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Fatigue tests of materials with the controlled energy parameter amplitude

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Abstract

The paper presents a procedure of the determination of the fatigue energy characteristic diagram by using a controlled strain energy parameter which can be an alternative to the well-known stress and strain fatigue curves description of structural materials. The work contains the results of fatigue tests carried out in accordance with the procedure shown in the paper. Obtained test results were presented on diagrams and critically discussed.

Keywords: strain energy density parameter, fatigue life, stress, strain

1. Introduction

In order to estimate the fatigue lifetime of machine elements and structures, fatigue characteristic quantified through proper criteria, such as the stress - based criterion requiring σ_a - N_f (S -N) curve, the strain -based criterion of Manson-Coffin, etc. are necessary. An alternative to the classical approach above mentioned is represented by energy models proposed by Lachowicz (2001), Smith et al. (1970), Glinka et al. (1995), Gołoś (1988), Macha E. and Sonsino M. (1999). Rozumek D. et al, (2010), aimed at estimating the fatigue lifetime by combining both stress- and strain

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based approaches an energy curve can be expressed as:

$$W_a = \frac{\sigma_f'^2}{E}(2N_f)^{2b} + \sigma_f' \varepsilon_f' (2N_f)^{b+c}. \tag{1}$$

that is a relation obtained indirectly from multiplication Manson- Coffin-Basquin curve. Moreover, in some energy criteria, the evaluation of the dissipated plastic energy is performed by using the Ramberg-Osgood law, whose parameters n’ and K’ have to be estimated from half of life when hysteresis stress-strain loops are stabilized. Such a plastic energy can be evaluated through the expressions:

$$\Delta W_p = \frac{2(1-n')}{1+n'}(2K')^{-\frac{1}{n'}}(\Delta\sigma_{eq})^{\frac{(1+n')}{n'}}, \tag{2}$$

$$\Delta W_p = \frac{1-n'}{1+n'}\Delta\sigma\Delta\varepsilon_p. \tag{3}$$

Nevertheless, as demonstrated Mrozinski (2008 and 2012) in his research, these parameters change during the lifetime; this observation entails that a wrong lifetime assessment can be obtained by using constant parameters throughout the fatigue process, especially for a group of cyclically unstable materials. Thus, there is the need to determine the energy fatigue characteristic directly from experimental outcomes.

Tests conducted by controlling the energy parameter are difficult to perform, due to a lack of proper control system of strength machines (Marcisz et al., 2014; Macha, 2009). It should be noted that during tests of materials with the controlled energy parameter in the LCF range, the relationship between stresses and strains changes significantly, particularly in cyclically unstable materials. Therefore, tests with controlled strain or controlled force do not fully characterize fatigue properties of such materials.

The aim of this research is to present the procedure of determining the energy fatigue characteristics of structural materials using the strain energy parameter.

Nomenclature

E	Young’s modulus
M_a	amplitude of bending moment
N_f	number of cycles to failure
t	time
W	strain energy parameter
W_a	amplitude of energy parameter
ν	Poisson’s ratio
σ_a	amplitude of nominal stress
σ	stress
σ_u	ultimate tensile stress
σ_y	yield stress
$\Delta\varepsilon_p$	plastic strain range
ε'_f	fatigue ductility coefficient
ε	strain
b	fatigue strength exponent
c	fatigue ductility exponent
n'	cyclic strain hardening exponent
K'	cyclic strength coefficient

2. Description of the energy parameter

The energy parameter model, W(t) (Kasprzyczak et al. ,2013) is expressed by half product of the stress value, σ(t), and the absolute value of the difference of strains, calculated by subtracting from the current strain, ε(t), the plastic strain, ε_i^{pl}, registered at the time instant t_i, when the stress, $\sigma(t_i)$, reaches zero and remains constant until the time instant, t_{i+1}, when the stress again is equal to zero, $\sigma(t_{i+1}) = 0$. Then, the new registered value of plastic strain, ε_{i+1}^{pl} replaces the previous one, ε_i^{pl}. During calculations of the strain energy parameter history, W(t), the constant value of plastic strain, ε_i^{pl}, is replaced by the subsequent values of plastic strain, ε_{i+n}^{pl}, defined in the moments, t_{i+n}, when the stress, $\sigma(t_{i+n})$ becomes zero, where n = 1, 2, 3 , ... The history of the strain energy parameter is calculated by using the following equation:

$$W(t) = 0,5\sigma(t)\cdot\left|\varepsilon(t) - \varepsilon_i^{pl}\right|, \tag{4}$$

where $\varepsilon_i^{pl} = \varepsilon(t_i)$, while $\sigma(t_i) = 0$.

