ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 18, No. 1. 2012

Fatigue Strength of Weathering Steel

Ludvík KUNZ [*], **Petr LUKÁŠ**, **Jan KLUSÁK**

Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, 616 62 Brno, Czech Republic

crossref http://dx.doi.org/10.5755/j01.ms.18.1.1335

Received 02 July 2011; accepted 18 September 2011

Fatigue behaviour of Atmofix 52 steel (comparable to COR-TEN® steel) exposed to atmospheric corrosion for 20 years was investigated. S-N curves for load symmetrical cycling and cycling with stress ratio $R = 0$ were determined on specimens detracted from a failed transmission tower. The data were compared with those on material without a rust layer. The fracture surfaces and, in particular, the sites of fatigue crack initiation were analyzed.

Substantial decrease of fatigue life and fatigue limit due to corrosion exposition was found. Based on observation of surface layer with corrosion products and on fractographic analysis of failed specimens conclusions on fatigue damage mechanism were drawn. No grain boundary corrosion, which can be responsible for fatigue crack initiation, was observed. Initiation of fatigue cracks was related to surface roughness and took place exclusively on corrosion dimples.

Keywords: fatigue of weathering steel, corrosion pits, fatigue notch factor.

1. INTRODUCTION

Weathering steels have been used since a long time in bridges, large structural applications, transmission towers, containers and marine transportation. Such engineering structures have to often withstand cyclic loading for a long time and steadily fulfill safety standards. Weathering steels of the trademark COR-TEN® were established and patented in the thirties of the last century in the USA. Similar steels marked Atmofix have been developed in former Czechoslovakia in the sixties of the last century and subsequently broadly applied to engineering constructions in traffic and power distribution network. They were developed to obviate the need for surface treatment like painting. A stable rust-like protecting layer develops and regenerates continuously on their surface when subjected to the influence of weather. Due to their chemical composition these steels exhibit good resistance to atmospheric corrosion when compared to unalloyed steels. Formation, duration, cohesion and protective effect of the covering layer depends also upon the character of the atmosphere.

Though weathering steels exhibit good corrosion resistivity, the continuous regeneration of the protective layer results in mass losses and reduction of component dimensions. Moreover, there is an effect of development of surface morphology and a danger of formation of corrosion cracks in the surface layer. All these effects are closely related to the fatigue performance of engineering structures. Long time application of weathering steels raises presently the questions of the safety factors, particularly concerning the remaining fatigue life [1]. The safety of structures like bridges, which are operated since many years in atmospheric conditions and often also in salt solution during the winter months, is of increasing significance [2]. The chemical composition and kinetics of development of protective corrosion rust layer (often called patina) on Atmofix steels have been a matter of research in the past, however the fatigue damage mechanism was not studied in sufficient detail. The investigation of corrosion kinetics and development of a rust layer brought evidence of an increase of surface roughening, which can be related with substantial decrease of fatigue strength [3, 4]. The fatigue strength decrease can be related to the surface roughness expressed in terms of maximum height of the profile or arithmetic mean deviation R_a [5]. On the other hand, in some papers, e. g. in [6] the influence of corrosion cracks, which can develop in exposed material, is being considered the most decisive factor deteriorating the fatigue performance.

The evaluation of the remaining lifetime of components fabricated from weathering steels and applied for long time needs both the experimental determination of the drop of fatigue performance due to exposure and simultaneously to identify the damage mechanism in the particular case. There is a basic difference when the damage is caused by the development and growth of corrosion cracks in base material below the corroded layer and in the case of development of surface roughness due to corrosion pitting.

The aim of this study was to experimentally determine the reduction of fatigue strength of Atmofix 52A steel, which is in use for transmission towers in the rural atmosphere in Bohemia for more than 20 years and to investigate the mechanism of fatigue damage.

2. MATERIAL AND EXPERIMENTS

Fatigue tests were performed on specimens machined from an angle iron of ~7 mm in thickness, which was detracted from a transmission tower. The material has been in service for more than 20 years. The location of the tower was in central Bohemia in a rural countryside.

The chemical composition of Atmofix 52A steel is given in Table 1.

