditions. In this paper the procedures for the experimental and the numerical service-strength evaluations of cast, forged and welded aluminium-alloy components are presented. We also present the results of investigations of the influence of corrosion as well as the methods for accelerated test approval; these are then validated and a practical approach recommended.

(Keywords: service evaluation, strength of materials, structural durability, corrosion-fatigue-influence)

0 INTRODUCTION

The demands of the automotive industry for lightweight design and weight saving can only be fulfilled by going to the limits of the materials' properties, the manufacturing process, the behaviour of the structural part and the behaviour of the system. An increase in the reliability is required, but at the same time there is a desire to reduce test costs, coupled with efforts to improve the methods of numerical design.

Structural durability validation covers, on the one hand, special event loading and loading during misuse, and, on the other hand, service fatigue loading, characterized by the criteria of the structural yield point, the fracture behaviour and the fatigue strength ([1] and [2]), Fig. 1. Whereas an experimental proof of the strength safeguards the product safety, the numerical service strength evaluation serves as a pre-design procedure.

An intensive cooperation between the Fraunhofer Institute for Structural Durability and System Reliability (LBF), Darmstadt, and the Technical Faculty, Ljubljana, was started about 40 years ago by **Jože Hlebanja** and **Ernst Gassner**, and was continuously supported by co-workers and younger scientists. One of them, who contributed not only to this cooperation but also to the development of structural durability validation, was **Matija Fajdiga**. This cooperative research, especially the investigations related to the **structural durability of aluminium components**, which were supported by the EU ([3], [4] and [6]), are of great value.

This paper is a review of the results of all the available investigations about the structural durability of aluminium components, the study of which was initiated and supported by experts from AUDI AG, BMW AG, Daimler Chrysler AG, Porsche AG and Volkswagen AG, and carried out by authors of Ref. [1]. In it the procedures for the experimental and the

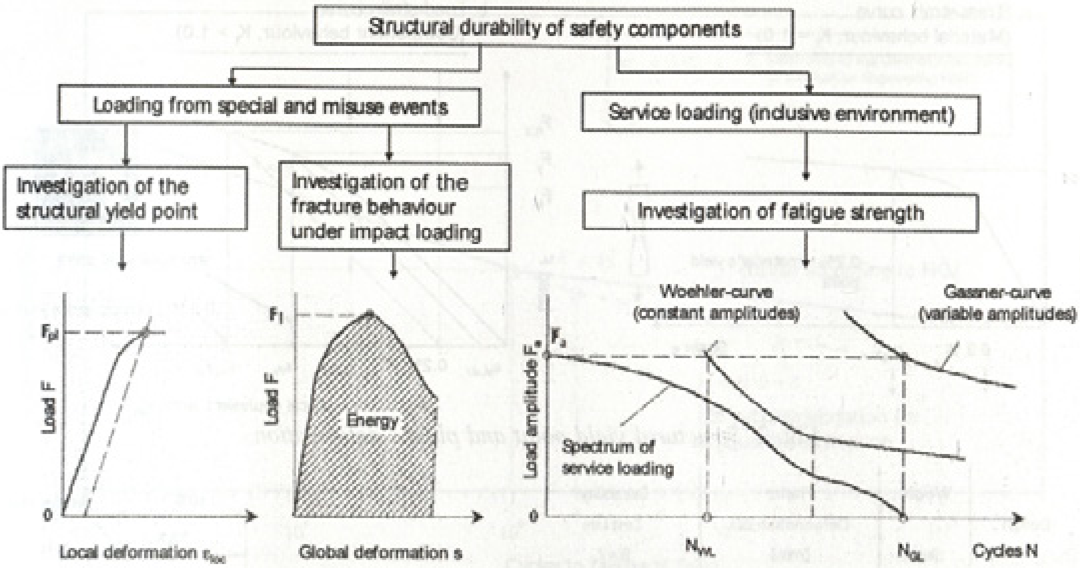

Fig. 1. *Partition of the structural durability*

numerical service-strength evaluation of cast, forged and welded aluminium-alloy components are presented. Furthermore, the results of the investigations of the influences of corrosion as well as the methods for accelerated test approval are presented, validated, and a practical approach is recommended.

