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LOAD SEQUENCE INFLUENCE ON LOW CYCLE FATIGUE LIFE

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Key words: low cycle fatigue (*LCF*) tests, durability, load history.

Abstract

The study reviews basic issues relating to low cycle fatigue of metals and methods of describing the results of tests in this respect. Particularly examined are relationships between fatigue life and the strain range applied in tests, material strength properties, size of the hysteresis loop as well as the load sequence. Algorithms are presented to calculate the area of cyclic hysteresis loop registered in low cycle fatigue tests. The results of research are an element of expanding knowledge on construction element durability estimates.

WPŁYW OBCIĄŻEŃ NA PRZEBIEG NISKOCYKLOWEJ TRWAŁOŚCI ZMĘCZENIOWEJ

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Słowa kluczowe: badania zmęczeniowe niskocyklowe (*LCF*), trwałość, historia obciążeń.

Streszczenie

Zaprezentowano przegląd podstawowych zagadnień niskocyklowego zmęczenia metali i metod opisu wyników badań w tym zakresie. W szczególności rozpatrzono związki między trwałością zmęczeniową a zakresem odkształceń zadanych w testach, właściwościami wytrzymałościowymi materiału, wielkością pętli histerezy oraz sekwencją obciążeń. Przedstawiono algorytm do obliczania pól powierzchni pętli histerezy cyklicznej rejestrowanych w próbach niskocyklicznego zmęczenia. Wyniki badań są elementem poszerzania wiedzy z zakresu szacowania trwałości elementów konstrukcji.

Introduction

Knowledge about the fatigue characteristics of construction materials, among others such as durability under low cycle fatigue conditions, is significant with respect to estimating the life of construction elements at the structure design stage, during operation as well as in analysis of construction overhaul life assessment and possibilities of its extension (MISHNAEVSKY 1997, FUCHS et al. 1980, KOCAŃDA, SZALA 1991, *Problemy badań*... 1993). The hysteresis loop of material subject to cyclic loads includes valuable information on the details on the cyclic behavior of material and its resistance to fatigue. The shape of the hysteresis loop registered during low cycle fatigue tests and its characteristic sizes when stabilized depend on the type of material and load conditions – e.g. its width at a stress level of zero is equal to the plastic strain range $\Delta\varepsilon_{pl}$, which determines durability in a low cycle fatigue tests.

Review of relationships describing the low cycle fatigue of metals

The basic equation describing the behavior of metals with respect to low cycle fatigue is an experimental relationship formulated by Manson and Coffin (KOCAŃDA et al. 1989) associating the number of cycles to destruction N_f with the plastic strain range $\Delta\varepsilon_{apl}$:

$$N_f^k \Delta\varepsilon_{apl} = C \tag{1}$$

where:

k, C – material constants.

For low-carbon and low-alloyed steel as well as stainless austenitic steel of strength amounting to $R_m < 700$ MPa, the exponent $k \cong 0.5$.

The constant C, characterizing the degree of steel plasticity, is determined by the following relationship:

$$C = \frac{1}{2} e_{rz} = \frac{1}{2} \ln \frac{100}{100 - Z} \tag{2}$$

where:

e_{rz} – real strain,
Z – reduction of area at static fracture, expressed in %.

The widest application in this area is the Morrow's formula (KOCAŃDA et al. 1989):

$$\varepsilon_{ac} = \varepsilon_{as} + \varepsilon_{apl} = \frac{\sigma_f'}{E} \left(2N_f\right)^b + \varepsilon_f' \left(2N_f\right)^c \tag{3}$$

where:

σ'_f and b – fatigue strength coefficient and exponent;

ε'_f and c – cyclic plastic strain coefficient and exponent.

A similar composition to formula (3) is the equation proposed by Manson, based on data from a static tension test, in which the assumed fixed exponent is b = -0.12 and c = -0.6:

$$\Delta\varepsilon_{ac} = \Delta\varepsilon_{as} + \Delta\varepsilon_{apl} = 3.5\frac{R_m}{E}\left(N_f\right)^{-0.12} + \varepsilon_{rz}\left(N_f\right)^{-0.6} \tag{4}$$

A simplification of formula (3) useful for engineering calculations is the Langer's formula (KOCAŇDA et al. 1989):

$$\varepsilon_{ac} = \varepsilon_{apl} + \varepsilon_{as} = \frac{1}{4\left(N_f\right)^{0.5}}\ln\frac{100}{100-Z} + \frac{Z_{-1}}{E} \tag{5}$$

The first term of equation (5) is derived from the second term of equation (3), in which Langer assumed constants $\varepsilon'_f = 0.35\varepsilon'_{rz}$ and c = -0.5.

