Strain controlled cyclic tests on miniaturized specimens

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Abstract. The paper is dealing with strain controlled cyclic tests using a non-contact strain measurement based on digital image correlation techniques on proportional sizes of conventional specimens. The cyclic behaviour of 34CrNiMo6 high-strength steel was investigated on miniaturized round specimens with diameter of 2mm that were compared with specimens in accordance with ASTM E606 standards. The cycle asymmetry coefficient was R= -1. This application is intended to be used for life time assessment of in service components in future work which enables to carried out a group of mechanical tests from a limited amount of the experimental material. The attention was paid to confirm the suitability of the proposed size miniaturization geometry, testing set up and procedure. The test results obtained enabled to construct Manson-Coffin curves and assess fatigue parameters. The purpose of this study is to present differences between cyclic curves and cyclic parameters which have been evaluated based on conventional and miniaturized specimens.

1   Introduction

The current demands for cyclic properties of in service products are leading to use of a non-destructive techniques (NDT) or semi-destructive methods. The methods applied should not have any negative influence on its lifetime and can be used for a wide range of products. Base on NDT results, some relationships between mechanical properties and NDT properties can be found. That 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 bigger in case of cyclic loading and lifetime prediction. In case of time dependent fatigue, there are many methods how to estimate the fatigue strength based on Charpy impact energy, hardness test or tensile properties. But there is no easy way to do that in case of low cycle fatigue test where cyclic parameters are needed.

To avoid using correlation relationships between two variables, the miniaturized testing technique was developed for the direct determination of mechanical properties. The idea was to use a size miniaturization geometry which is related to ASTM standard [1] 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.

Using latest technologies, the role of scale factor plays less important rule in evaluation processes until the ultimate tensile strength (UTS) point [2] where the grain size [3], surface condition, residual stress and strain rate effect were considered. Very good results obtained with the miniaturized tensile specimens were confirmed in in [4-8]. The weak influence of the scale factor is

very promising in field of cycling loading where the normal stress does not exceed UTS, but on the other hand, the influence of probability of large specimens containing all-sized defects is still an open question.

To ensure that the surface conditions remain the same, in order to avoid surface scratches from the knife edges of an extensometer, a non-contact extensometer was employed for the strain controlled cyclic deformation. The Digital Correlation System (DIC) Mercury RT [9, 10] provides high measuring accuracy of measuring volumes from some square milimeters to square meters depending on the camera lens.

The aim of the study is to make the comparison between conventional and sub-sized specimens geometry for the future work dealing with the testing from in-service components using on-site sampling.

2   Materials and Methods

The experimental material was 34CrNiMo6 high-strength steel. Quasi-static tensile tests and strain controlled low cycle fatigue (LCF) tests were investigated here.

2.1   Material description

As the semi-product, the 34CrNiMo6 forged steel round bar with diameter of 95mm was used. The delivered condition of the steel was improved further through the quenching and tempering at 600°C to get optimum mechanical properties which are widely used in industry, see the tempering diagram in figure 1. After hardening a tempered fine-grained martensite was obtained. The chemical composition of the steel is summarized in table 1.
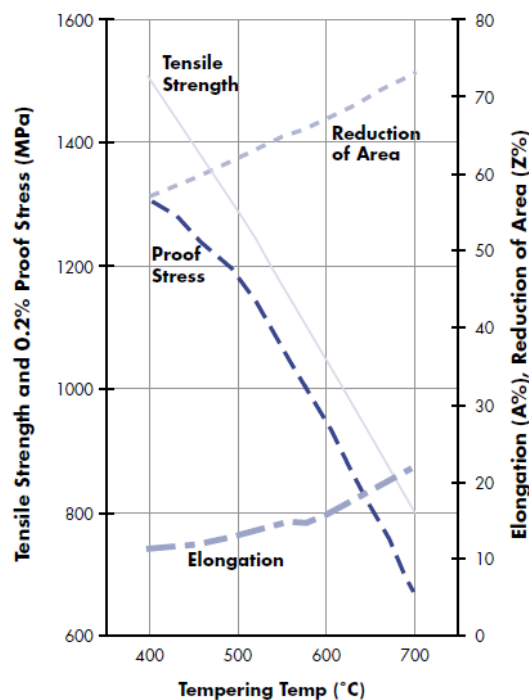

Figure 1. Tempering diagram [11].

