A Comparison of Fatigue Characteristics of Structural Steels Measured by means of Classic and Miniature Test Samples

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Abstract

The assessment of material mechanical properties degradation as a result of long-term service at cyclic loading, creep temperatures and/or their combination has been performed on the basis of various non-destructive methods. Nevertheless, their main disadvantage stems from the fact that these methods can give qualitative (and not quantitative) results and thus the remaining lifetime cannot be exactly evaluated.

New methods of mechanical testing were developed recently that are based on making use of miniature test specimens (e.g. Small Punch Test). The most important advantage of these method is the nearly non-destructive withdrawal of test material and small size of test specimen what is interesting in cases of remaining lifetime assessment when a sufficient volume of the representative material cannot be withdrawn of the component in question.

In opposite, the most important disadvantage of such methods stems from the necessity to correlate test results with the results of classical test procedures and to build up a database of material data in service. The correlations among the miniature test specimen data and the results of classical tensile tests, fracture toughnesss values and time to rupture characteristics at creep temperatures and, of course fatigue S – N curves are necessary for the remainig lifetime assessment of structure in long-time service.

The paper describes the results of fatigue tests performed on miniature tests specimens in comparison with classical fatigue tests for several steels applied in power producing industry. Special miniature test specimens fixture was designed and manufactured for the purposes of fatigue testing at the Zwick/Roell – Amsler 10HPF5100 test machine. The miniature test specimens were produced by water-jet cutting from the large test specimens. With respect to the specimen shape (See Figure), stress concentration and multiaxial stress situation had to be taken into consideration for the purposes of comparison with the classical test specimens.

Miniature Test Specimen for Fatigue Test

Introduction

In cases of cyclic loading of test specimens or structural components, the cumulation of cyclic plastic deformation causes failure below ultimate strength and even yield point values. The fatigue is still the prevailing cause of failure of metallic, plastic and ceramic components.

The basic mechanical characteristics of fatigue behaviour of structural materials are:

a) Woehler (S - N) curve describing relationship between the amplitude of loading and the resulting number of cycles to failure,
b) Manson-Coffin (ε – N) curve describing the relationship between the amplitude of deformation and the resulting number of cycles to failure,
c) Paris-Erdogan Law describing the relationship between the crack growth rate and the stress intensity factor.

All the three abovementioned material characteristics are used in engineering practice. The Woehler (S - N) and Manson-Coffin curves treat the material as a mechanical continuum and include all the stages of fatugue process, the Paris-Erdogan equation describes the macroscopic crack growth.

It is well known, that the specimen size has a negligible effect in case of uniaxial tensile loading, and thus yield point and the ultimate strength are not dependent on the cross section size, the failure process during fatigue loading depends on the specimen or component size, i.e. the increasing specimen size has a negative effect on the specimen life. This fact is caused primarily by the stress gradient in the respective cross section. This can be caused e.g. by bending loading or at specimens containing stress concentrators.

At present, questions on quantitative evaluation of remaining lifetime become urgent and because fatigue is the most frequent cause of materials degradation and resulting structural components failures, the most important means of remaining lifetime assessment is the evaluation of fatigue properties before and after some time of service.

The original material data are usually tested by means of classic test specimens, which can be hardly used in case of components in service, where there is no possibility to withdraw sufficient volume of representative material for the classic test specimen manufacturing. In such cases today, new modern methods of semi-destructive removal of a small volume of test material by grinding or an electro-discharge method are utilized. This makes it possible to produce a miniature test specimens only that, see Figure 1, that possess a distinctive stress concentration and resulting 3D stress state.

In comparison with the classic uniaxially loaded test specimens, the stress gradient within the miniature test specimens can have a similar effect as in the case of fatigue in bending.

Fatigue of classic and miniature test specimens

Miniature test specimens were produced by water jet procedure so that the direction of load action was the same as in the classic test specimens, see Figure 2. New special grips were designed for the purposes of miniature test specimens testing, see Figure 3. Their design makes it possible an exact test specimens gripping with respect to both longitudinal and transverse axes. The fatigue testing was perfomed by means of Zwick/Roell - Amsler 10 HPF5100 test machine.

