The Concept of the Fictitious Radius for the Assessment of Welded Joints of Wrought Magnesium.

C.M. Sonsino[a), Ö. Karakas [b), C. Morgenstern [c)

[a)] Fraunhofer-Institute for Structural Durability and System Reliability LBF, Darmstadt / Germany
[b)] Faculty for Engineering Science, Mechanical Engineering, University Pamukkale, Denizli/ Turkey
[c)] Adam Opel GmbH, Ruesselsheim/Germany

Abstract With regard to light-weight design of welded magnesium structures the investigation reported was carried out with three different types of MIG- and TIG-welded joints of the alloy AZ31(ISO-MgAl3Zn1), fully or partially penetrated butt welds, transversal stiffeners. The evaluation of the results showed that the local stress concept using the fictitious notch radius of r_f = 1.0 mm can be applied to magnesium welded joints from plates with thicknesses t ≥ 5 mm independently from the weld geometries. Design curves are proposed for different stress ratios, i.e. R = -1 as well as 0 and 0.5, which allow the consideration of residual stresses as well as load induced mean stresses. The results permit also the suggestion of $\Delta\sigma$= 28 MPa for r_f= 1.0 mm as FAT-value in the IIW-Fatigue Design Recommendations. This FAT-value is compared with the already known data for steel and aluminium joints. A linear relationship between the FAT-values and the Young's modulus is determined.

1 INTRODUCTION

The increased application of the finite element method in past decades established in the design of welded structures more and more local concepts [1], especially the hot-spot stress concept, Fig. 1 and 2a. However, the use of this concept is limited, when the fatigue critical area is not accessible by the extrapolation of the calculated structural stresses. Weld roots and other hidden details [2], Fig. 2b, fall into this category. For the assessment of such details different local stress concepts were developed in recent years [1], e.g. the concept of the micro-support according to [3 - 7] and the concept of the fictitious radius, too [8 - 10]. Certainly, both concepts are applicable also for not hidden weld notches, Fig. 2a.

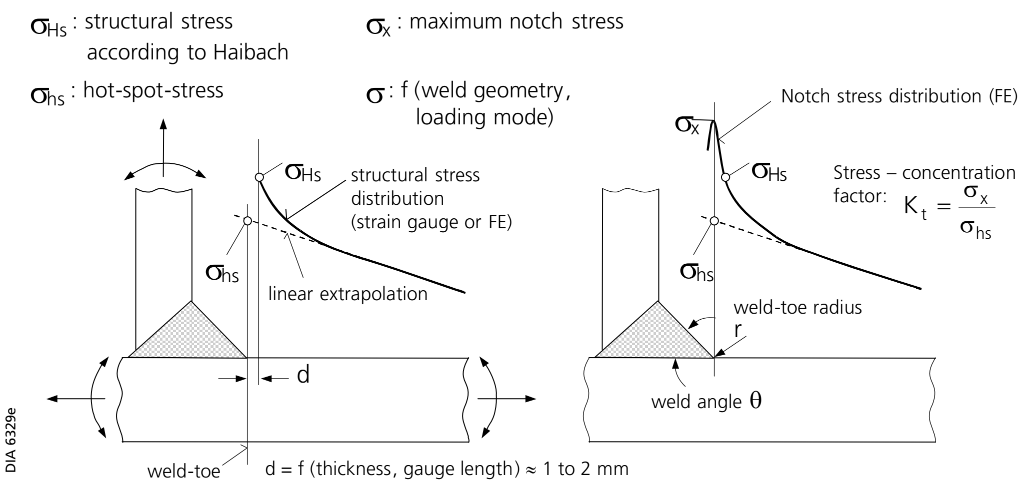

Fig. 1: Definition of stresses in a weld toe according to different design concepts

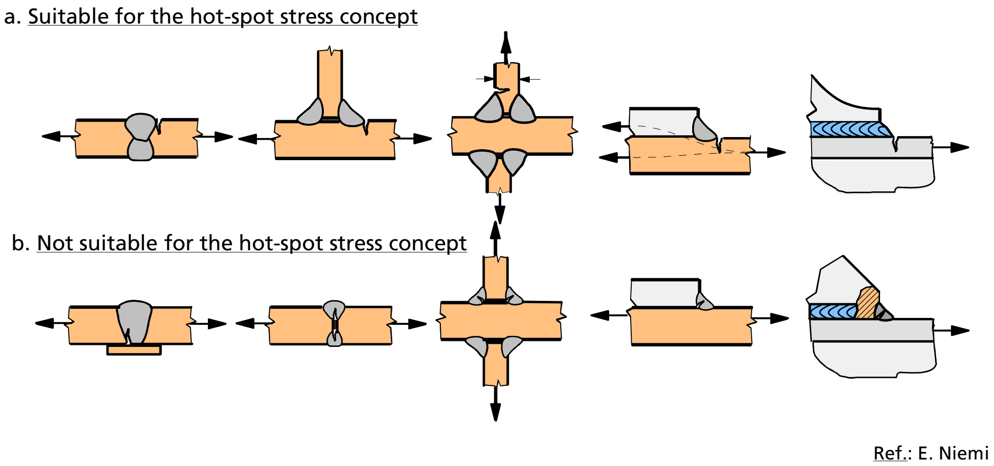

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Fig. 2: Limitations of the application of the structural hot-spot-stress approach

The micro-support concept requires the knowledge of the local material constant ρ* (substitute structural length), which is different for the base metal, heat affected zone and weld metal [6, 7]. Depending on the site of crack initiation the particular constant must be selected. The fact that these constants are not always available, limits the applicability of this concept. However, the concept of the fictitious radius which doesn't need any material constant is more universal. For steels with plate thicknesses $t \geq 5$ mm the fictitious radius of $r_f = 1.0$ mm delivered good results and is recommended already in different design codes [11, 12]. The same fictitious notch radius was verified for aluminium welded joints, too [10, 13 - 18]. However, for the fatigue design of magnesium welded joints from plates with $t \geq 5$ mm and significant stress concentration, there is until now no evidence if a fictitious radius of $r_f = 1.0$ mm, as suggested for steels and aluminium [9, 11, 13], will be applicable. The database of recent investigations with the welded magnesium alloy AZ31 [19] allows to answer this question, as reported in the following.

