EXPERIMENTAL VERIFICATION OF DIFFERENT PARAMETERS INFLUENCING THE FATIGUE S/N-CURVE

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ABSTRACT

For the construction, design and operation of nuclear components the appropriate technical codes and standards provide detailed stress analysis procedures, material data and a design philosophy which guarantees a reliable behavior throughout the specified lifetime. Especially for cyclic stress evaluation the different codes and standards provide different fatigue analyses procedures to be performed considering the various (specified or measured) loading histories which are of mechanical and/or thermal origin and the geometric complexities of the components. In order to fully understand the background of the fatigue analysis included in the codes and standards as well as of the fatigue design curves used as a limiting criteria (to determine the fatigue life usage factor), it is important to understand the history, background as well as the methodologies which are important for the design engineers to get reliable results.

The design rules according to the technical codes and standards provide for explicit consideration of cyclic operation, using design fatigue curves of allowable alternating loads (allowable stress or strain amplitudes) vs. number of loading cycles (S/N-curves), specific rules for assessing the cumulative fatigue damage (cumulative fatigue life usage factor) caused by different specified or monitored load cycles. The influence of different factors like welds, environment, surface finish, temperature, mean stress and size must be taken into consideration.

In the paper parameters influencing the S/N-curves used within a fatigue analysis, like different type of material, the surface finish, the temperature, the difference between unwelded and welded areas, the strain rate as well as the influences of notches are verified on the basis of experimental results obtained by specimens testing in the LCF regime for high strain amplitudes. Thus safety margins relevant for the assessment of fatigue life depending on the different influencing parameters are shown and compared with the safety factors implemented in the different technical codes and standards.

Keywords: Fatigue analysis, S/N-curves, low cycle fatigue, influence of welds, influence of surface finish, influence of temperature, material.

1. INTRODUCTION

The basis for construction, design and operation of nuclear structures, systems and components (SSC) are national technical codes and standards like the ASME-Code Section III, the French RCC-M Code, the British Standard BS 5500 or the German KTA Safety Standards. The basic philosophy in the design of SSC is to demonstrate that the function and the integrity is guaranteed throughout the lifetime. It is important that the design concept according to the German standard accounts for most possible operational failure modes and provides rational margins of safety against each of them. Some of the potential failure modes which SSC designers should take into account are for example: (1) Excessive elastic deformation including elastic instability, (2) Excessive plastic deformation, (3) Brittle fracture, (4) Fatigue and (5) Corrosion.

During design stage a complete picture of the state of stresses within the component, structure or system obtained by calculation or measurement of both mechanical and thermal stresses during transient and steady state operation has to be created. It has to be demonstrated that all stresses (primary, secondary) as well as environmental loads are within the allowable stress limits given by the codes and standards, and the usage factor developed by a fatigue analysis (peak stresses) is well below the limiting value (cumulative fatigue life usage factor U).

It is possible to prevent failure modes caused by fatigue by imposing distinct limits on the peak stresses at the highest loaded regions of the SSC or by reducing the load cycles since fatigue failure is related to and initiated by high local strains. The design rules according to the technical codes and standards provides for explicit consideration of cyclic operation, using design fatigue curves of allowable alternating loads (allowable stress or strain amplitudes) vs. number of loading cycles (S/N-curves), specific rules for assessing the cumulative fatigue damage caused by different specified or monitored load cycles. The influence of different factors like welds, environment, surface finish, temperature, mean stress and size must be taken into consideration in an appropriate way.

The motivation to perform the test was to get more and reliable data for loading conditions with high strain amplitudes (caused e.g. by postulated load cases or faulted conditions in high stressed areas) in the low cycle fatigue (LCF) regime also considering the influencing factors above mentioned. All the tests were performed on air environment, the influence of other environmental conditions , e.g. high temperature water environment, was not a topic of the investigations.