The low correlation between the stress amplitude σ_a and the number of cycles N_f inclined Langer to replace σ_a with the fatigue limit Z_{-1} for the symmetrical cycle. According to conducted research (MACHUTOV 1981), the value of Z_{-1} may be determined by the following relationship:

$$Z_{-1} = \gamma \cdot R_m \tag{6}$$

where:

γ – steel characteristic.

For $R_m \leq 700$ MPa, coefficient $\gamma = 0.4\div0.55$ $\gamma = 0.4$ is generally applied.

The study (MACHUTOV 1981) proposes the following formula to calculate the entire strain:

$$\varepsilon_{ac} = \varepsilon_{apl} + \varepsilon_{as} = \frac{1}{4\cdot\left(N_f\right)^{0.5}}\cdot\ln\frac{100}{100-Z} + 0.435\frac{R_u}{E\cdot N_f}\cdot k_s \tag{7}$$

where:

R_u – fracture stress,

$k_s = 0.09\div0.12$. $k_s = 0.1$ is generally applied.

Formulas (3), (5) and (7) refer to the symmetric cycle at fixed load.

MACHUTOV (1981) proposed – for nonsymmetrical cycles, for which the plastic strain amplitude is lower than in symmetrical cycles – applying the following average plastic strain amplitude in formula (5):

$$\varepsilon_{apl,śr} = \varepsilon_{apl}\frac{1+R_\varepsilon}{1-R_\varepsilon} \tag{8}$$

$$R_\varepsilon = \frac{\varepsilon_{\min}}{\varepsilon_{\max}} \tag{9}$$

where:

$\varepsilon_{\min}$, $\varepsilon_{\max}$ – minimum and maximum cycle strain.

The decreasing of the fatigue limit in nonsymmetrical load cycles is taken into account by introducing into the second term of equation (5) – the following relationship:

$$f(R_\varepsilon) = \frac{1}{1 + \frac{Z_{-1}}{R_m} \cdot \frac{1+R_\varepsilon}{1-R_\varepsilon}} \tag{10}$$

The Langer's formula (5), after taking into account relationships (8) and (10), adopts the following form in nonsymmetrical cycles:

$$\varepsilon_{ac} = \frac{1}{4\left(N_f\right)^{0.5} + \frac{1+R_\varepsilon}{1-R_\varepsilon}} \cdot \ln \frac{100}{100-Z} + \frac{Z_{-1}}{E\left(1 + \frac{Z_{-1}}{R_m} \cdot \frac{1+R_\varepsilon}{1-R_\varepsilon}\right)} \tag{11}$$

Formula (11) may be presented as the following in a general entry:

$$\varepsilon_{ac} = \frac{1}{4} \varepsilon_{rz} \cdot f\left(N_f\right) \cdot f\left(R_\varepsilon, N_f\right) + \frac{Z_{-1}}{E} \cdot f\left(R_\varepsilon\right) \tag{12}$$

where:

$$f\left(R_\varepsilon, N_f\right) = \frac{1}{\left[1 + 0.25 \cdot \left(\frac{1+R_\varepsilon}{1-R_\varepsilon}\right) N_f^{-0.5}\right]} \tag{13}$$

According to equation (13), the influence of the cycle's asymmetry R_e on the amplitude of the elasto-plastic strain within the range of number of cycles $N = 5 \cdot 10^2$ to $N = 5 \cdot 10^5$ is not large.

In recommendations (Machutov et al. 1987), the following should be entered instead of Z_{-1} in formula (11): for steel of $R_m \leq 1200$ MPa for $Z \leq 30\%$ – $Z^x = Z_{-1}$ while for steel of $Z > 30\%$ – $Z^x = Z_{-1}/2+15$.

Analysis of shape and properties of the cyclic hysteresis loop

Macroscopic changes occurring in the metal during cyclic loads are presented in the shape of a cyclic hysteresis loop, for this reason the description of the loop and cyclic strain curve is an issue of fundamental meaning upon analyzing low cycle fatigue.

The cyclic strain curve, generated by combining peaks of stabilized hysteresis loop respective for various strain ranges, is determined by the Ramberg – Osgood formula:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K'}\right)^{\frac{1}{n'}} \tag{14}$$

where:

K' and n' – respectively cyclic strength coefficient and cyclic strengthening exponent.