1 THE EVALUATION OF SERVICE STRENGTH

1.1 Fracture strength

The relevant design criterion for a special event, for example, pressing a wheel against the curbstone edge when parking or when hitting a pothole with front wheel at braking, is usually the component's yield point. However, depending on the material and the component, a misuse criterion may become more relevant. The component's yield point is defined as the local equivalent strain or the corresponding equivalent stress, causing a plastic deformation of an allowable size, Fig. 2. A prerequisite is that neither an unacceptable global deformation of the component remains nor the required fatigue strength of the component decreases.

Experimental investigations to determine the component's yield point are carried out with vehicle- and component-relevant quasi-static loading, simulating the relevant special event. A recording of the load-local strain behaviour is recommended, making it possible to evaluate the material's fatigue behaviour and make a comparison with calculation results. Fig. 3 shows the investigations on cast wheels (material G-AlSi7Mg T6), which were preloaded on the inner-rim side before the experimental structural durability validation was carried out. During preloading a special, seldom-occurring event is simulated, when the user drives over a "speed bump" or curbstone. Under such a loading a plastic, simply non-detectable, deformation can occur on the wheel, which could decrease the structural durability because of premature fatigue cracks on the rim, as shown in Fig.3.

Within the pre-design process the component yield point may be estimated by elastic/plastic finite-element analysis based on the monotonic stress-strain curve for the local stress state. If any indications exist that plastic deformations may cause damage, fatigue testing with a load spectrum derived from the component's service-load history is recommended.

The relevant design criterion for misuse events, for example, high-speed curbstone impact, is the fracture behaviour during impact loading, with which fractures without deformation, e.g., brittle fractures, must be excluded.

1.2 Fatigue strength

The fatigue strength of aluminium alloys decreases continuously for a large number of stress cycles. Based on experience, the knee point of the Woehler curve is assumed to be between $1 \cdot 10^6$ and $2 \cdot 10^6$ cycles. However, it may diverge from this, de-

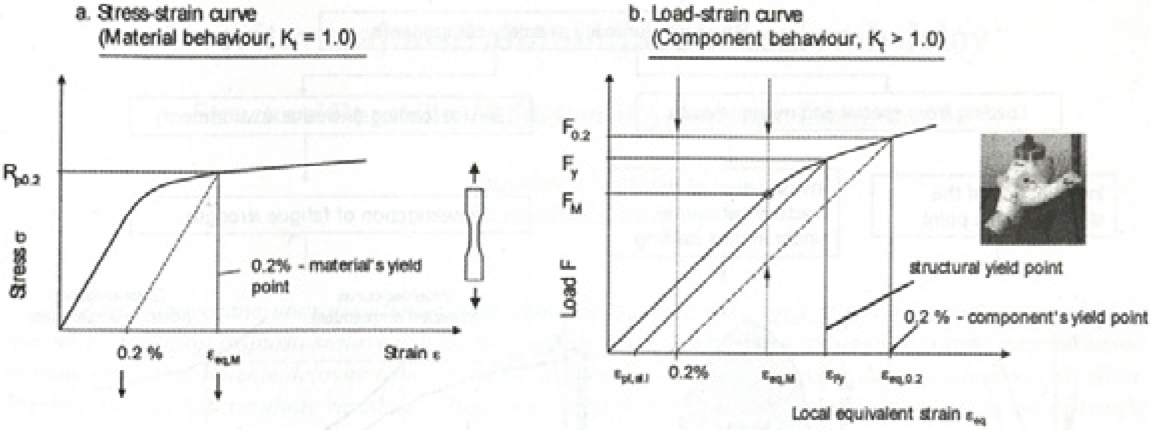

Fig. 2. *Structural yield point and plastic deformation*

Design	Weight [kg]	Plastic Deformation ΔD [mm]	Durability Test Life [km]
A	10.9	- 0.85	cracks at 4 979 ≈0.5
B	11	-0.55	cracks at 10 141 ≈1.0
C	11.35	-0.35	without cracks 14 920 >1.5

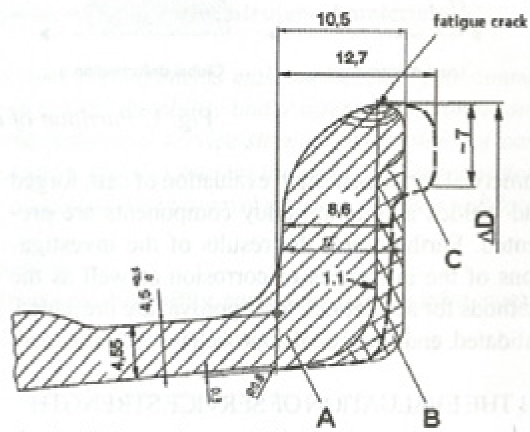

Fig. 3. *Influence of the rim design on plastic deformation and durability*

pending on the component, the material and the loading mode. As separately manufactured specimens do not inherit the shape, the surface condition and the residual stresses of the component, a direct transmission of the specimen's test results to the components is not possible.

