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ACCELERATED DETERMINATION OF THE FATIGUE LIMIT AND THE S-N CURVE BY MEANS OF THE THERMOGRAPHIC METHOD FOR X5CrNi18-10 STEEL

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Abstract: A new thermographic method that enables simultaneous accelerated determination of the fatigue limit and the S-N curve was presented in this paper. The fatigue limit determination method was based on a constant rate of temperature rise occurring in second phase of the specimen fatigue life. The S-N curve determination method was based on energetic parameter with assumption of its dependency on the stress amplitude. The tests made on X5CrNi18-10 steel under reversed bending revealed that the fatigue limit value obtained from accelerated thermographic tests as compared to the value obtained from full test differs by 5.0 %. The S-N curve obtained by accelerated thermographic method fits inside 95 % confidence interval for the S-N curve obtained from full test.

Key words: Fatigue Limit, S-N Curve, IR Thermography

1. INTRODUCTION

Thanks to modern, fast and high sensitivity thermographic cameras it is possible to record surface temperature distribution of the tested object (specimen) and thus obtain among other things a new information about physical phenomena connected with loading and the change of strain state in structural members. This research focuses on phenomena related to temperature changes induced by monotone tension and compression load (i.e. Litwinko and Oliferuk, 2009; Lipski, 2014a; Lipski and Boroński, 2012) and fatigue load under both uniaxial and multi-axial loading (i.e. Doudard et al., 2007; Poncelet et al., 2010; Lipski and Skibicki, 2012; Skibicki et al., 2013). Based on these and other works it is possible to introduce new strength testing methods, including those related to the fatigue of materials and structures.

The S-N curve and the fatigue limit are basic parameters defining fatigue strength properties of the material under cyclic load, particularly in case of so called stress approach. The fatigue tests are long-lasting and expensive. For example the minimum number of specimens required to obtain the S-N curve depends on the type of test program conducted and ranges from 12 to 24 for data on design allowables or reliability data (ASTM E 739-91 (Reapproved, 2004)). The fatigue limit can be determined using the Up-and-Down method (also known as Staircase method) widely used all over the world. That method involves consecutive testing of several dozen specimens at 2-10 million cycles, which significantly influences duration of tests. A test of an individual specimen can last even several days, thus making it expensive as well. Hence researchers struggle to develop new or to improve existing methods for accelerated determining of fatigue limit. Thanks to those methods it is possible to significantly cut cost of fatigue tests by reduction of the quantity of specimens and shortening test duration.

One of proven and recognized methods of fatigue limit testing is the Locati method. Using that method it is theoretically possible to estimate fatigue limit based on a single specimen, which is gradually loaded until its failure. Analytical (computational) part of that method is based on the Palmgren-Miner's linear cumulative damage rule. Hoverer, the slope of the S-N curve must be known. The new method of fatigue limit calculation by Locati method where the slope of the S-N curve is determined on the same specimen by thermographic method was presented by Lipski (2014b).

Effects of temperature changes induced by fatigue loading can be used for development of accelerated methods for determining fatigue limit and fatigue curves. The researcher who first used thermography to explore the a surface temperature distribution of a specimen and thereby determine the fatigue limit in year 1986 was Risitano (La Rosa and Risitano, 2000). This method was used or modified, among others, in the works of Luong (1995, 1998), Cura et al. (2005) and Galietti et al. (2014). According to a similar concept, the fatigue limit is determined using the Lock-In method (Li et al, 2012, Kordatos, 2013). In these studies the fatigue limit is determined as a rule for axial load based on the assumption that there is temperature stabilization period in phase 2 of the fatigue life (Fig. 1 – line A). Luong also used Risitano methodology to determine the fatigue limit of XC55 steel under four-point rotating bending with 100 Hz of loading frequency.

The thermography can be also used to rapid determination of the fatigue curve. Fargione et al. (2002) proposed that the integration of the area under the temperature rise over the entire number of cycles of a specimen (area under line A – Fig. 1, especially under line A in phase 2) remains constant and is independent of the stress amplitude, thus representing a characteristic of the material. Amiri and Khonsari (2010a, 2010b) used the rate of temperature rise in phase 1 for prediction of fatigue failure.

