Strain controlled fatigue of 40X steel

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Abstract: The fatigue strength of 40X steel at 25 °C was determined following ASTM E606M standard for strain-controlled tests. The studied experimental dependence was modelled with a power function as well as with the functions and coefficients described in the standard. The material expresses plastic properties for cyclic loadings above 0.2% strain amplitude.

Keywords*: 40X ALLOY, FATIGUE, ASTM E606-M*

1. Introduction

We have a new hydraulic testing machine designed for both static and cyclic (dynamic) testing of materials at different temperatures. Below are shown results from fatigue tests of cylindrical specimens of 40X steel, performed according to ASTM E606M standard [1], i.e. with strain-controlled cycles. The 40X steel is a structural alloy steel used in heavy-duty components like shafts, springs and gears [2].

1.1 Short literature survey

Vakulenko et al. studied effect of the quality of the surface layer on the fatigue characteristics, [3]. They published data for fatigue tests of normalized 40X steel, obtained under fatigue cycles with an asymmetry factor of 0.3. The published data ranges from 7500 cycles of life at 600 MPa maximal stress to 500 million cycles at 400 MPa maximal stress. They have found that surface treatment of the samples increases their longevity on average by 3–5 times for loading amplitudes up to 530 MPa and more for higher amplitudes.

Shetulov et al. show fatigue data for 40X steel in the range 200 MPA – 650 MPa, [4]. They analyze the dependence of the fatigue curve on the test frequency, as the cycles to failure increase with increase the frequency.

Loktev et al. also analyze the influence of high frequency (20 kHz) on fatigue properties of 40X steel [5]. They obtained yield strain of 604 MPa and 924 MPa strength.

C.M. Sonsino holds the view that physically a knee point does not exist, as the Woehler-curves change their slope fluently in the transition range (from finite to high-cycle fatigue strength). The knee point is solely a parameter for strength estimations [6]. In this paper, he reviews strength and fatigue properties and gives recommendations for fatigue life design of different materials.

Chapter [7] describes most of the theory taught to the students. We met there the ideas for damages, cracks, fracture of specimens, fatigue, notches etc.

Most articles about materials fatigue talk about Woehler curves and the dependency of the number of cycles to failure on the stress amplitude and shape. However, in [7, p. 677] and in the standard ASTM E606M, an alternative – strain-based approach is explained for fatigue life determination.

Significant dispersion of results for Woehler curves can be seen in many articles. However, However, B. Boardman in ASM Handbook [7] shows a few diagrams from a strain-controlled approach to determine cycles to failure that have low dispersion.

1.2 Purpose

The aim was to master the work with the new machine in fatigue tests according to the ASTM E606M standard and to study the fatigue destruction of 40X steel.

2. Material and specimens

The specimens from 40X steel are cylindrical with 8.0 mm test diameter, 30 mm cylindrical test section, 130 mm long, 10 mm gripping diameter and 16 mm transition radius. The working diameter has to have *Rz* = 6.3 µm roughness. These specimens were used for both static test and cyclic tests.

With their gauge length of 25.0 mm, these test pieces are non-proportional.

Published properties usually refer to quenched state. However, material for the specimens is in its delivery state, not quenched.

3. Testing equipment

Fig. 1 *Testing machine Zwick-Roell HA-250.*

The hydraulic machine was equipped with a 250 kN load cell and 100 kN hydraulic grips. The strain was measured with a strain gauge Sandner EXA 25-2.5o with a 25 mm base length.

The testing machine is equipped with threaded holders designed for fatigue tests. However, the present data were obtained using the mentioned specimens designed for the hydraulic grips.

The hardware and software realizing machine control, measurement of monitored parameters and data registration are advanced and sophisticated.

4. Experimental plan

Determination of the tensile strength properties using 3 specimens and test procedure described in standard ISO 6892 – part 1.

Determination the number of cycles to failure for alternating sinusoidal cycle with strain amplitudes in the following order: 0.18%, 0.20%, 0.22%, 0.25%, 0.30%, 0.35%, 0.40%, 0.50% and 0.60%. The middle strain is zero.

We think that all tests should be done with equal maximal accelerations of the moving machine parts. For an oscillating system, acceleration is proportional to the strain amplitude and on the square of frequency:

$$\varepsilon_a \nu^2 = const. \tag{1}$$

For the used fixtures, this *const.* = 70 %Hz^2. This means that the cyclic frequencies were set between 20 Hz and 11 Hz for the planned strain amplitudes.

Two series were tested with mentioned maximal strains. For the first one, we have set the machine to stop cycles when the maximal force begins to decline due to the development of a big crack. For the second series, we set the machine to stop the test when the specimen breaks and the force becomes zero.