Two types of flat specimens for fatigue tests machined according to Fig. 1 were used. The first type was machined

---

[*] Corresponding author. Tel.: +420-604-873893; fax.: +420-541-218657.
E-mail address: *kunz@ipm.cz* (L. Kunz)

Table 1. Chemical composition of Atmofix 52A, wt %

C	Si	Mn	P	S	Cu	Ni	Cr	Al
0.12	0.25 – 0.75	0.30 – 1.00	0.055	0.04	0.30 – 0.55	0.30– 0.60	0.50 – 1.25	0.01

in such a way that the corrosion layer covered the two frontal sides of the specimen gauge length having 10 mm width. The remaining two sides were milled. The sharp edges of the gauge length after machining were made round with a radius of 0.5 mm. The thickness of the specimen was determined by the thickness of the angle iron. The cross-section was about 70 mm^2. The second specimen type was machined in such a way that the corroded layer was milled away. Thus, the second type of specimen was characteristic for the base material. Its thickness was about 5.5 mm. An example of the specimen with corroded layer is shown in Fig. 2. The specimen heads were slightly reground by reason of good fastening in the grips of the fatigue machine.

Fatigue tests were performed in load control on a resonant fatigue machine Schenck PVQO at frequency of about 40 Hz. Tests with the highest stress amplitudes were conducted on a servohydraulic testing machine Zwick/Roell Amsler MC25 at a frequency of 10 Hz or 3 Hz with the aim to prevent the heating of specimens.

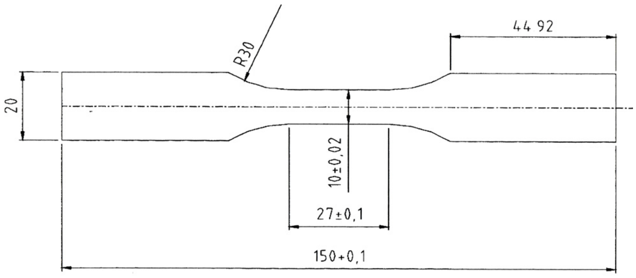

Fig. 1. Dimensions of specimens for fatigue tests

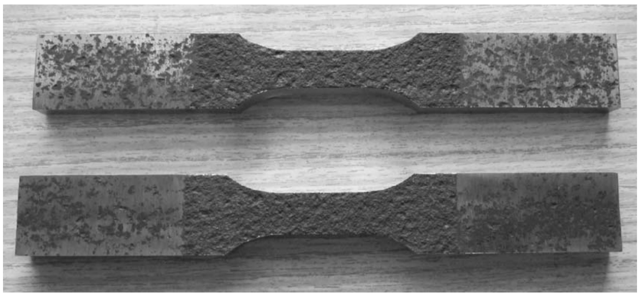

Fig. 2. Fatigue specimens with corroded layer

Fatigue fracture surfaces were observed in a scanning electron microscope (SEM) JEOL 6460. The standard metallographic observation of material structure and corrosion layer was performed by means of standard light microscopy.

3. RESULTS

The experimentally determined S-N data for loading with the stress ratio $R = -1$ (R is defined as the ratio of the minimum to maximum stress in a loading cycle) are shown in Fig. 3. Arrows in the figure indicate run-out specimens, i. e. specimens with fatigue life higher than 10^7 cycles. The fatigue life of specimens, which have two sides of the gauge length with a corrosion layer, is substantially lower than that of base material. The full lines describe the best fit of all data corresponding to the failed specimens. The fatigue limit, depicted by the horizontal dashed line, was determined as the stress amplitude at which three specimens remained unbroken after application of 10^7 cycles.

S-N curves describing the fatigue strength under cyclic loading with the stress ratio $R = 0$ are shown in Fig. 4. Again, the detrimental effect of the corrosion layer is obvious.