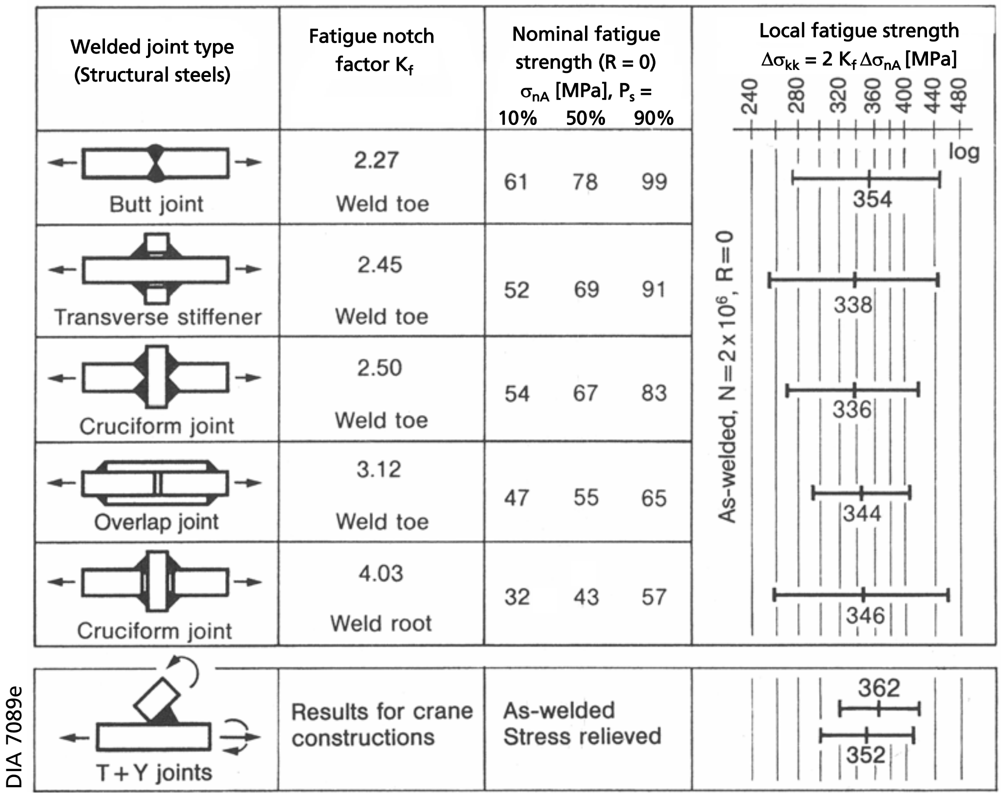
2 SHORT EXPLANATION OF THE LOCAL STRESS CONCEPT USING THE FICTITIOUS NOTCH RADIUS OF $r_f = 1.0$ mm

The theoretical background of this concept is based on Neuber's micro-support theory [3] assuming

$$r_f = r_r + \rho^* \cdot s \qquad (1)$$

where r_f is the fictitious notch radius, r_r the real radius, ρ^* the micro-support constant and s the multiaxiality constant. For structural steels $\rho^* = 0.4$ mm and $s = 2.5$ according to von Mises was suggested [3]. In the worst case of a crack, where the real radius is 0 mm, equation (1) renders $r_f = 1.0$ mm.

The modelling of different weld geometries with this radius transformed different fatigue strengths of the nominal stress system at $2 \cdot 10^6$ cycles in a more or less uniform local stress value [8, 9], Fig. 3.



Ref.: R. Olivier, V. B. Köttgen, T. Seeger

Fig. 3: Local fatigue stress ranges of welded steel joints for the fictitous radius r_f = 1.0 mm

In this investigation an allowable FAT-local stress range of $\Delta\sigma_{loc}$ = 225 MPa at N = 2 $\cdot$ 10^6 cycles was derived for P_s = 97.7% assuming a scatter of T_σ = 1: 1.50 and R = 0.5 for covering the influence of high tensile residual stresses on fatigue strength. This FAT-value is already suggested in design recommendations for the assessment of welded steel joints [11, 12].

3 MATERIAL PROPERTIES AND GEOMETRIES OF THE WELDED JOINTS

The chemical composition and mechanical properties of the investigated magnesium alloy are compiled in Table 1.

a. Chemical composition (in %)

Material	Al	Si	Fe	Cu	Mn	Ni	Zn	Mg
Magnesium AZ31 (ISO.Mg-Al3Zn1)	2.850	0.050	0.003	0.001	0.290	0.001	0.950	Rest

b. Mechanical properties

Material	Thickness d mm	$R_{p,02}$ MPa	R_m MPa	A_5 %
Magnesium AZ31 (ISO-MgAl3Zn1)	5.3	197	247	14.7

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Table 1: Material data

In Figs. 4a to 4c the geometries of the welded joints, in Fig. 5 the macro-sections and the position of the failures are presented. The radii were determined by a roughness measurement unit. The given maximum stress concentration factors were calculated by FE for the minimum values of the radii.

