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LOW CYCLE FATIGUE OF STEEL IN STRAIN CONTROLED CYCLIC BENDING

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Abstract: The paper presents a comparison of the fatigue life curves based on test of 15Mo3 steel under cyclic, pendulum bending and tension-compression. These studies were analyzed in terms of a large and small number of cycles where strain amplitude is dependent on the fatigue life. It has been shown that commonly used Manson-Coffin-Basquin model cannot be used for tests under cyclic bending due to the impossibility of separating elastic and plastic strains. For this purpose, some well-known models of Langer and Kandil and one new model of authors, where strain amplitude is dependent on the number of cycles, were proposed. Comparing the results of bending with tension-compression it was shown that for smaller strain amplitudes the fatigue life for both test methods were similar, for higher strain amplitudes fatigue life for bending tests was greater than for tension-compression.

Key words: Lifetime, Strain Control, Bending, Push-Pull, Tension-Compression

1. INTRODUCTION

Most often fatigue tests for a range of low number of cycles (Low Cycle Fatigue) are performed at a controlled strain (Walat et al., 2015) and the high range of cycles (High Cycle Fatigue) tests are characterized by a study in strength-controlled environment (Karolczuk et al., 2015). Such tests are carried out for tension-compression and torsion of thin specimens. However, in the case of bending or torsion of full specimens, as is the case of many experimental studies, the torque causing bending or torsion is controlled and therefore the tests are conducted in terms of large number of cycles (Achtelik et al., 1996). In the literature to describe the fatigue test results for tension-compression both stress and strain models are used (Niesłony et al., 2012; Zhao et al., 2007; Shul'ginov 2008, Lee, Song, 2006). However there is a significant amount of fatigue tests for bending, often pendulum rather than rotary. It turns out that for bending, due to the stress (strain) gradient, those two types of models are not equal. There aren't many studies comparing stress and strain fatigue curves (models). For stress curves some comparison might be found in (Manson and Muralidharan, 1987; Troschenko, 1996, Megahed 1990). While in (Krzyżak et al., 2014) authors prove that changes in bending plane has an effect on fatigue strength relative to the constant surface bending (pendulum bending). Results from these comparisons show that on the level of fatigue limit the loading method does not affect fatigue life. However for higher stress levels fatigue strength obtained from bending tests is higher than corresponding push-pull results. There is no comparison of this kind for strain curves.

Therefore, the present study compares the fatigue life curves of 15Mo3 steel obtained from new test stand capable of conducting pendulum bending with controlled strain amplitude with push-pull results. The results for push-pull tests were taken from the literature (Boller and Seeger, 1987).

2. STRAIN-LIFE CURVES

The most well-known equation allowing to describe fatigue properties from strain-controlled tests is proposed by Manson-Coffin-Basquin (MCB) for the strain-life curve ($\varepsilon_a - N_f$):

$$\varepsilon_{at} = \varepsilon_{ap} + \varepsilon_{ae} = \varepsilon' f\left(2N_f\right)^c + \frac{\sigma'_f}{E}\left(2N_f\right)^b, \tag{1}$$

where: E – Young's modulus; ε'_f, c – coefficient and exponent of the plastic strain, respectively; σ'_f, b – coefficient and exponent of the fatigue strength, respectively.

This model (1) can only be used when it is possible to distinguish elastic ε_{ae} and plastic ε_{ap} parts of the strain amplitude ε_{at} (Niesłony et al., 2008, Basan et al., 2011).

Then for cyclic loadings we get:

$$\varepsilon_{ae} = \frac{\sigma_a}{E} \tag{2}$$

and

$$\varepsilon_{ap} = \varepsilon_{at} - \varepsilon_{ae}. \tag{3}$$

The relation between stress and strain amplitude is described with Ramberg-Osgood equation:

$$\varepsilon_{at} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'}. \tag{4}$$

where: K' – coefficient of cyclic strength; n' – exponent of cyclic hardening.

However we often face the problem with distinguishing elastic and plastic parts of strain amplitude. This problem occurs for example when the stress amplitude σa is greater than twice yield strength of the material 2R'e (Marcisz et al., 2012)

$$\varepsilon_{at} = \varepsilon_{ap} + \varepsilon_{ae} + \varepsilon_{ane} = \varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} + \left(\frac{\sigma_a}{K''}\right)^{1/n''}, \tag{5}$$

where: ε_{ane} – unelastic strain amplitude.

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Another problem is shown in (Radhakrishnan, 1992), where authors prove that the importance of plastic deformation amplitude in the expression (1) depends on fatigue life, therefore c is not a constant value.

