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COMPARATIVE ANALYSIS OF CYCLIC PROPERTIES OF METALS OBTAINED IN CONDITIONS OF STRESS AND STRAIN RANGE DIVERSIFICATION CONTROL ON THE EXAMPLE OF C45 STEEL

Grzegorz Szala

Uniwersity of Technology and Life Sciences in Bydgoszcz
ul. Prof. Kaliskiego 7 85-789 Bydgoszcz, Poland
tel.: +48 52 340 82 95, fax: +48 52 340 82 71
e-mail: gszala@utp.edu.pl

Abstract
Cyclic properties of metals are obtained in conditions of sinusoidal loading at stress constant temperature or at constant amplitude of total strain. In the first case fatigue is characterized by the S-N Wohler curve applied in calculations in the range of high cycle fatigue. In the second case fatigue is characterized by the Mason-Coffin curve (ε_{ac} - $2N_f$) applied in low cycle fatigue calculations. Characteristic that enables transformation of the curve into the one and suitable reverse transformation is the Ramberg-Osgood (ε – σ) cyclic strain curve. In the paper there was confirmed that there are differences between (σ - N) and (ε_{ac} - $2N_f$) curves determined in stress and strain control conditions. The fact may have an essential influence on results of fatigue calculations in amplitude variable loading conditions (i.e. random loading or programmed) that values belong to both ranges LCF and HCF of fatigue.

Keywords: *fatigue of materials, fatigue life curves, cyclic properties of materials*

1. Introduction

Elements of machines and designs in operating conditions are subjected to variable loading and in general case to randomly variable loading. If the source of loading are i.e. vibrations of a system with defined distribution of masses it causes loading from mass forces (soft loading) and consequently to this loading cyclic properties are determined in tests where variable stress is a parameter. If the source of loading is variable distribution i.e. as a result of misalignement of shaft gudgeons in a clutch (hard loading) then cyclic properties are determined in tests where variable strain is the parameter [1].

The above statement has an essential value in the case of tests and calculations in ranges of high cycle loading and low cycle loading. In the first case calculations are based on the S-N curve, while in the second case calculations are based on the Mason-Coffin curve. In operating conditions randomly variable loading appears and it is possible the high values are in the range of LCF and small values in the range of HCF. So there is doubt if the change of calculation conditions in LCF and HCF connected with acceptance of the Mason-Coffin curve for calculations in the first case, and the S-N curve in the second one does not lead to significant misteakes. No doubt there is a significant lack of consistency.

The answer on the above question results from the analysis of fatigue characteristics in the shape of σ - N and ε_{ac} - $2N_f$ curves and (Ramberg - Osgood) cyclic strain curves ε – σ, obtained in conditions of stress and strain “control”.

The aim of the paper is comparative analysis of cyclic properties of metals obtained in conditions of control of stress (σ – N curves) and strain (ε_{ac} - $2N_f$ curves) range changes fo C45 steel.

Scope of the paper covers description of:
- tests in the conditions of static loading,
- tests in conditions of cyclic loading,
- comparative analysis of fatigue characteristics obtained in conditions of controlled stress with fatigue characteristics obtained in controlled strain conditions.

The paper is concluded with reference to fatigue life calculation methods in operating loading conditions that values lie in the range of HCF and LCF.

Tests are performed for the following assumptions:

- C45 steel is a material assumed for tests
- cyclic properties of C45 steel are estimated in sinusoidal stress conditions and total strain with constant amplitude and asymmetry coefficient of cycles R=-1,0.

2. Experimental tests

2.1. Test object

For tests there are assumed specimens with a shape shown in fig. 1, made with the accordance to the standard: PN – 74/ H-04327.