The procedure for determining the strain energy parameter (the points corresponding to the various steps of the calculation are shown in Fig. 1):

- Step 1. Point 0 is a starting point where particular values of stress, strain and energy parameter are equal: $\sigma(t_0) = 0$, $\varepsilon(t_0) = 0$, $\varepsilon_0^{pl} = 0$, thus $W(t_0) = 0$.
- Step 2. Point A: $\sigma(t_A) = \sigma_A$, $\varepsilon(t_A) = \varepsilon_A$, $\varepsilon_A^{pl} = \varepsilon_0^{pl} = 0$, $W(t_A) = \frac{1}{2}\,\sigma_A\left|\varepsilon_A - \varepsilon_0^{pl}\right| = \frac{1}{2}\sigma_A\varepsilon_A$.
- Step 3. Point B: $\sigma(t_B) = \sigma_B = 0$, $\varepsilon(t_B) = \varepsilon_B$, $\varepsilon_B^{pl} = \varepsilon_B^{pl}$, $W(t_B) = \frac{1}{2}\,\sigma_B\left|\varepsilon_B - \varepsilon_B^{pl}\right| = 0$.
- Step 4. Point C: $\sigma(t_C) = \sigma_C$, $\varepsilon(t_C) = \varepsilon_C$, $\varepsilon_C^{pl} = \varepsilon_B^{pl}$, $W(t_C) = \frac{1}{2}\,\sigma_C\left|\varepsilon_C - \varepsilon_B^{pl}\right|$.
- Step 5. Point D: $\sigma(t_D) = \sigma_D = 0$, $\varepsilon(t_D) = \varepsilon_D$, $\varepsilon_D^{pl} = \varepsilon_D^{pl}$, $W(t_D) = \frac{1}{2}\,\sigma_D\left|\varepsilon_D - \varepsilon_D^{pl}\right| = 0$.
- Step 6. Point E: $\sigma(t_E) = \sigma_E$, $\varepsilon(t_E) = \varepsilon_E$, $\varepsilon_E^{pl} = \varepsilon_D^{pl}$, $W(t_E) = \frac{1}{2}\,\sigma_E\left|\varepsilon_E - \varepsilon_D^{pl}\right|$, etc.

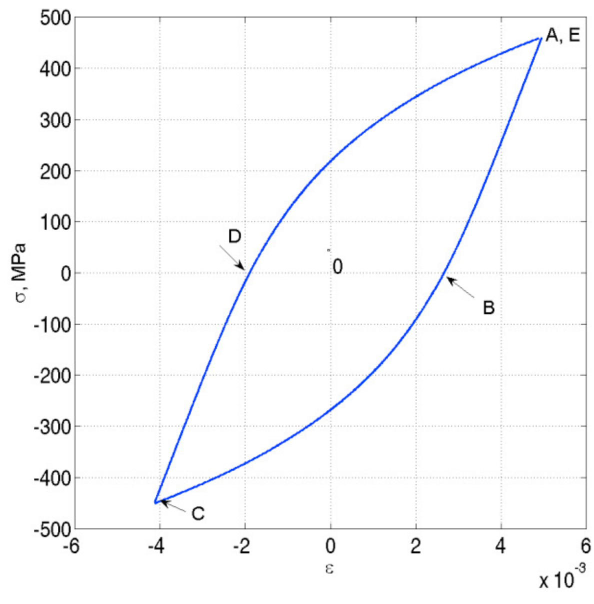

Fig. 1. Exemplary hysteresis loop with indicated the points used for energy parameter calculation

3. Experiments

In order to verify effectiveness of the above defined strain energy parameter, experimental tests have been performed in laboratory by using fatigue stand MZGS 100Ph equipped with an additional computer control system (Fig. 2). The purpose of the system is to maintain the desire value of the operating parameters during the test. The computer interface of control program is shown in Fig. 3. Before starting the tests mechanical properties of the material must be provided in field 2 as well as the desired value of the strain energy parameter amplitude. It is necessary also the introduction values of PID controller parameters 3, these parameters have a large impact on the

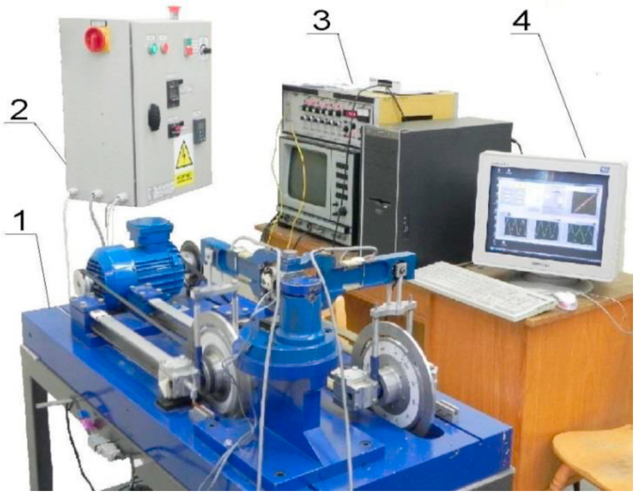

Fig. 2. Fatigue test stand: 1 – MZGS 100Ph , 2 – Control cabinet, 3- Strain bridge, 4- Computer with control system