The cyclic strengthening exponent n' for steel of $\frac{R_{0.2}}{R_m} \leq 0.8$ may be adopted, according to (MACHUTOV et al. 1987), as equal to the strengthening exponent at static tension, in accordance with the following formula:

$$n = 0.75 \cdot \frac{\lg\left(\frac{R_u}{R_{0.2}}\right)}{\lg\left[\ln \frac{\frac{100}{100 - Z}}{\frac{R_{0.2}}{E} + 0.2 \cdot 10^{-2}}\right]} \tag{15}$$

Masing's description the hysteresis loop assumes that loop branches are described based on the static tension curve drawn on a 2:1 scale. The cyclic strain curve was used in other propositions for this purpose – moving the peaks of stabilized loops in tension or compression halfcycles to a common point. The equation describing the Masing's curve is similar to formula (14), taking into account scale transformation:

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{16}$$

as such the ascending and descending hysteresis loop branches are as follows:

$$\varepsilon - \varepsilon_r = \frac{\sigma - \sigma_r}{E} + 2\left(\frac{\sigma - \sigma_r}{2K'}\right)^{\frac{1}{n'}} \tag{17}$$

$$\varepsilon_r - \varepsilon = \frac{\sigma_r - \sigma}{E} + 2\left(\frac{\sigma_r - \sigma}{2K'}\right)^{\frac{1}{n'}} \tag{18}$$

Subsequent load recurrences in Masing's model are executed in accordance with these relations, while the material *remembers* the coordinates of the beginning of the current and previous recurrences, whose loops are outside the currently executed hysteresis loop. When the strain and stress in the current recurrence reach a value at which level the recurrence of the previous began, the current hysteresis loop closes and further strain takes place according to the same relation as prior to commencing the presently closed loop.

The analysis of influence of material property changes under conditions of cyclic loads and variable sequence loads (including overloads) on the fatigue life and shape of the hysteresis loop, are also a significant factor taken into account upon estimating the durability of structural components, and are subject of many presentations at conferences (e.g. KALETA 1996, LEE et al. 1987, MROZIŃSKI 1998). However, most frequently described in professional literature studies on the influence of load history on the fatigue characteristics, relate to fatigue crack propagation and less frequently to low cycle research. An extensive analysis of fatigue properties in combination with changes in the shape of the hysteresis loop under various testing and operating conditions is presented in monographs (KOCAŃDA et al. 1989, GOSS 1982, GOSS 2004). The results of the above-mentioned analyses and the low cycle characteristics of materials as well as load parameters are an essential element of methodology for assessing the durability of construction elements (SOBCZYKIEWICZ 1983) – mainly with respect to methods of summarizing damages, as well as when disregarding these methods (GASSNER et al. 1961, SZALA 1980), e.g. by comparing the fatigue characteristics determined under constant amplitude and random load. They have already made their mark in international standards relating to supervision and control over the technical state of construction elements (RTO/AGARD 1999).

The study (KŁYSZ 2000) presents the results of low cycle fatigue tests on 18G2A and St3SY steel under $\Delta\varepsilon = \text{const}$ load conditions applied in various configurations (variable load sequence or with overload cycles – tension or compression). The nature of the changes was assessed with respect to the shape of the hysteresis loop compared to typical courses.

In the case of a standard test for the strain range $\Delta\varepsilon = \text{const}$, the registered hysteresis loops in selected load cycles is presented in Fig. 1, while

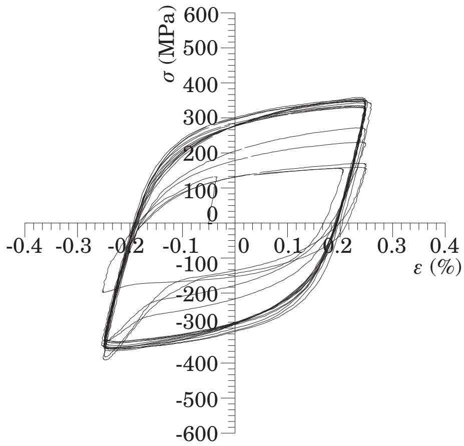

Fig. 1. Course of a hysteresis loop in selected cycles for a specimen tested in a fixed strain range ε = ±0.25% – steel 18G2A

the change in load amplitude (minimum and maximum stresses) in subsequent cycles is presented in Fig. 2. Typical characteristics are visible for the tested material in this type of test:

– symmetrical changes in load amplitudes (minimum and maximum values),
– the hardening/softening of material in subsequent load cycles (in this case the softening of material in the first few hundred load cycles, followed by the hardening of material in the subsequent thousands of cycles),
– the occurrence of minimum amplitude value after a few hundred cycles (a certain type of stabilization) as well as its sudden drop immediately prior to specimen destruction,
– clear deformation of the hysteresis loop's shape in cycles immediately prior to specimen destruction.