Fig. 4 shows the empirically derived shape of the Woehler curve recommended for the pre-designing of the components from wrought or cast aluminium alloys according to the local stress concept when the specific component data are missing. The available, published quantitative material data are summarized in [1].

In Fig. 5 a generalized Woehler-curve for welded aluminium joints is presented. Compared to the aluminium base material the fatigue strength of the welded joint is less by a factor of between 1.3 and 3.0, assuming an equal stress distribution along the highly stressed section. The tensile strength, R_m, and the yield strength, $R_{p0.2}$, of the base material have only a minor influence on the fatigue strength.

Residual tensile stresses caused by the change of microstructure as well as the solidification may degrade the fatigue strength. Such a degradation prevails in the range of large numbers of cycles ($N>1\cdot10^6$). When the magnitude of the residual stresses is known they may be assessed like mean stresses. Otherwise, it is recommended to cover the effect of residual stresses by choosing the allowable stresses resulting from the fatigue loading with R=0.

In the case of a fatigue-life estimation under variable-amplitude loading the recommended slopes of the Woehler curve are k=5 in the cycle region of $N<1\cdot10^7$ and k' = 2k–2 in the region of $N>1\cdot10^7$, as shown in Figs. 4 and 5.

For the design of welded joints the automotive industry normally applies the structural stress concept ([5] and [6]). The structural stress incorporates the influence of the weld geometry and the loading mode, but should not be mistaken for the maximum notch stress or the hot-spot stress [5], Fig. 6.

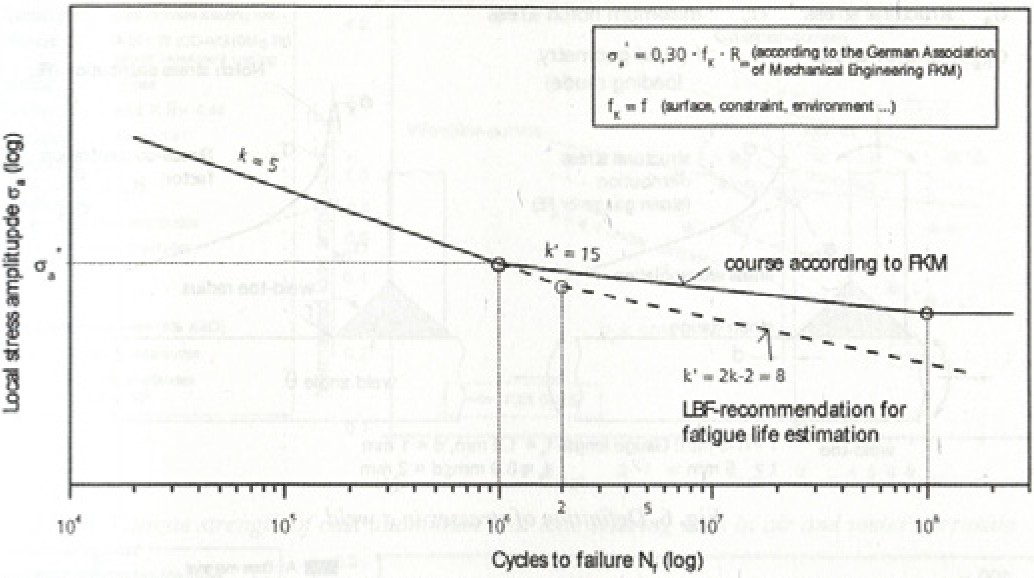

Fig. 4. *Schematical presentation of the Woehler-curve for components of wrought and cast aluminium alloys*