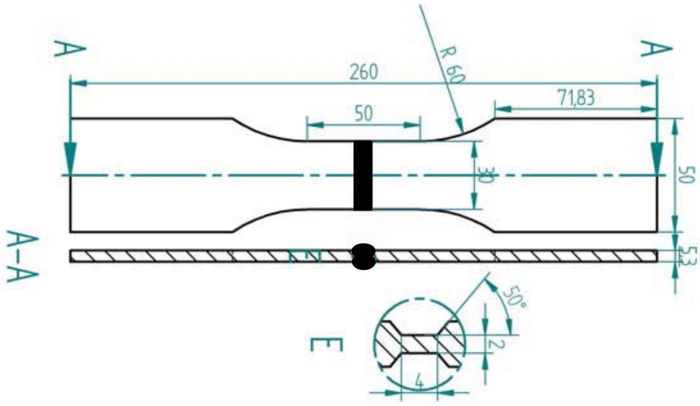

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Fig. 4a: Butt weld, fully penetrated; r_{min} = 1.72 mm, $K_{t,max}$ = 1.64

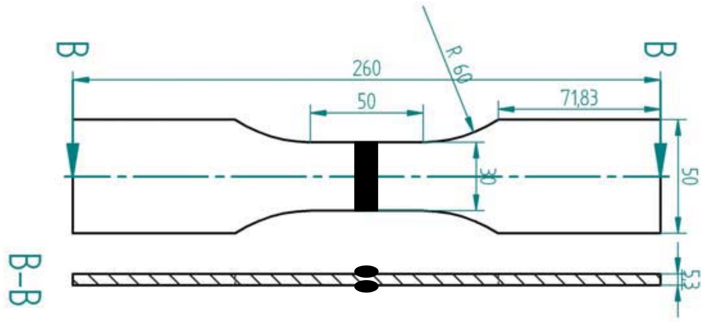

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Fig. 4b: Butt weld, partially penetrated; Gap: 2.8 – 3.2 mm, r_{min} = 0.05 mm, $K_{t,max}$ = 19.43

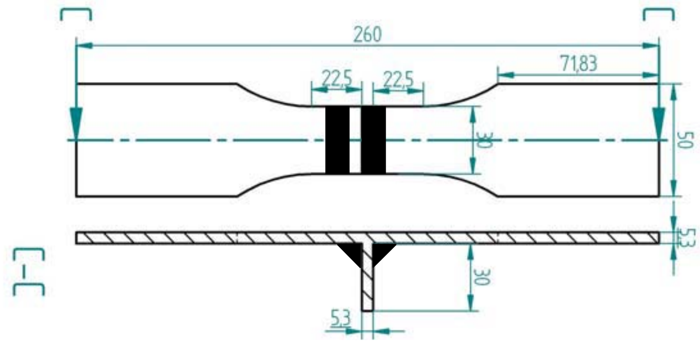

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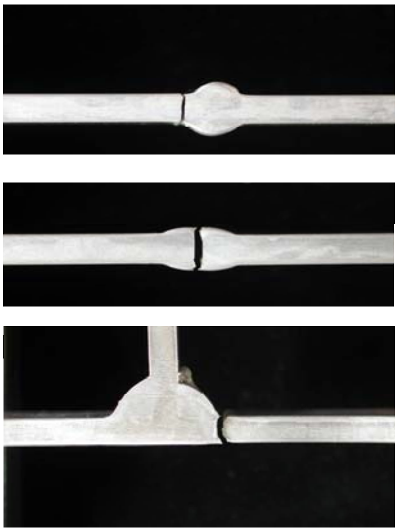
Fig. 4c: Transversal stiffener; r_{min} = 0.56 mm, $K_{t,max}$ = 2.03



a. Butt weld, fully penetrated
Crack initiation at weld toe

b. Butt weld, partially penetrated
Crack initiation from weld root

c. Transversal stiffener
Crack initiation at weld toe

Thickness : t = 5.3 mm

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Fig. 5: Macrocuts of the welded joints with the critical cross sections

The fully penetrated butt welds and the transversal stiffener were manufactured by MIG-welding, the partially penetrated butt welds by TIG-welding, the filler metal was AZ61 A. The hardness distributions measured are displayed in Fig. 6. The hardness distribution is given only for displaying the different material zones and is not in relation to the sites of crack initiation. As shown in Fig. 5 the cracks were always initiated in the weld toes and notch roots where the stress concentration is the highest.

a. Magnesium AZ31 (MgAl3),
fully penetrated but weld

b. Magnesium AZ31 (MgAl3),
transversal stiffener

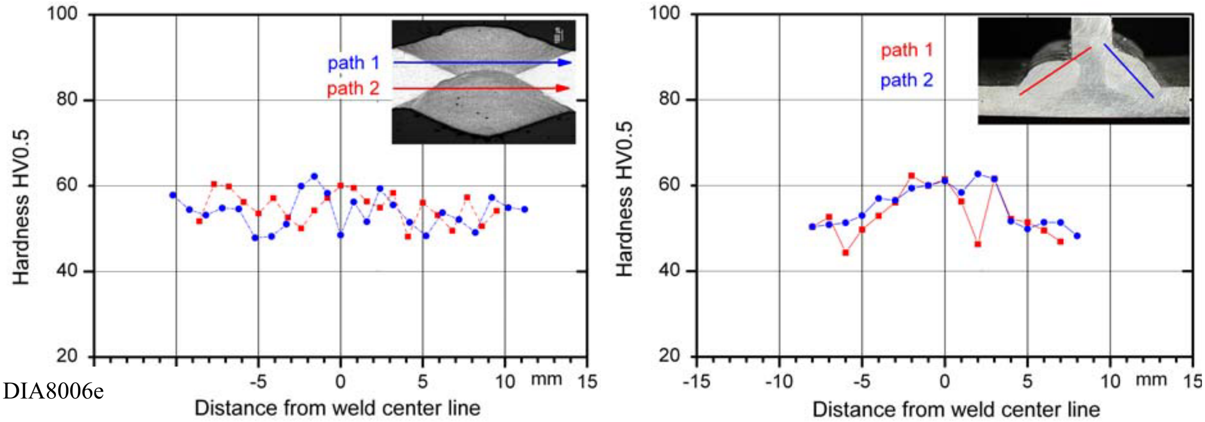

Fig. 6: Measured hardness distributions

4 TEST RESULTS

In Figs. 7 to 9 the obtained results under fully reversed (R = -1), pulsating (R = 0) and with high mean - stress (R = 0.5) loading are presented in the nominal stress system. The tests were load controlled with a frequency of
$f = 15$ to $30\ s^{-1}$ under room temperature in air. For each specimen type 8 to 25 tests were carried out.