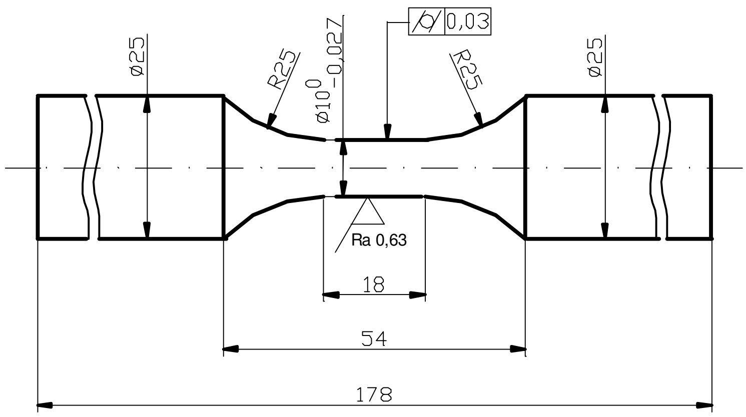

Fig. 1 Specimen for tests with the accordance to PN – 74/ H-04327.

Specimens were made of C45 toughened steel. Chemical composition of C45 steel with accordance to the standard PN-EN 10083-1+A1:1999 and PN-EN 10083-2+A1:1999 and with accordance to own tests are presented in the table 1.

Table 1. Chemical composition of C45 steel

	Contents in %								
	C	Mn	S	P	Si	Cr	Mo	Ni	Cr+Mo+Ni
			Max						
According to **PN-EN**	0,42÷0,5	0,5 ÷ 0,8	0,045	0,045	0,4	0,4	0,1	0,4	0,63
According to own test	0,476	0,593	0,027	0,015	0,201	0,16	0,047	0,116	0,323

Tests in conditions of static and cyclic loading were performed on the INSTRON 8501 fatigue machine with a control – measurement unit additionally equipped with extensometers, data acquisition system ESAM TRAVELLER 1 and a PC computer.

2.2. Test results in static loading conditions

The curve obtained with accordance to the standard PN-EN 10002-1+AC1 in the range of tension and compression is placed in fig. 2, whereas mechanical properties are presented in the table 2.

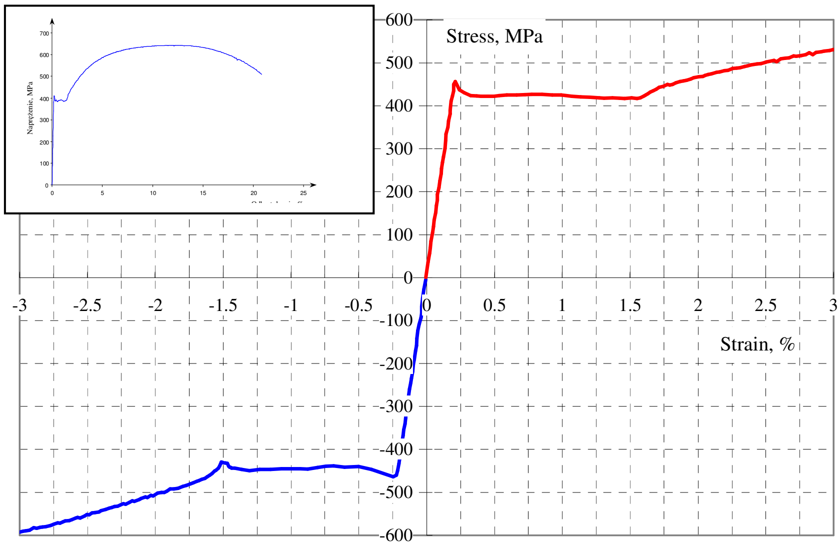

Fig. 2 Tension and compression test of C45 steel in condition of static loading

Table 2. Static properties of steel C45

	Static properties of steel C45					
	R_e	R_m	R_u	E	Z	A_5
	MPa	MPa	MPa	MPa	%	%
Average value	446.3	713.3	1098.0	215000	44.3	24.3
Standard deviation	12.3	21.7	46.6	10000	4.7	3.5

2.3. Test results in cyclic loading conditions

a) Determination of Ramberg-Osgood (σ – ε) cyclic strain curve

The rule of determination of individual points of the curve (σ - ε) was described in the paper [2]. Point of the curve means the top of hysteresis loop (point A) in the phase of stabilization of cyclic properties. Because the phase, as it was shown in the paper [3], does not appear significantly in in whole fatigue life of the specimen, there was assumed a loop from a half of fatigue life. Cyclic strain curve determined in the range of controlled stress conditions (3) and the cyclic strain curve determined in the range of controlled strain conditions (2) were shown on the background of the static tensile curve (1) in fig. 3 .

