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Division I

EVALUATION OF THE FATIGUE LIFE OF AISI 347 SPECIMENS WITH SMALL NOTCHES BASED ON LOCAL STRAIN CONSIDERATIONS

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ABSTRACT

The use of materials data for cyclic loading determined on unnotched specimens to predict the fatigue life of notched components has a long tradition, specifically when it comes to nuclear engineering. The basic principle is, that the material behaviour of the unnotched specimens can be transferred to what the material is exposed to be in a notch's root. This principle has been proven for large notches. However, what happens when the notch is fairly small? Can the fatigue life still be predicted on the grounds of what has been considered as the local strain or Neuber approach? A key reference in that regard is the Neuber equation or generally the load versus notch stress, notch strain - or any combination of those - relationship. In a larger study, unnotched and notched specimens from the metastable austenitic steel AISI 347 have been tested and characterized, which has provided a database, which may give some answer to the question raised above.

The unnotched specimens considered here had a cross-section diameter of 10 mm while the notch radii of the notched components were only 0.5 and 0.35 mm, respectively. Notch radii of such dimensions will easily reach a fully plastic condition once the material has exceeded the yield limit, because the difference in load between yield start in the notch and full plastification is relatively small. This fully plastic state exceeds the validity of the Neuber equation and needs respective corrections to be made. In this paper it is shown how such corrections can be obtained through a finite element analysis and how this applies to the cases mentioned above.

INTRODUCTION

Repeated loading exceeding yield, even at microscopic level, causes degradation due to fatigue – also expressed as damage - leading to a defined macroscopic failure after a certain number of load cycles. For the characterization of such a material's fatigue resistance at lowest complexity, unnotched specimens are tested uniaxial under constant amplitude. Along the gauge length of the specimen with a cylindrical and hence continuous cross-section a homogeneous stress and strain state is established, and in turn stress and strain can be easily determined from the external forces or deformations applied, provided a load cell and an extensometer are applied to the test equipment.

Real components seldom have a continuous shape but rather a variable, where this variability – also expressed as notches – leads to an inhomogeneous distribution of loading in general or stresses and strains as an example. For the fatigue assessment, the stress (or strain) concentrations in the vicinity of notches are of special importance, because they also lead to an inhomogeneous condition of material degradation. From a mechanics and hence engineering approach those concentrations need to be considered and formalized, which is done through definitions of a nominal stress (or strain) and a stress (or strain) concentration factor. The approach by Neuber (1961) basically uses those concentration factors for the nominal stress and possibly also nominal strain yielding the local stress and strain respectively.

From a pure experimentation point of view the concentration factors can be determined when comparing fatigue life results for unnotched and notched components in terms of stress, strain or even both. It happens that the stress concentration factors determined that way may not be constant and be lower than those determined from handbooks or through a pure numerical evaluation. A similar situation in the opposite way may happen if considerations may be based on strains, which is a rather unusual but also an eligible way. The reasons for those differences are various but a certainly dominant reason is plasticity. While a stress concentration factor K_σ may be maximum up to the incident of yield in the notch, it will drop while yielding increases in the notch and will reach a minimum even down to a value of 1.0 when a fully plastic condition is achieved. Such a condition is easily achieved in case a notch is small.

In this paper, experimental results from fatigue tests performed on notched and unnotched specimens are presented. In parallel numerical evaluations have been made for the unnotched and the notched specimens using a plasticity model calibrated on results from tests on unnotched specimens. Measuring local strains in notch roots can become cumbersome if not impossible, while measuring a specimen's displacement is much easier. However, combining the measured displacement with a numerical model can easily allow local stresses and strains in a notch root to be determined and can lead to realistic results in case an appropriate constitutive model can be found, that allows the material's non-linear relationship to be well described.

This paper is organized as follows: first the stress-strain relationship of the material for cyclic loading is established from results of specific tests and the plasticity model is adjusted to allow its use in finite elements analysis. In the section thereafter, the notch strain in a specimen under loading is analysed by finite elements analysis, after providing a review of conventional notch effect assessment approaches. The third section comprises fatigue test data and the evaluation of S-N curves for stress and strain and a comparison of those data with respect to fatigue lives of notched and unnotched specimens. The paper concludes with a summary on how fatigue data obtained from unnotched specimens could be transferred to fatigue behaviour even in a fully plastic condition.