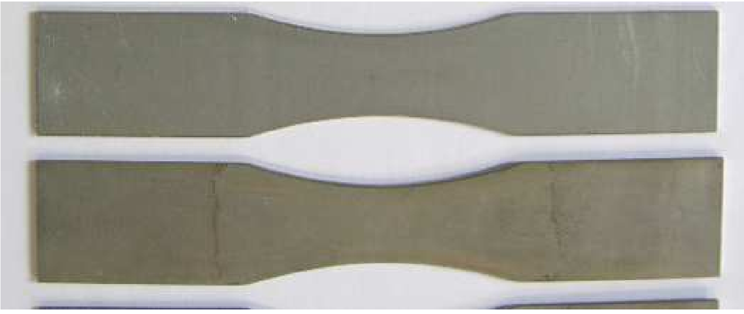

Figure 1. Classic fatigue test spesimens

Figure 2. Miniature fatigue test specimens

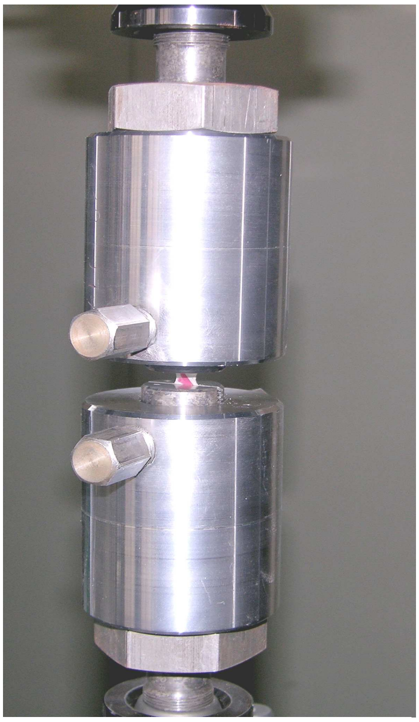

Figure 3. Miniature test specimens grips

Experimental results

By means of COSMOS/M SW, FEM models of stress concentration were calculated for both the classic and the miniature test specimens, see Figure 4. Stress concentration factor in the case of the miniature test specimen was determined to be

$$\alpha = \frac{\sigma_{max}}{\sigma_{nom}} = 1{,}33 \text{ ,} \qquad (1)$$

where

σ_{max} is the maximum stress determined by means of the FEM model and

σ_{nom} is the nominal stress

Examples of the obtained results are given in Figures 5 – 8, where S-N curves for classic test specimens and miniature test specimens (for both the nominal stress and the stress concentration) are compared.

Note: The experimental results in this paper come from a commercial tests and thus the chemical composition of the tested materials is not specified. Seven different steels were fatigue loaded (R = 0,1) at room temperature, four examples of obtained results are shown in Figures 5 – 8.

Conclusion

It is well visible from the abovementioned figures, that the S – N curves of miniature test specimens have a steeper course in comparison with the classic ones for all the tested materials. Within the high-cycle fatigue range above 1,5x10^5 to 10^7 cycles, the S – N curves intersect. At present there is no unique general correlation between the classic and miniature test specimen results.