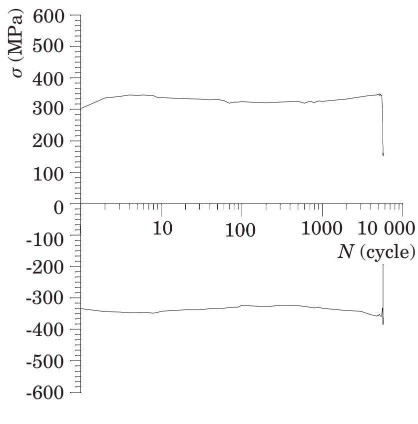

Fig. 2. Course of maximum and minimum stress values in subsequent hysteresis loops from Fig. 1 – steel 18G2A

Such processes are typical for metals. Only the proportions between particular curve fragments are subject to change, depending on the range of strain that the specimens are subject to, i.e. on their durability to destruction.

The following tests were applied to test the behavior of material under low cycle fatigue conditions in various load sequences (strain ranges):

test *A* – load with respect to strain $\pm\varepsilon$=const on subsequent levels of strain (e.g. ±0.10%, ±0.13%, ±0.16%, ±0.19%, ±0.22%, ±0.25%, ±0.28%, ±0.31%, ±0.34%, ±0.37%, ±0.40%) for a given number of cycles on each level,

test *B* – single overload in the first load cycle and further as in test *A*,

test *C* – single underload in the first load cycle and further as in test *A*,

test *D* – load with respect to strain range $\pm\varepsilon$ = const on subsequent levels of strain in reverse order to test *A* (i.e. ±0.40%, ±0.37%, ±0.34%, ... etc.) for a given number of cycles on each level.

Examples of hysteresis loop courses at subsequent strain levels of test *A* are presented in Fig. 3. A clear change in stress amplitude in subsequent cycles is visible for the first smallest strain level (0.1%). The plotted loops for subsequent levels of strain reflect the beginning and end of each test stage. In these cases, changes in stress amplitudes in hysteresis loops are insignificant. Very well reflected test conditions, symmetry and regularity are visible in the generated hysteresis loops at all strain levels – it is a classic result for this type of tests. The gradual deformation of the hysteresis loop's shape is also visible at the final stage of the test (for strain level 0.4%).

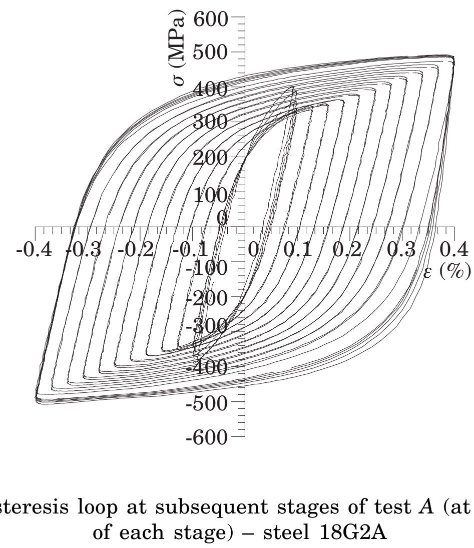

Fig. 3. Course of a hysteresis loop at subsequent stages of test *A* (at the beginning and end of each stage) – steel 18G2A

Figure 4 presents a change in stress value (minimum and maximum) respective for two identical *A* tests. The symmetry and regularity generated in the results is typical also in this case. At subsequent stages, the stress range increases for increasing strain ranges. The loading force decreased in the first three stages (at strain levels of 0.10%, 0.13%, 0.16%) – the material softened during the cycles. In subsequent stages of tests (for strain ranges from 0.19%) the force would generally increase (except, possibly, a very short period at the beginning of each stage) – the material would harden. Similarly with regard to minimum forces. It may be stated that the material responds to the load applied in a typical manner.

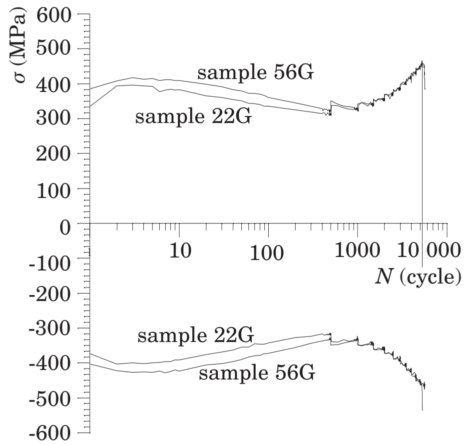

Fig. 4. Change in minimum and maximum stress values for a specimen tested according to test *A* – steel 18G2A

The hysteresis loops for specimens tested in *B* and *C* tests are presented in Fig. 5a (specimen in the first overload cycle) and 5b (specimen in the first underload cycle). The changes in stress amplitudes registered in both these tests are presented in Fig. 6. As shown, the applied overload or underload cycle introduced asymmetry to the generated results compared with the results of test *A* (Fig. 3) – in the first cycles for the lowest strain range as well as for the remaining stages of the test. In these cases, changes in stress amplitudes in subsequent load cycles clearly pertain to one (maximum or minimum value), while the other one changes much less.