STRESS-STRAIN RELATION AND PLASTICITY MODEL

A general characterization of the stress-strain behaviour of the austenitic steel AISI 347 (X6CrNiNb1810) is made here in terms of experiments at ambient and elevated temperature (240 °C) and the adjustment of a plasticity model.

Strain Increase Tests with Unnotched Specimens

For the characterization of the stress-strain behaviour of the material under cyclic loading in the low cycle fatigue (LCF) and high cycle fatigue (HCF) regime, unnotched specimens as shown in Figure 1 have been used.

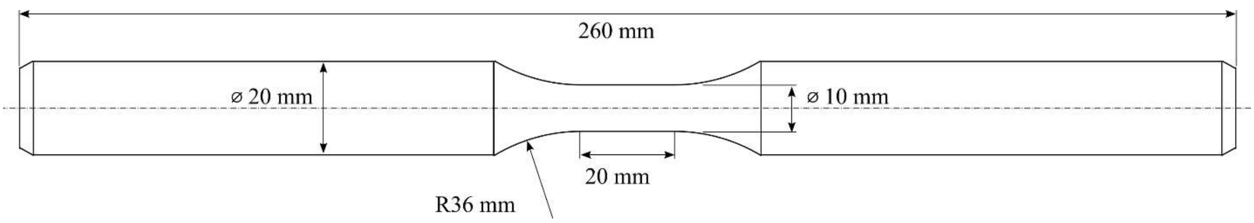

Figure 1. Geometry of unnotched specimen.

The specimens were fatigue tested in a servo-hydraulic testing machine and equipped with an extensometer in the minimum gauge section, to control the total strain amplitude. Tests were performed at WPT TU Dortmund (room temperature) and at the MPA University of Stuttgart (elevated temperature) under strain-control at fully reversed constant amplitude loading ($R = -1$). A strain increase test (SIT) has been performed at room and elevated temperature respectively. In an SIT a specimen is cycled at an initial level of strain amplitude for a defined number of cycles before the strain amplitude is increased by a certain amount and cycling continues with the same number of defined cycles, followed again by an increase of the strain amplitude and so forth, until the specimen fractures. This allows the stress-strain hysteresis to be measured at different strain levels and different stages of the material's degradation. At very high strain amplitudes, the hysteresis loops on a given amplitude are no longer stable, but the accumulated strain and continued damage leads to ratcheting-like effects.

Plasticity Model

For the computational determination of the notch strain, an accurate model of the cyclic stress-strain behaviour under repeated loads is required. The approach used in this study is based on the Chaboche plasticity model (Chaboche, 1989 and 1991) with three back stress components α_i summed up to the total back stress α. The implementation in the ANSYS APDL software is used, where the model is formulated in terms of the components of the back-stress rates $\dot{\alpha}_i$, which depends on the parameters C_i, γ_i and σ_0 as well as with the elastic modulus E and the Poisson ratio ν.

$$\dot{\alpha}_i = \frac{2}{3} C_i \dot{\varepsilon}^{pl} - \gamma_i \left| \dot{\varepsilon}^{pl} \right| \alpha \qquad (1)$$

A similar approach was also used in Heckmann et al. (2021), but here in this paper the model is fitted for two different temperatures. The selected hysteresis and the model after adjustment are shown in Figure 2.