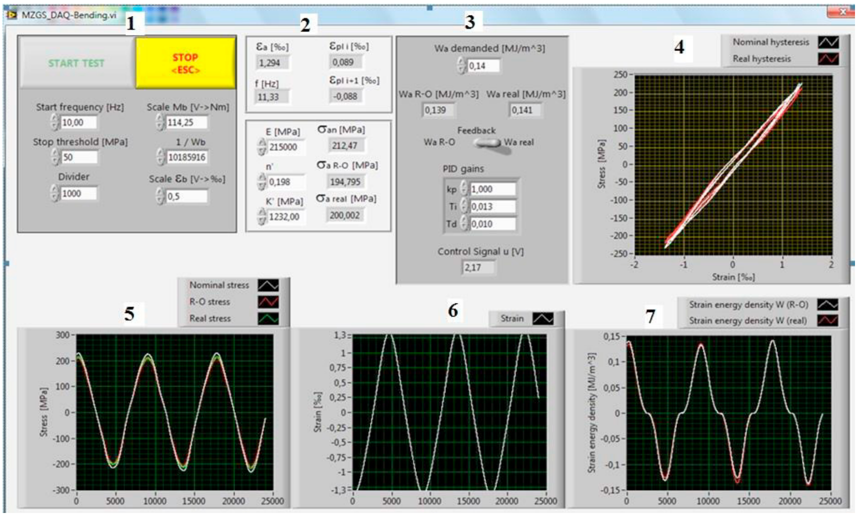

Fig. 3. Interface of the control program: 1 – Start/Stop buttons and configuring fields, 2 – material parameters and values of stress and strain measurements, 3 – field for introducing value of demanded strain energy density parameter amplitude and from feedback ones and PID controller parameters, 4 – graphs of hysteresis loops based on measurement data, 5, 6 and 7 – stress, strain and strain energy parameter history respectively

degree of stability of the operation of fatigue stand. During the tests strain values are taken from strain gauges placed on specimen and the load values are determined from strain gauges located on the bending lever. Both signals are

recorded and displayed in diagram 5 and 6 (Fig. 3). Then strain energy parameter is calculated according to relation (4) and displayed in graph 7 (Fig. 3). Additionally, in graph 4 are shown hysteresis loops.
Since in the MZGS 100Ph machine during service only the angular velocity can be controlled, therefore the control of the tests is carried out in accordance with the algorithm shown in Fig. 4.

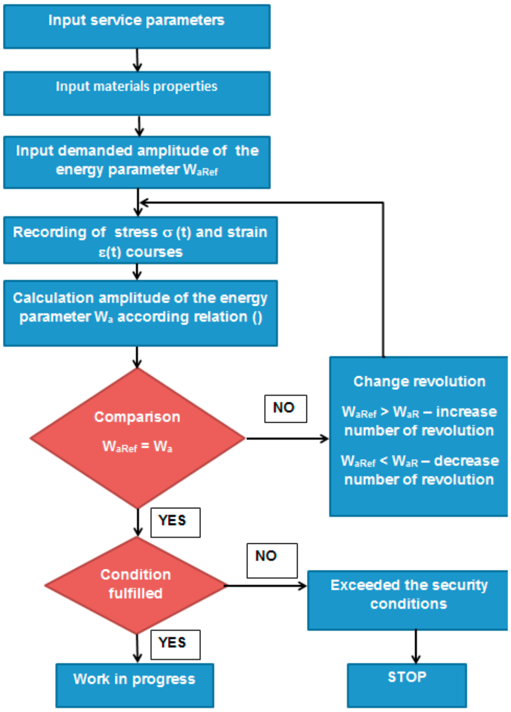

Fig. 4. Algorithm for conducting tests with the controlled strain energy amplitude parameter in the MZGS 100Ph fatigue stand

Fatigue tests performed on round solid cross-section specimens of 10 mm diameter made of C45 steel (Tab. 1) under 5 different levels of loading quantified through the energy parameter as: $W_a = 0.2, 0.27, 0.3, 0.4, 0.5$ MJ/m^3.