A decrease in maximum loads with a nearly stable minimum load level was observed on lower levels of strain for a specimen initially overloaded, while specimens initially underloaded experienced a decrease in minimum loads – with a nearly stable maximum load level.

In the case of the specimen initially overloaded, the maximum stress level in the first 4 stages of the test was higher than in the case of the

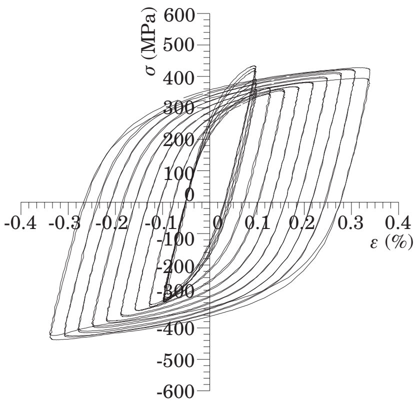

Fig. 5a. Course of a hysteresis loop at subsequent stages of test B (at the beginning and end of each stage) – steel 18G2A

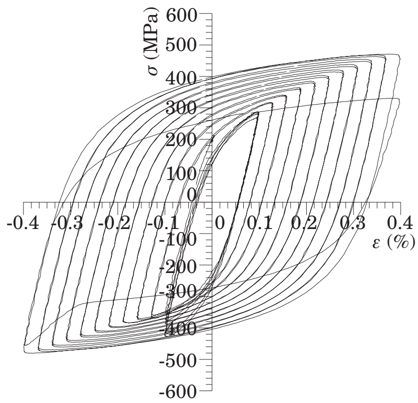

Fig. 5b. Course of a hysteresis loop at subsequent stages of test B (at the beginning and end of each stage) – steel 18G2A

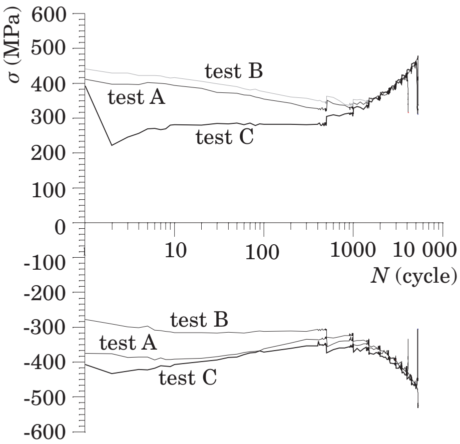

Fig. 6. Change in minimum and maximum stress values for specimens tested according to tests A, B and C – steel 18G2A

specimen in test A, which resulted in durability reduction, despite the fact that the stress range was greater for the specimen in test A. With regard to the specimen initially underloaded (test C), the minimum stress level (compression) was higher throughout the entire test than in test A, while maximum stress levels were initially significantly lower than in test A, but in subsequent stages they quickly increased and exceeded those in test A. Ultimately the durability of the specimen in test C was near the durability of the specimen in test A.

The course of registered hysteresis loops examined in test *D* is presented in Fig. 7. In subsequent stages of the test, despite a decreasing strain range, the stress level remained at a nearly unchanged level (Fig. 8) (this confirmed the occurrence of material memory effect) and did not demonstrate characteristics that were typical of test *A*. As a result, the durability of the specimen decreased compared to the specimen from test *A* and the test was not performed on all strain levels such as it was performed in test *A* – the test was completed at strain level ±0.22%.