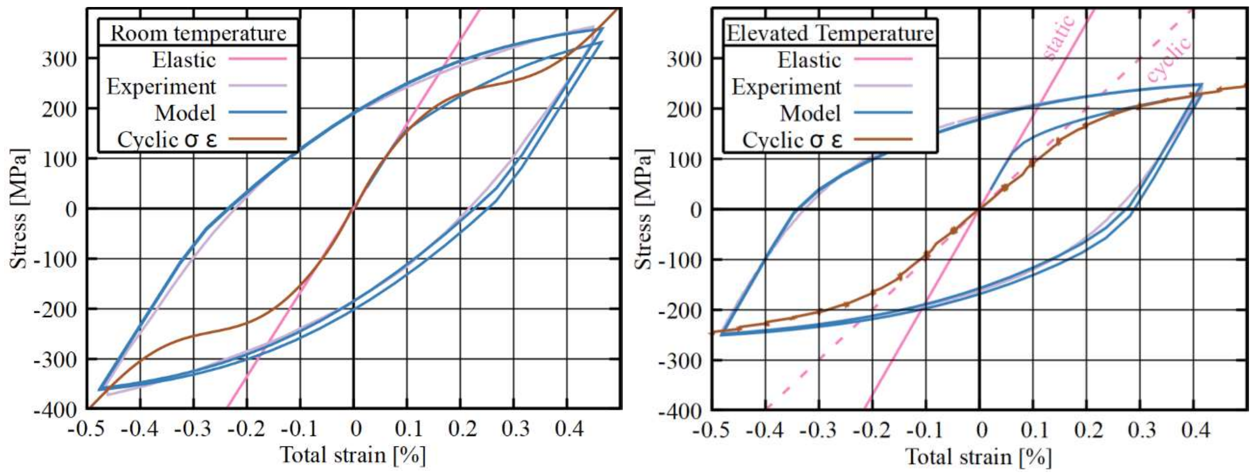

Figure 2. Stress-strain relation and fitting result of the plasticity model at the two temperature levels

The strain levels correspond to one of the cycles with highest stable strain amplitude levels in the strain increase test. In the figure, also a stress-strain relation (σ-ε) for the cyclic load is shown. The Chaboche material parameters obtained with this approach are documented in Table 1.

Table 1. Chaboche model parameters

	ε	σ_0	C_1	γ_1	C_2	γ_2	C_3	γ_3
Low T	0.5	122	2e6	7.73e4	1.30e5	5.60e2	1.52e4	3.34e3
240 °C	0.45	95	1.61e6	7.68e4	1.17e5	6.05e3	5.35e4	4.07e2

As a remark to the procedure, the Chaboche parameters depend not only on the temperature, but also on the selected strain amplitude level. For any computation of a finite element analysis using the adjusted plasticity model, this is of importance in case of an inhomogeneous strain distribution within a structure being present. This is valid in the following, where it can be seen as a result of the specific austenitic steel and its plasticity. Additional plasticity parameter adjustments have been done at different strain amplitudes, and the results are discussed later as a sensitivity analysis.

ON THE LOCAL STRAIN IN THE NOTCH ROOT

To assess complex-shaped structures with respect to their loading at arbitrary locations such as in notches, a relationship has to be established between those stresses and strains and the external loads applied. In engineering this starts by defining a nominal stress (and strain) in simple mechanical terms, such a load divided by a minimum cross-section. However, to get to the true stresses and strains further attempts have to be made. The two specimen geometries with notches considered here are shown in Figure 3. The difference between the two geometries is only the radius in the notch (0.5 mm and 0.35 mm).

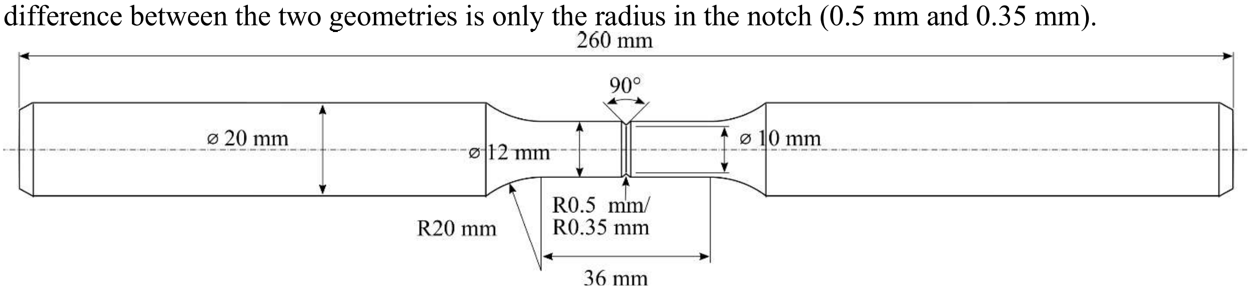

Figure 3. Specimen geometry with two different notch radii

Neuber's Approach

Reference to determine stresses and strains in a notch root will be the relationship established by Neuber (1961), relating the nominal stress σ_N with the local stress and strain in the notch root, σ_L and ε_L determined along the gauge length of the unnotched specimen and using a stress concentration factor K_t, where K_t is considered to be the ratio between local stress in the notch root and nominal stress. In the case of pure elastic behaviour or small scale yielding this relationship can be expressed as

$$\sigma_N^2 K_t^2 = E \sigma_L \varepsilon_L \qquad (2)$$

Neuber's rule may also be written differently as

$$K_t^2 = K_\sigma \cdot K_\varepsilon \qquad (3)$$

where K_σ represents the ratio between local stress and nominal stress and K_ε the ratio between local strain and nominal strain, where nominal strain has to be determined in accordance to the nominal stress or in other words in accordance to the nominal stress versus nominal strain relationship. Up to yielding it applies that $K_t = K_\sigma = K_\varepsilon$, while beyond yielding K_σ drops and K_ε increases accordingly.