2. USE OF DESIGN FATIGUE CURVES

Reviewing fatigue analyses for nuclear SSC it becomes apparent that the majority is similar to or identical with those in the ASME-Code Section III, like the German KTA Standards. The ASME design fatigue curves for carbon and low alloy steels as well as austenitic stainless steels are based on stress amplitude and cycles to failure data which were obtained mainly from small smooth-machined specimens tested under strain controlled loading at room temperature and air environment (Langer 1962, Jaske 1977, Dierks 1979). The design curves were derived by introducing factors of 2 on stress and 20 on cycles, whichever gave the lowest curve and is meant to account for real effects (size, environment, scatter of data) occurring during plant operation (ASM Criteria 1963). The fatigue design curve in the British Standard BS 5500 was derived from fatigue test data obtained under axial load from welded specimens. The reason therefore was that the presence of a weld could reduce fatigue strength because of the inevitable presence of weld defects. But all of the pressure vessel and piping fatigue design rules are based essentially on the same approach based on data (primarily low-cycle fatigue) from tests carried out on machined specimens, mainly with plain unwelded specimens tested under strain control. Conservative S/N-curves are developed and used for the fatigue analysis in conjunction with stress concentration factors K_t or fatigue strength reduction factors K_f to take into account the structural discontinuities in the components and structures including welds (WRC 1998).

Different procedures exist in the German technical rules for pressure vessels AD-Merkblatt and the European Standard EN 13445 (2002) for unfired pressure vessels. The approach uses also S/N-curves with stress concentration factors like the ASME Code but much more advice is given about the use of the stress concentration factors to be adopted for weld details. Additional explicit factors in form of an equation or a curve are given to account for the influence of temperature, surface finish and weldment, size and mean stresses (Roos 2000). Further German codes and rules used in mechanical engineering and machinery are the FKM-Guidelines (1998) and the former RKF-Guidelines (1986) with detailed requirements for the determination of alternating stress amplitudes.

Fatigue data are generally obtained from unwelded specimens and are plotted in the form of nominal stress amplitude S_a vs. the number of cycles N to failure. The total strain range $\Delta\varepsilon_{at}$ obtained from the tests is converted to nominal stress range $2S_a$ by multiplying the strain range by the modulus of elasticity E at test temperature. Most of the S/N-curves given in the codes and standards are to be applied for specific steels (e.g. distinguish between steels of different ultimate tensile strength R_m).

3. INFLUENCING PARAMETERS

Material

Materials (seamless pipes) used for the strain controlled fatigue tests with stress ratio R=-1 are the ferritic materials 15 NiCuMoNb 5, 20 MnMoNi 55 and 15 MnNi 63, the martensitic material X 20 CrMoV 12 1 and the austenitic material X10 CrNiNb 18 9. The characteristic strength, ductility and fracture mechanics properties are shown in Table 1, the data of the welding materials are shown in Table 2.

All of the strain-controlled fatigue tests were performed in the LCF regime with high strain ranges (Obst 1989). The number of cycles to crack initiation and the number of cycles to failure showed no significant difference for the ferritic materials, Figure 1. The results of the fatigue tests with the austenitic material are shown in Figure 2. Figure 3 includes all data from smooth specimen testing as well as the mean data S/N-curve based on number of cycles to crack initiation and on the number of cycles to specimen failure.

Strain rate

The influence of strain rate was investigated with the ferritic material 15 NiCuMoNb 5 at room temperature (RT) and at temperature 350 °C. The strain rate variation was 12, 25, 50 100 and 250 % per minute. Neither at RT nor at 350 °C the number of cycles to crack initiation and the number of cycles to failure were influenced by the different strain rates, Figure 4 and 5.