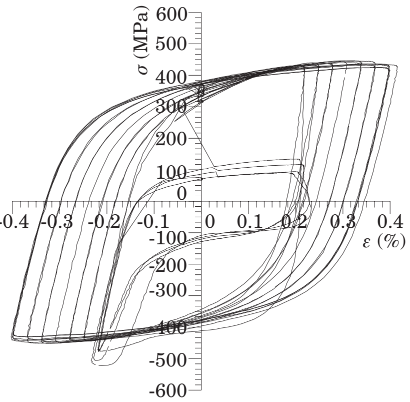

Fig. 7. Course of a hysteresis loop at subsequent stages of test *D* (at the beginning and end of each stage) – steel 18G2A

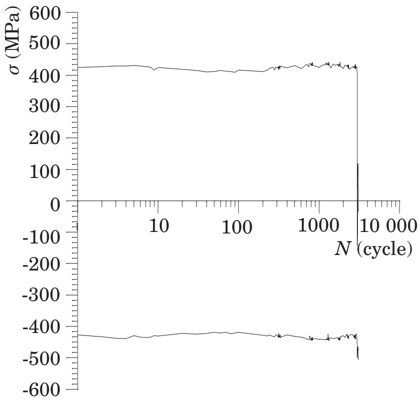

Fig. 8. Change in minimum and maximum stress values for a specimen tested according to test *D* – steel 18G2A

Algorithm to cyclic hysteresis loop area calculation

Another parameter associated with low cycle tests, which includes information on the process of material fatigue as well as the amount of energy required until destruction, is the hysteresis loop area. Strains at a micro level are irreversible plastic deformations, which is connected with energy dissipation, believed to be the main factor resulting in material damage and formation of fatigue micro cracks. The basis of most energy criteria applied to describe fatigue life as well as the cumulative fatigue damage hypothesis is the assumption that plastic deformation energy absorbed by the material volume unit during one load cycle is equal to the hysteresis loop area (Kocańda et al. 1989, Goss 1982, Polák 1991, Kujawiński 1991). The analysis methodology within this respect as well as the results of calculations for 18G2A and St3SY steel are presented below.

Every low cycle fatigue test registers *n* hysteresis loops, each of a specified number of load cycles N_j. They are registered in the form of points (ε_i, σ_i), where i=1,2,...,k-1, with k as the number of measuring points of a given hysteresis loop (Fig. 9).

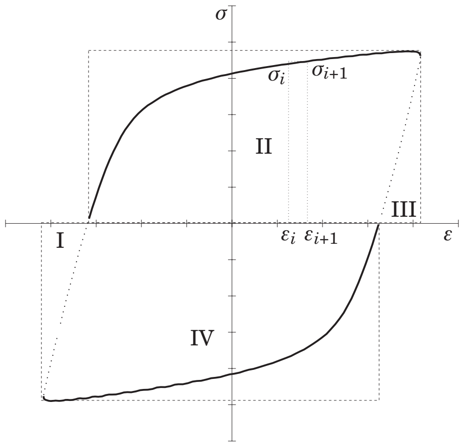

Fig. 9. Diagram of a hysteresis loop to calculated area

Domain / Value	I	II	III	IV
$\varepsilon_{i+1} - \varepsilon_i$	+	+	–	–
$0.5 \cdot (\sigma_{i+1} + \sigma_i)$	–	+	+	–
Area	–	+	–	+

If the trapezoid method is adopted to calculate the areas of hysteresis loops, fragments of the loop's area included between two experimental points $(\varepsilon_i, \sigma_i)$, $(\varepsilon_{i+1}, \sigma_{i+1})$ and the axis of coordinate system, are determined by the following formula:

$$P_i = 0.5 \cdot abs\left(\sigma_i + \sigma_{i+1}\right) \cdot abs\left(\varepsilon_{i+1} - \varepsilon_i\right) \tag{19}$$

On the basis of the analysis of a typical hysteresis loop shape (Fig. 9) in domains I–IV, in which fields P_i are added to (domains II and IV) or deducted from (domains I and III) the cumulative field P of the entire hysteresis loop, the final formula for the entire hysteresis loop area may be written as follows:

$$P = \sum_{i=1}^{k-1} \mathrm{sgn}(\varepsilon_{i+1} - \varepsilon_i) \cdot \mathrm{sgn}(0.5 \cdot (\sigma_{i+1} + \sigma_i)) \cdot P_i \tag{20}$$

Typical hysteresis loop coordinate properties were taken into account (the '+' and '-' symbols in the Table under the Figure signify that the stated values are positive or negative in a given domain, while the field P_i is added or subtracted upon summing domains under/over hysteresis loop curves).

Fig. 10 presents examples of changes in the hysteresis loop areas in subsequent load cycles for selected specimens in various strain ranges $\Delta\varepsilon$ = const, with the load ratio R = -1. The hysteresis loop areas do not change considerably for a significant part of the test, but the size of these changes increase along with an increase in strain range (size of hysteresis loop). More significant changes in hysteresis loop areas – mainly their decline, occur at the final stage of tests.