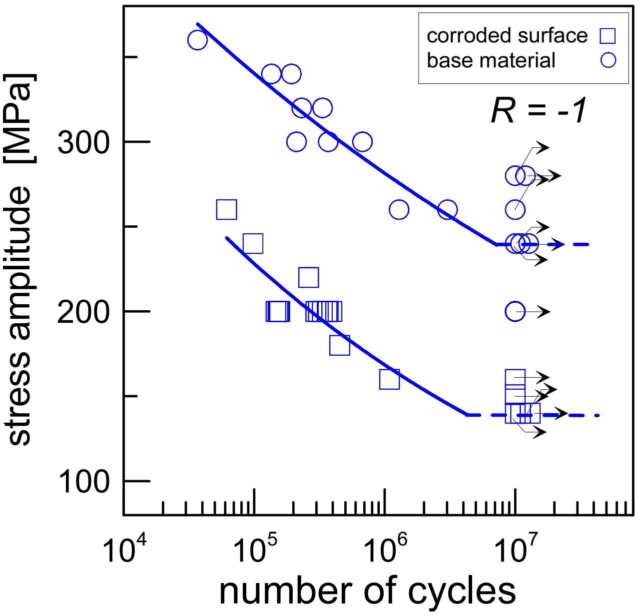

Fig. 3. Fatigue life of Atmofix 52 steel with corrosion layer and base material for stress symmetrical loading

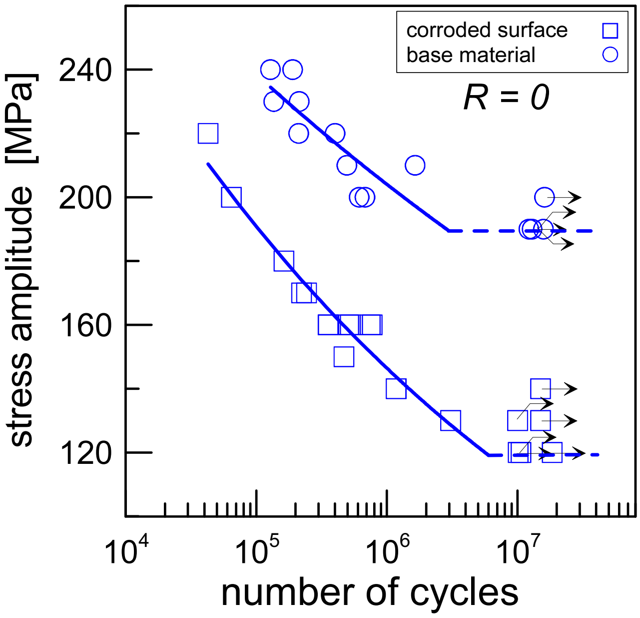

Fig. 4. Fatigue life of Atmofix 52 steel with corrosion layer and base material for pulsating loading in tension

The examination of the fracture surfaces of specimens with corroded layer by means of SEM clearly demonstrates that the fatigue cracks initiate exclusively on corroded surfaces. An example of such observation can be seen in

Fig. 5. Arrows indicate three initiation sites of fatigue cracks on the corroded surface. Initiation on ground surface was never observed.

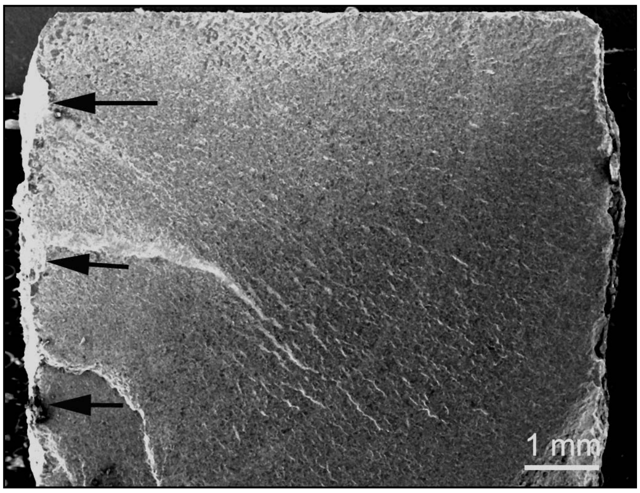

Fig. 5. Fatigue fracture surface. Arrows indicate the sites of crack initiation on the corroded surface