Table 1: Material properties (BM - base material; WM – welding material; L – longitudinal specimen; T – transverse specimen, RT – room temperature)

Seamless pipe	MPA Des.	Yield strength [MPa]		Tensile strength [MPa]		Elongation A_5 [%]		Charpy-Energy A_V (ISO-V,tran.) [J]		E-Modu at temp. [GPa]	Temp. [°C]
		BW	WM	BW	WM	BW	WM	BW	WM		
15 NiCuMoNb 5	E 21	499 (L)	600	659 (L)	676	20	28	138-170	152	RT → 210 350°C → 190	±0
20 MnMoNi 5 5	196	488 (T)	658	618 (T)	702	26	26	196 - 228	136	RT → 210	±0
15 MnNi 6 3	H 23	377 (T)	514	544 (T)	584	33	27	160 - 171		RT → 210 250°C → 190	±0
X 20 CrMoV 12 1	P 13	602 (L)	-	802 (L)	-	20	-	70	-	RT → 210	20
X 10 CrNiNb 18 9	R 17	252 (L)	-	561 (L)	-	55	-	148	-	RT → 210	20

Table 2: Welding Material

Base material	Welding material	
	Trade-mark	DIN designation
15 NiCuMoNb 5	Böhler DMO – IG	SG Mo 5424
	Tenacito 65 R	-
	Union S3 NiMo 1/OP 41 TT	S3 NiMo 1
20 MnMoNi 5 5	Böhler DMO – IG	SG Mo 5424
	CONARC 70	E KB NiMo
	Union S3 NiMo 1/UV 420 TT R	S3 NiMo 1
15 MnNi 6 3	Union I 1.2 Ni	-
	SH V 370	EY 4276 1 NiB
	Union S2 Ni 370/UV 421 TT	S2 Ni1
X 20 CrMoV 12 1	CM 2 – IG	SG CrMo 2
	Fox 20 MVW	E CrMoWV 12820+
	20 MVW UP	UP S2 CrMOWV 12
X 10 CrNiNb 18 9	SAS 2 IG R	SG X 5 CrNiNb 18 9
	Fox SAS 2R	-
	Thermanit HE/OP 70 Cr ELC	UP X 2 CrNiNb 18 9