The K_t factor depends on the notch geometry and can be either obtained from handbooks or through numerical evaluations. In the case of the notches having been considered here K_t-values turned out to be 2.87 for the 0.5 mm notch, and 3.18 for the 0.35 mm notch respectively when using the formulas derived by Peterson (1974).

Polynomial Approach

An alternative and possibly more general option is to perform an elastic-plastic simulation with Finite Elements (FE) Analysis, using the adjusted Chaboche model (see Figure 2 and Table 1). The software used to perform this computation is ANSYS Mechanical. Considering the rotational and axial symmetry of the specimen, the resulting geometry is shown in Figure 4. As an example the plastic equivalent strain for a selected loading (2 mm shaft displacement) is visualized in Figure 5.

Figure 4. Finite Elements Analysis: Half model with rotational symmetry

This example visualizes that the von Mises equivalent strain is concentrated close to the surface of the notch root, where the plastic equivalent strain reaches up to 1.7 %, whereas it is below 0.1 % far from the notch. For the assessment of the notch strain, a load increase test is performed, with 10 cycles per load step (all steps after the first one are stable). This allows to compute the corresponding maximum (maximal tensile load) and minimum (maximal compressive load) total strains on the different load levels, together with the total force (relevant for the nominal stress σ_N) and also the extensometer deformation for a finite gauge length (8 mm here). While the stress and strain state in the notch root is in general not uniaxial, it is verified that the strains are dominated by the component parallel to the specimen axis, which allows to interchangeably use the equivalent strain or the uniaxial strain in the further assessment of load amplitudes. Hence, the simulation generates a table for the relation between nominal stress σ_N, the extensometer strain ε_X, and the local strain ε_L for the different simulated loads; the results between the latter is shown in Figure 6. The nominal stress level is indicated by text labels.

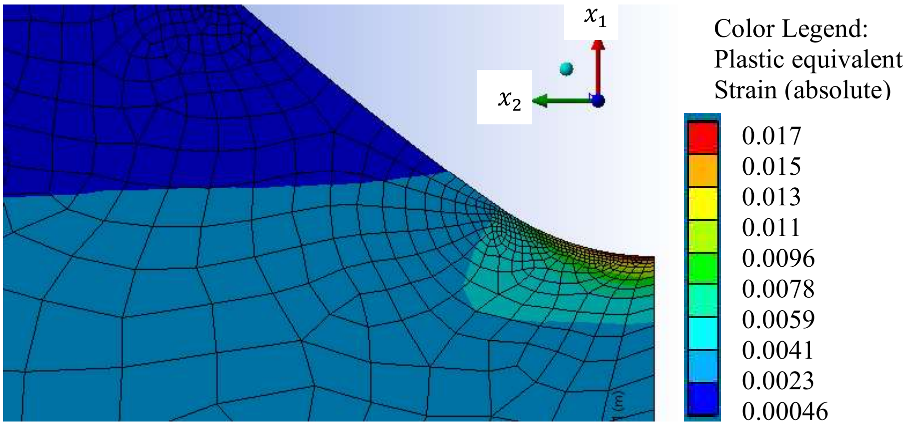

Figure 5. Finite Elements Analysis of the notched specimen:
Example for plastic equivalent strain analysis, detail of the notch root.