Table 1. Chemical composition % of 34CrNiMo6 steel

C	Si	*Mn*	Ni	*P*	S	*Cr*	*Mo*
0.36	0.22	0.75	1.67	0.01	0.01	1.55	0.25

2.1   Methods

Firstly, the investigation of material homogeneity was carried out by means of tensile tests where the samples were extracted from the surface and middle section of the steel bar. Most crucial part was to obtain the Young modulus of elasticity for further evaluation of cyclic parameters. Secondly, the strain-controlled LCF testing was conducted on conventional and sub-sized specimens. Based on tensile and LCF results, Manson-Coffin curves were constructed and cyclic parameters were obtained. All tests were carried out at room temperature.

2.1.1   Tensile tests. Round test bars with the reduced gage section (8mm) were prepared in the longitudinal direction. Tests were conducted on electro-mechanical testing system Zwick Roell with a load capacity of 250kN. Samples were pulled at a constant strain rate of 0.0004s-1. The tests were performed according to ČSN EN ISO 6892-1 (close to ASTM E 8 – 01): 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 25mm. 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).

2.1.2   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 0.35 to 2%. As the reference values, the conventional specimens 8mm in diameter was used in accordance with ASTM standards. The specimen geometry is illustrated in figure 2.
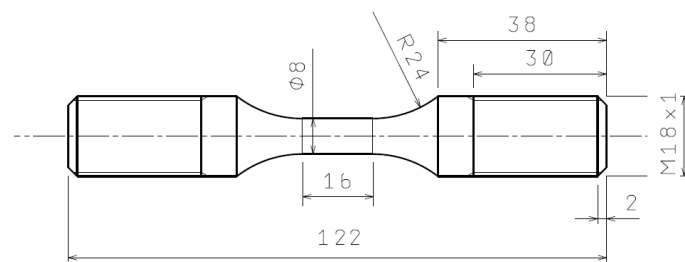

Figure 2. Conventional specimen geometry in accordance with ASTM standard E606, D8.

The sub-size specimen was designed to meet some recommendations from ASTM standard E606 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 dimesions 4x20x40 mm. The draft of the sub-sized specimen geometry with 2mm diameter is depicted in figure 3. Because there is no acute shortage of experimental material in the current case, the larger geometry was used in experiment and its dimensions are depicted in figure 4.
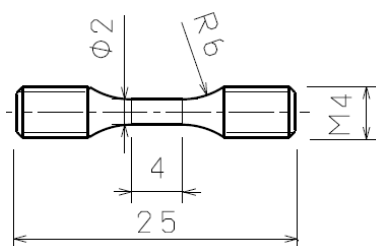

Figure 3. The draft of sub-size specimen geometry.
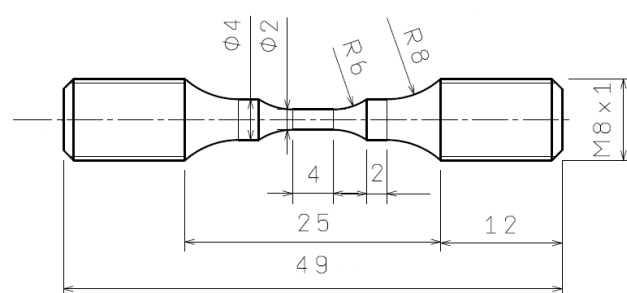

Figure 4. Sub-size specimen 2mm in diameter, D2.

