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Fatigue Life Estimation Based on the Correlation between the Plastic Strain Energy per Cycle and the Specimen Heating During Cycling

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Abstract

A fatigue life prediction method for a specimen subjected to axial low cycle loading is proposed assuming that the internal heating during cycling is the result of the conversion of plastic strain hysteresis energy to heat. Smooth cylindrical specimens of a Cr-Mo quenched and tempered steel were subjected to a fully reversed strain control loading for five strain amplitudes, determining the stress-strain response, the mechanical properties and the fatigue life. During testing, the surface temperature evaluation of the specimen was continuously measured using the infrared thermographic technique. The number of cycles to failure is determined by equaling the plastic strain hysteresis energy per cycle, represented by the area enclosed by the loop, analytically related to fatigue life, and the thermal energy calculated based on the temperature increment. A good agreement between experimental and predicted fatigue lives was observed.

Key words: *fatigue, strain energy, infrared thermography*

Introduction

Extensive investigations regarding the estimation of the fatigue behavior of a material provided by thermographic methods have documented a close correlation between the surface temperature increment and the plastic strain energy released per cycle [3, 5, 7, 8, 9].

The plastic strain hysteresis energy per cycle is a fatigue damage indicator, correlated with the fatigue life/number of cycles to failure. Assuming that the internal heating during cycling is the result of the conversion of the plastic strain hysteresis energy to heat, is possible to calculate the number of cycles to failure, by equaling the thermal energy based on temperature measurement with the plastic strain hysteresis energy.

The model for fatigue life estimation was verified by testing smooth cylindrical specimens of a Cr-Mo quenched and tempered steel subjected to a fully reversed strain control loading, to determine the area enclosed by the hysteresis loop and the number of cycles to failure. The surface temperature of specimens was continuously measured using a FLIR infrared camera, offering the thermal energy corresponding to the mechanical energy dissipated during plastic deformation.

The fatigue life values calculated based on the proposed model are in good agreement with the experimental results.

Theoretical Models Relating Stress, Strain, Energy and Fatigue Life

The cyclic stress-strain curve widely used in the analysis of low cycle fatigue problems, has proved to be a modern strain-based approach to long life fatigue behavior of smooth or notched parts. During cyclic loading, the stress-strain relation takes the form of a hysteresis loop, presented in Figure 1 [2, 4].

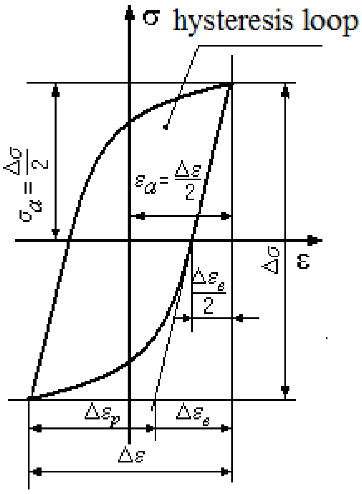

Fig. 1. Stress-strain hysteresis loop defining the main characteristics

The cyclic stress-strain curve is the locus of tips of the stable hysteresis loops obtained for different fully reversed strain amplitudes, *Δε*, presented in Figure 2. Usually a power function is assumed to relate the cyclic stress and strain, with the cyclic strain hardening exponent *n'*.

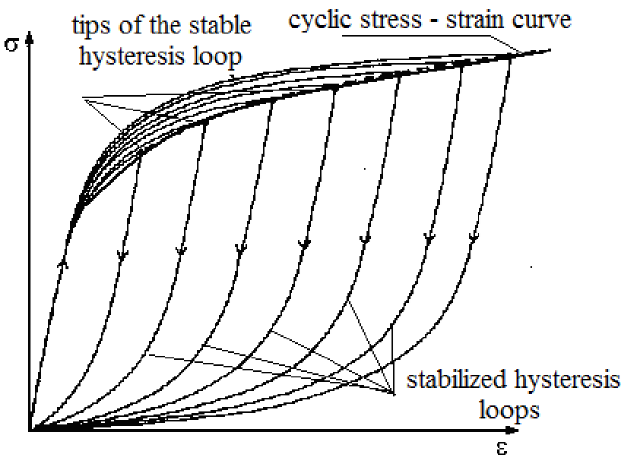

Fig. 2. Cyclic stress-strain curve defining the main characteristics

The total strain range is the sum of the elastic and plastic components, described by the following equation [1,2].

$$\frac{\Delta\varepsilon}{2} = \varepsilon_f' N^c + \frac{\sigma_f'}{E} N^b \qquad (1)$$

where $\varepsilon_f^{'}$ is the fatigue ductility coefficient; *c* – the fatigue ductility exponent; *N* – the number of cycles to failure; $\sigma_f^{'}$ – the fatigue strength coefficient; *b* – the fatigue strength exponent.