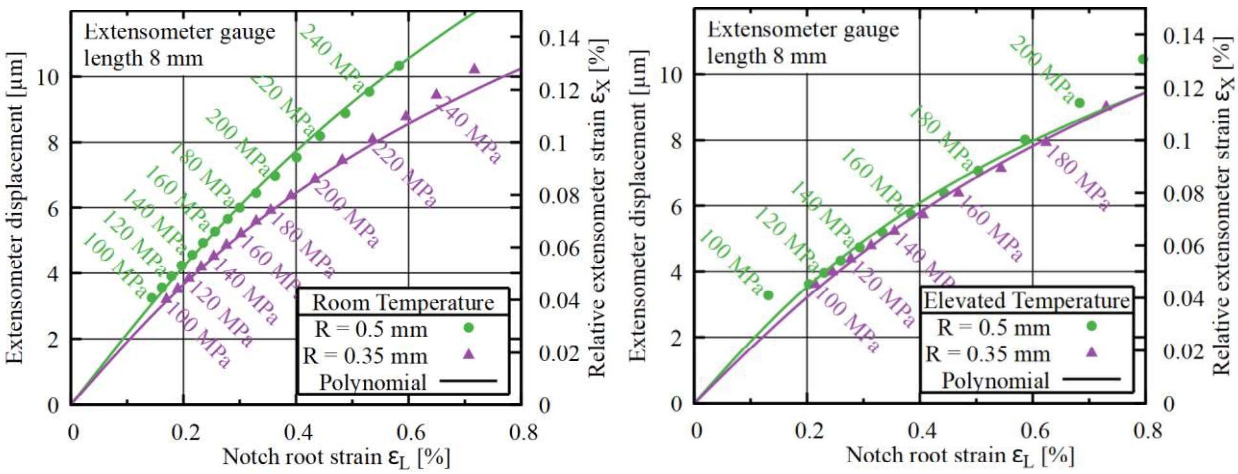

Figure 6. Relation between FE-calculated notch root strain and FE-calculated extensometer strain for the 0.5 mm notch and the 0.35 mm notch for room temperature (left) and elevated temperature (right).

The dependence of the local strain in the notch root ε_L on the deformation (measured with the extensometer) has a clear non-linearity for larger strains, as expected. The relation between the FE-computed local strain ε_L and the FE-computed extensometer strain ε_X can be approximated by to the following function:

$$\varepsilon_L = e_1 \varepsilon_X + e_3 \varepsilon_X^3 \qquad (4)$$

The parameters e_1 and e_3 have been made dependent on the notch radius, and the temperature, as the stress-strain relation is temperature dependent (different extensometer lengths would affect the two coefficients). The sensitivity study with different materials parameters indicates that the dependence on the material parameters is present, and in turn a parameter set was chosen which validity range corresponds to the investigated strain range. The derived parameter e_1 and e_3 are shown in Table 1.

Table 2. Approximation parameters for Eq. (4) with an extensometer gauge length of 8 mm

	Room temperature		Elevated temperature	
Notch radius	e_1	e_3	e_1	e_3
0.35 mm	4.11	131	4.72	146
0.5 mm	3.67	50.6	4.16	187

The linear term e_1 can be interpreted as a strain concentration factor, and the e_3 can be related to plastic effects leading to corrections at higher strain levels.

FATIGUE TESTS AND ASSESSMENT

In this section, the fatigue testing procedures are presented; the underlying experiments were also presented by Acosta et al. (2021). The test of notched specimens is compared with the two local strain assessment approaches, and finally, the fatigue life of notched and unnotched specimens is compared.

Local Strain in Fatigue Tests

In the test program, fatigue tests were performed on unnotched specimens at ambient temperature (9 tests) and at elevated temperature (13 tests). Tests on the notched specimens were performed under load-control, since the deformations measured with an extensometer on the gauge length might only be used to validate numerical evaluations but not provide adequate information with respect to the notch root (the validity of strain-control by using an extensometer mounted outside of the notch is strictly limited). Two specimens (one for each notch radius), however, were equipped with an extensometer and tested in a load increase test, allowing to measure the extensometer deformation ε_X and the nominal stress. The comparison of this measurement (at room temperature) with the simulation is shown in Figure 7; at elevated temperatures only numerical results are shown. The observed range of extensometer strains on a specific load level is indicated by vertical bars; this variation becomes higher as the nominal stress increases. Note that at room temperature the computed extensometer strain at a given nominal stress is very similar for both notch radii, while the measured extensometer strain differs especially in the compressive phase. Here, the simulation yields a symmetric result regarding tension and compression, while the measurement does not.

