Characterization of Low Cycle Fatigue Parameters of Rotor Steel using Sub-sized Specimens

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Abstract. The paper is dealing with strain controlled cyclic testing method employing a novel strain-control technique based on digital image correlation (DIC) in low-cycle fatigue (LCF) region. The cyclic behaviour of 22CrMoNiWV 8-8 rotor steel was investigated on sub-sized round specimens with a diameter of 2 mm in gage length and total length of 20 mm. These results were compared with results obtained using conventional specimens designed in accordance with the ASTM E606 standard. The attention was paid to confirm the suitability of the proposed sub-sized geometry, testing set up and procedure. The test procedure and results obtained enabled to record hysteresis loops, construct Manson-Coffin curves and obtain cyclic material properties in LCF region.

1 Introduction

There is still growing demand for cyclic properties of in service products. Many testing methods applied in this field are non-destructive (NDT) nature. But base on NDT results, which brings an advantage in some ways and disadvantages in others. The main issue is the accuracy in the mechanical properties evaluation which decreases with the increasing number of correlations and also there is a need for a large database of various materials. The problem becomes larger in case of cyclic loading and lifetime prediction. But there is no easy way to do that in case of low cycle fatigue test (LCF) where cyclic parameters are needed. To avoid using correlation relationships between two variables, the miniaturized testing technique using sub-sized specimens was developed [1] for the direct mechanical properties evaluation of LCF parameters. The idea was to use a size miniaturization geometry which is related to ASTM standard [2] and use the same loading conditions. That brings some simplification in evaluation processes and helps to extend the applicability of this method in case of acute shortage of experimental material. Very good results obtained with the sub-sized tensile specimens were confirmed in [3-6] and was already used for a number of applications like characterization of ECAP processes [7] or high strength chromium steel with hardness above 800 HV [8]. Furthermore, some studies were performed also with the use of small scale of LCF specimens [9-10]. But still here is an influence of failure probability caused by a presence of defects in material which depends on experimental volume of the material [11]. This factor is still an open question. A
non-contact extensometer was employed for the strain controlled cyclic deformation. The Digital Correlation System (DIC) Mercury RT [12] provides high measuring accuracy of measuring volumes from some square millimeters to square meters depending on the camera settings.

The aim of the present work was to analyze the impact of size effect on cyclic material properties in LCF region obtained employing conventional and sub-sized specimens.

2 Materials and Methods
The rotor steel 22CrMoNiWV 8-8 was used as the experimental material. Standard quasi-static tensile tests and strain controlled low cycle fatigue (LCF) tests were carried out to obtain its LCF parameters employing the conventional and the sub-sized specimen geometry. All test were conducted at room temperature.

2.1 Material description
As the experimental material, a disc of steel 22CrMoNiWV 8-8 has been taken under the investigation. The disc was made by cutting a 50 mm slice from a 605 mm diameter rod. The microstructure of the rotor steel is composed of tempered bainite with an average grain size of 70 µm measured by the mean linear intercept method in accordance with ASTM E112 standard. The microstructure of investigated steel is depicted in Figure 1 and chemical composition is summarized in Table 1.

![Microstructure of rotor steel 22CrMoNiWV 8-8, 100x.](image)

Figure 1. Microstructure of rotor steel 22CrMoNiWV 8-8, 100x.

| Table 1. Chemical composition by weight % of 22CrMoNiWV 8-8 steel. |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|
| C   | Si   | Mn   | Ni   | P     | S     | Cr    | Mo    |
| 0.23 | 0.038 | 0.67  | 0.68  | 0.004 | 0.001 | 2.07  | 0.85  |

2.2 Experimental methods
At the beginning of the experiment work, the differences in mechanical properties of the large steel disc were investigated by means of conventional tensile tests in accordance with European standard. The extraction of all tensile specimens was done from two sections close to the surface and the center of the disc in the tangential direction. Then, the conventional and sub-sized LCF specimens were extracted out in the same orientation as in the case of tensile tests. The sample preparation consists of three major steps in machining such as turning, longitudinal grinding and polishing in order to achieve
a specific surface roughness. The strain-controlled LCF tests were conducted on conventional and sub-sized specimens. Based on LCF results, cyclic parameters were obtained.