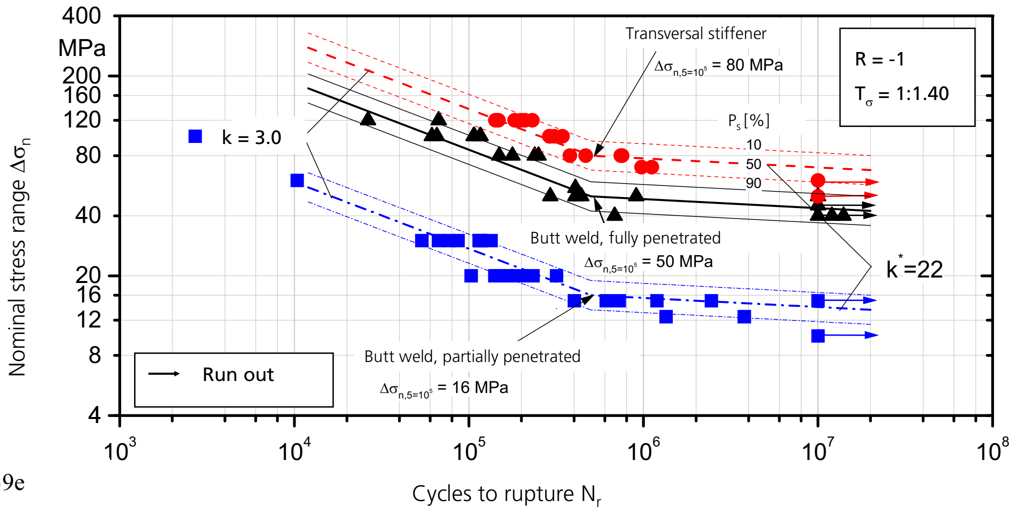

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Fig. 7: Woehler-curves of welded magnesium joints in the nominal stress system under fully reversed loading

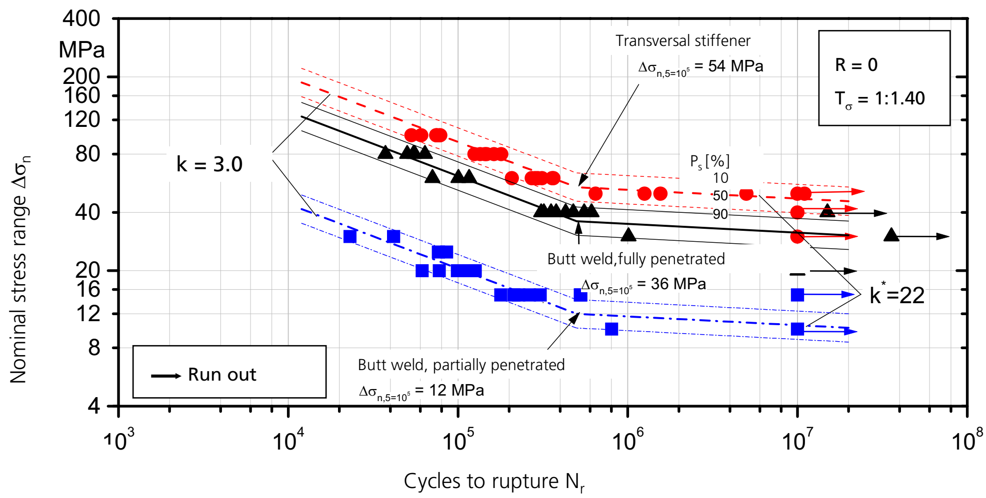

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Fig. 8: Woehler-curves of welded magnesium joints in the nominal stress system under pulsating loading

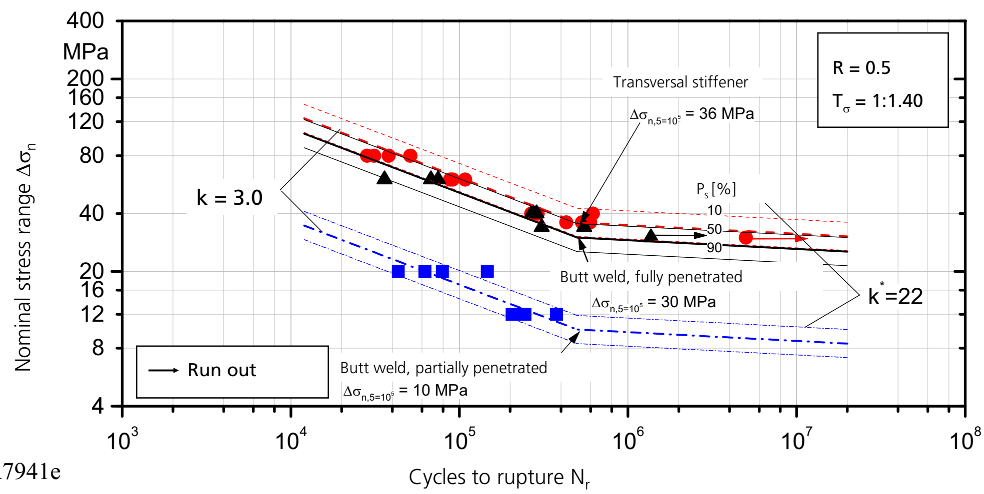

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Fig. 9: Woehler-curves of welded magnesium joints in the nominal stress system under high mean-stresses

The evaluation of the test results reveal following features:

- The knee point of the SN-curves lies at $5 \cdot 10^5$ cycles. (An early knee point is for magnesium alloys not unusual [20].)
- The slope of the SN-curves in the medium cycle range is k= 3.0 ($k = \log \Delta\sigma / \log \Delta N$).
- After the knee point into the high-cycle fatigue regime a decrease of fatigue strength of 10 % per decade, i.e. k*= 22, is assumed according to experiences with light-metal alloys and considering possible tensile residual stresses [21].
- All test results are covered with the uniform scatter range T_σ =1:1.40 (T_σ = 1: σ_a (P_s = 10 %) / σ_a (P_s = 90 %)) according to the concept of the uniform SN-curve [22].