Furthermore different authors have proposed different empiric models subordinating total strain amplitude on the number of cycles.

Langer's (1962) proposal can be one of the examples. It is commonly used in many studies and is prompted by Manson (1965, 1979) and Chopra (1999)

$$logN_f = A - B\,log(\varepsilon_{at} - C), \tag{6}$$

where: A, B, C – material constants.

Another model was proposed by Kandil (2000) and Gorash and Chen (2013):

$$log\varepsilon_{at} = A - B\,log(N_f) + C\,log^2(N_f), \tag{7}$$

where: A, B, C – material constants.

As in the case of cyclic bending tests where there is no possibility to distinguish elastic and plastic parts of total strain amplitude the MCB model (1) cannot be used. However both (6) and (7) or any other empirical form of strain-life model can be used. It can be for example combination of (6) and (7):

$$log(\varepsilon_{at} - D) = A - B\,log(N_f) + C\,log^2(N_f), \tag{8}$$

where: A, B, C, D – material constants.

Very rich overview of fatigue life models can be found among others in (Kurek et al., 2015).

The newly proposed form of the strain-life curve model (8) requires the calculation of four material constants as well as the popular MCB model (1).

3. EXPERIMENT

In this paper we will present new test stand for fatigue tests under bending and capable of experimental studies with controlled strain in the range of a small number of cycles (LCF). Operation of the machine was verified on the basis of experimental tests on specimens made of steel commonly used in the power industry – 15Mo3 (16Mo3, 1.5415) (Boller and Seeger, 1987). Finally the strain controlled experimental data for tension-compression and pendulum bending was compared.

The Manson-Coffin-Basquin curve (1) for tension-compression on the basis of results from three different tests collected in (Boller and Seeger, 1987) can be written as:

$$\varepsilon_{at} = 0.229(2N_f)^{-0.470} + \frac{766.5}{210000}(2N_f)^{-0.094}, \tag{9}$$

and Ramberg-Osgood curve (4) as:

$$\varepsilon_{at} = \frac{\sigma_a}{210000} + \left(\frac{\sigma_a}{1035}\right)^{1/0,202}. \tag{10}$$

Our studies were performed on the newly constructed machine, as shown in Fig. 1.

The idea behind this machine is that using the screw on the eccentric we can set the deflection of machine arm acting on the specimen, that deflection is set as constant and controlled by the micrometer. This way we obtain a constant strain amplitude on specimen. One of those specimens after experiment is shown in Fig. 2.

Additionally, during the test, bending torque is monitored. At the time, when this torque drops significantly, the initiation of fatigue crack occurs but further tests allow us to obtain total fatigue life of the tested specimen.

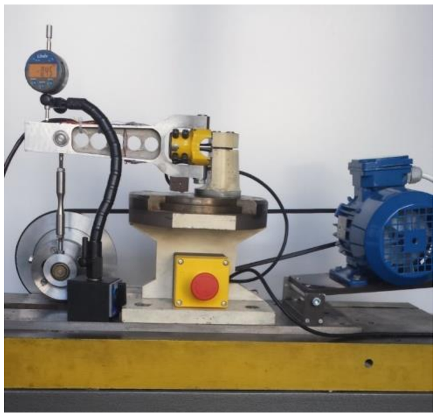

Fig. 1. Strain controlled stand for bending loading

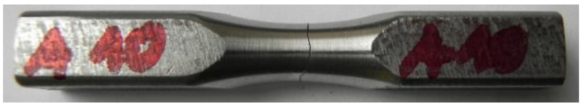

Fig. 2. Specimen with fracture after bending loading

The study determined the fatigue life both to the initiation point and total fatigue life. At the fatigue crack initiation point there is a sharp drop of the bending moment acting on specimen which correlate with the appearance of visible cracks on a specimen of a size of less than 1 mm.

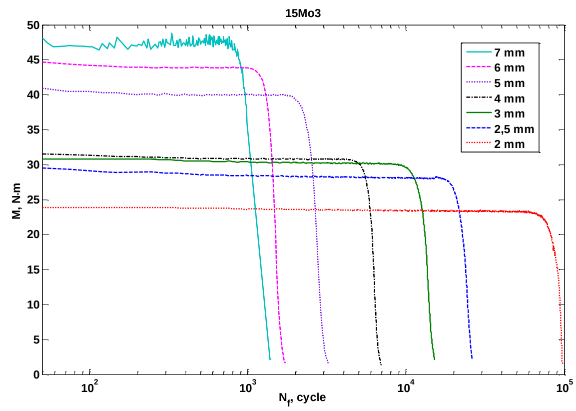

Fig. 3. Change of the moments causing bending as a function of number of cycles at a constant strain amplitudes

In the Fig. 3 change of the moment depending on time at fixed arm deflection amplitudes, which means a constant strain, was presented. The graph shows that the material slightly weakens cyclically. From the analysis of moment changes it can be seen that for larger deflection amplitudes we obtain larger amplitudes of bending moment and consequently lower fatigue durability.