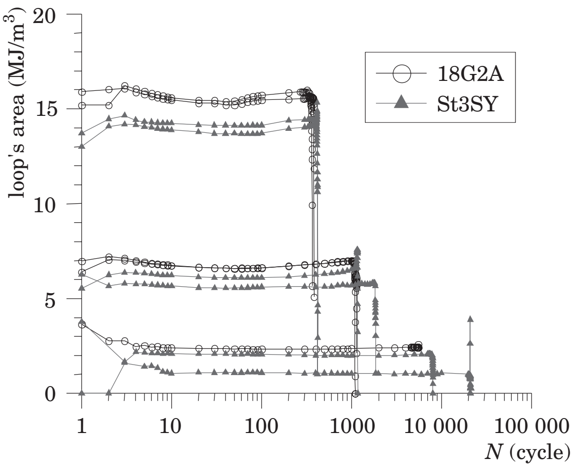

Fig. 10. Change in the hysteresis loop area in subsequent load cycles for selected specimens of St3SY and 18G2A steel tested in various strain ranges and R = –1

Similar changes in the sum of hysteresis loop areas as a function of the number of cycles to destruction is presented in Fig. 11 (in two coordinate systems). Curves with similar courses were obtained for particular strain ranges.

Table 1 presents the results of calculations relating to the size of hysteresis loop areas P (for the 2^{nd} and 3^{rd} cycle reflecting the mid-life values of a given specimen and the last prior to specimen destruction) as well as the sum of hysteresis loop areas ΣP for the specimens tested in the study. Figure 12 presents relationships between the determined sizes of hysteresis loop areas P and fatigue until destruction N_f of the specimens.

Comparing product hysteresis loop areas P from Table 1 and the number of cycles to destruction N_f for particular specimens with a determined area sum ΣP, it is possible to assess the consistency of both sizes, which would signify that the area of a given hysteresis may be a parameter enabling the estimation of the final fatigue life of the specimen. Table 2 presents the values of the relative error of such estimation, determined as $\delta = N_f \cdot P/\Sigma P$.

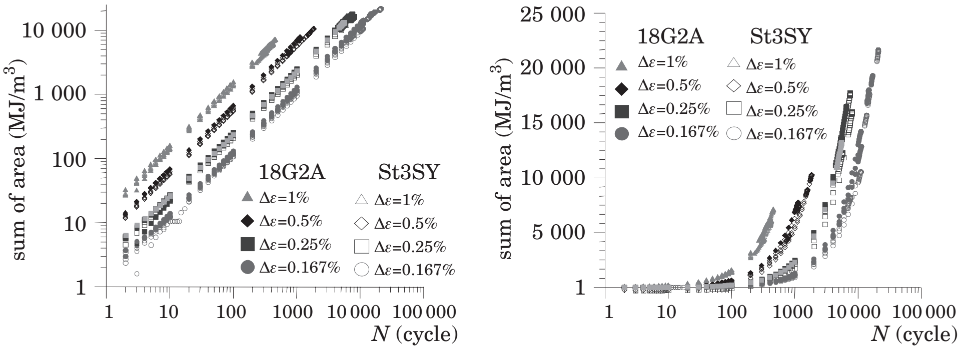

Fig. 11. Change in the sum of hysteresis loop areas for selected specimens of St3SY and 18G2A steel tested in various strain ranges and $R = -1$

Table 1

Size of hysteresis loop areas Pi in selected load cycles

Specimen	N_f cycles	P 2nd cycle (MJ/m^3)	P 3rd cycle (MJ/m^3)	P 1/2N_f cycle (MJ/m^3)	P final cycle (MJ/m^3)	ΣP (MJ/m^3)
9G	332	12.61	13.48	13.37	9.32	4378.04
12G	368	15.20	16.22	15.85	9.93	5733.29
10G	385	15.90	16.03	15.50	11.85	5930.83
8G	461	16.24	15.98	15.44	11.40	7067.97
24G	1109	6.40	7.04	6.84	-	7488.82
25G	1139	6.96	7.20	6.85	4.49	7761.58
21G	5392	2.87	2.80	2.55	-	13642.70
1G	5531	3.64	2.77	2.39	2.43	13251.93
5G	5573	2.12	2.63	2.45	1.62	13548.29
29G	6568	3.44	2.69	2.51	-	16500.29
26G	11151	1.51	1.47	1.29	0.05	14223.85
6G	14759	1.30	2.45	1.23	0.15	18017.75
13G	17003	2.01	1.72	1.16	-	19301.46

The best estimation is obtained for hysteresis loop areas corresponding to the mid-life cycle of specimens – the error does not exceed 2.5%. The estimation error may be significant in the remaining cases. The conclusion from these comparisons would be optimistic if not for the fact that the knowledge of the hysteresis loop area in a cycle reflecting specimen mid-life values is impossible to achieve until its durability is known. It would be more beneficial to be able to estimate the final durability of the specimen on the