5 FINITE ELEMENT MODELLING OF THE WELD TOES AND ROOTS WITH THE FICTITIOUS RADIUS

The aim in the application of the local stress concept is to find a fictitious radius rendering a master curve with minimum scatter, reasonably unifying all results obtained with the different joint geometries. Such a curve can be used as a design basis.

For transferring the nominal stresses from Figs.7 to 9 into the local stresses for r_f = 0.05 to 1.20 mm following specification for the calculation of the stress concentration factor based on previous experiences was applied:

- 2-D quadratic elements with 8 nodes,
- quadratic function for the displacement of the nodes,
- linear stress and strain function within the elements,
- plane stress conditions,
- uniform displacement distribution applied at the extremity,
- highly stressed area meshed with elements having dimensions equal to r/20, where r is the notch radius.

The linear-elastically calculated local principal stresses are also equivalent stresses according to von Mises because of the uniaxial stress state on the surface from where the cracks are initiated. Fig. 10 displays a modelling example for a notch radius of r_f = 1.0 mm.

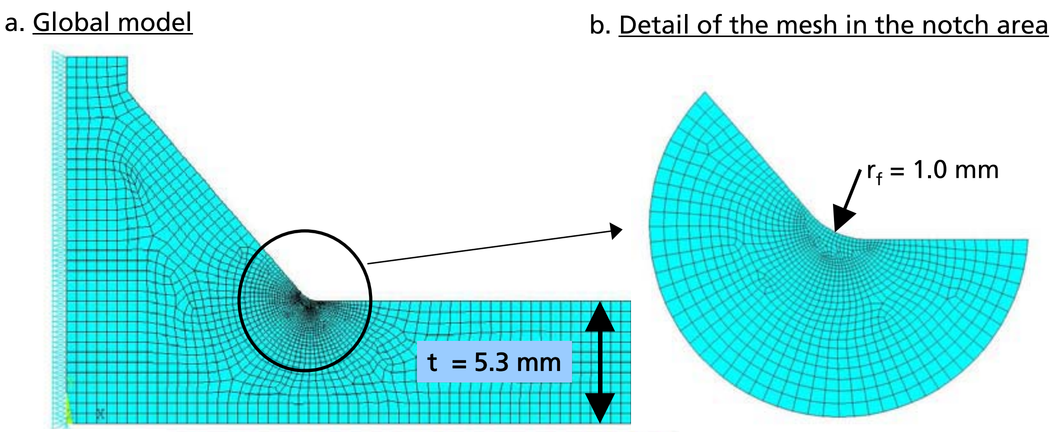

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Fig. 10: FE-model of the weld toe of the transversal stiffener with the fictitious radius r_f = 1.0 mm

In Figs.11 to 13 Woehler-curves are presented in the local stress system for the fictitious notch radius r_f =1.0 mm for all three investigated joint geometries. The compilation of all results obtained in the nominal stress system with different specimens in one SN-curve in the local system with R = -1 as well as 0 and R = 0.5, respectively, renders a uniform slope of k = 3.0. The reason of the larger stress scatter T_σ for fully reversed loading (R = -1) in Fig. 11 compared to the narrower scatter for pulsating loading (R=0 and R=0.5) in Fig. 12 and 13 can be explained by the following fact: Due to distortions of the joints caused by the welding process, under axial loading secondary stresses are superposed. The consideration of these secondary stresses renders locally R-values between –2 to 0, which result the observed large scatter under fully reversed loading (R = -1) due to the high mean-stress sensitivity (steeper slope of the Haig-diagram) in this range. However, for pulsating loading (R = 0) and for loadings with higher mean-stresses (R= 0.5) this effect is not as pronounced as under fully reversed loading because of the shallower slope of the Haigh-diagram, which explains the narrower scatter band, Fig. 14. Probably with ideal geometries without distortion the scatters would be much narrower as the secondary bending would not occur.

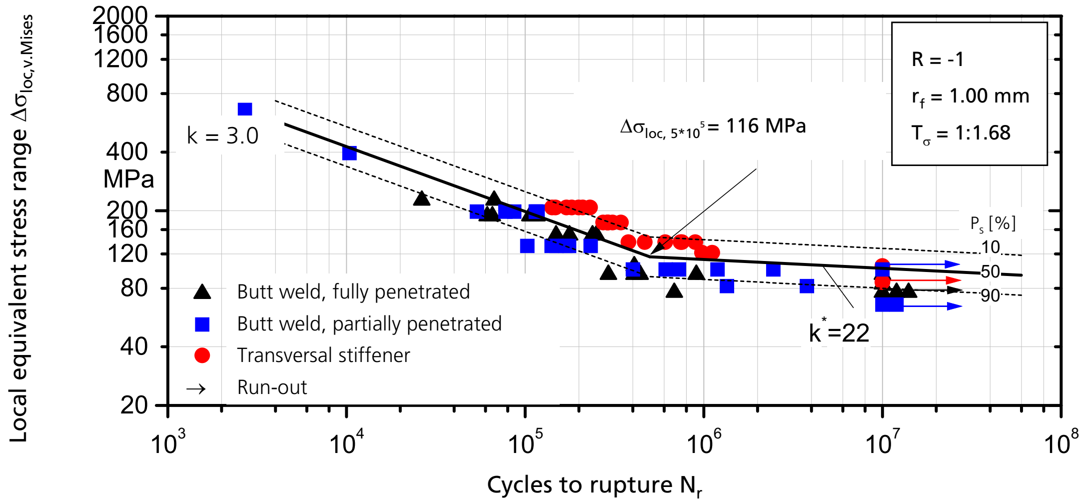

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Fig. 11: Local fatigue strength of different welded joints for the fictitious radius of r_f = 1.0 mm and for fully reversed loading