All tests were carried out in a temperature chamber at 25 °C.

5. Results and discussion

5.1 Tensile test properties

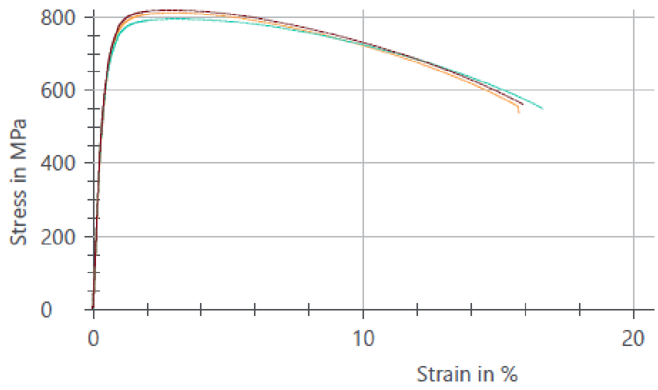

Fig. 2 *Stress-strain diagram of 40X steel in tension, T = 25 °C.*

From the **static tensile test**, made by standard ISO 6892-1, were obtained 195 ± 5 GPa elastic modulus, 649 ± 11 MPa proof stress at 0.2% plastic deformation, 809 ± 12 MPa ultimate strength, (15.8 ± 0.5)% elongation at break and (51 ± 2)% reduction of area in the neck.

Pay attention that these deformations were obtained using an extensometer with 25 mm gauge length and non-proportional specimens.

5.2 Results from cyclic tests

Tests were conducted following standard ASTM E606M, i.e., strain-controlled fatigue tests. We set the cycling frequency, a strain amplitude, the mean strain is zero, and the machine follows these instructions and records the stress for each cycle until the specimen breaks.

The following data is processed on Excel. Figure 3 shows the stress amplitude recorded for cyclic loading with 0.4% alternating strain. Authors usually divide similar diagrams into III stages. In this case, the first and second stages contain 8170 cycles. The III-rd stage contains only 280 cycles, or 3.3 % of the time to break completely. In the test with 0.3% alternating strain, the III-rd stage is 5.5% from total cycles to complete break.

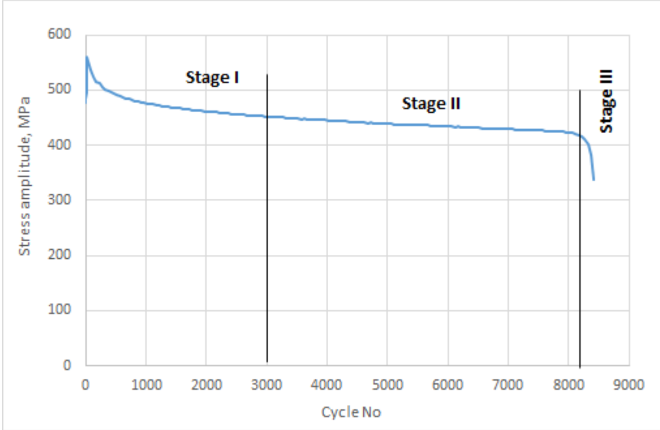

Fig. 3 Recorded stress amplitude at ± 0.4% strain amplitude cyclic loading.

We accept the end of the second stage as a failure criteria. The resulting diagram is shown in Fig. 4.

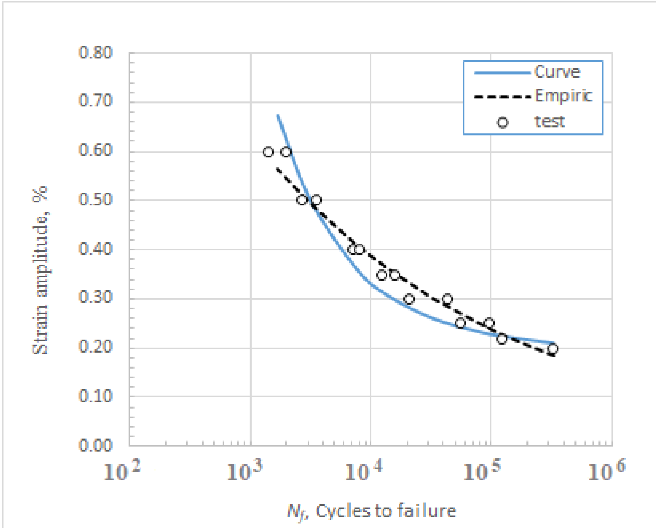

Fig. 4 Number of cycles to failure according to the strain amplitude.