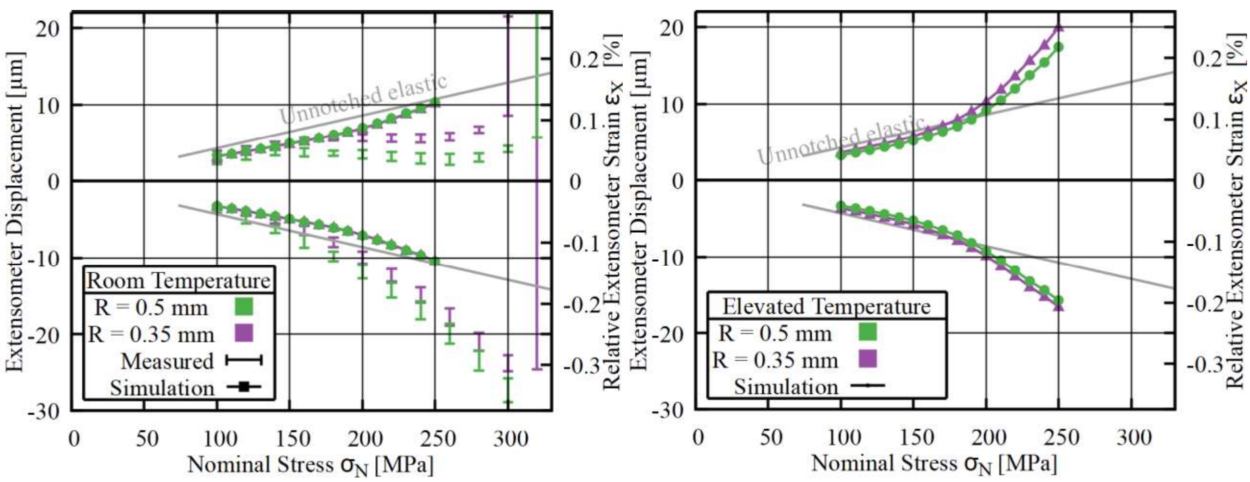

Figure 7. Measured extensometer strain for different nominal stresses (bars indicating the range on each stress level) and comparison with the simulation (line-connected points).

This result indicates that the adjusted Chaboche plasticity model is not able to accurately predict the relation between nominal stress and extensometer strain. In the test, a clear tendency to a noncentral average strain is observed, as one would expect in any stress-controlled test. While the Chaboche plasticity model can simulate ratcheting effects for load ratios $R > 0$, the comparison of experiment and Finite Elements Analysis shows that the noncentral average strain observed in the test with load rations $R = -1$ is not reproduced in the simulation. Therefore, the local strains computed in the simulation for the actual nominal stress amplitudes are of limited accuracy.

As an improvements, the relation proposed in Eq. (4) is considered – the notch root strain ε_L is not considered as a function of the nominal stress σ_N, but as a function of the measured extensometer strain ε_X. This compensates the simulation artifacts related to the plasticity model, by relying on an additional measured parameter. However, this procedure is only applicable to the room temperature tests; the plain numerical results are used at elevated temperature instead.