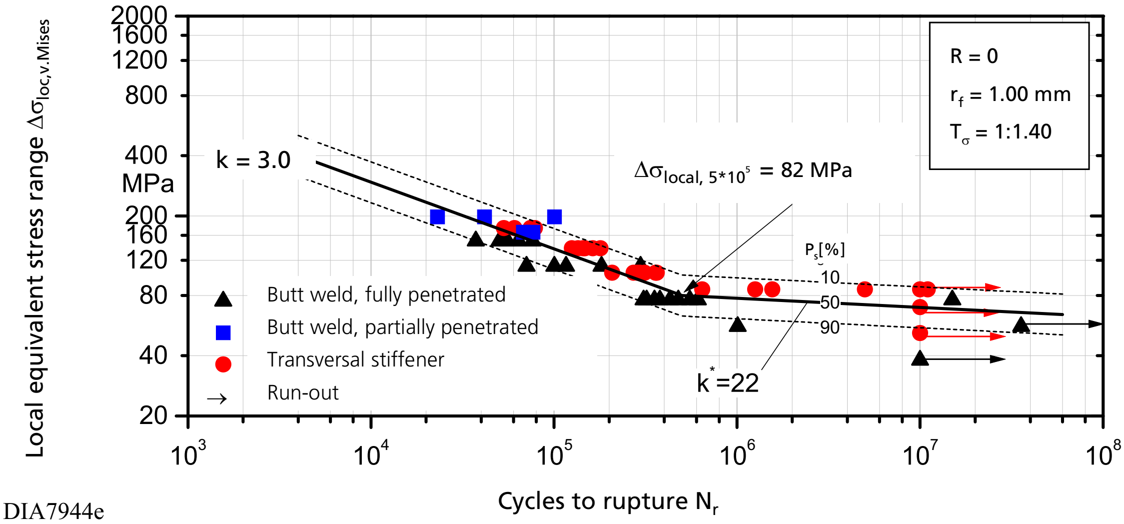

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Fig. 12: Local fatigue strength of different welded joints for the fictitious radius of r_f = 1.0 mm and for pulsating loading

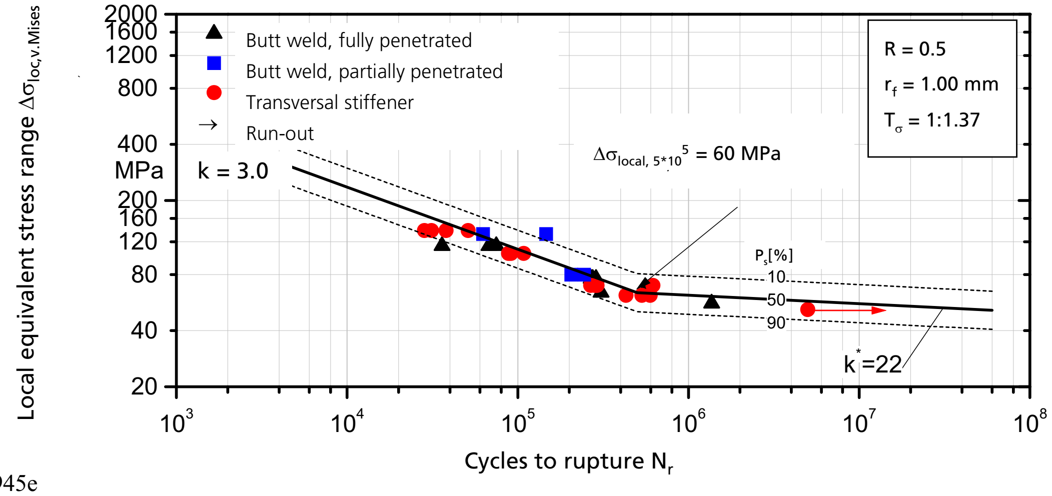

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Fig. 13: Local fatigue strength of different welded joints for the fictitious radius of r_f = 1.0 mm under high mean stresses

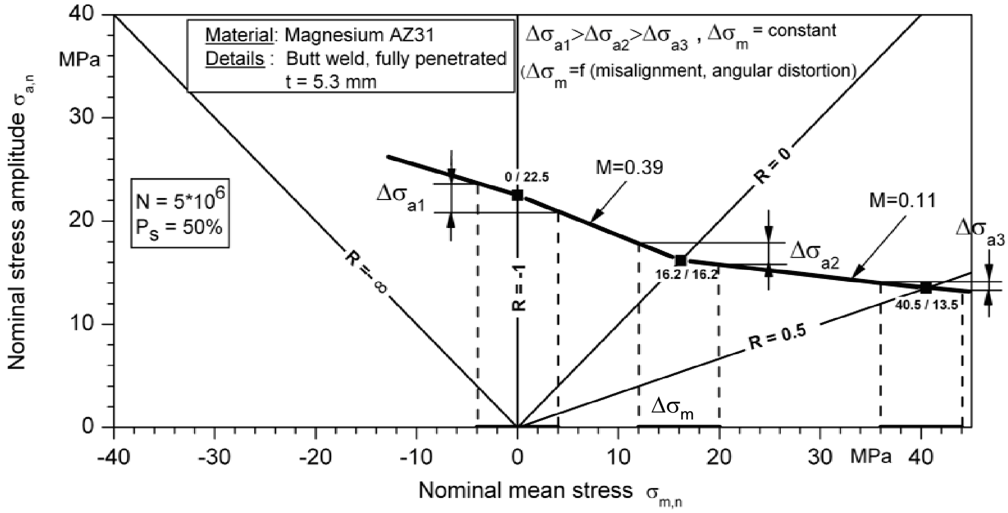

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Fig. 14: Haigh-diagram for the welded magnesium alloy AZ31

Local Woehler-curves were calculated as mentioned already for fictitious radii between r_f = 0.05 mm to 1.20 mm for all investigated joint geometries with t = 5.3 mm thickness. Fig. 15 displays the obtained scatters $T_\sigma^* = [\ \sigma(P_s = 10\%) / \sigma(P_s = 90\%)\ ] = 1 : T_\sigma$ after the statistical analysis. The reasons of the larger scatter for R = -1 was already explained.