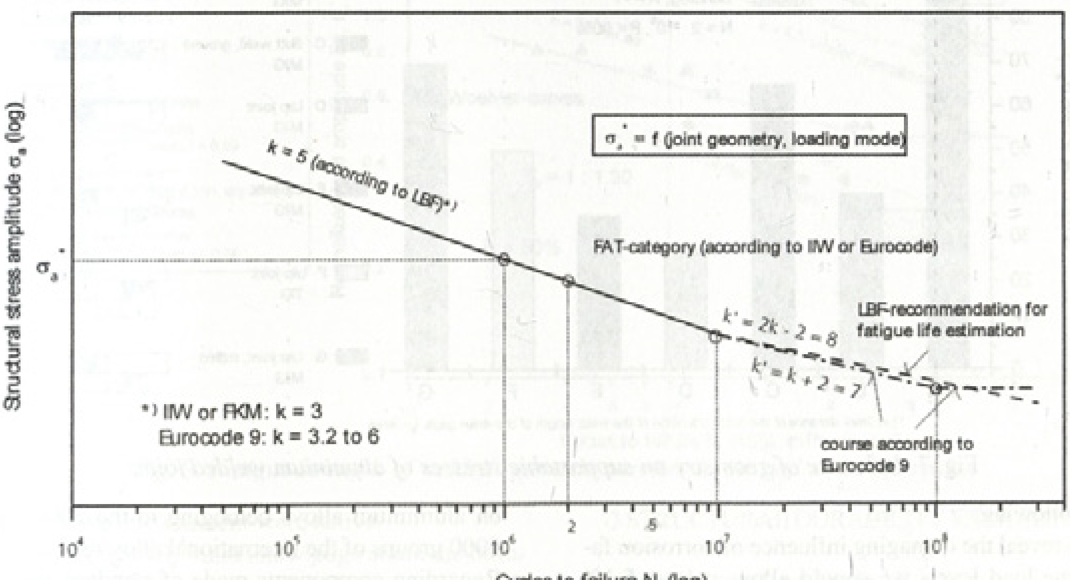

Fig. 5. *Schematical presentation of Woehler-curves for aluminium welded joints*

The local geometry substantially influences the endurable structural stresses of welded joints [6], Fig. 7. If no specific data are available a structural stress of σ_a*(R=-1, N=1·10^6, P_s=90%) = ±40 MPa may be used for the pre-design.

2 THE INFLUENCE OF CORROSION

If components are exposed to a corrosive environment during service the experimental as well as the analytical proof must take into account the influence of the corrosion [7].

For instance, for a cast steering rod and a welded rear-axle carrier the Woehler and Gassner curves resulting from constant and variable amplitude loading in air and in a corrosive medium (5% NaCl) are displayed in Figs. 8 and 9. The applied stress variation and the spectra are presented in Figs. 10 and 11.

Concerning the effect of corrosion on the fatigue strength special attention should be paid to