Curves from the fig. 3 were described with following formulas:

- for the case of controlled stress

$$\varepsilon = \frac{\sigma}{215000} + \left(\frac{\sigma}{1121}\right)^{5,5} \tag{1}$$

- for the case of controlled strain

$$\varepsilon = \frac{\sigma}{215000} + \left(\frac{\sigma}{1232}\right)^{5,06} \tag{2}$$

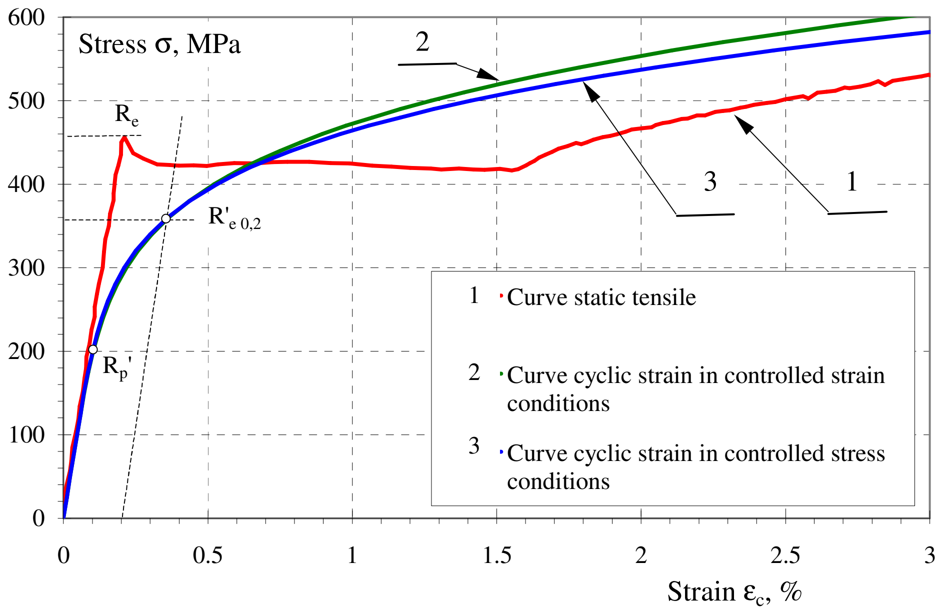

Fig. 3 Curves: static tensile (1), cyclic strain in stress controlled conditions (3) and cyclic strain in controlled strain conditions (2) of steel C45

b) (σ – N)curve

Performing tests in conditions of sinusoidal stress with constant amplitude σ_a the N number of cycles leading to fatigue cracking is determined . These data lead to a point of the fatigue curve. Repeating test for different values of σ_a we obtain set of points that enables to determine the curve (σ – N) with a method of linear regression. In fig. 4 there was shown the curve (σ – N) determined on the base of 15 test results.