There is one specimen tested at 0.18% strain amplitude. It endured 500 000 cycles, and the test was stopped without fracture.

5.3 Mathematical interpretation

The standard ASTM E606M describes a mathematical apparatus for interpreting such tests. Main equations and definitions [1, Appendix X1]:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \frac{\Delta\varepsilon_p}{2} \tag{2}$$

Where $\Delta\varepsilon$ is total axial strain for a cycle loop and $\Delta\varepsilon/2$ is strain amplitude, $\Delta\sigma/2$ is stress amplitude and $\Delta\varepsilon_p$ is plastic strain for the whole cycle.

Recognizing that

$$\frac{\Delta\sigma}{2} = K'\left(\frac{\Delta\varepsilon_p}{2}\right)^{n'} \tag{3}$$

we may express the cyclic stress-strain curve by the following equation:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \tag{4}$$

Equations for Fatigue-Life relationships:

$$\frac{\Delta\sigma}{2} = \sigma_f^{'}(2N_f)^b \quad (5)$$

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'}(2N_f)^c \quad (6)$$

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \quad (7)$$

Where N_f are cycles to failure and $2N_f$ is the number of reversals. These constants have the following names:

$n^{'}$ = cyclic strain hardening exponent,

b = fatigue strength exponent,

c = fatigue ductility exponent,

$K^{'}$ = cyclic strength coefficient,

$\sigma_f^{'}$ = fatigue strength coefficient,

$\varepsilon_f^{'}$ = fatigue ductility coefficient,

E = Young's modulus.

5.4 Discussion

The software calculates for each cycle the plastic strain using Eq. (8), which follows from Eq. (2):

$$\Delta\varepsilon_p = \Delta\varepsilon - \frac{\Delta\sigma}{E} \quad (8)$$

The check showed that software calculates elastic modulus for each cycle and presents the plastic strain in millimetres. For the test shown in Fig. 3, the obtained modulus at the end of II-nd stage is 165 GPa, and the development of the plastic deformation, expressed in %, is shown in Fig. 5.

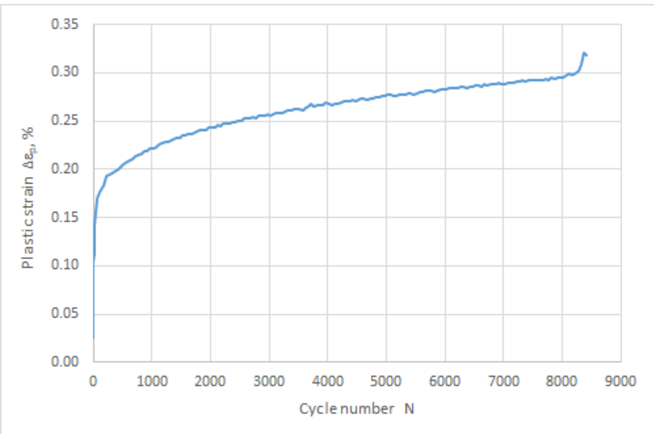

Fig. 5 Development of plastic strain for a test with 0.4% strain amplitude.

The typical three stages of fast growing, steady growing and catastrophic failure are well visible in Figs. 3 and 5. For each test there are no definite (constant) amplitudes of the stress and the plastic strain, representative for use in Eqs. (5) and (6).

We decided to use the values of stress and plastic strain *at the end of the II-nd stage*, as representative values for use in Eqs. (5), (6) and (7).

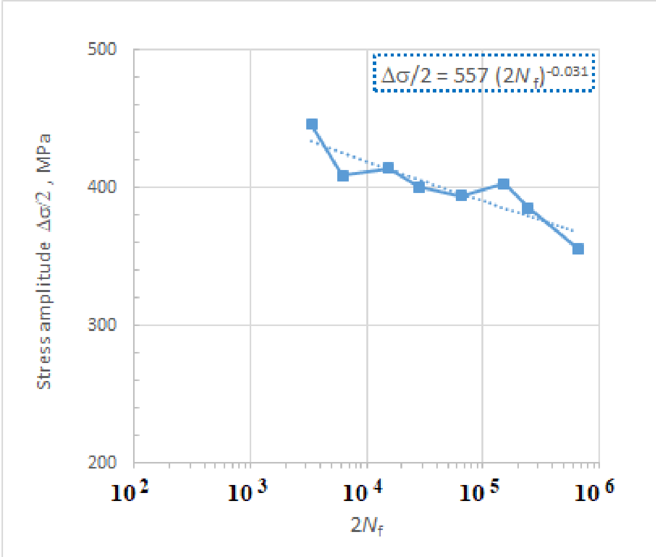

Fig. 6 Stress amplitude at the time of failure expressed with eq. (5) up to 0.33 million cycles