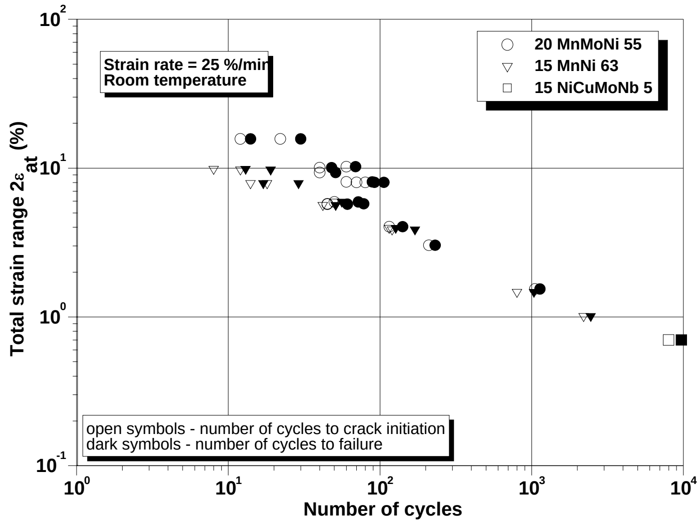

Figure 1: Fatigue data for ferritic material acc. to Tab. 1

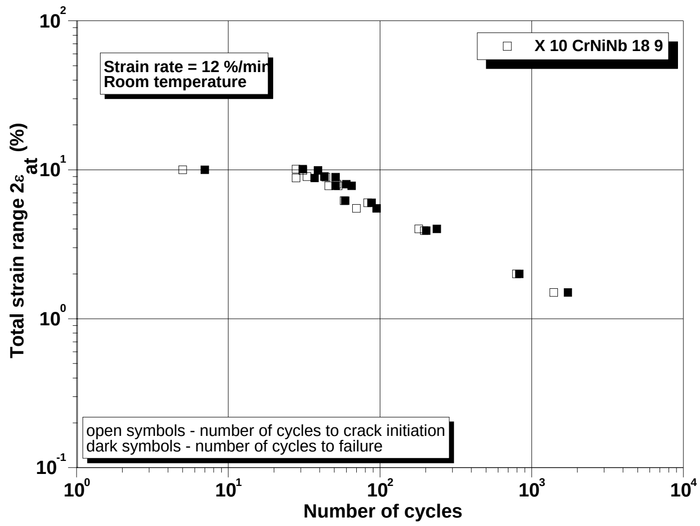

Figure 2: Fatigue data for austenitic material acc. to Tab. 1

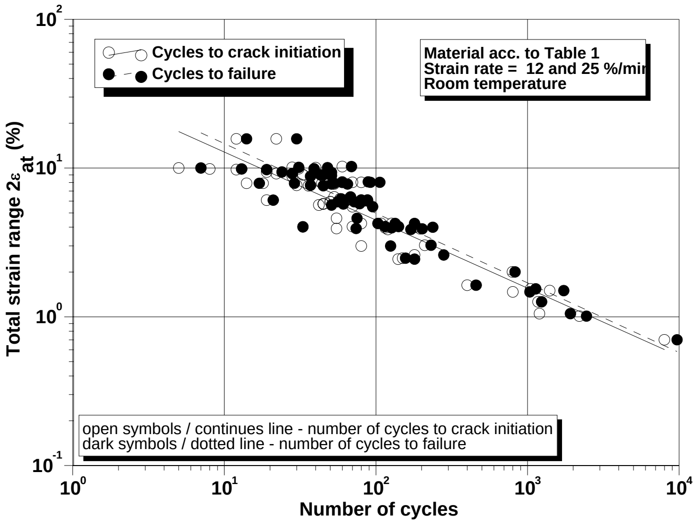

Figure 3: Fatigue data and mean data curve for all material acc. to Tab. 1

Temperature

The use of fatigue design curves is restricted in the nuclear codes and standards to a specific maximum temperature below the creep range. Using design fatigue curves it is necessary to adjust the allowable stresses to account for different modulus of elasticity E at operating temperature which might be different from that one used to develop the design curves. The stress amplitude S_a must be multiplied by the ratio of the modulus of elasticity given by the design fatigue curve to the value of the modulus of elasticity used in the analysis. Another approach is given in the German AD S2 rules and the European Standard EN 13445 (2002) where the influence of temperature must be adjusted by a cycle depending factor f_T.

The influence of temperature was investigated with the ferritic materials 15 NiCuMoNb 5 (RT and temperature 350 ^oC) and 15 MnNi 63 (RT and temperature 250 ^oC). The tests were performed in the regime of high strain ranges, Figure 6 and 7. For material 15 MnNi 63 the crack initiation as well as the failure curves for the temperature 250 ^oC are above the curves developed at RT. The reason is the higher strength behaviour at temperature 250 ^oC compared to RT.

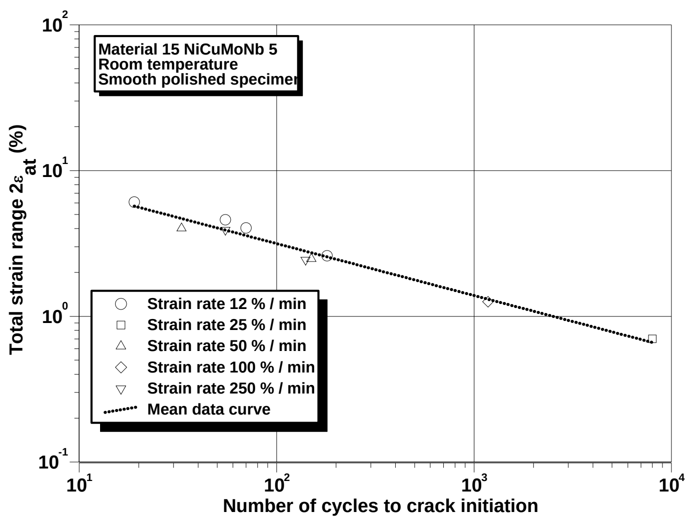

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Figure 4: Influence of strain rate on fatigue data at room temperature