The plastic strain hysteresis energy required for fatigue failure is the sum of the hysteresis energy dissipated in each cycle. The stable value of the hysteresis energy dissipated on each cycle, *ΔW*, can be calculated from the experimental recorded hysteresis loop. The plastic strain hysteresis energy per cycle can also be analytically expressed as [1]:

$$\Delta W = \frac{1-n^{'}}{1+n^{'}}\Delta\sigma\Delta\varepsilon_p\,. \tag{2}$$

The stress amplitude, σ_a, can be expressed as:

$$\sigma_a = \frac{\Delta\sigma}{2} = \sigma_f^{'}N^b\,, \tag{3}$$

and the plastic strain amplitude, ε_{pa}, can be expressed as:

$$\varepsilon_{pa} = \frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{'}N^c \tag{4}$$

where *N* is the number of cycles to failure.

Introducing equation (3) and equation (4) into equation (2), the dissipated plastic strain energy per cycle is related to the number of cycles to failure:

$$\Delta W = 4\frac{1-n^{'}}{1+n^{'}}\sigma_f^{'}\varepsilon_f^{'}N^{b+c}\,. \tag{5}$$

The total plastic strain energy required for fatigue failure, W_p, is obtained as the sum of the N hysteresis energies dissipated on each cycle:

$$W_p = 4\frac{1-n^{'}}{1+n^{'}}\sigma_f^{'}\varepsilon_f^{'}N^{1+b+c}\,. \tag{6}$$

The equation (6) can be rewritten as:

$$W_p = 4\sigma_f^{'}\varepsilon_f^{'}\frac{c-b}{c+b}N^{1+b+c}\,, \tag{7}$$

or

$$W_p = 4N\frac{1-n^{'}}{1+n^{'}}\frac{\varepsilon_f^{'}}{\sigma_f^{'\frac{1}{n^{'}}}}\sigma_a^{\frac{1+n^{'}}{n^{'}}}\,. \tag{8}$$

The internal heating during cycling is the result of the conversion of the plastic strain hysteresis energy to heat. The thermal energy measured during cycling based on temperature increment of the specimen is:

$$Q = mc_p\Delta t \tag{9}$$

where *Q* is the thermal energy, J; *m* – mass of the sample, kg; c_p – specific heat capacity, J/kg·°C; *Δt* – temperature increment, °C;

By equaling the plastic strain hysteresis energy for fatigue failure, eq. (7), and the thermal energy based on temperature increment, eq. (9), the number of cycles to failure can be estimated.

Experimental Program

Material and samples

Smooth cylindrical specimens are shown in Figure 3.

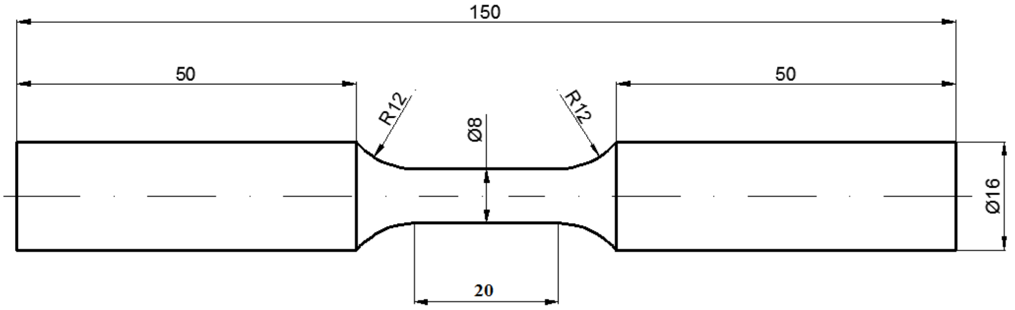

Fig. 3. Specimen geometry

The specimen have been prepared from a Cr-Mo quenched and tempered steel. The chemical composition of the steel is presented in Table 1, and the material properties are presented in Table 2.