This quantity of cycles is adopted as an initiation of a fatigue crack. In the Fig. 4 strain amplitudes as a function of number of cycles leading to initiation for material 15Mo3 were established. The data come from literature for tension-compression and own research for oscillatory bending as a function of number of cycles for initial bending and total lifetime.

Cross-section of the specimen after fatigue tests under pendulum bending is shown in Fig. 5. The photograph clearly shows

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a neutral plane of bending and the symmetry of the fatigue crack process.

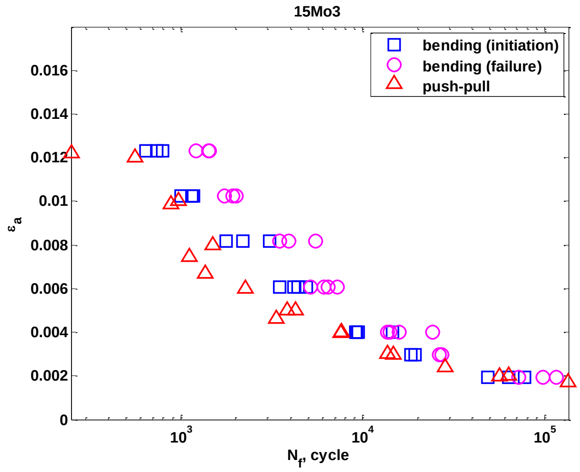

Fig. 4. Experimental strain amplitudes as a function of number of cycles

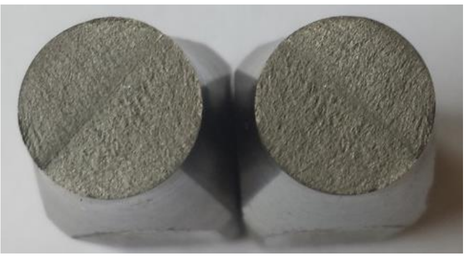

Fig. 5. Cross-section of the specimen after fatigue tests under pendulum bending

4. COMPARISON OF FATIGUE LIFE CURVES

Fig. 6 shows the fatigue strain-life curves for pendulum bending and tension-compression according to the Kandil proposal (7) and Fig. 7 as proposed by Langer (6). In addition the calculation of the model proposed by the authors (8) is shown in Fig. 8.

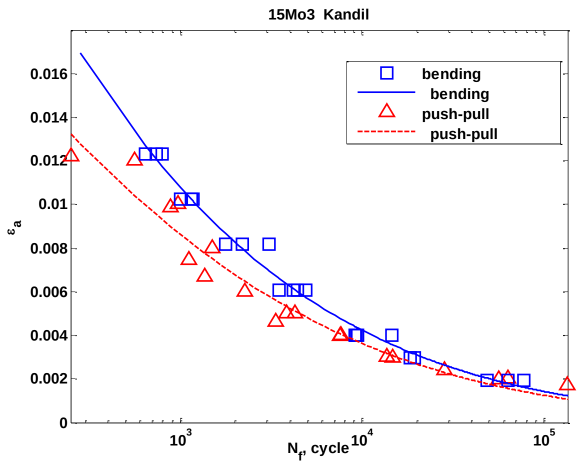

Fig. 6. Strain-life curves according to Kandil's model for both push-pull and bending tests

Then, for all analyzed curves the correlation parameter R-squared was determined both for tension-compression (Tab. 1) and bending (Tab. 2). From the analysis of data it should be noted that relatively similar statistical parameters were obtained for the analyzed models. By analyzing the shapes of fatigue curves it can be seen that for Langer's proposal for higher strain amplitudes both curves for bending and push-pull tests are very close. The two other models lack this flaw. What is more, author's proposal (8) is shaped like a letter 'S' which is sometimes advised for stress-life models (Kurek et al., 2015).