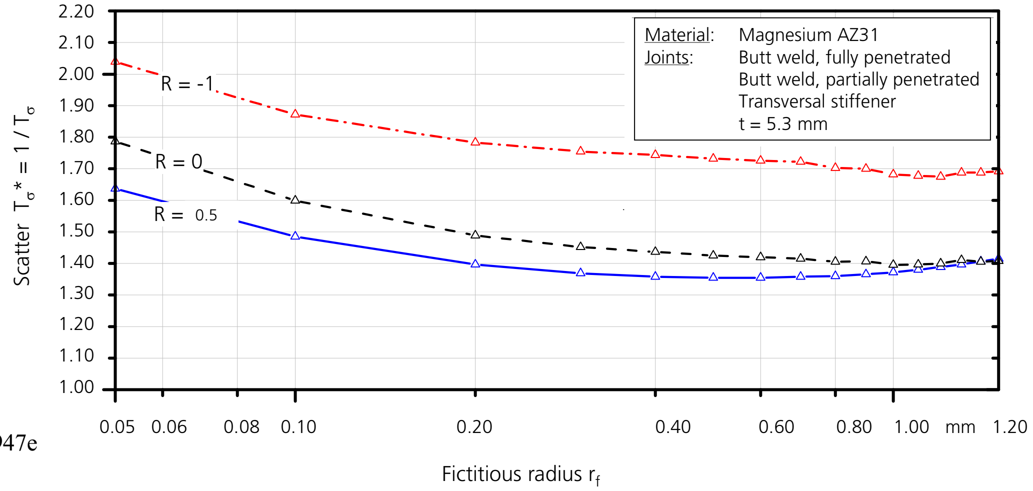

Fig. 15: Influence of the fictitious radius r_f on the scatter $T_\sigma^* = 1/ T_\sigma$

The course of al three curves reaches a minimum scatter between $0.6 \leq r_f \leq 1.0$ mm. However, as in the IIW-fatigue design regulations [11] for welded steel and aluminium joints already $r_f = 1.0$ mm is suggested, this value should be kept also for magnesium welds with plate thicknesses of $t \geq 5$ mm from the standpoint of uniformity in design codes. The present results were obtained only with t = 5.3 mm thick joints. But the experiences with welded steel and aluminium joints allow the assumption that the results can be applied to thicker connections, too.

6 RECOMMENDED MASTER CURVES FOR FATIGUE DESIGN WITH THE FICTITIOUS RADIUS $r_f = 1.0$ mm

For fatigue design of magnesium welded joints using the local stress concept allowable data must be derived from present results. For this, following prerequisites are required:

- Allowable values according to IIW-recommendations [11] must be derived for a probability of survival of P_s = 97.7%; this corresponds to a probability of confidence of P_c = 95 %.

- The effect of high tensile residual stresses on fatigue strength must be considered by a stress-ratio of R = 0.5.

Assuming a scatter of $T_\sigma = 1 : 1.50$ for welded joints and the Gaussian Log-Normal distribution, values for $P_s = 97.7$ %, i.e. mean value minus two standard deviations (m –2 s), are obtained by reduction of the experimental values with $P_S = 50\%$, Figs. 7 - 9, by the safety factor of $j_\sigma = 1.37$.

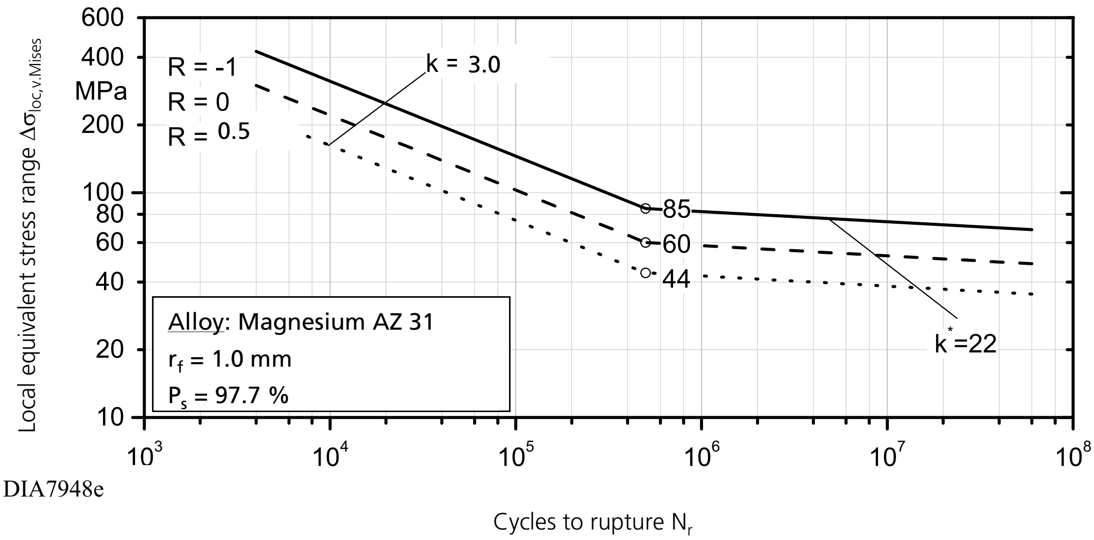

Fig. 16: Master design curves for the fictitious radius of $r_f = 1.0$ mm

The resulting master design curves are presented in Fig.16 for the stress ratios R = -1 as well as 0 and 0.5. This allows a fatigue design considering high residual stresses by the curve for R = 0.5,moderate residual stresses by R = 0 and neglectable residual stresses by R = -1, if additional mean stresses are not present. Otherwise, they must be taken into account corresponding to the already given influence of the displayed R-values in Fig. 16. Table 2 compiles the allowable local stress ranges for $N = 5 \cdot 10^5$ cycles and $P_s = 97.7$ %.