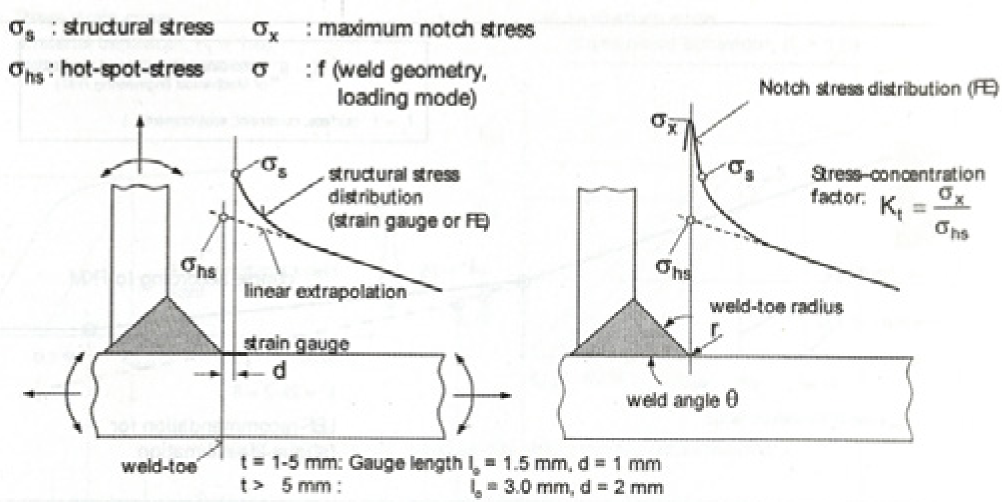

Fig. 6. *Definition of stresses in a weld*

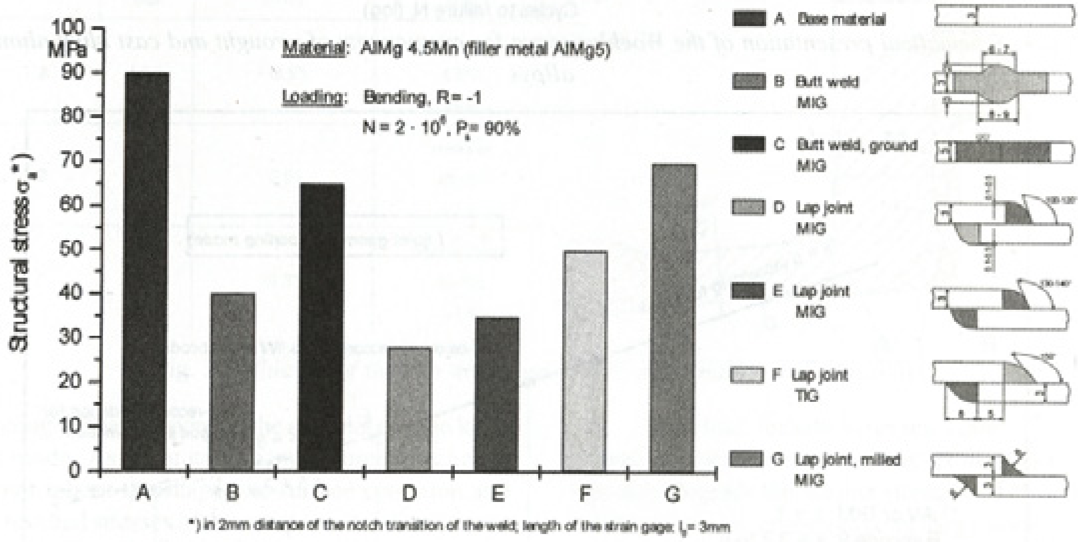

Fig. 7. *Influence of geometry on supportable stresses of aluminium welded joints*

the following:

- To reveal the damaging influence of corrosion fatigue load levels we should allow at least $5{\cdot}10^6$ cycles.
- During corrosion the slopes of the Woehler curves do not change. A constant slope of k = 4 is recommended.
- Available results show a significant drop in the fatigue strength due to the corrosion being less during random loading. If the surface is not treated (coated, shot-penned) the fatigue strength after $5{\cdot}10^6$ load cycles reduces to 50% under constant-amplitude loading and to 20–25% under variable-amplitude loading. This applies to the intensified corrosive conditions imposed in the laboratory on aluminium alloys belonging to the 5000 and 6000 groups of the international alloy register.
- Regarding components made of standard alloys, service experience has confirmed the following approach: the damaging influence of corrosion for a real component can be covered by proof testing in air with a 15% increase in the fatigue loads, provided the component's yield point is not exceeded. Otherwise, a design life increased by a factor of 2 must be proven [1].
- Although cast skin and shot-penning diminish the strength drop due to corrosion this effect should be neglected in the numerical design process. In the case of corrosion protection (surface coats) the design process may be conducted as if no

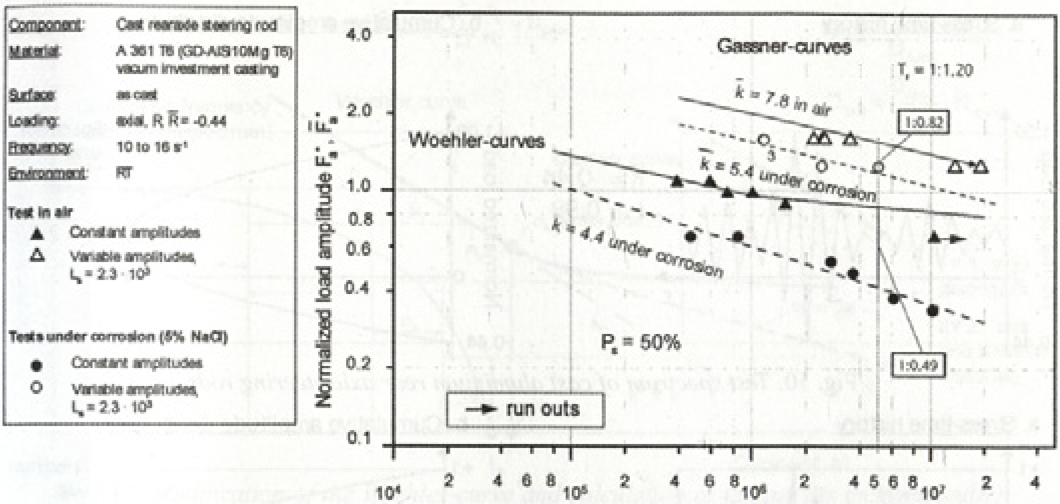

Fig. 8. *Fatigue strength of cast aluminium rear axle steering rods in air and under corrosion*