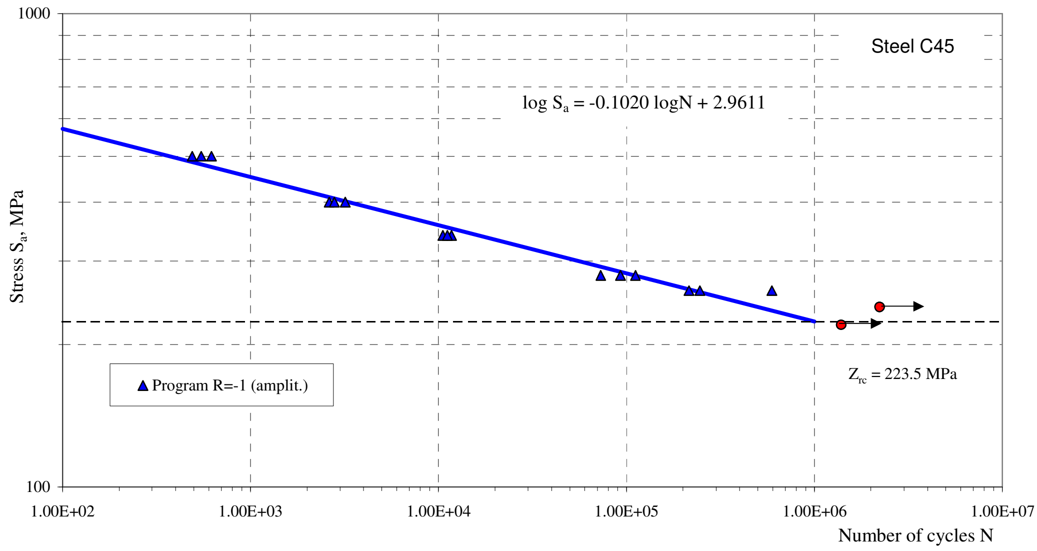

Fig. 4 Wohler curve for C45 steel

The curve is described by the formula (3)

$$\log \sigma_a = -0{,}1020 \log N + 2{,}9611 \qquad (3)$$

c) (ε_{ac} - $2N_f$) curve

Curves (ε_{ac} - $2N_f$) are determined in tests in total strain conditions with constant amplitude. The number of $2N_f$ refers to each value of ε_{ac} amplitude in these tests. These data give the set of points that enable to determine the curve (ε_{ac} - $2N_f$) which was shown in

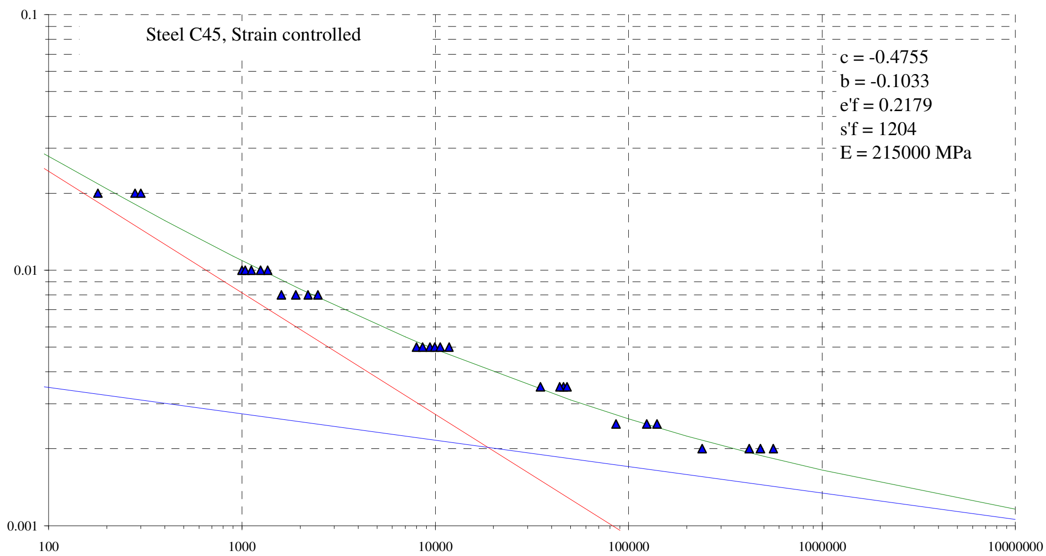

Fig. 5. Mason-Coffin (ε_{ac} – $2N_f$) curve for C 45 steel

and the formula describing the curve is:

$$\varepsilon_{ac} = \frac{1204}{E}(2N_f)^{-0,1033} + 0,2179(2N_f)^{-0,4755} \tag{4}$$

3. Analysis of test results

With reference to the aim of the paper the analysis of the test results will be based on comparison of fatigue life curves obtained in different conditions of loading. The comparison needs a propor transformation of test results with an application of the cyclic strain curve.

