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# Degradation of Material Mechanical Properties and Its Evaluation Using Miniature Test Specimens

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**Abstract:** The paper deals with part of the tasks solved in the framework of the research plan "Research into Service Degradation of Advanced Constructional Materials", which had been solved in ŠKODA VÝZKUM s.r.o. since the year 2004 and was finished in 2010. The objective of the research plan was the development of both existing and new methodologies describing in a complex way degradation of new types of materials applied at production of engineering equipment, structures and their parts, used in the power and the transport industry. Attention in this paper is focused on the results of fatigue tests performed on miniature tests specimens in comparison with classical fatigue tests for several steels applied in power producing industry.

**Keywords:** Material degradation, Experimental measurements, Computer simulations

## 1. Introduction

The objective of the research plan MSM 4771868401 "Research into Service Degradation of Advanced Constructional Materials" was the development of both existing and new methodologies describing, in a complex way, degradation of new types of materials applied at production of engineering equipment, structures and their parts, used in the power and the transport industry. The plan had been solved in ŠKODA VÝZKUM s.r.o. (now Výzkumný a zkušební ústav Plzeň s.r.o.) since the year 2004 and was finished in 2010. The paper is the logical continuation of the papers [1] and [2].

- Evaluation of the level of degradation of constructional materials' mechanical properties, especially the correlation of the results of destructive and non-destructive experimental procedures.
- Evaluation of the degree of damage of structures and structural elements due to various service conditions.
- Prediction of negative phenomena of degradation processes occurring in the structure of material, which the structures or the structural elements are made of.
- Evaluation of residual lifetime of the structures and the structural elements.

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The research plan included, among others, partial tasks focused on the testing of mechanical properties of constructional materials by means of tests on small test specimens.

The assessment of mechanical material properties degradation as a result of a 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 (but not quantitative) results and thus the remaining lifetime cannot be exactly evaluated.

New methods of mechanical testing that are based on making use of miniature test specimens were developed recently (e.g. Small Punch Test). The most important advantage of these methods is the nearly non-destructive withdrawal of test material and small sizes of test specimens, which 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 addition, the testing of mechanical properties of constructional materials by means of tests on small test specimens is important in many practical cases, in which it is not possible to take a sufficient amount of representative sample of the material from the structural element for the manufacturing of the classical test specimens.

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

The results of fatigue tests performed on miniature tests specimens were compared 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 testing machine. The miniature test specimens were made of large test specimens by means of a water-jet cutting. With respect to the specimen shape (see Fig. 2), stress concentration and multiaxial stress situation had to be taken into consideration for the purposes of comparison with the classical test specimens [3].

## 2. Fatigue behaviour of structural materials

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

Basic mechanical characteristics of fatigue behaviour of structural materials are:

a) Wöhler (S-N) curve describing the 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 coefficient.

All the three abovementioned material characteristics are used in engineering practice. The Wöhler and Manson-Coffin curves treat the material as a mechanical continuum and include all the stages of fatigue process, the Paris-Erdogan equation describes the macroscopic crack growth [4].

It is a well known fact that the test specimen size has a negligible effect in case of a uniaxial tensile loading, and thus the 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 a stress gradient in the respective cross section. This can be caused e.g. by the coefficient of a sample size, the coefficient of the geometric quality of a surface and the stress concentrator.

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 service time.

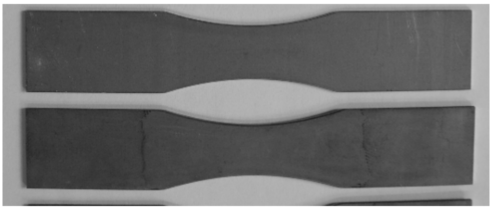
Original material data are usually tested by means of classical test specimens, which can be hardly used in case of components in service, where there is no possibility to withdraw a sufficient volume of representative material for the classical test specimen manufacturing. Today, in cases like that new modern methods of a 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, see Fig. 2.

In comparison with the classical 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.

## 3. Experimental equipment description

First (in the framework of commercial order) fatigue tests to determine the S-N curves at R = 0.1 in tensile on classical test specimens (see Fig. 1) at room temperature were performed. Altogether 7 various materials were tested. Regarding the possibility of utilising the results obtained on those classical specimens and regarding the sufficient amount of remaining test specimens it was suitable to perform fatigue tests on small test specimens as well. But it was necessary to manufacture miniature test specimens, (see Fig. 2), grips for their fastening on a testing machine and to perform fatigue tests themselves on miniature test specimens [5,6].