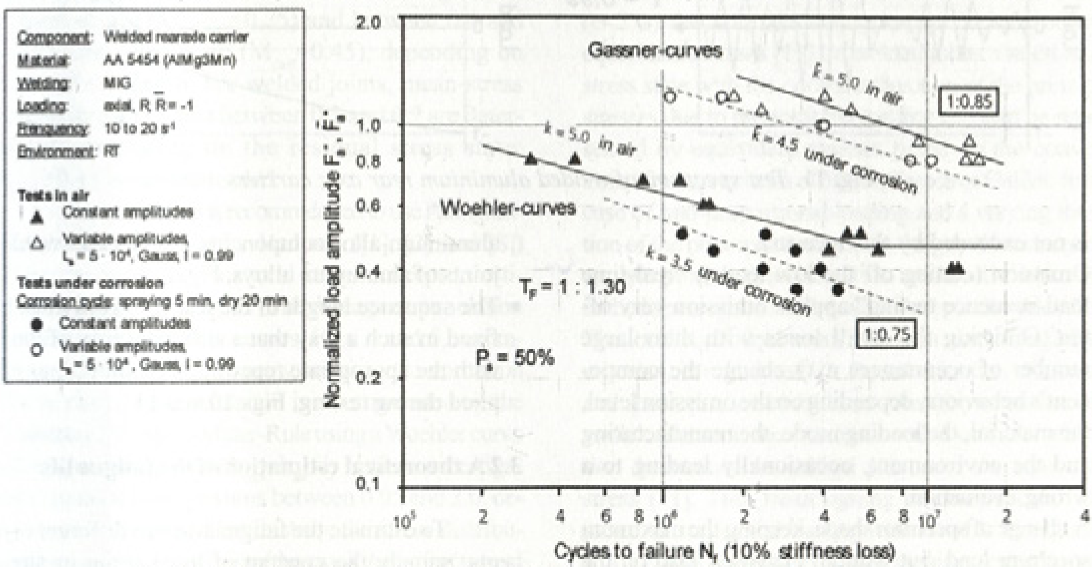

Fig. 9. *Fatigue strength of welded rear axle carriers in air and under corrosion*

corrosive environment were active.

- So far, generally valid knowledge about the influence of distinct corrosion cycles on fatigue behaviour and knowledge about an appropriate selection of service-like environmental conditions are still missing. Thus, for future testing concepts, first of all a unification of simulated environmental conditions is to be recommended, for example, a 5-min period of salt spraying with 5% NaCl solution followed by a drying period of 20 to 25 min.

Investigations on preconditioning with subsequent fatigue loading in air do not have a real influence on the fatigue strength. Therefore, corrosive preconditioning should not be recommended to assess fatigue corrosion.

3 STRUCTURAL DURABILITY VALIDATION

3.1 Experimental validation

The experimental validation of structural durability must be based, on the one hand, on representative operational stress spectra including the loading sequence, and on the other, be carried out in a time- and cost-saving way [8]. Therefore, it is necessary to accelerate the durability testing for which the different possibilities exist:

- The increase of the maximum and of all other spectrum loads with a simultaneous decrease of the spectrum size. This modification is suitable only when the structural yield point of the component