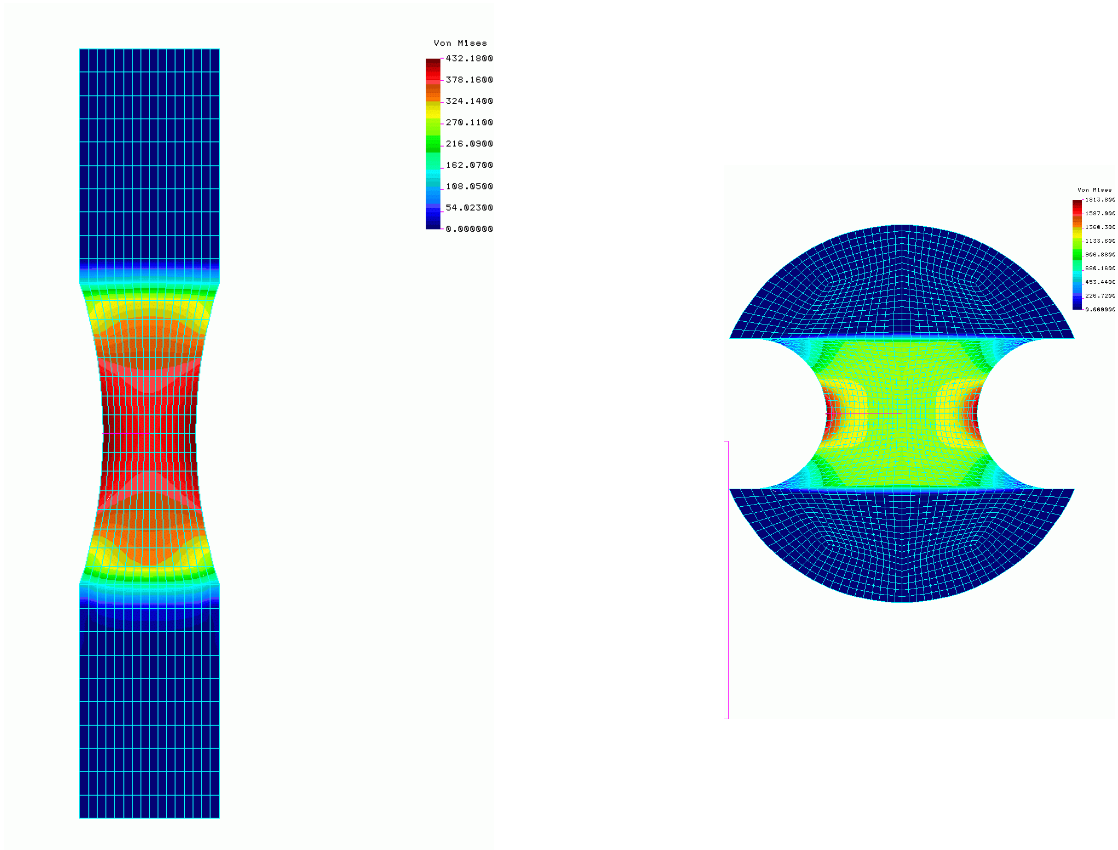

Figure 4. FEM models of classic and miniature test specimens

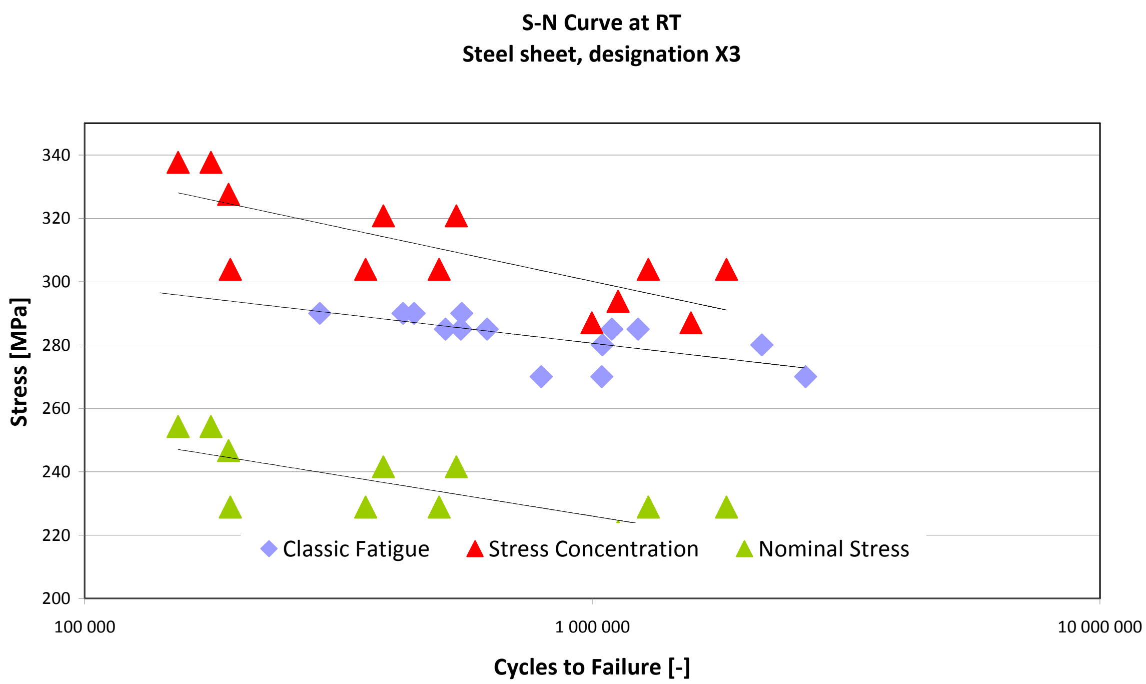

Figure 5. An Example of S-N Curve of the X3 Steel