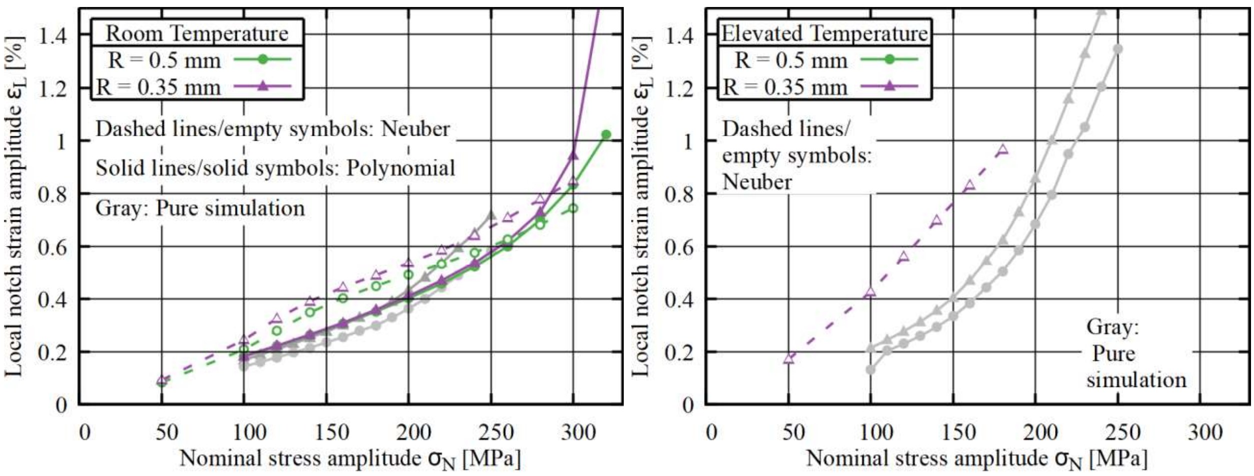

Figure 8. Local notch root strain as a function of the nominal stress amplitude

In the comparison of the notch effect, the intermediate step of the extensometer strain allows a correction with the polynomial approach. The plain simulated strains (grey) are shown as a comparison for both room temperature.

Assessment of Notch Effect on Fatigue Life

The cycles until failure (the criterion imposed is a load drop of 25 %) for the unnotched specimens are directly usable in an ε-N curve (strain amplitude vs. number of cycles to failure). For the assessment of the notched specimen, the strain amplitude has to be corrected (taking the elastically computed strain amplitude from the nominal stress σ_N as a starting point, $\epsilon_N = E\sigma_N$). The comparison of the notched and unnotched specimens is shown in Figure 9. This diagram is to be read as follows: A fatigue test of a notched specimen is performed up to a certain number of failures for a specific nominal strain amplitude (grey point). However, the local strain amplitude is higher and has to be corrected (vertical arrow), which allows a comparison with the unnotched specimen tests (red points).

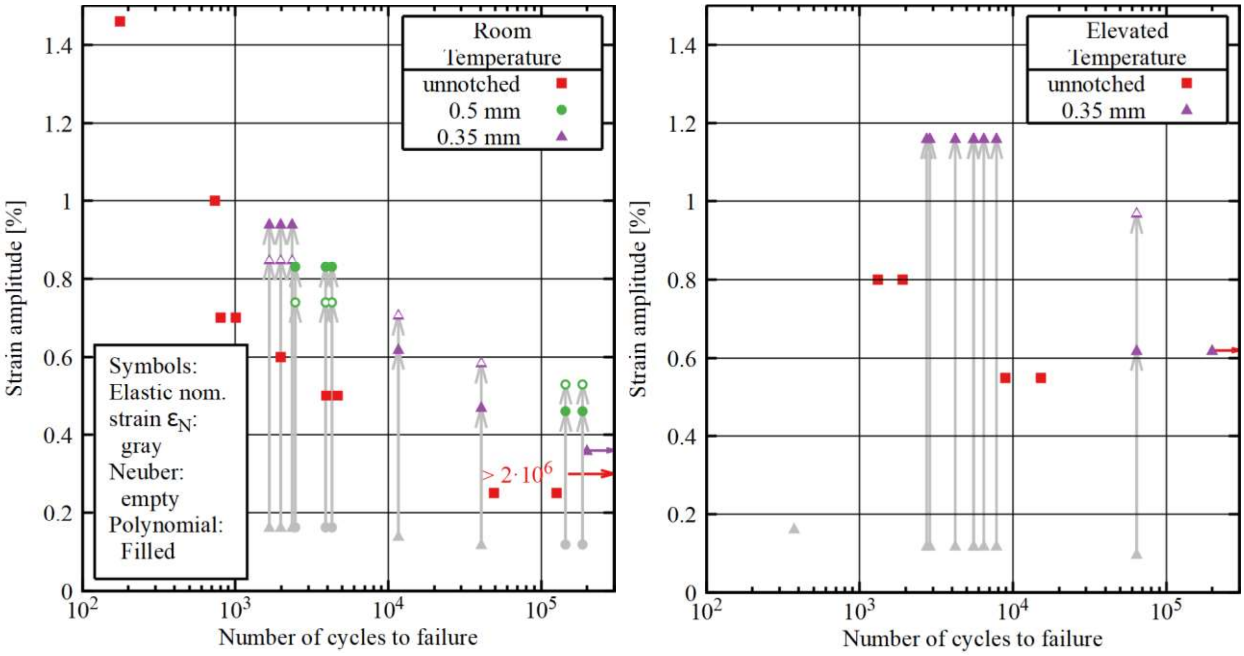

Figure 9. Fatigue diagrams at room temperature (left) and elevated temperature (right).