Classical specimens were made of a metal sheet of the thickness of 2 mm in maximum using the water jet technology. Miniature test specimens were produced so that the direction of load action was the same as in the classical test specimens – see Fig. 2. New special grips were designed for the purposes of miniature test specimens testing, see Fig. 3. Their design enables an accurate test specimens gripping with respect to both longitudinal and transverse axes. Further it was necessary to make grips for clamping the manufactured small test specimens because producers of testing machines supply grips only for the standardized test specimens. Grips are mechanical, with knurled inserts (see Fig. 3). The inserts ensure a precise clamping of a specimen both in a vertical and a horizontal axis and at the same time they eliminate the risk of the specimen slip during the subsequent cycling.



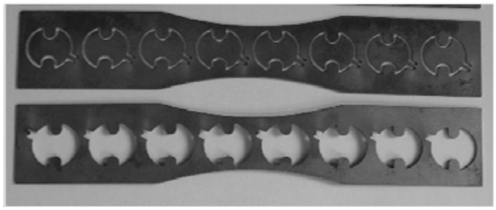


**Fig. 1.** Classical test specimens for fatigue tests

**Fig. 2.** Small tests specimens for fatigue tests

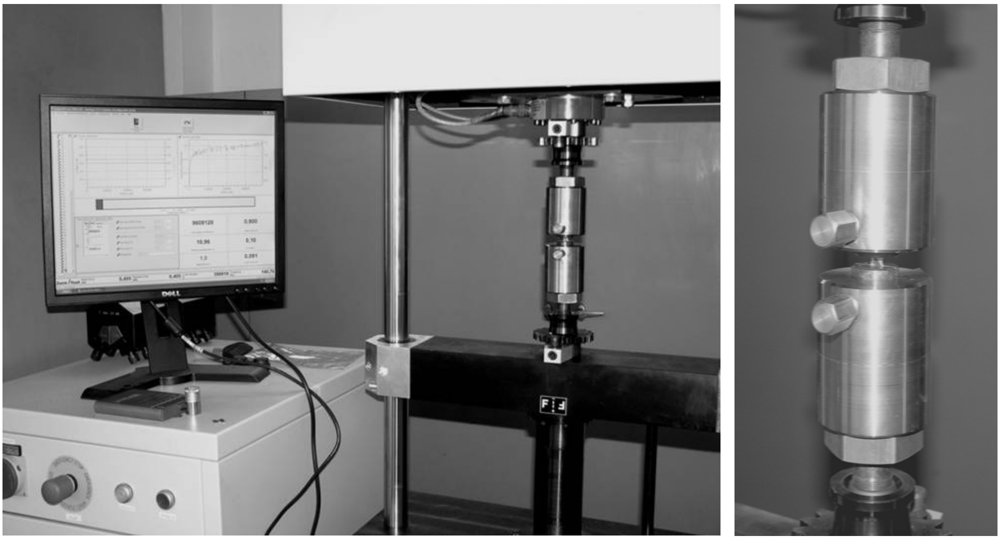


**Fig. 3.** Workplace for fatigue testing on small test specimens and the miniature test specimens grips (taken from [2])

The fatigue testing was performed by means of the Zwick/Roell – Amsler 10 HPF5100 testing machine. This testing machine can vibrate in a sufficiently precise way even at low loading forces.

## 4. Results

After performing the fatigue tests it is necessary to process the obtained results. To determine the S-N curve it is necessary to know stress at which the test specimen was cycled and the number of cycles up to a fracture.

At classical specimens the stress concentration is neglected. At small specimens the geometry of the test specimen causes a higher stress concentration in the critical section. To determine and compare coefficients of stress concentration models of both the classical and the miniature test specimens were created in the COSMOS/M software FEM (see Fig. 4). They were used for the calculation of stress concentration coefficients.

A stress concentration coefficient in the case of the miniature test specimen was determined to be

$$\alpha = \frac{\sigma_{\max}}{\sigma_{nom}} = 1.33 \ , \tag{1}$$

where $\sigma_{max}$ is the maximum stress determined by means of the FEM model and $\sigma_{nom}$ is the nominal stress given by the relation

$$\sigma_{nom} = \frac{F}{b \cdot s} , \tag{2}$$

where $F$ is the acting force, $b$ is the specimen width in the critical point and $s$ is the specimen thickness.

The value of the stress concentration coefficient for the critical section of miniature test specimens $\alpha$ = 1.33 should be defined more precisely using a denser grid of the FEM model. But in this precision only the thousandth digit places are concerned.