In the first case there will be performed transformation of the curve (ε_{ac} - $2N_f$) into the (σ_a – N) system. For each strain ε_{ac} from the curve (ε_{ac} - $2N_f$) – fig. 5 there is a proper value of stress amplitude σ_a read from the (σ – ε) curve – fig. 3. The set of points from fig. 5 transferred into the system (σ_a – N) was marked green and shown in fig. 6 on the background from fig. 4,

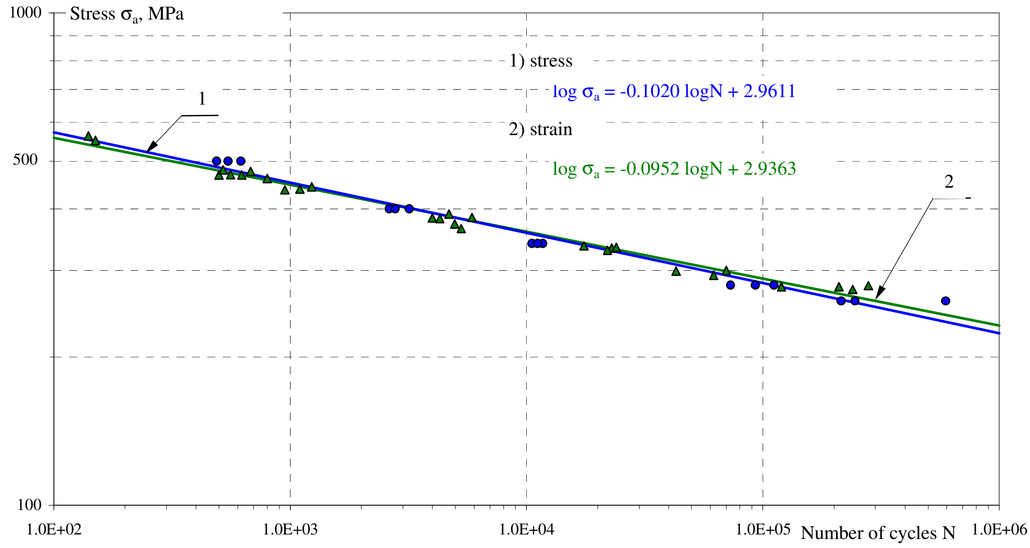

Fig. 6. Comparison of Wöhler curves determined in conditions of „controlled" stress (blue colour) and „controlled" strain (green colour) for C45 steel.

and the formula describing the curve for the set is:

$$\log \sigma_a = -0,0952 \log N + 2,9363 \tag{5}$$

Comparing differences in fatigue life on the ends of the test range for σ_a=550 MPa and 250 MPa their relative values are obtained on the level:

$$\delta_{550} = \frac{N_\sigma - N_\varepsilon}{N_\sigma} \cdot 100 = 21,64\% \tag{6}$$

and

$$\delta_{250} = \frac{N_\sigma - N_\varepsilon}{N_\sigma} \cdot 100 = -36,1\% \tag{7}$$

where: N_σ – number of cycles to fatigue crack for the „controlled" stress amplitude,
N_ε - number of cycles to fatigue crack for the „controlled" strain amplitude.

Similar transformation was performed converting suitable data from the curve (σ - ε) – fig. 4 into the coordinate system (ε_{ac} - $2N_f$) applying the curve (σ - ε).