2.2.1 Tensile tests. Round test bars with initial gage length of 50 mm and gage diameter of 10 mm were prepared. Tests were conducted on electro-mechanical testing system Zwick Roell with a load capacity of 250 kN. Samples were pulled at a constant strain rate of 0.0004 s\(^{-1}\). The tests were performed according to ČSN EN ISO 6892: Metallic materials – Tensile testing – Part 1: Method of test at room temperature. A longitudinal deformation of a loaded specimen was measured by means of mechanical extensometer with initial gauge length of 25 mm. Dimensions of the samples were measured prior to testing and after the test for determination of stress and plastic behavior quantities determination (Young’s modulus - E, Proof stress - YS, Ultimate Tensile Strength - UTS, Elongation – A and Cross Section Reduction - CSR).

2.2.2 Strain-controlled LCF tests. Tests were conducted under variable strain controlled loading conditions with the cyclic asymmetry coefficient \(R = -1\) and the sinusoidal shape. The aim was to cover the total strain amplitudes from until 1.5% if possible. The lowest strain level is given by the number of cycles which specimen not survived before reaching the maximum count of 100 000 cycles. As the reference values, the conventional specimen 8 mm in diameter was used in accordance with ASTM standard E606. The specimen geometry is illustrated in Figure 2.

The sub-size specimen was designed to meet some recommendations from above mentioned standard as much as possible. The attention was also paid to design the reduced section which would fit in case of on-site sampling where the extracted sample has dimensions 4x20x20 mm. The draft of the sub-sized specimen geometry with 2 mm diameter is depicted in Figure 3.

In case of the sub-sized specimen, the initial gage length \(L1\) of the optical extensometer was set to 3 mm. Prior to testing, the speckle pattern was sprayed on specimen surface in order to ensure deformation measurements using 2D version of DIC system, see Figure 4.

Further evaluation was done based on Basquin’s law (1) where stress amplitude \(\sigma_a\) depends on number of cycles to failure \(N_f\) and fatigue strength exponent \(b\) and fatigue strength coefficient \(\sigma_f^*\).
\[ \sigma_a = \sigma_f^{'}(2N_f)^b \]  

Mansson-Coffin relation in plastic deformation \( \varepsilon_{ap} \) is described by equation (2) where \( \varepsilon_f^{'} \) is coefficient of ductility in fatigue and \( c \) is ductility exponent.

\[ \varepsilon_{ap} = \varepsilon_f^{'}(2N_f)^c \]  

The total amplitude of the deformation \( \varepsilon_{at} \) can be expressed as

\[ \varepsilon_{at} = \frac{\sigma}{E} \cdot (2N_f)^b + \varepsilon_f^{'} \cdot (2N_f)^c \]  

where \( \bar{E} \) is the Young modulus of elasticity. The elastic modulus was determined from two unloading parts of a saturated hysteresis loop in both tension \( E_t \) and compression \( E_c \) sides. \( E_t \) and \( E_c \) were determined in accordance with ČSN ISO 12106 [13]. Young modulus was used in order to refine the determination of the plastic deformation when the total strain is decomposed into elastic and plastic components. The cyclic deformation curve can be estimated based on equation (4) where \( K \) is cyclic hardening coefficient and \( n \) is cyclic hardening exponent.

\[ \sigma_a = K' \cdot \varepsilon_{ap}^{n'} \]  

The material cyclic properties were estimated in accordance with geometrical meaning of formula (1), (2) and (4). The parameters were determined based on power law regression analyses of variables in a fully-logarithmic scale. Moreover the transition life \( N_r \) is calculated based on relationship (5).