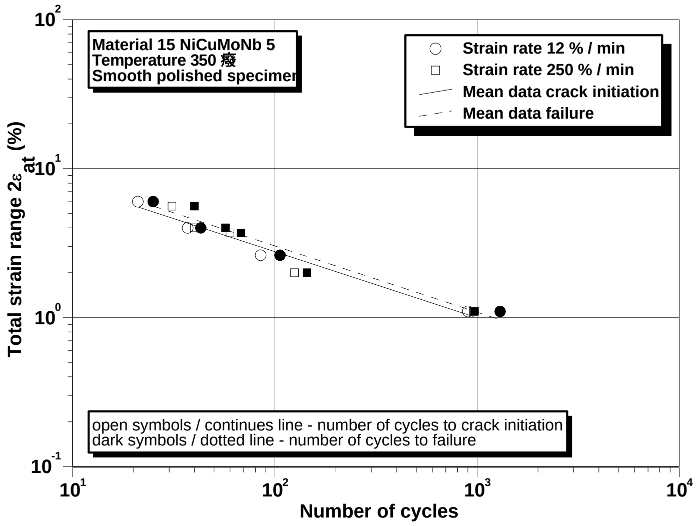

Figure 5: Influence of strain rate on fatigue data at temperature 350 °C

Surface finish

In the codes and standards there are different and specific requirements concerning the surface finish of components especially for welded regions, for different vessel and piping products and different joints. Stress indices are available for use of the code equations determining the stress amplitudes. A special regard to the influence of surface finish depending upon peak-to-valley height R_z is given in the AD-Merkblatt and the European Standard EN 13445 (2002). The influence of the surface finishing is described by the surface factor f_o which is defined by

$$\mathbf{f_o = \frac{\sigma_{a,f}(R_z)}{\sigma_{a,f}(R_z < 6\,\mu m)}}$$

where $\sigma_{a,f}$ is the sustainable stress amplitude for different R_z values.

The influence of the surface finish was investigated with the ferritic material 20 MnMoNi 55 at RT. The result from the smooth polished (R_z=1.39 µm) specimen (Figure 1) were compared with data developed with smooth finished (R_z=6.95 µm) specimen and with roughened (R_z=43.6 µm) specimen, Figure 8. All test data are covered by a narrow scatter band.

Weldments

To investigate the influence of welds specimens were fabricated with weld material (Table 2) as well as with the heat affected zone in the test area of concern. For the materials 15 NiCuMoNb 5, 15 MnNi 63 and X20 CrMoV 12 1 the curves for crack initiation for weld specimen are above the curves obtained for the base material. For the materials 20 MnMoNi 55 and X10 CrNiNb 18 9 the curves for crack initiation for weld specimen are below the curves obtained for the base material. All test data with welds are shown in Figure 9.