R	$\Delta \sigma_{loc, al}$ in MPa
-1	85
0	60
0.5	44

Table 2: Allowable local stress ranges for magnesium welded joints ($r_f = 1.0$ mm, $N = 5 \cdot 10^5$, $P_s = 97.7$ %)

However, these curves are not yet in agreement with the IIW-Regulations [11] with regard to the knee points. But as the IIW-Regulations assume the worst case with high tensile residual stresses [21, 23], the present results can be transmitted in following way:

- The SN-curve can be drawn through the point of the allowable stress range $\Delta\sigma_{loc,al} = 44$ MPa for R = 0.5 at $N = 5 \cdot 10^5$ with $P_s = 97.7$ % with the slope of k = 3.0 till $N = 1 \cdot 10^7$ cycles, Fig 17 [21, 23]. The stress range of $\Delta\sigma_{loc,al} = 28$ MPa at $N = 2 \cdot 10^6$ can be used as the FAT-value for the IIW-Recommendation.
- After $N = 1 \cdot 10^7$ cycles the SN-curve is continued for constant amplitude loading with k* = 22.0 (10 % strength decrease from one decade to the next one), Fig. 17 [21, 23]. For cumulative damage calculations the slope of k´ = 5.0 should be used after the knee point with the allowable damage sum D = 0.5, Fig. 17 [23].

In cases where good manufacturing quality or low tensile residual stresses can be proved, then a better fatigue behaviour, like in Fig. 16, should be allowed.

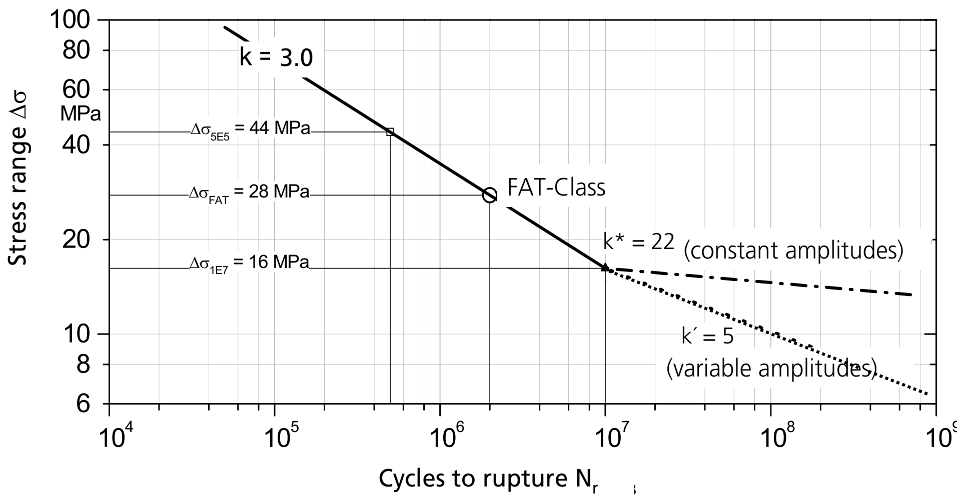

Fig. 17: Suggested SN-curve for the IIW-Recommendations

The already known values for the allowable notch stress for $r_f = 1.0$ mm for steel and aluminium weldments and the now determined value for magnesium can be presented in one plot in dependency of the particular Young's modulus, Fig. 18.

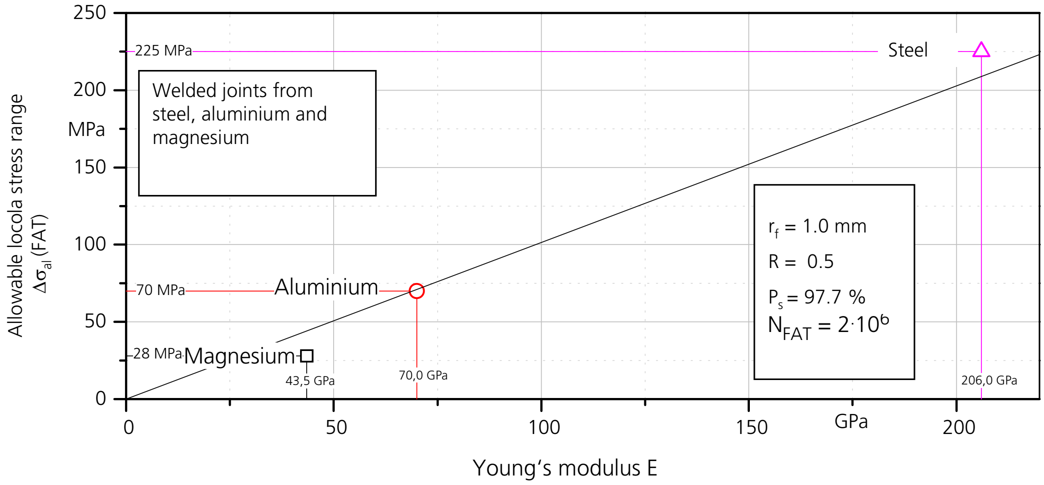

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Fig.18: Relation between FAT-values for r_f =1.0 mm and Young's modulus

7 SUMMARY

The present work delivers for the first time data for fatigue design with welded joints of the wrought magnesium alloy AZ31. The local stress concept using the fictitious notch radius of r_f = 1.0 mm, also considering present experiences with welded aluminium and steel joints, can be applied to magnesium welded joints from plates with thickness of $t \geq$ 5 mm independently from the weld geometry (fully or partially penetrated butt welds, transversal stiffeners). Master design curves are proposed for different stress ratios, i.e. R = -1 as well as 0 and 0.5, which allow the consideration of residual stresses as well as load induced mean stresses. The results permit also the suggestion of $\Delta\sigma$ = 28 MPa as FAT-value for r_f = 1.0 mm in the IIW-Fatigue Design Recommendations.

Finally, a linear relationship among the particular FAT-values of steel, aluminium and magnesium and their appertaining Young's modulus exists. The FAT-values are compiled in Tab. 3.

Notch stress $\Delta\sigma_{loc}$ in MPa ($N_{FAT} = 2 \cdot 10^6$, R = 0.5, P_s = 97.7 %)			
Material	Steel	Aluminium	Magnesium
r_f = 1.0 mm	225	70 (71)	28

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Tab 3: FAT-values for the fictitious radius of r_f = 1.0 for steel, aluminium and magnesium alloys

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Contact person: c.m.sonsino@lbf.fraunhofer.de