The unnotched specimens show a larger fatigue strength than the one for notched specimens at similar nominal strain (grey points for the notched cases), and the tests for specimens with the sharper notch (triangles) show shorter fatigue lives than the ones for notches with larger radius (circles). In the assessment with the Chaboche-model based relation on the extensometer strain, the tests for notched and unnotched specimens agree – while there is a trend to higher strains (or numbers of cycles to failure) at room both temperature levels for the notched specimens.

SUMMARY AND CONCLUSION

In this paper, the fatigue lives from fatigue tests with notched and unnotched specimens were compared. The austenitic steel AISI 347 (X6CrNiNb1810) was tested at room temperature (in air and in water) and at elevated temperature (in air). The assessment challenge is the determination of the unmeasurable local strain amplitude ε_L. In the presented approach, this quantity was determined based on the material's plasticity behaviour $\sigma(\varepsilon)$, on the nominal stress σ_N and the strain of an extensometer ε_X. applied outside the notch This required the testing of unnotched and notched specimens equipped with extensometers in load increase tests in addition to constant amplitude tests to be evaluated with respect to the fatigue life. The flow chart of the testing and computation is shown in Figure 10 (the Neuber approach, although limited, is also included as an alternative path).

The proposed workflow was tested with one material, two notch geometries and two temperature levels. Apparently, this concept can be transferred also to other notch geometries and materials. A lesson learned in this procedure was that even with an elaborated plasticity model, the prediction of the deformation of a laboratory specimen under uniaxial load is not very accurate at higher strains, due to the presence of inhomogeneous strain field in the vicinity of the notch. The third-order odd polynomial approach for the correlation of extensometer strain and local strain seems to be a promising opportunity to compensate simulation-related difficulties and to use additional information obtained in the test in the assessment.

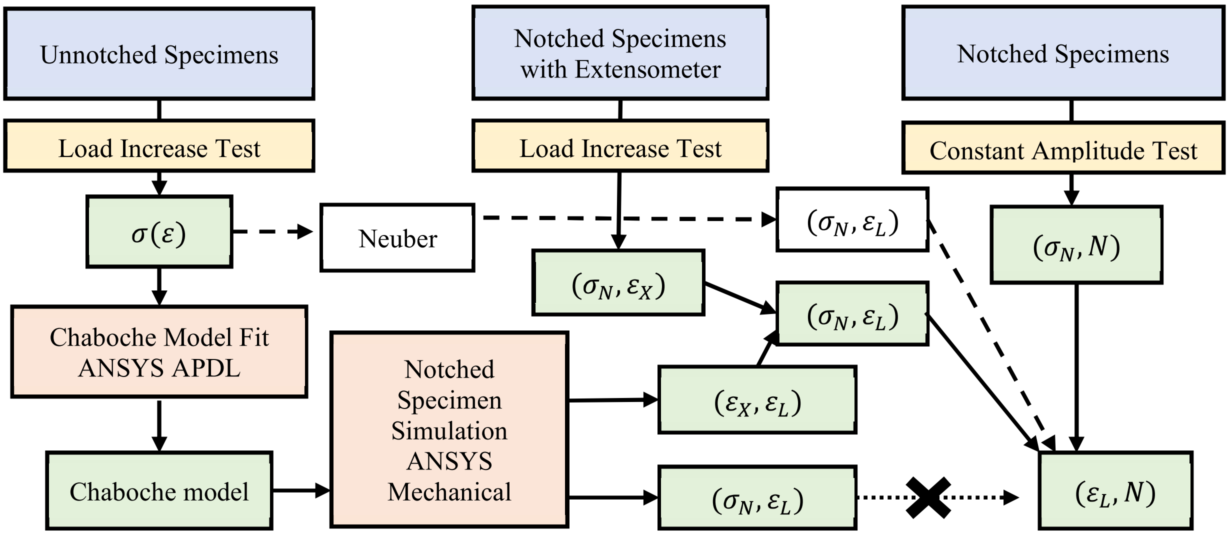

Figure 10. Flow chart of the assessment of notched fatigue specimens.

The fatigue life assessment showed that a careful assessment of the local strain is required to understand the notch effect on the fatigue strength, and the transferability of laboratory fatigue tests to actual structure assessments. The proposed polynomial formulae can be seen as non-linear generalization of notch factor assessment rules established for elastic material behaviour.

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