In case of the sub-sized specimen, the initial gauge length of the optical extensometer was set to 3mm. The test setup as well as the detail of the specimen surfece are illustrated in figure5 and figure 6.
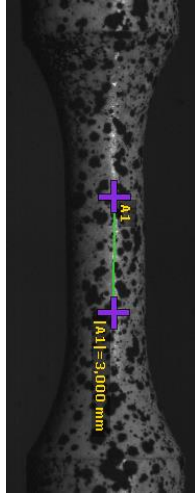

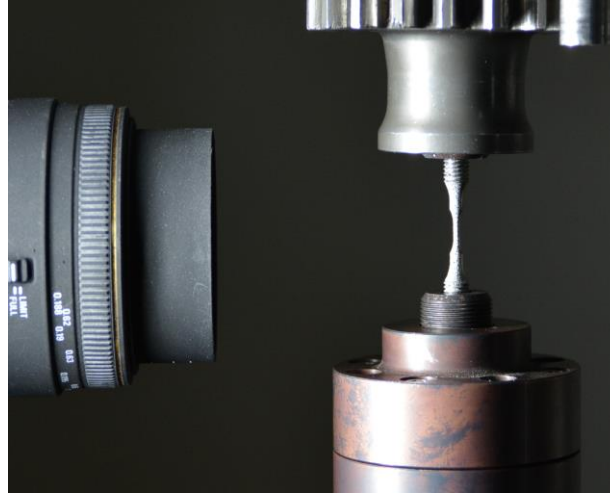**Figure 5.** Initial gauge length of optical system.

Figure 6. The test setup of sub-size specimens includs servo-hydraulic testing machine and one CCD camera.

Further evaluation was done based on Basquin's law (1) where stress amplitude σ_a depends on number of cycles to failure N_f and fatigue strength exponent b and fatigue strength coefficient σ_f'.

$$\sigma_a = \sigma_f'\left(2N_f\right)^b \tag{1}$$

Mansson-Coffin relation in plastic deformation ε_{ap} is described by equation (2) where ε'_f is coefficient of ductility in fatigue and c is ductility exponent.

$$\varepsilon_{ap} = \varepsilon_f'\left(2N_f\right)^c \tag{2}$$

The total amplitude of the deforamtion ε_{at} can be expressed as

$$\varepsilon_{at} = \frac{\sigma'}{E} \cdot \left(2N_f\right)^b + \varepsilon' \cdot \left(2N_f\right)^c \tag{3}$$

where Young modulus E is needed. The cyclic deformation curve can be estimated based on equation (4) where K' is cyclic hardennig coefficient and n' is cyclic hardenning exponent.

$$\sigma_a = K' \cdot \varepsilon_{ap}^{n'} \tag{4}$$

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.

3   Results and Discussion

Tensile test results show slight differences in tensile properties over the steel bar cross section area. The Young modulus that is required for further evaluation of low cycle fatigue tests was found to be 205GPa.

Table 2. Tensile test results of 34CrNiMo6 steel

	E	YS	UTS	A	CSR
	GPa	MPa	MPa	%	%
Surface	204.5	916.4	1040.3	18.6	64.2
Middle	205.0	892.9	1010.5	18.3	63.9

Relationships among variables have been found and the material cyclic properties of conventional and sub-size specimens were estimated based on formula (1), (2) and (3). For both specimen geometries the results are shown in table 3.

Table 3. Cyclic material properties of 34CrNiMo6 steel

	σ'_f Mpa	b -	ε'_f -	c -	K' MPa	n' -
D2	1175.6	-0.0683	0.42	-0.6481	1277,0	1.0409
D8	1049.3	-0.0491	0.46	-0.6368	1079.9	0.0716