\[ N_r = \left( \frac{\sigma_f^{'}E}{\varepsilon_f^{'}(2N_f)} \right)^{\frac{1}{c-b}} \]  

3 Results and Discussion

Tensile test results did not show a differences in tensile properties over the large steel bar cross section area. The values in Table 2 are represented by mean and standard deviation \( \sigma_{SD} \) of three repetitions.

|        | E   | \( \sigma_{SD} \) | YS  | \( \sigma_{SD} \) | UTS | \( \sigma_{SD} \) | A   | \( \sigma_{SD} \) | CSR | \( \sigma_{SD} \) |
|--------|-----|-------------------|-----|-------------------|-----|-------------------|-----|-------------------|-----|-------------------|
| Surface| 209.3 | 1.3 | 679.0 | 2.9 | 785.2 | 0.8 | 20.7 | 0.1 | 70.5 | 0.1 |
| Center | 210.3 | 0.8 | 676.7 | 3.1 | 782.0 | 0.7 | 20.9 | 0.1 | 70.5 | 0.1 |

The evaluation of \( \bar{E} \) was done on saturated hysteresis loops depicted in Figure 5. Each strain level corresponds to one loop of each specimen type. In this picture, 7 points can be seen which are represented by total strain amplitudes \( \varepsilon_{at} \) in percentage 0.25, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.5. Relationships among variables have been found and the material cyclic properties of conventional and sub-sized specimens were estimated based on formula (1), (2), (3), (4) and (5). For both specimen geometries the results are shown in Table 3.

|        | \( \varepsilon_f^{'} \) | b | \( \varepsilon_f^{'} \) | c | \( K' \) | n' | \( N_r \) |
|--------|-----------------|---|-----------------|---|--------|----|--------|
| D2     | 196.2 | -0.0419 | 1.13 | -0.7324 | 767.5 | 0.0541 | 1764 |
| D8     | 193.1 | -0.0437 | 0.90 | -0.7146 | 711.9 | 0.0584 | 1525 |
Using Manson-Coffin-Basquin equation (4), the fatigue life behaviour was estimated and the fully-logarithmic plot of the strain amplitude versus the number of cycles to failure was done in Figure 6.

4 Conclusion
It was shown that the tensile properties of experimental material are homogeneous despite of large diameter of steel disk, see tensile test results in Table 2. Based on these results, the negligible impact of the sampling location on LCF test results can be noted. For decomposition of total strain the \( \bar{E} \) modulus was used (3) due to the fact that its value is decreasing along with the rising total strain amplitude. \( \bar{E} \) was determined from loading and unloading part of a saturated hysteresis loops, Figure 5, where the range for this data set is from 185 to 208 GPa. Loops obtained using both specimen types look very similar throughout the measured strain range. The average modulus of conventional (\( \bar{E} = 193.1 \) GPa) and sub-sized (\( \bar{E} = 196.2 \) GPa) specimens was found. Slight differences can be observed between both results in MC curves, Figure 6, and cyclic material properties, Table 3. The differences in these properties are not significant but they are observable in elastic region (\( E \) 1.5%; \( \sigma' \) 1.3%; b...
In plastic region the differences are greater ($\varepsilon'$ 25.0%; $c$ 2.5%; $K'$ 7.8%; $n'$ 7.3%). The shift in transition life $N_T$ (5) is 15.6%. Increasing disparities between both obtained results appearing at higher total strains above $\varepsilon_\text{aw}$ 1% which may be associated with different buckling response of both test setups and specimen geometries to increasing applied stress.

The possibility of using the sub-sized specimens to obtain cyclic material properties by LCF tests was presented in this paper. The results obtained with sub-sized specimens appear to be sufficient for material description in fatigue life behavior equal to conventional ones without any correlation. The results of cyclic material properties once more confirmed that the sub-sized geometries are comparable to the conventional ones in LCF region.

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