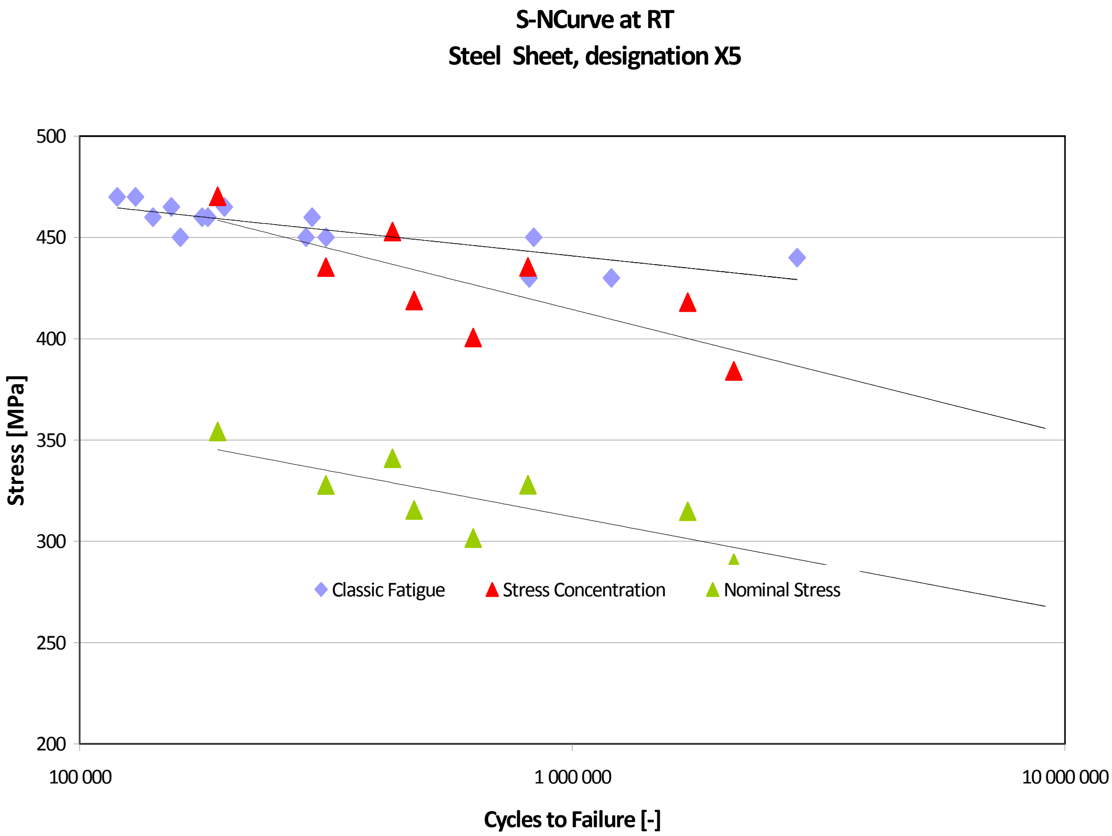

Figure 6. An Example of S-N Curve of the X5 Steel

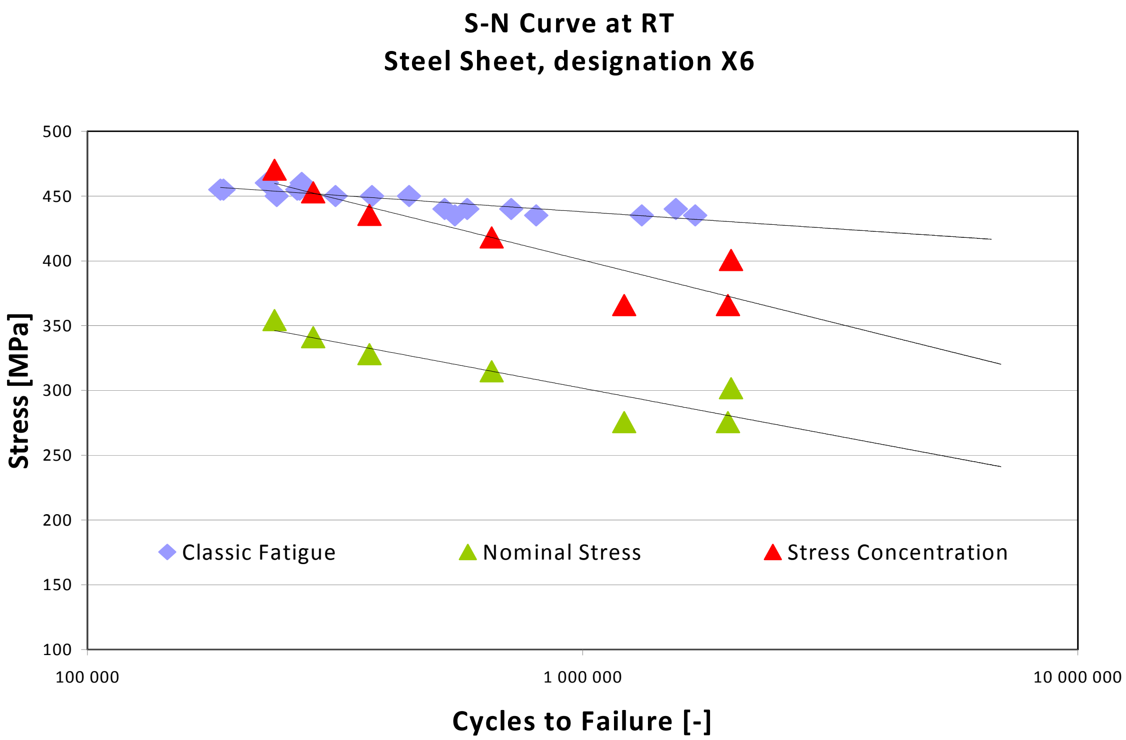