Results of the trasformation were shown in fig. 7, where on the background of the curve (ε_{ac} - $2N_f$) from fig. 5 suitable data were applied that give another curve described by the formula:

$$\varepsilon_{ac} = \frac{1411}{E}(2N_f)^{-0,1246} + 0,4991(2N_f)^{-0,5699} \tag{8}$$

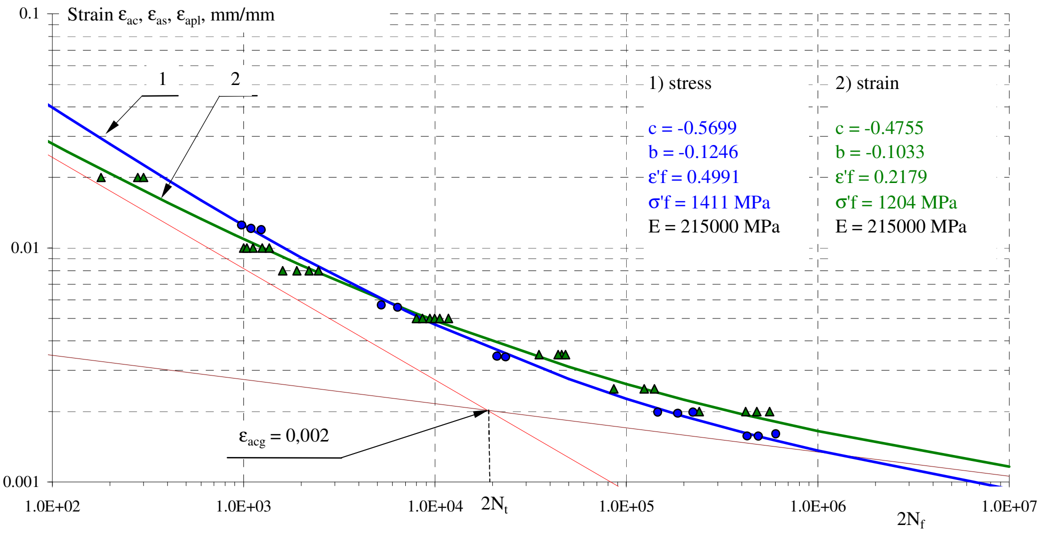

Fig. 7. Comparison of Manson-Coffin (ε_{ac} – $2N_f$) curves determined in conditions of: „controlled" stress (blue colour) and „controlled" strain" (green colour) for C 45 steel

Comparing differences of fatigue life on the ends of the test range for ε_{ac} = 0,03 and 0,0015 their relative values are obtained as follows:

$$\delta_{0,03} = \frac{2N_\sigma - 2N_\varepsilon}{2N_\sigma} \cdot 100 = 51,36\% \tag{9}$$

and

$$\delta_{0,0015} = \frac{2N_\sigma - 2N_\varepsilon}{2N_\sigma} \cdot 100 = -190,1\% \tag{10}$$

Relative differences in fatigue life described by formulas (6), (7) and (9), (10). Their influence on fatigue life calculations in variable amplitude loading is essential. To confirm its importance it is neccesary to perfom suitable calculations what will be an essence of the other paper.

4. Summary

There are essential insights resulting from the presented test results. They have crucial value for the choice of the proper calculation method of fatigue life of contructional elements.

From fig. 3 it results that constructional C45 steel after hardening and tempering is subjected to cyclic weakening in the range of minor values of amplitudes $\sigma_a \leq 420$ MPa, and then it is subjected to cylic hardening for higher values of stress amplitudes $\sigma_a > 420$ MPa. Cyclic yield stress $R'_{e0,2}$ is significantly lower then yield stress R_e determined in conditions of static loading. The fact states about the weakness of assumptions of yield stress R_e as a criterion of ranges of LCF and HCF that decide on assumptions of suitable fatigue curves (σ - N) or (ε_{ac} – $2N_f$) in fatigue life calculations. The above statement finds its confirmation also in course of the curve (σ - N) in the range of stresses $\sigma_a > R_e$ (the curve does not change its character) what states that the curve (σ - N) can be also applied in the range of low cycle fatigue (LCF).

Relativly small differences between curves determined in conditions of „controlled" stress amplitude and the „controlled" total strain one point on the possibility of their interchangeable application in fatigue life calculations.

Generally there is a set rule that for dynamic operating loading the (σ – N) curves are applied whereas for kinematic loading the (ε_{ac} – $2N_f$) curves are applied [3] .

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