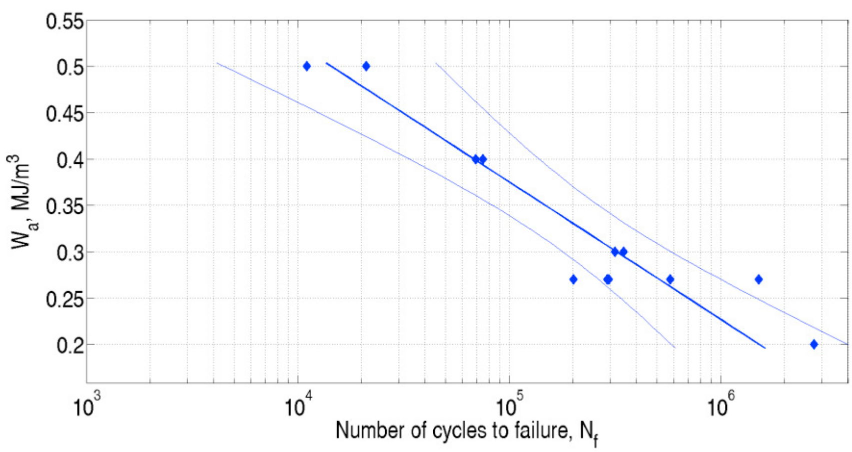

Fig. 5. The fatigue energy characteristic curve of C45 steel

Table 1. Mechanical properties of C45 steel.

σ_Y (MPa)	σ_U (MPa)	E (GPa)	ν	A_5 (%)
547	739	215	0.29	17.5

The obtained results allow determine the energy characteristic curve ($W_a - N_f$) of the material (Fig. 5). Regression coefficients were determined according to the ASTM Standard E 739-91. The correlation coefficient at the significance level $\alpha = 0.05$ is equal to 0.94.

$$\log N_f = A + m \cdot W_a, \quad (5)$$

where:
A = 7.53 and m = -6.75 are determined parameters of the regression equation.

The bold blue line represents the line described by Eq. (5), and two slim lines represent 95% confidence interval.

4. Conclusions

The paper presents the procedure for determining the strain energy curves for structural materials directly from experimental tests. This characteristic is essential in the fatigue life estimation algorithm especially for variable-amplitude or random loading. Various hypothesis related to the cumulative fatigue damage can be employed once the parameters A and m of the curve are known.

References

Lachowicz CT. Calculation of the elastic–plastic strain energy density under cyclic and random loading, Int. J. Fatigue 2001;23:643-652.

Smith K., Watson P., Topper T. A stress-strain function for the fatigue of metals. J. Materials, 1970;5:767-779.

Glinka G., Shen G., Plumtree A. A multiaxial fatigue strain energy density parameter related to the critical fracture plane. Fatigue and Fracture Engineering Materials and Structures, 1995;18:37-46.

Gołoś K. An energy based multiaxial fatigue criterion. Engineering Transactions, 1988;36:55-63.

Macha E., Sonsino M. Energy criteria of multiaxial fatigue failure. Fatigue Fract. Engng. Mater, Struct., 1999;22:1053-1070.

Rozumek D., Marciniak Z., Lachowicz C. T. The energy approach in the calculation of fatigue lives under non-proportional bending with torsion. Int. J. of Fatigue 2010;32(8):1343-1350.

Rozumek D., Marciniak Z. Fatigue properties of notched specimens made of FeP04 steel. Materials Science 2012;47(4): 462-469.

Mrozinski S. Stabilization of cyclic properties in metals and its influence on fatigue life. Rozprawa nr 128, Uniwersytet Technologiczno-Przyrodniczy, Bydgoszcz 2008 (in Polish)

Mrozinski S., Golanski G. Influence of temperature on analytical description of cyclic properties of martensitic cast steel. Journal of Metallurgical Engineering 2012;1(1):30-34

Marcisz E., Marciniak Z., Rozumek D, Macha E. Fatigue characteristic of aluminium alloy 2024 under cyclic bending with the controlled energy parameter, Key Engineering Materials 2014;592-593:684-687.

Marcisz E., Marciniak Z., Rozumek D, Macha E. Energy fatigue characteristic of C45 steel subjected to cyclic bending, Key Engineering Materials 2014;598:147-152.

Macha E., Słowik J., Pawliczek R. Energy based characterization of fatigue behavior of cyclically unstable materials, Solid State Phenomena 2009;147-149:512-517.

Rozumek D., Marciniak Z. Control system of the fatigue stand for material tests under combined bending with torsion loading and experimental results, Mechanical Systems and Signal Processing 2008;22(6):1289-1296.

Kasprzyczak L., Macha E., Marciniak Z. Energy parameter Control system of strength machine for material test under cyclic bending and torsion, Solid State Phenomena Vol. 198 (2013) pp. 489-494

Kasprzyczak L., Macha E.: Energy Parameter Control System of Strength Machine for Material Tests under Polyharmonic Bending and Torsion, Journal of Vibration and Control, Online Version of Record Dec 11, 2013, doi: 10.1177/1077546313514764, pp.6