Figure 7. An Example of S-N Curve of the X6 Steel

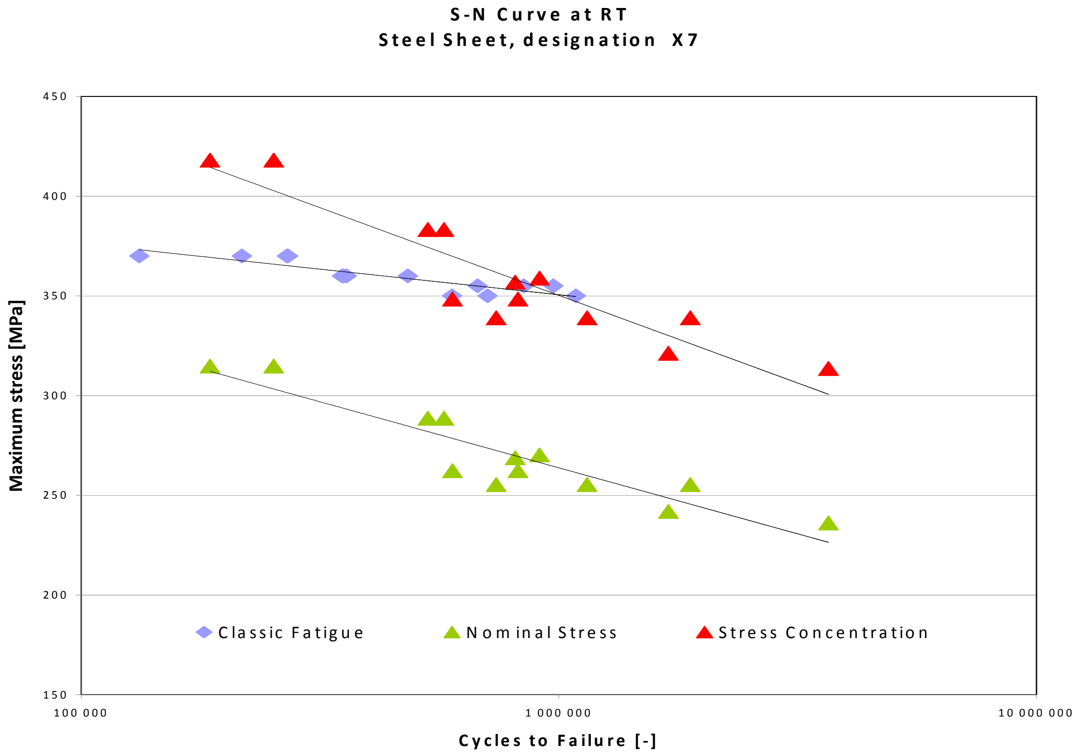

Figure 8. An Example of S-N Curve of the X7 Steel

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