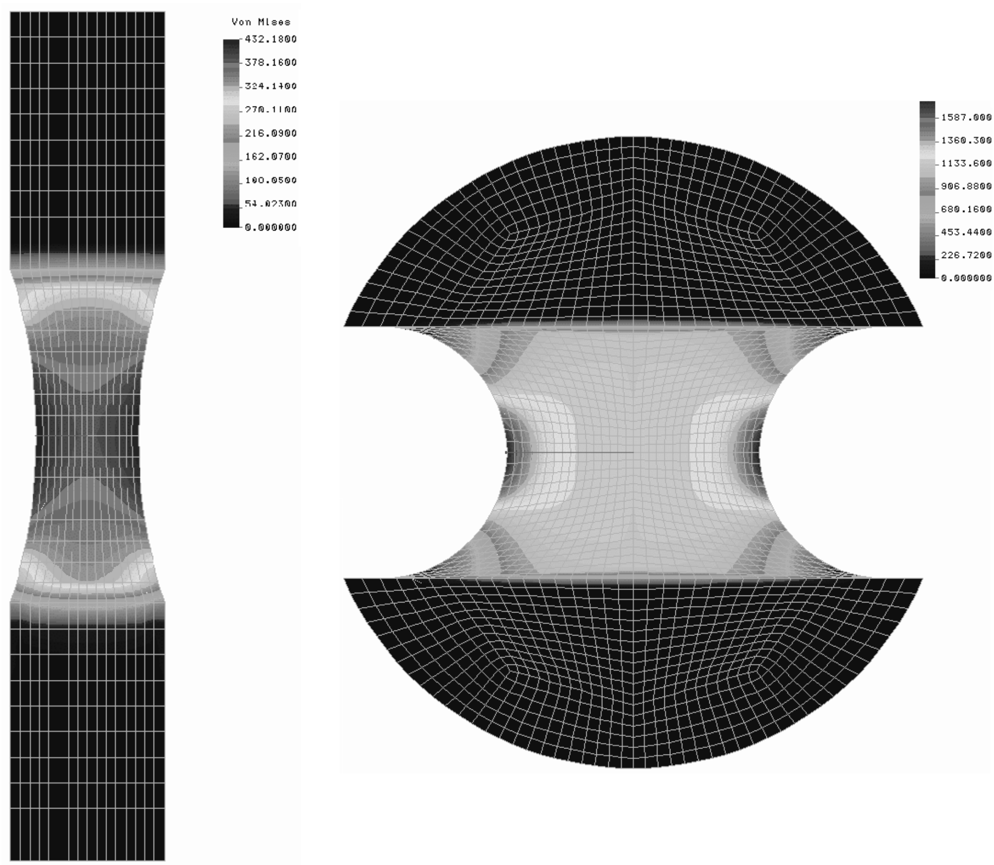



**Fig. 4.** FEM models of classical and miniature test specimens

Four examples (of seven tested materials) of the obtained results are given in Figs. 5 to 8, where S-N curves for classical test specimens and miniature test specimens (for both the nominal stress and the stress concentration) are compared. In graphs in Figs. 5 to 8 maximum stresses at repeated loading (at standard presentation stress amplitudes are plotted) are shown. Note: Due to the fact that materials of the commercial order are concerned, the chemical composition of the tested materials is not specified.

In the framework of the commercial order the customer required 3 million cycles at maximum, which is evident from graphs in Figs. 5 to 8, in which the straight line of the S-N curves is missing. Asterisk markers in graphs represent the results of the fatigue tests on the miniature test specimens without the consideration of the stress concentration in the critical point. Triangular markers are the results multiplied by the correlation coefficient $\alpha = 1.33$. This coefficient is identical with the stress concentration coefficient given in [7]. In each graph the gradient of curves obtained on the basis of the measurements on miniature test specimens in comparison with the classical fatigue tests is completely different. The obtained results cannot be correlated uniformly and thus it is necessary to investigate the influence of the specimen shape, geometry and final machining in detail.