Table 2

Size of relative estimate error δ

Specimen	δ 2nd cycle	δ 3rd cycle	δ $1/2N_f$ cycle	δ final cycle
9G	0.96	1.02	1.01	0.71
12G	0.98	1.04	1.02	0.64
10G	1.03	1.04	1.01	0.77
8G	1.06	1.04	1.01	0.74
24G	0.95	1.04	1.01	-
25G	1.02	1.06	1.01	0.66
21G	1.13	1.11	1.01	-
1G	1.52	1.16	1.00	1.01
5G	0.87	1.08	1.01	0.67
29G	1.37	1.07	1.00	-
26G	1.18	1.15	1.01	0.04
6G	1.06	2.01	1.01	0.12
13G	1.77	1.52	1.02	-

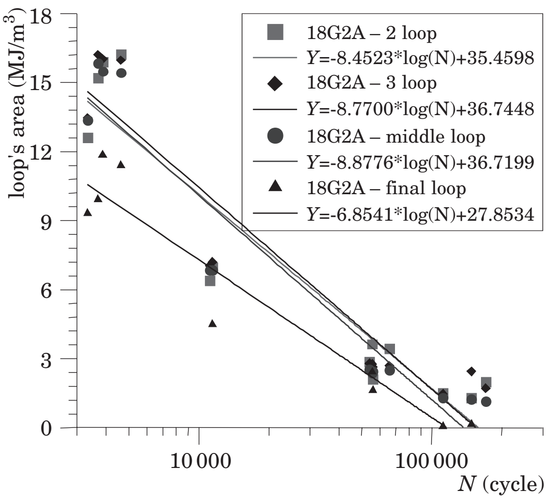

Fig. 12. Relationship $P = f(N_f)$ between the size of the hysteresis loop area P and durability until specimen destruction N_f

basis of, for example, hysteresis loops from the 2nd or 3rd load cycles, since this would indicate a significant decrease in testing time and lower costs. The presented relationships are material characteristics of a given material type and a given a load type – analogous to, for example, the Morrow's curve.

Fig. 13 presents the correlation between the area sum ΣP as a function of the number of cycles to destruction N_f for particular specimens of both tested steels, along with respective regression equations.

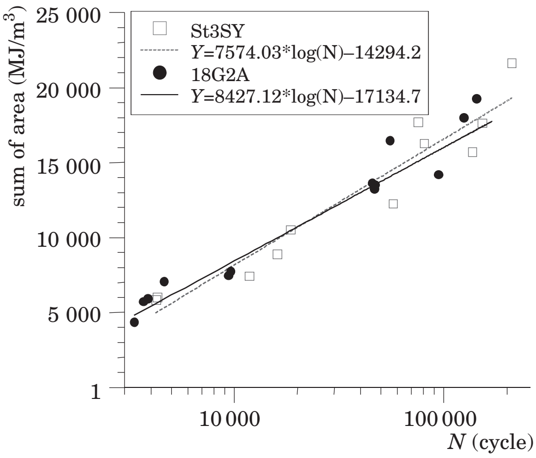

Fig. 13. Relationship of the area sum ΣP as a function of the number of cycles until destruction N_f for particular specimens and steel

Conclusions

The problem of metal low cycle fatigue is mathematically widely described with relationships connecting basic material characteristics and fatigue test parameters. They may be useful to apply in practical fatigue analysis as well as be a basis for comparing the properties of various materials.

Changes in the shape and size of hysteresis loop areas registered during low cycle fatigue tests indicate a wide range of regularities that characterize test conditions and include information on the destruction process. Hysteresis loop areas, or their sum in subsequent load cycles during fatigue tests, may be correlated with the durability of specimens tested to destruction.

The sum of hysteresis loop areas is a critical parameter in analyzing the fatigue life of tested material. The presumption based on the size of hysteresis loops reflecting cycles equal to mid-life values seems to generate the smallest error. Adopting hysteresis loop area sizes for analysis from the 2nd or 3rd load cycle may generate durability estimations with accuracy of around 30–50%, but exceptions to this rule should be taken into account, which compared with the significant benefits of this approach may be worth considering.

An important fact resulting from the presented relationships between the sum of hysteresis loop areas and the number of cycles is that they adopt values from a range of 4 orders of magnitude, while the correlation between strain range and the number of cycles on Manson-Coffin graphs have a range of 2 orders of magnitude, signifying a 100-fold higher sensitivity to the benefit of the former. Greater precision of all estimates based on the analysis of hysteresis loop areas should be expected.

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