The comparision of the cyclic bahaviour was done using cyclic stress-strain curves (CSSC) where the single regression through all points have been made in figure 7. As can be seen in figure 8, no significant differences can be observed.
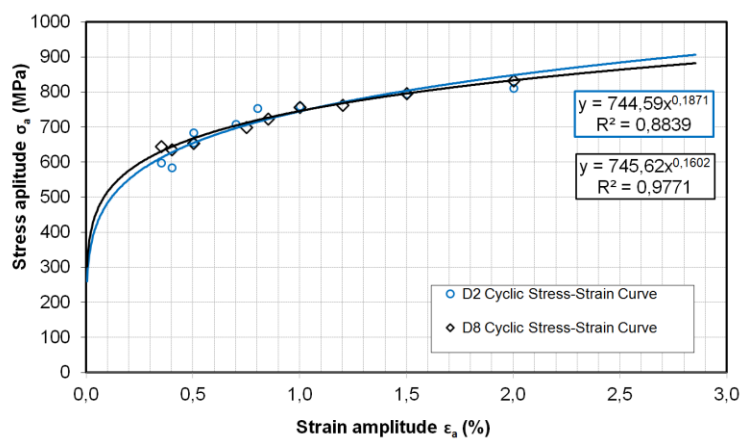

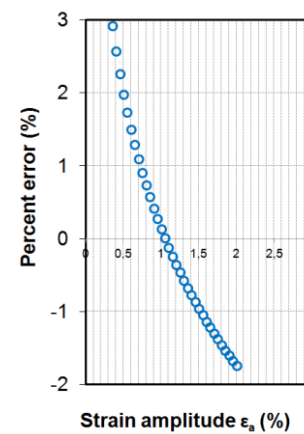**Figure 7.** Cyclic stress-strain curves.

Figure 8. Percent error of CSSC.

Using Manson-Coffin-Basquin equation (3), 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 9.
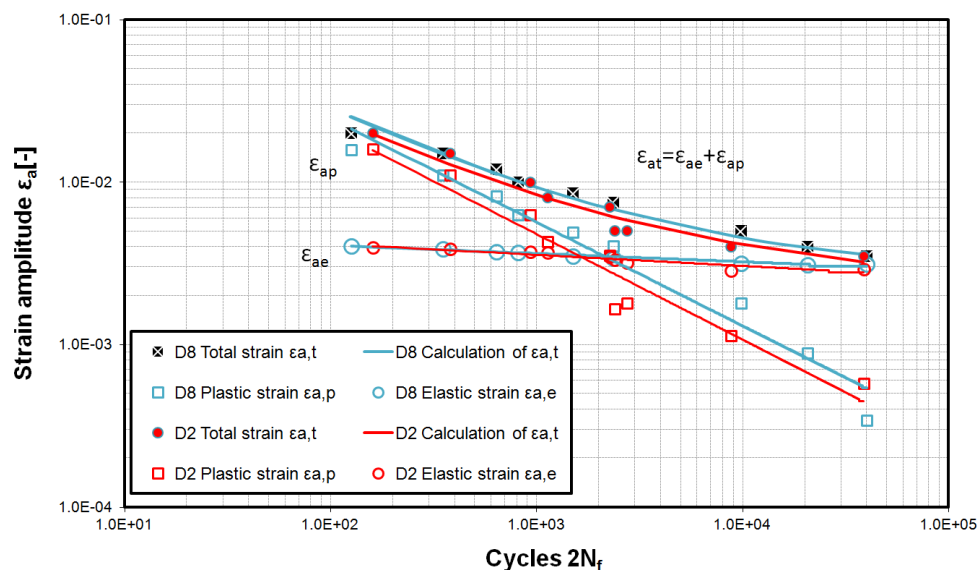

Figure 9. Manson-Coffin curves.

It should be noted that the differencies in cyclic behaviour, figure 8 and 9, may be caused by buckling at highest strain amplitudes and by surface condition effects which play an important role at high number of cycles to failure.

4   Conclusions

The possibility of using sub-size specimens to obtain cyclic material properties by LCF tests was presented in this paper. The results obtained with small sized specimens provide conservative results on the safe side in fatigue life behaviour estimation without any correlation. The results of cyclic material properties and CSSC obtained confirmed that the sub-size geometries are compareble to the conventional ones and representative results can be obtained even with small sized specimen geometries . In the future work, the material data obtained here will be used as an input for durability software analyses for finite element methods investigations.

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