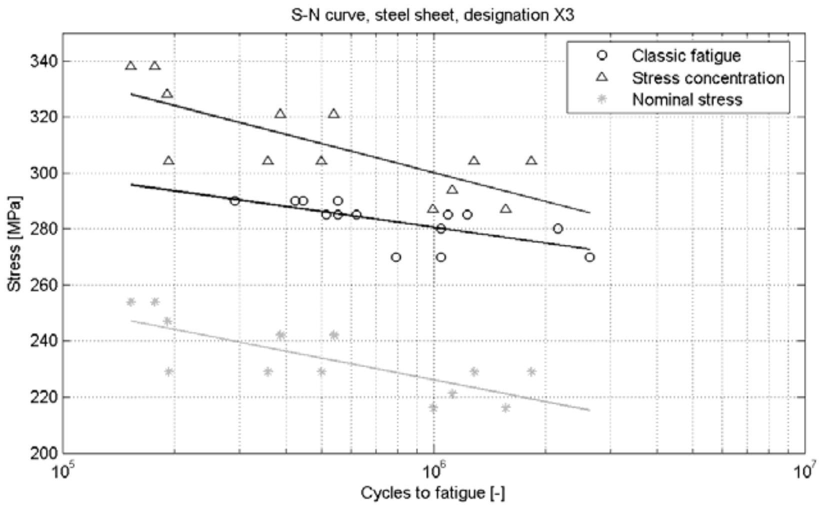



**Fig. 5.** S-N curve of the X3 steel example

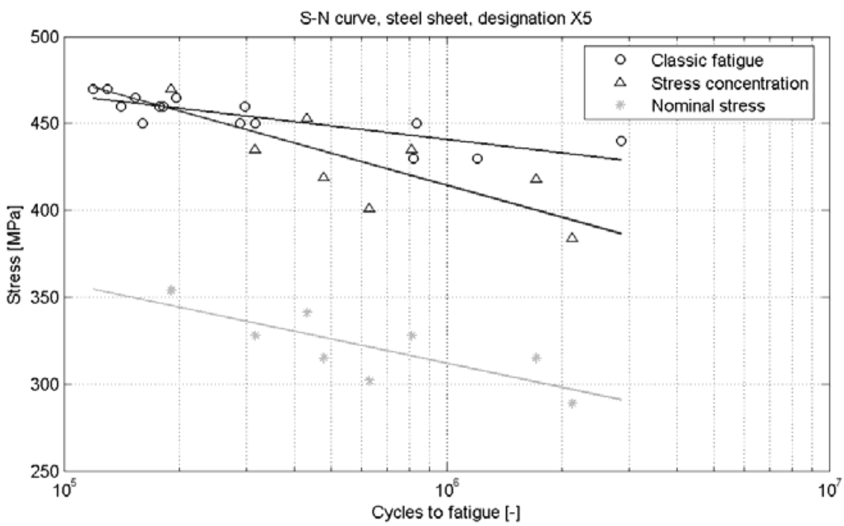



**Fig. 6.** S-N curve of the X5 steel example

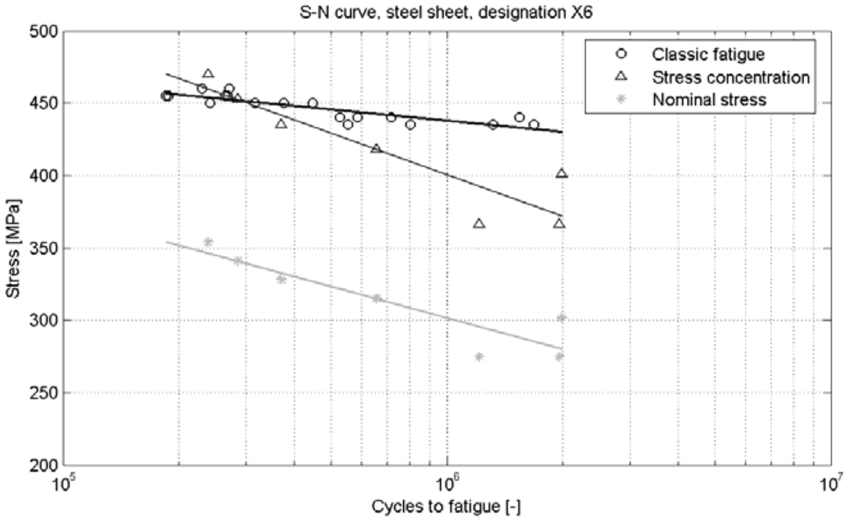



**Fig. 7.** S-N curve of the X6 steel example

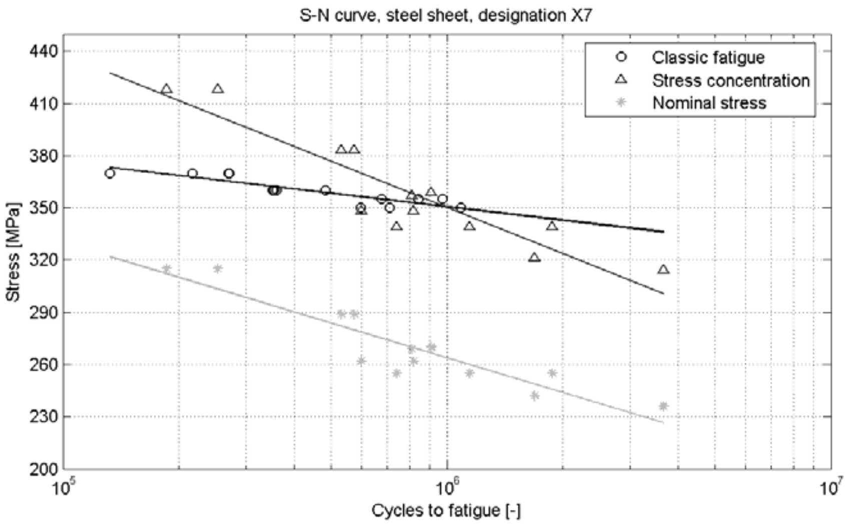



**Fig. 8.** S-N curve of the X7 steel example

## 5. Conclusion

It is evident from Figs. 5 to 8 that the S-N curves of the miniature test specimens have a steeper course in comparison with the classical ones for all the tested materials. Within the high-cycle fatigue range above $1.5 \cdot 10^5$ to $10^7$ cycles the S-N curves intersect. At present there is no unambiguous general correlation between the classical and miniature test specimen results.

The results of the seven-year solving of the research plan are presented in 145 titles of ŠKODA VÝZKUM s.r.o. research reports. So far 37 papers have been published in scientific journals, 170 ones in conference proceedings, 10 chapters have been published in books and 46 other outputs have come into existence (e.g. introduction of a new methodology, etc.). The overview of the process of solving the research plan and of the achieved results is given especially in the research reports, e.g. [8 - 10].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### References


[1] Polach P., "Research into the processes causing the constructional materials degradation," in *Proceedings of 47th International Scientific Conference Experimental Stress Analysis 2009*, Marvalová B., Petríková I., Čapek L., eds., Sychrov, June 2009 (TU of Liberec, Liberec, 2009), pp. 207-214, CD-ROM. ISBN 978-80-7372-483-2.

[2] Polach P., "Evaluation of the Processes Causing the Constructional Materials Degradation," in *Proceedings of 48th International Scientific Conference Experimental Stress Analysis 2010*, Šmíd P., Horváth P., Hrabovský M., eds., Velké Losiny, May 2010 (Palacky University, Olomouc, 2010), pp. 361-368, CD-ROM. ISBN 978-80-244-2533-7.