Table 1. Chemical composition of the tested steels in percentage weight

No.	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**	**Cu**	**Ti**
1	0.3052	0.2718	1.179	0.0171	0.0106	1.190	0.2561	0.0502	0.0233	0.101	0.00072
2	0.3096	0.2651	1.182	0.0119	0.0078	1.180	0.2847	0.0512	0.0225	0.0974	0.00143
3	0.3111	0.2687	1.142	0.011	0.00706	1.156	0.2549	0.0503	0.0215	0.0934	0.00113
Average	***0.3086***	***0.2685***	***1.167***	***0.0133***	***0.0084***	***1.175***	***0.2652***	***0.050567***	***0.0224***	***0.097267***	***0.00109***

Table 2. Mechanical properties of the tested steels

Specimen section d_o [mm]	**L_0 [mm]**	**L_u [mm]**	**A [mm]**	**R_m [N/mm^2]**	**$R_{p0,2}$ [N/mm^2]**
8	40	46.8	17.0	1150	855

Quantitative thermographic method

During testing the surface temperature evaluation of the specimen was continuously recorded by an infrared high resolution thermographic camera FLIR E50. A specialized software (*FLIR Tools*) was used to convert the FLIR camera readings into surface temperature values. The samples were black printed in order to increase the diffusivity of the sample surface.

Fatigue test procedure

The fully reversed tension-compression low cycle fatigue test were conducted under strain control at a frequency of 1 Hz at five different strain amplitudes, until failure.

The fatigue tests were carried out at room temperature using a fully computerized servohydraulic testing machine, INSTRON 8801, with ± 50 N (maximum loading) and an extensometer for strain measurement. The experimental setup is presented in Figure 4.

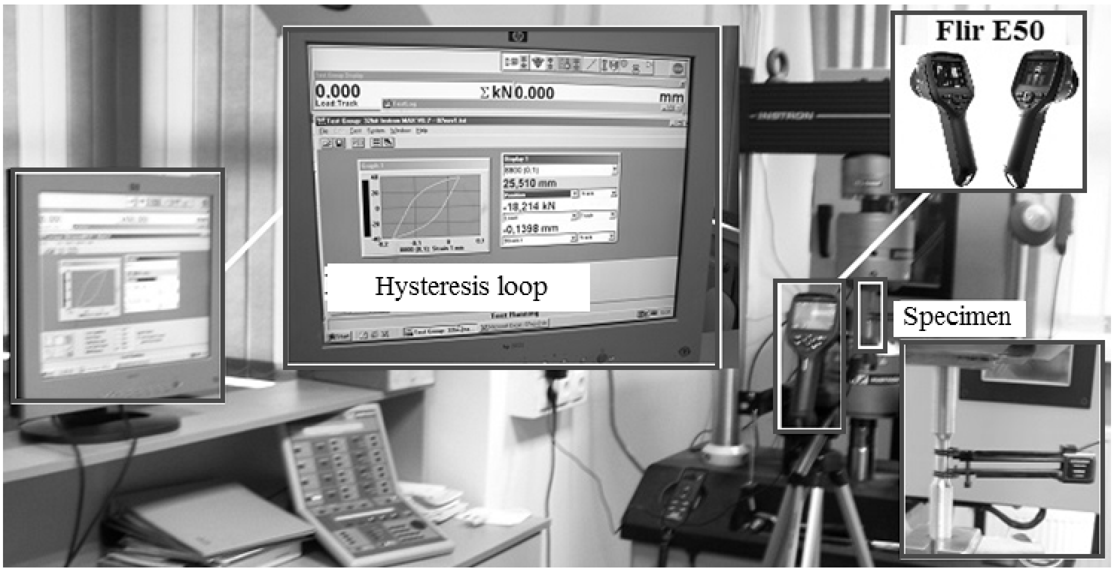

Fig. 4. Experimental setup

Results and discussion

The experimental tests led to the following results: stable hysteresis loops, cyclic σ -ε curve, low cycle material characteristics (σ_f', ε_f', *c, b, n*'), ε-*N* curve, number of cycles to failure and sample temperature increments. Figure 5 present the stable hysteresis loops for ε_{at} = 0,67%.