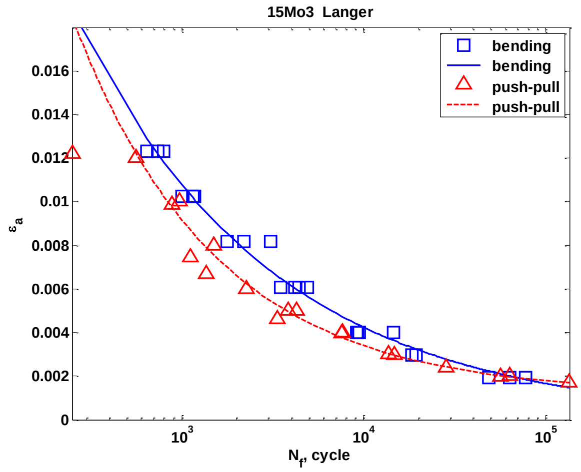

Fig. 7. Strain-life curves according to Langer's model for both push-pull and bending tests

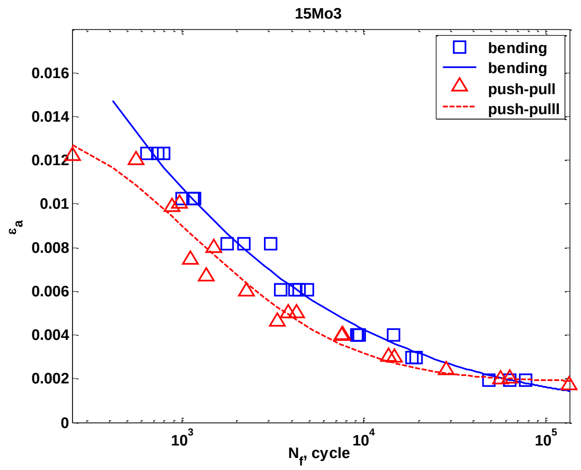

Fig. 8. Strain-life curves according to Author's model

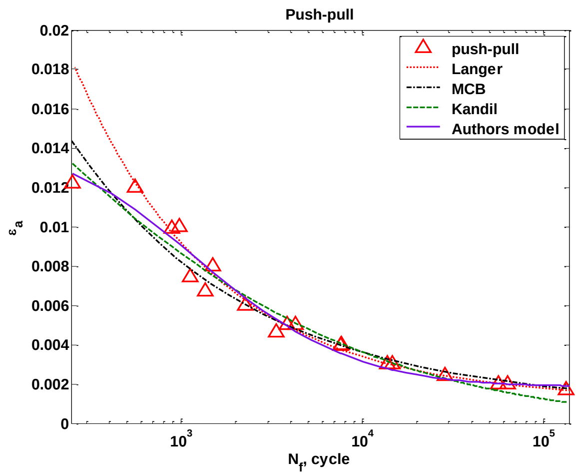

Fig. 9. Strain-life curves for push-pull tests

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In addition, Fig. 9 and 10 summarize the characteristics appropriate for tension-compression and pendulum bending to compare the curve shapes obtained for different states of the load. In the case of tension-compression most popular Manson-Coffin-Basquin (1) curve was added to the comparison.

Tab. 1. Push-pull

Model	R^2
Kandil	0.9488
Langer	0.9438
Authors	0.9676

Tab. 2. Bending

Model	R^2
Kandil	0.9857
Langer	0.9843
Authors	0.9854

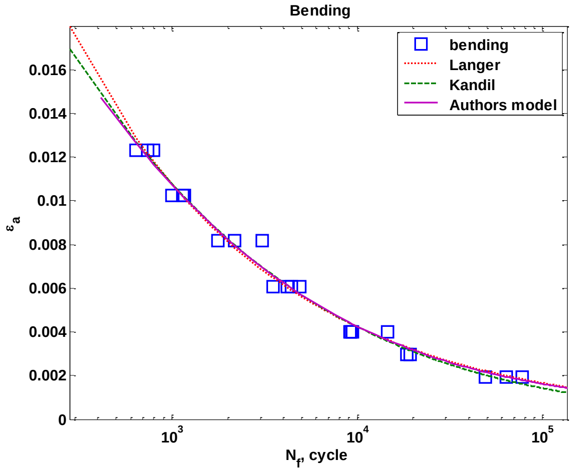

Fig. 10. Strain-life curves for bending tests

5. CONCLUSIONS

1. The newly designed and built test stand is capable of experimental studies with controlled strain for bending in the range of a small number of cycles (LCF).
2. Preliminary experimental studies of pendulum bending, with controlled strain amplitude, have shown that fatigue life for bending is close to tension-compression tests for small loading and lager for high strain.
3. Further verification of the correlation between the bending fatigue curves for other materials is necessary.
4. In the future strain-controlled test for pure torsion and combination of bending and torsion should be performed.

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