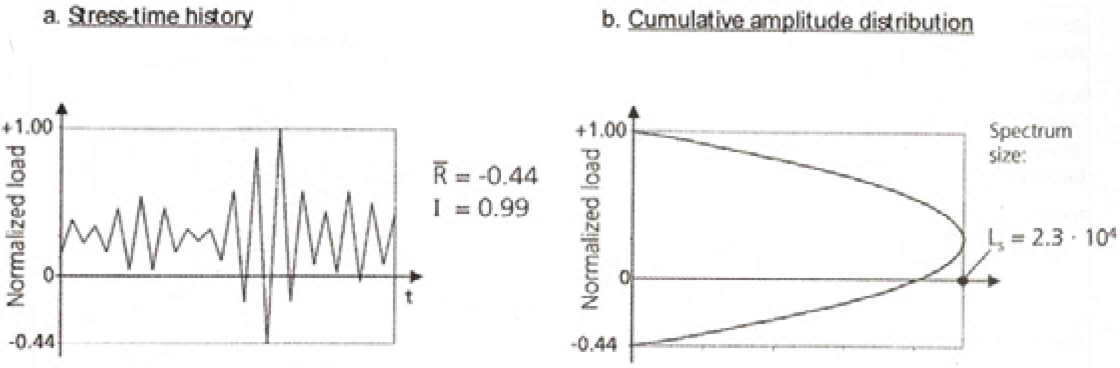

Fig. 10. *Test spectrum of cast aluminium rear axle steering rods*

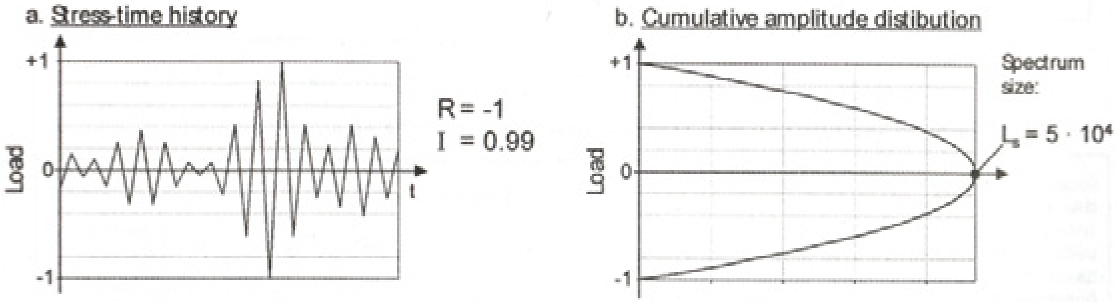

Fig. 11. *Test spectrum of welded aluminium rear axle carriers*

is not exceeded by this measure.

- Omission (cutting off the low loads); "real-time load-sequence testing" applies omission very often. Omitting the small loads with their large number of occurrences may change the component's behaviour, depending on the omission level, the material, the loading mode, the manufacturing and the environment, occasionally leading to a wrong evaluation.
- A change of spectrum shape, keeping the maximum spectrum load, but with an increased load on the lower levels. Here, the omitted small spectrum loads and the corresponding decreased total frequency are compensated by the increased loads, maintaining the damage content of the design spectrum.

The modified load spectra should obey the following rules:

- The load spectrum must contain a sufficient number of cycles, $2 \cdot 10^6$ up to $5 \cdot 10^6$, to cover the eventually occurring effects of fretting and environmental corrosion as well as the degradation of the fatigue strength in the region of a large numbers of cycles.
- The equivalence of the damage caused by the test and the design spectrum, which should be verified by calculation with a modified Palmgren-Miner rule using Woehler curves for wrought or cast aluminium-alloy components, Fig. 4, or for welded joints of aluminium alloys, Fig. 5.
- The sequence length of the test spectrum must be fixed in such a way that a sufficient mix of loads with the appropriate repetition is achieved, as applied during testing, Figs.10 and 11.

3.2 A theoretical estimation of the fatigue life

To estimate the fatigue life two different concepts, namely the concept of local strain or stress for cast and forged components, and the concept of structural stress for welded joints, are used. Correspondingly, the local stress concept utilizes a local stress Woehler curve, as shown in Fig. 4, and the structural stress concept a structural stress Woehler curve, as shown in Fig. 5. A comparison of the experimentally generated strength data with the data derived from a German design guideline (FKM) [9] or from the Uniform Material Law shows large differences caused by the influences of component manufacturing. It is therefore advisable to use data obtained with specimens removed from components or with components.

The local stress concept covers the mean-stress effects with the material-related mean-stress sensitivity parameter $M = [\sigma_a(R{=}-1) / \sigma_a(R{=}0)]-1$. It