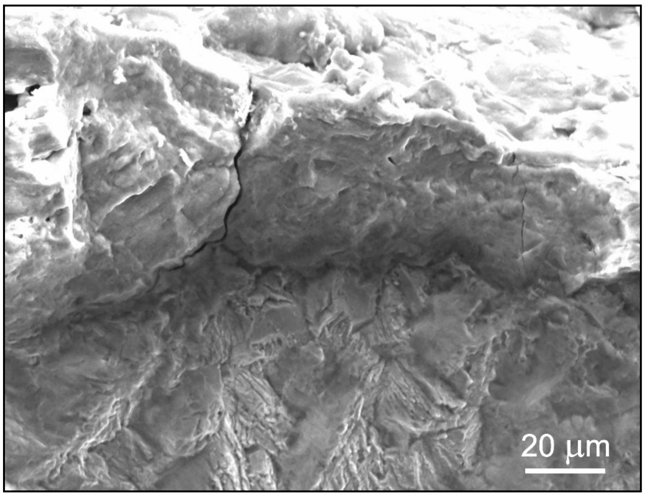

Fig. 6. Cracks in the corrosion layer on the specimen surface

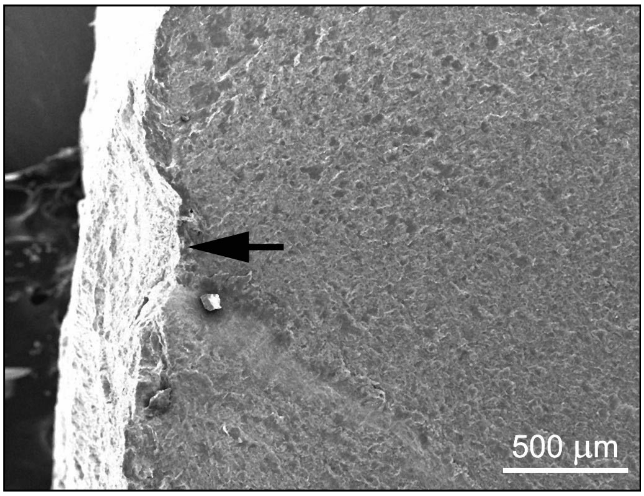

Fig. 7. Initiation of fatigue crack on the surface corrosion dimple marked by the arrow. Stress symmetrical loading

The fracture surface of a failed specimen at higher magnification is shown in Fig. 6. The layer of rust (in the upper part of the figure) contains cracks. However, they do not grow further into the base material. i. e. they are not responsible for initiation of fatigue cracks which determine the lifetime under cyclic loading. They very often turn to the rust/base material boundary and separate the rust from the un-corroded material.

Detailed examination of fatigue crack initiation sites in specimens with corrosion layer brought an evidence of initiation at corrosion dimples. An example is shown in Fig. 7. The arrow indicates the dimple, from which the fatal fatigue crack started to propagate. Similar observation was made on decisive majority of specimens loaded at both stress ratios. An example of a dimple initiating the crack under loading with $R = 0$ is in Fig. 8.

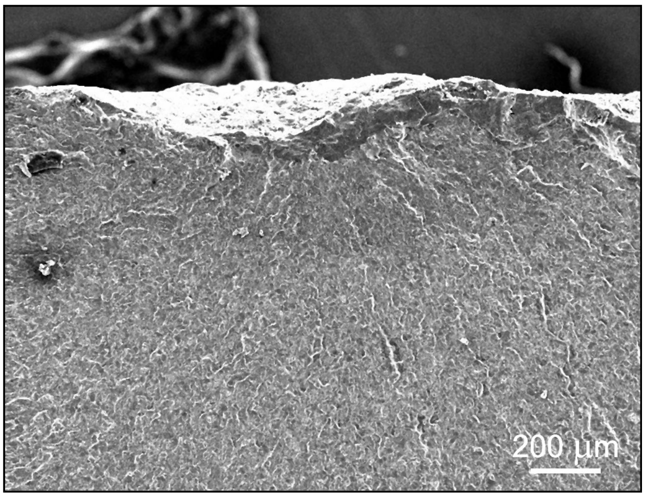

Fig. 8. Initiation of fatigue crack on corrosion dimple in the case of fatigue loading with $R = 0$