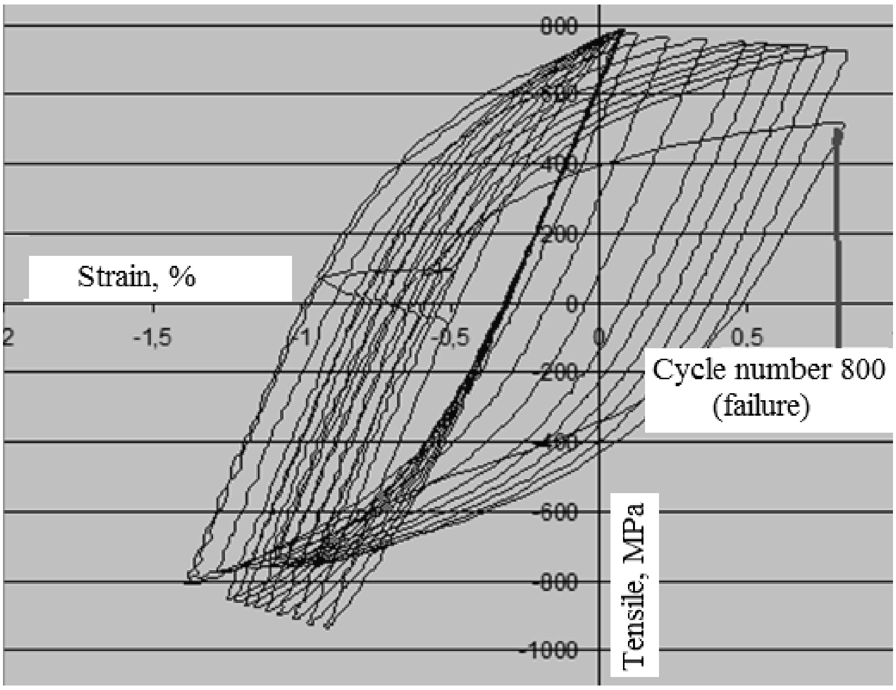

Fig. 5. Stable hysteresis loops for ε_{at} = 0,67%.

The total strain amplitude, the elastic strain amplitude, the plastic strain amplitude are presented in Figure 6 and the material low cycle characteristic are the following: σ_f' = 1271; ε_f' = 0.071; c = -0.459; b = -0.078; n' = 0.170. The experimental test results are presented in Table 3.

Figure 7 shows the temperature evolution of the specimen during cycling for three total strain amplitudes. A relative low temperature increment can be observed.

In order to verify the applicability of the proposed model, the numbers of cycles to failure were calculated for two values of temperature increment: 2°C and 3°C (Table 4). The thermal energy and the plastic strain hysteresis energy are calculated as specific energy per unit volume, J/mm^3. The volume of the sample in the calibrated area is 800 mm^3, $c_p = 730$ J/kg·°C and $\rho = 7850$ kg/m^3.