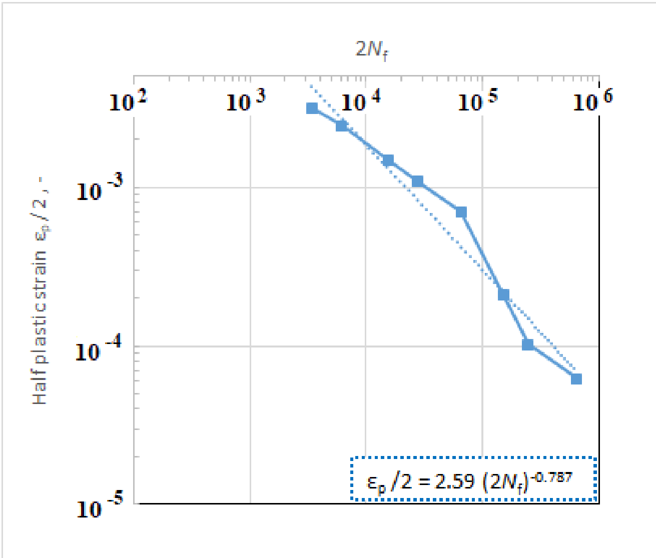

Fig. 7 Half of the plastic deformation at the time of failure expressed with eq. (6)

From Figs. (6) and (7) is visible that Eqs. (5) and (6) do not fit very well the whole diagrams. Probably, we should use one set of constants for $N_f \leq 10^5$ cycles and another for bigger fatigue lives.

Finally, Eq. (7) fits this experimental data best when the equation is used with E = 181 GPa. The relationship of *strain amplitude on cycles to failure* calculated with Eq. (7) and the mentioned coefficients ($\sigma_f^{'}$ = 557 MPa, b = -0.031, $\varepsilon_f^{'}$ = 2.59, c = -0.787, and E = 181 GPa) is shown in Fig. 4 as "Curve".

The mentioned curve does not looks well despite the complicated model with 5 constants. The power function (9) fits better this experimental data (up to 0.33 mil. cycles) and its graph is shown in Fig. 4 as "Empiric".

$$\frac{\Delta\varepsilon}{2} = 2.75\, N_f^{-0.213} \quad [\%]\ (9)$$

6. Conclusion

The proof stress $R_{p0.2}$ = 649 ± 11 MPa was obtained from tensile tests.

The fatigue strength of 40X steel was determined following ASTM E606M standard for strain-controlled fatigue tests.

The studied experimental dependence, Fig. 4, was modelled with a power function - Eq. (9), as well as with equation (7), according to the dependences and coefficients described in the standard.

At 0.2% strain amplitude, the stress amplitude is 355 MPa and it almost does not change till the brittle fracture after 0.33 million cycles. For higher cyclic loads the plastic strain grows, like in Fig. 5, and the stress amplitude relaxes, similar to shown in Fig. 3.

Assuming that Eq. (7) and determined coefficients are correct enough, we can predict strain amplitude of 0.183% and endurance limit σ_{-1}= 332 MPa for 10^7 cycles to failure and 50% survival.

7. Acknowledgments

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8. References

1. ASTM E606/606M-12 Standard Test Method for Strain-Controlled Fatigue Testing.
2. Characteristics of 40X-brand steel, https://metinvestholding.com/en/products/steel-grades/40x
3. K. Vakulenko, I. Kazak, V. Matsevityi. Effect of the state of surface layer on 40x steel fatigue characteristics. East. Eur. J. of Enterpr. Techn., **35 (81)**, pp. 18–24 (2016) https://doi.org/10.15587/1729-4061.2016.69644
4. D.I. Shetulov, V.V Mylnikov, O.B. Kondrashkin, A.I. Pronin, E.A. Chernyshov. Application of Interpolation Functions in the Express Evaluation of Parameters of Fatigue Resistance. Int. J. of Appl. and Fund. Res. **№ 3** (2017) URL: www.science-sd.com/471-25288
5. A.A. Loktev, V.V. Korolev, E.A. Gridasova. IOP Conf. Series: *Materials Science and Engineering* **687** (2019) 022036. IOP Publishing doi:10.1088/1757-899X/687/2/022036
6. C.M. Sonsino. Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety. Int. J. of Fatigue. **Volume 29, Issue 12**, December pp. 2246-2258, (2007)
7. B. Boardman. Fatigue Resistance of Steels. Chapter in ASM Handbook, Volume 1: *Properties and Selection: Irons, Steels, and High-Performance Alloys*. ASM International. pp. 673 – 688. (1990)