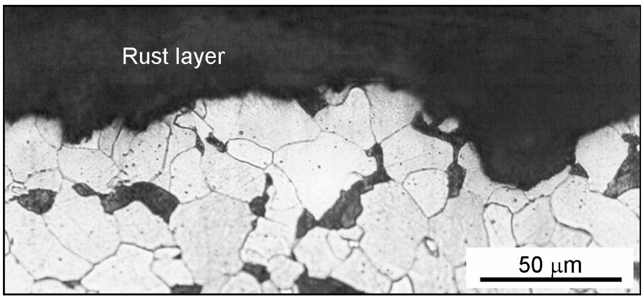

Fig. 9. Material strcuture below the rust layer. No corrosion cracks are present in the surface layer

The structure of the surface layer of the exposed material as observed on metallographically prepared section perpendicular to the surface is shown in Fig. 9. Below the rust layer the ferritic-pearlitic structure can be seen. The structure consists of uniform polyhedral grains. There are no corrosion cracks there or visibly deteriorated grain boundaries, which can serve as fatigue crack starters.

4. DISCUSSION

It is obvious that the lifetime of exposed material is substantially lower than that of the base material both for stress symmetrical cycling and pulsating cycling in tension. The fatigue limit defined on 10^7 cycles for loading with the stress ratio $R = -1$ is 240 MPa for the base material and 140 MPa for material after 20 yearlong weather exposition. The ratio of fatigue limits is 1.71. The fatigue limits for pulsating loading in tension ($R = 0$) are 190 MPa for the base material and 120 MPa for material after exposition. The ratio of fatigue limits is slightly lower than that for the case of symmetrical cycling, namely 1.58.

The qualitative explanation of the deterioration of fatigue properties due to corrosion, which can be found in literature, is based either on the influence of corrosion cracks developing in material and thus facilitating the fatigue crack initiation or on the decrease of fatigue limit due to the development of surface roughening. In the case studied no corrosion cracks were observed in material below the surface rust layer. The cracks observed in the rust layer did not penetrate into the base material. This discharges the effect of corrosion cracks or cracks which appear in the corrosion layer as starters of fatigue cracks, i. e. the damage mechanism reported in [6]. This finding, however, is related to the particular environment in which the material under examination was exposed. The basic information on corrosion conditions in the Czech Republic based on measurements, which has been performed since the eighties of the last century, can be found e. g. in [7].

The decrease of fatigue strength of weathering steels in relation to the time of exposure has been determined experimentally in papers [3 – 5] on specimens exposed to atmospheric corrosion. Results of this work, obtained on material detracted from parts of transmission towers used for a long time in Bohemia confirm the strong negative influence of exposition on fatigue performance of weathering Atmofix 52A steel.

It is well known tat the quality of surface influences the fatigue strength. That is why the experimentally observed decrease of fatigue life with the time of exposure is possible to correlate with increasing roughness [4, 5] expressed in terms of maximum height of the profile or arithmetic mean deviation R_a. However, as far as to the author's knowledge, no attempt to predict quantitatively the influence of surface roughness on the decrease of fatigue limit of corroded weathering steels was made up to now.

The fact that the corrosion dimples are sites of the crack initiation indicates that their stress concentration factor should be responsible for the observed decrease of the fatigue strength. The fractographic observation of failed specimens reveals the largest dimples, which initiated fatigue cracks resulting in final fatigue failure. This enables, provided the dimensions of a dimple are known, to evaluate its fatigue notch factor K_f, characterizing the decrease of fatigue limit due to presence of a notch. The fatigue notch factor is defined as the ratio of the fatigue limit of a smooth specimen to the fatigue limit of a notched specimen.

Fig. 10 shows the dimple on material surface, which resulted in crack initiation and finally fatigue failure. To evaluate the dimple dimensions a sphere was fitted to the dimple. Is diameter, as can be seen, is in this particular case equal to 970 µm. The depth of the dimple below the surrounding surface is 210 µm, again according to Fig. 10.