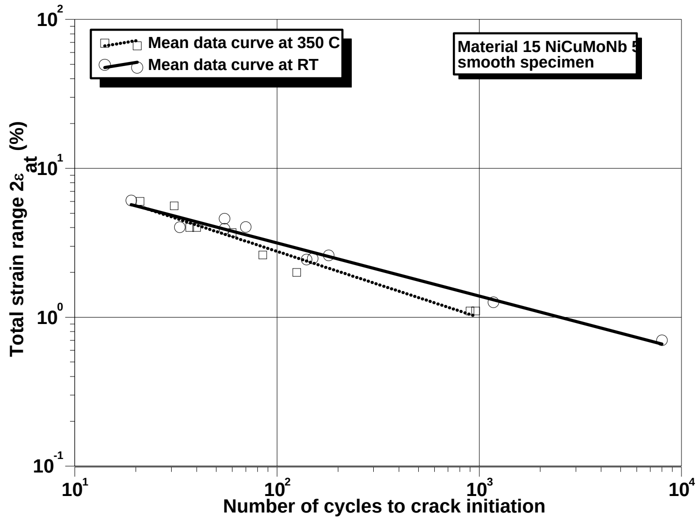

Figure 6: Influence of temperature between RT and 350 ^oC

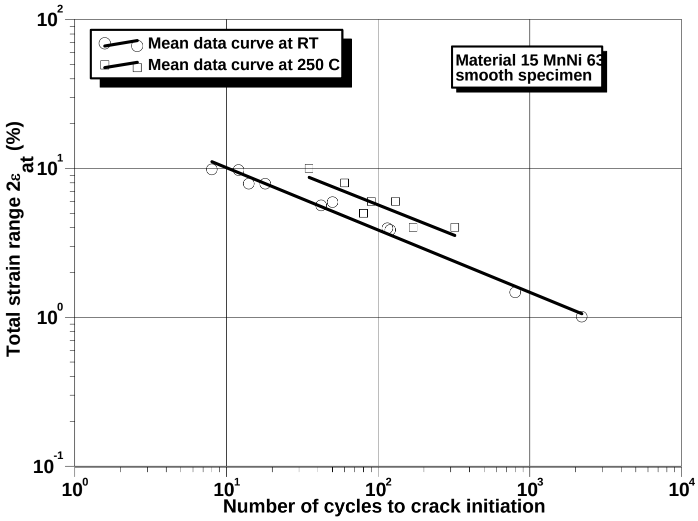

Figure 7: Influence of temperature between RT and 250 ^oC

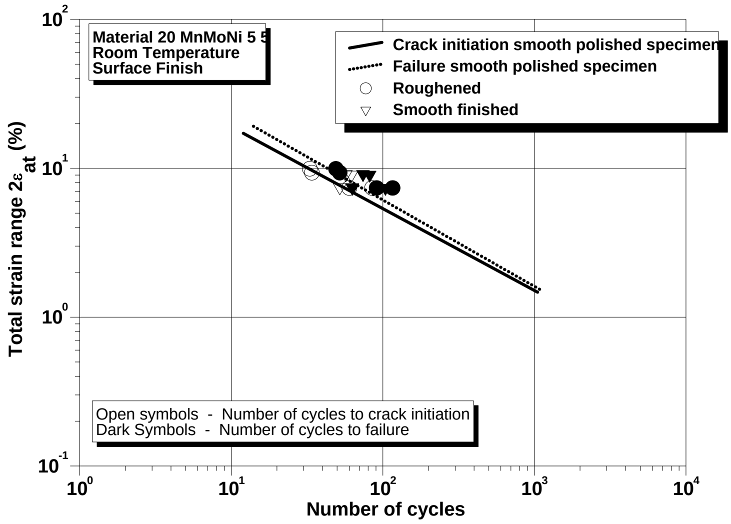

Figure 8: Influence of surface finish on the fatigue data

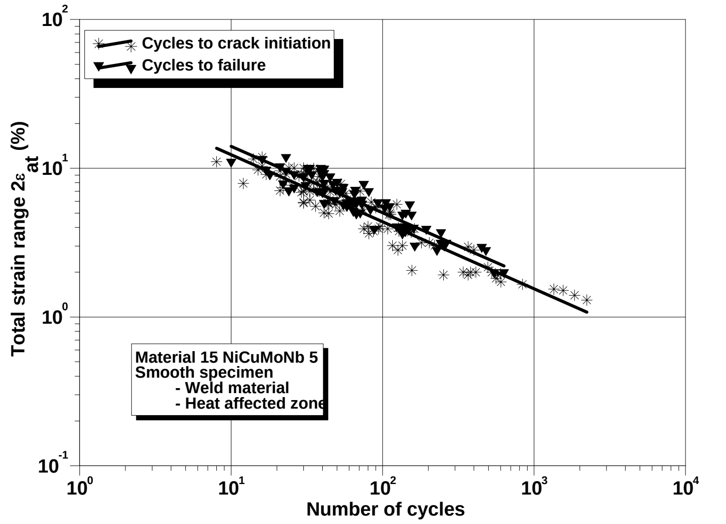

Figure 9: Influence of welds on the fatigue data

Other factors influencing the fatigue S/N-curve

In this paper other factors influencing the fatigue S/N-curve, like the size, the mean stress and environmental conditions are not investigated.