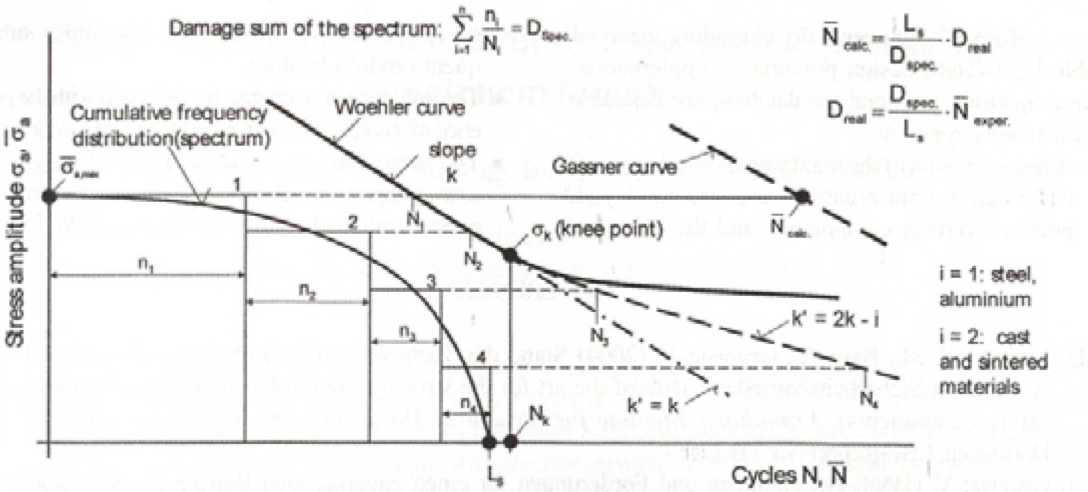

Fig. 12. *Modification of the Woehler-curve and calculation of fatigue life (schematically)*

has values between 0.2 and 0.3 for wrought aluminium alloys ($M_{wrought}$=0.25) and between 0.4 and 0.5 for cast aluminium (M_{cast}=0.45), depending on the tensile strength. For welded joints, mean-stress sensitivity parameters between 0.2 and 0.7 are determined, depending on the residual stress state; M_{weld}=0.45 is recommended.

Furthermore, it is recommended to use Palmgren-Miners-Rule modified by Haibach ([1], [2] and [8]) within the local and structural stress concept to estimate the fatigue life, Fig. 11. The damage accumulation is based on the Woehler curves, Figs. 4 and 5, recommended above. If components are prone to corrosion effects, damage accumulation is recommended by the elementary Palmgren-Miner-Rule using a Woehler curve with a constant slope of $k_{corr}=k_{air}-1$. Various investigations revealed damage sums between 0.05 and 2.0, depending on the stress-time history, the stress distribution and the failure criterion (the cracking or fracture of a test specimen). A real damage sum of D_{real} = 0.5 is recommended for use with the fatigue-life estimation [10]. In the case of a large mean-stress variation, smaller damage values should be used.

Assuming proportional loading and a constant direction for the principal stresses, multi-axial fatigue loading of wrought aluminium-alloy components can be assessed by equivalent stresses based on the distortion energy (Mises) or the shear-stress criterion (Tresca); in the case of cast alloys the normal (principal) stress criterion (Galilei) should be used. In the case of changing the principal stress directions the use of the distortion energy or the shear-stress criterion is not appropriate. They may lead to significantly over-estimated fatigue lives of components with ductile material (e>10%) behaviour; thus a ductility-dependent modification is needed. For less ductile cast alloys (e<2%) the normal stress criterion delivers correct equivalent stresses [11]. In welded joints a multi-axial stress state with the constant direction of the principal stresses due to proportional loading can also be represented by equivalent stresses based on the conventional fracture criteria of Mises, Tresca or Galilei. In the case of non-proportional loading and a varying direction of the principal stresses, the fatigue-life estimation applying these criteria results in an unrealistic increase in the life compared to the case of proportional loading. The local equivalent stress, based on a modified Mises criterion, is calculated for the combination of normal and shear stresses in different interference planes of a surface element; the maximum value of the combination determines the critical plane and the equivalent stress [11]. The pre-designing of components, subjected to multi-axial loading with variable amplitudes, still contains large uncertainties requiring experimental verification.

4 CONCLUSIONS

The state-of-the-art knowledge and the already-existing experience make the reliable design of aluminium components feasible. However, in future experimental investigations of components' structural durability the local stresses or strains, with their dependencies on manufacture, geometry, and loading, should be determined, because the resulting data are more appropriate than the data derived from specimen testing or taken from guidelines. Such data may form a basis for verifying calculations and for the transfer of data to other components and for different loading modes.

To profit by eventually extending the available lightweight design potentials, supplementary investigations to extend the database are desirable. This mainly concerns:

- A determination of the maximum allowable plastic deformation with regard to the structural yield point of various components and the effects of special events on the fatigue life under subsequent random loading.
- The influence of temperature combined with the presence of a corrosive environment and random loading.
- The improvement of the accuracy of fatigue-life assessment methods for welded aluminium components, also when they are multi-axially loaded.

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