The stress concentration effect of a notch can be simply calculated by means of finite element method. The result of the numerical determination of the stress distribution around the dimple with the above-evaluated dimensions on the specimen gauge length loaded by uniaxial tension is shown in Fig. 11. The calculation, yields the elastic stress concentration factor $K_t = 1.63$.

The knowledge of the theoretical stress concentration factor K_t and the notch size enables to predict the fatigue notch factor K_f.

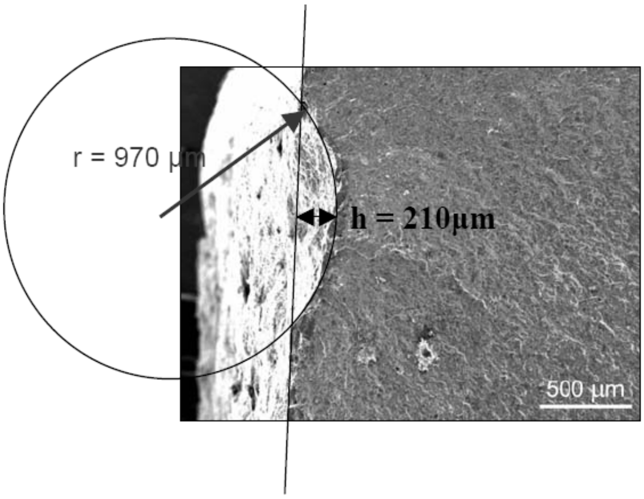

Fig. 10. Approximation of a dimple by a sphere for calculation of elastic stress concentration factors

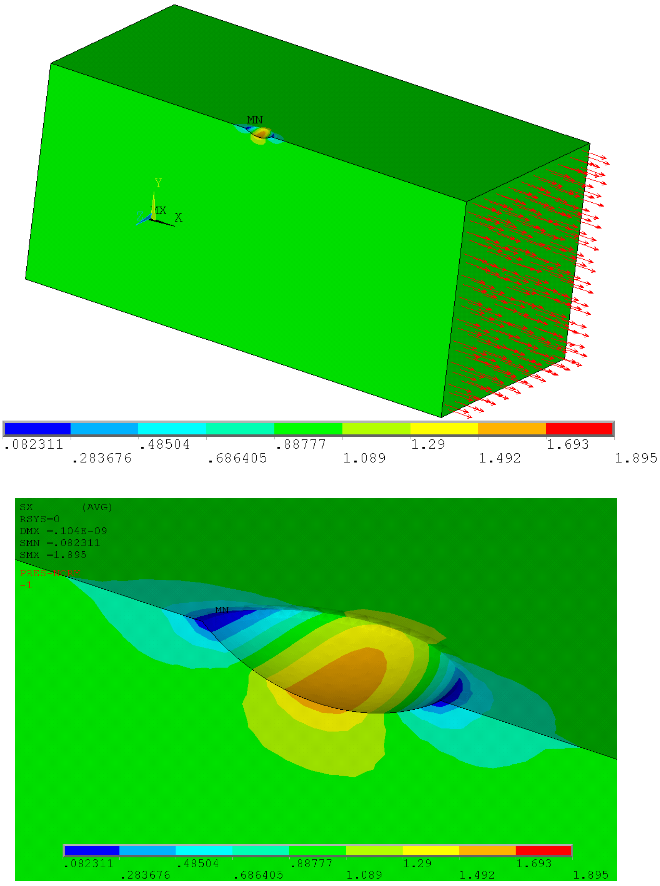

Fig. 11. MKP calculation of the distribution of the σ_{xx} stress component in the vicinity of the corrosion dimple located in the specimen gauge length loaded in uniaxial tension

The relation between the theoretical stress concentration factor K_f and the fatigue notch factor K_t is given by the equation $q = (K_f - 1)/(K_t - 1)$, where q is the fatigue notch sensitivity [8]. Strictly speaking, the equation holds only for stress symmetrical cycling.