Most of the code and standards fatigue S/N-curves has been determined using small laboratory specimens. However failure stress amplitudes are lower for components because of size effects caused by different stress gradients or statistical effects of material characteristics. Size effects should be covered in the nuclear codes within the factors 2 on stress or 20 on cycles. In all the ASME-based codes and standards the fatigue design curves are plotted in terms of stress amplitude independent of mean stress, the curves are showing already the full effect of maximum mean stress. The evaluation of the effect of mean stresses is accomplished by use of the modified Langer-Goodman Diagram, where mean stress is plotted as the abscissa and the amplitude of the alternating stresses is plotted as the ordinate. Thus, for the adjusted fatigue curve there should not be any mean stress present which will cause fatigue failure in less than the given cycles. In non-nuclear codes the influence of mean stresses is taken into account individually by a factor representing the mean stress sensitivity.

Despite of the factors 2 and 20 there have been relatively few corrosion fatigue failures in carbon or low-alloy steel components in LWR's and quite a lot of discussions are under way concerning the influence of environment to the fatigue design curves (crack initiation and crack growth under environmental conditions). Data from specimens testing indicated that fatigue life shorter than the fatigue design curve values are possible, if the tests are carried out under low frequency loading conditions in oxygenated water environment at elevated temperatures (Fatigue Conference 2000 and 2002), but up to now there is no clear picture about the necessity to change the fatigue design curves. The investigations performed to determine corrosion-assisted crack growth rates for pressure boundary materials exhibit a big scatter as shown by Kußmaul (1997).

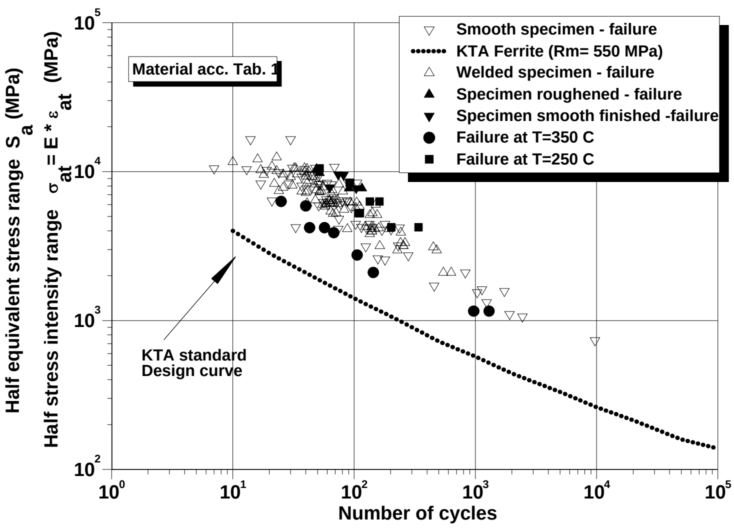

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Figure 10: Fatigue data and KTA design curve

CONCLUSIONS

Fatigue is a potential failure mode for components and structures of nuclear power plants. For the explicit consideration of cyclic operational loads (mechanical and/or thermal) in different technical codes and standards specific fatigue analysis methods are available. The fatigue S/N-curve influencing factors are treated in the different codes and standards in different ways.

Based on the results of the fatigue tests shown in the LCF regime up to 10.000 load cycles and high strain amplitudes as for the nuclear codes and standards the following conclusions can be drawn, Figure 10:

- For the materials investigated all test data of smoothed specimens are covered by the code design curve on the safe side.
- For the material 15 NiCuMoNb 5 neither at RT nor at 350 °C the number of cycles to crack initiation and the number of cycles to failure were influenced by strain rates up to 250 % per minute.
- The influence of temperature is adequate addressed by considering the ratio of the modulus of elasticity using the S/N-curves, but the strengthening or softening behavior of the materials at temperature has also to be considered.
- The surface finish up to peak-to-valley height values of R_z=43.6 µm (roughened specimen) showed no influence on the S/N-curves for the materials investigated within the LCF regime.

As mentioned the design curves were derived by introducing factors of 2 on stress and 20 on cycles to account for real effects (size, environment, scatter of data). Considering effects like change in material, changing strain rates, different temperatures, different surface finish as well as the influence of welds in the LCF regime they are well controlled using the code design curve.

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