[3] Fine M.E. and Chung Y.W., "Fatigue Failure in Metals," in *ASM Handbook Vol.19, Fatigue and Fracture*, (ASM International, 1996), pp. 63-72. ISBN 978-0871703859.

[4] Klesnil M. and Lukáš P., *Fatigue of Metal Materials at Mechanical Stress* (Academia, Praha, 1975). (in Czech)

[5] Volák J., Mentl V., Chvostová E., Chocholoušek M. and Kindelmann P., *Influence of the Test Specimen Shape of the "Small Punch" Type on the Fatigue Tests Results, Research Report VYZ 1212/2009* (ŠKODA VÝZKUM s.r.o., Plzeň, 2009). (in Czech)

[6] Mentl V., Chocholoušek M., Volák J. and Kindelmann P., "Steel fatigue characteristics correlation for energy industry measures on standard and miniature test specimens," in *Proceedings of the 4th Conference Increases in Fatigue of Power Generating Equipments Components in Power Stations*, Chocholoušek M., Liška V., eds., Srní, October 2009 (ŠKODA VÝZKUM s.r.o., Plzeň, 2009), pp. 163-166. ISBN 978-80-7043-827-5. (in Czech)

[7] Francisko P., *Fatigue Characteristics of Material Determined Using Small Test Specimens, PhD. Thesis* (FME UWB in Pilsen, Plzeň, 2004). (in Czech)

[8] Polach P. and Kepka M., *Starting Points and Partial Tasks of the Research Plan MSM 4771868401 "Research into Service Degradation of Advanced Constructional Materials", Research Report VYZ 0729/2004* (ŠKODA VÝZKUM s.r.o., Plzeň, 2004). (in Czech)

[9] Polach P., *Grand Summary and Seventh Year of Solving of the Research Plan MSM 4771868401 "Research into Service Degradation of Advanced Constructional Materials", Research Report VYZ 1301/10* (ŠKODA VÝZKUM s.r.o., Plzeň, 2010). (in Czech)

[10] Polach P., "Research of the processes causing the constructional materials degradation in energy engineering," *All for Power*, **5**(1), pp. 125-129 (2011). ISSN 1802-8535. (in Czech)