The notch sensitivity q is generally a function of a notch geometry and depends also on material. A few hypotheses for the explanation of the dependence of q on notch geometry have been proposed. For the purpose of this work an approximation based on a large number of experimental results on notch sensitivity of mild steels published in [9] can be used. The diagram, valid for symmetrical cycling, (Fig. 8 in [9]) yields for the notch having the radius $r = 970$ μm the value of $q = 0.8$. Than under the assumption that the decrease of fatigue limit of exposed material is given by the notch effect of the corrosion dimple with $K_t = 1.63$, the fatigue notch factor for symmetrical loading is $K_f = 1.5$. This value is in reasonable agreement with the experimentally determined value 1.71 for symmetrical loading. In other words, the simple fatigue notch theory can reasonable quantitatively predict the decrease of fatigue limit due to presence of corrosion dimples.

Similar prediction for pulsating cycling in tension cannot be done, simply because there are no available experimental or theoretical data on the notch sensitivity for cycling with the tensile mean stress.

5. CONCLUSIONS

Twenty years long atmospheric corrosion causes significant decrease of fatigue strength of Atmofix 52A steel. The fatigue limit under stress symmetrical loading is 240 MPa for base material and 140 MPa for material after corrosion exposition. For fatigue loading in pulsating tension the corresponding values are 190 MPa for base material and 120 MPa material with corrosion layer.

Fatigue cracks initiate at corrosion dimples. No cracks starting in the rust layer and continuing into the base material were observed.

No corrosion cracks in the surface layer of material below the rust layer were observed.

The decrease of fatigue limit due to corrosion was quantitatively predicted for symmetrical cycling on the basis of the fatigue notch factor, which was calculated from the dimensions of the corrosion dimple, which initiated the fatigue fracture. A good correlation with experiment was found.

Acknowledgments

This work was supported by the project FT/TA5/076, Ministry of Industry and Trade of the Czech Republic. This support is gratefully acknowledged.

REFERENCES

1. **Seeger, T., Degenkolbe, J., Olivier, R.** Admissible Stresses for the Fatigue Design of Weathering Structural Steels after Six Years' Exposure *Stahl Eisen* 11 (11) 1991: pp. 101 – 110 (in German).
2. **Albrecht, P., Lenwari, A.** Fatigue Strength of Weathered A588 Steel Seams *Journal of Bridge Engineering* 14 (6) 2009: pp. 436 – 443. http://dx.doi.org/10.1061/(ASCE)1084-0702(2009)14:6(436)
3. **Kocich, J., Ševčíková, J., Bartoš, J.** Changes of Fatigue Strength of Atmofix Steel in Process of Atmospheric Corrosion *In: Proc. of the Conference Únava materiálů a konstrukcí* ÚZVÚ Škoda, Plzeň 1984: pp. 64 – 71 (in Slovak).
4. **Kocich, J., Ševčíková, J., Tuleja, S.** Effect of Atmospheric Corrosion on the Mechanical Properties of the Weathering Steel Atmofix 52A *Corrosion Science* 35 (1 – 4) 1993: pp. 719 – 725.
5. **Ševčíková, J., Kocich, J.** Fatigue Limit Decrease Caused by Atmospheric Corrosion in the Weathering Steel 15 127 *Materials Engineering* (*Materiálové inžinierstvo*) 6 1999: pp. 39 – 44 (in Slovak).
6. **Pošvářová, M., Matocha, K.:** Rizika chování patinujících ocelí použitých na mostních konstrukcích *Silnice železnice* 4 (4) 2009 (in Czech).
7. **Kreislová, K., Knotková, D., Koukalová, A., Křivý, V., Rozlívka, L., Podjuklová, J., Laník, T.** Corrosion Behaviour of Weathering Steels in the Czech Republic *In: Proc. of the 2nd Int. Conf. Corrosion and Metal Protection* CD ISBN 978-80-903933-6-3, SVÚOM Praha, 2010.
8. **Klesnil, M., Lukáš, P.** Fatigue of Metallic Materials. Elsevier/Academia, Prague, 1992: 220 p.
9. **Pilkey, W. D.** Peterson's Stress Concentration Factors. Second Edition. J. Willey & Sons Inc., New York, 1997. http://dx.doi.org/10.1002/9780470172674

Presented at the 20th International Baltic Conference "Materials Engineering 2011"
(*Kaunas, Lithuania, October 27–28, 2011*)