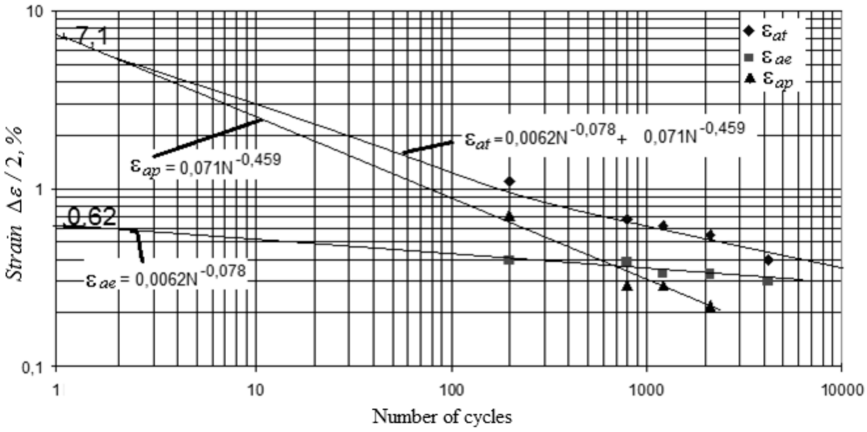

Fig. 6. $\varepsilon_a - N$ curves and LCF material characteristics

Table 3. Experimental test results

Nr. crt.	ε_{at} = (Δε/2),%	σ_a = Δσ/2, **MPa**	ε_{ae}, %	ε_{ap} x10^3	*N*	**Loop area, Nm**
1	0.40	620	0.302439024	0.097560976	4203	1.158
2	0.55	675	0.329268293	0.220731707	2117	2.398
3	0.62	684	0.333658537	0.286341463	1217	3.473
4	0.67	785	0.382926829	0.287073171	800	3.903
5	1.1	804	0.392195122	0.707804878	200	10.613

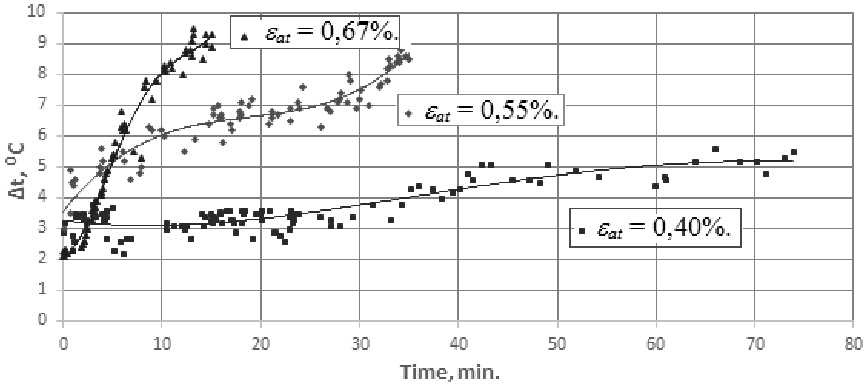

Fig. 7. Temperature evolution during test

Table 4. Calculated number of cycles to failure

Temperature increment: 2 °C	**Temperature increment: 3 °C**
$Q = 11,46 \cdot 10^{-3}\ J/mm^2$	$Q = 17,19 \cdot 10^{-3}\ J/mm^2$
$0.32 \cdot N^{-0.537} = 11.46 \cdot 10^{-3}; N^{-0.537} = 0.0358$	$0.32 \cdot N^{-0.537} = 17.19 \cdot 10^{-3}; N^{-0.537} = 0.0537$
$-0.537 \cdot \lg(N) = -1.446;\ \lg(N) = 2,692$	$-0.537 \cdot \lg(N) = -1.27;\ \lg(N) = 2,36$
$N = 493$ *cycles*	$N = 231$ *cycles*

Conclusions

The paper propose a fatigue life estimation model based on low-cycle material properties, which are experimentally determined or available in the literature, and the temperature evolution of the specimen during cycling, measured by using infrared thermography. A good agreement between experimental and estimated fatigue lives was observed, within a factor of two.

The results proved the suitability of thermographic techniques as an acceptable engineering means for fatigue life estimation of a particular material, saving much effort in experiment and computation.

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Estimarea duratei de viață la oboseală pe baza corelării energiei de deformare plastică pe ciclu de încercare şi creşterea temperaturii epruvetelor încercate la oboseală

Rezumat

In lucrare se prezinta o metodă de estimare a duratei de viață la oboseală a unei epruvete supusă la oboseală în domeniul durabilităților mici pe baza ipotezei că încălzirea internă în timpul încercării este rezultatul conversiei energiei de deformare plastică pe ciclu. Cinci epruvete cilindrice, realizate dintr-un oțel călit şi revenit Cr-Mo, au fost supuse unor cicluri de încărcare cu amplitudinea deformației constantă, determinându-se dependența tensiune – deformație, caracteristicile mecanice şi caracteristicile de material specifice oboselii în domeniul durabilităților mici. În timpul încercărilor, evaluarea temperaturii suprafeței epruvetelor a fost măsurată folosind tehnica termografică în infraroşu. Numărul de cicluri până la cedare prin oboseală este stabilit prin egalarea energiei de deformare plastică pe ciclu şi energia termică calculată pe baza creşterii temperaturii epruvetelor.