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However not all materials show temperature stabilization period during fatigue life in phase 2. This fact significantly limited the use of previously developed thermographic methods of rapid determination of the fatigue limit.

A new thermographic method for simultaneous determination of the fatigue limit and the S-N curve was presented in this paper. The fatigue limit determination method based on a constant rate of temperature rise occurring in phase 2 of fatigue life (Fig. 1 - line B). The S-N curve determination method is based on the parameter proposed by Fargione et al. (2002) with assumption of its dependency on the stress amplitude. Because this parameter is proportional to energy dissipated under cyclic load which is dependent on the stress level (Golański and Mroziński, 2012) then this assumption seems to be more appropriate.

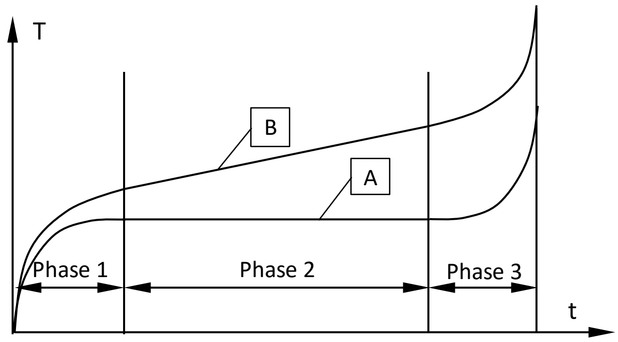

Fig. 1. The change in the temperature T during the fatigue test for material featuring phase 2 temperature stabilization (line A) and a constant rate of temperature rise (line B)

2. TEST DESCRIPTION

2.1. Test station

The tests were performed in the Department Laboratory for Research on Materials and Structures (certified by the Polish Centre for Accreditation – PCA AB 372) of the Faculty of Mechanical Engineering at the UTP University of Science and Technology using the reversed bending fatigue testing machine (with rotational frequency of 77 Hz).

The main item of the test station was the thermographic camera CEDIP Silver 420M (FLIR SC5200) equipped with high sensitivity InSb matrix cooled using Stirling pump.

Main parameters of the camera:
- resolution of sensor: 320x256 pixels, pitch 30 μm,
- spectral range 3.6÷5.0 μm,
- sensitivity below 20 mK (available: 8 mK),
- maximum frequency 140 Hz for the entire matrix (up to 25 kHz at lower resolution).

The thermographic camera recorded (at the constant frequency from 100 to 450 Hz depending on load level) the surface temperature distribution of the tested object (specimen) fixed in the testing machine. Camera images were transmitted via USB interface to PC with appropriate software, where they were digitally stored directly on HDD in form of PTW format files.

The following software was installed in the computer:
- VirtualCAM allowing two-way communication between PC and the thermographic camera via USB 2.0 interface,
- CIRRUS Front End which was the user interface used to control the CEDIP camera,
- ALTAIR allowing downloading, storage and advanced processing of thermographic images.

2.2. Test specimen

Test specimens were made of cold-drawn bars from corrosion resistant austenitic X5CrNi18-10 (1.4301) steel. The proof stress for this steel $R_{p0.2}$ is 706 MPa and the ultimate tensile strength R_m is 798 MPa.

Chemical composition of the specimen material is specified in Tab. 1.

Tab. 1. Chemical composition of the specimen material (wt %)

	C	Mn	Si	P	S	Cr	Ni	N
Acc. to PN-EN 10088-1:2014-12	≤0.07	≤2	≤1	≤0.045	≤0.015	17÷19.5	8÷10.5	≤0.11
For tested specimens	0.02	1.53	0.61	0.07	0.016	18.75	8.22	-

The geometry of applied specimens is shown in Fig. 2.

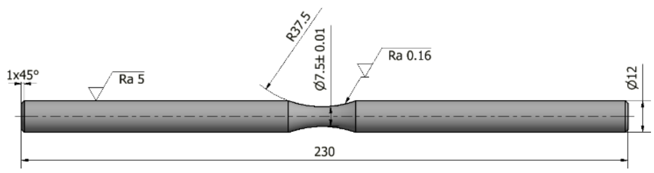

Fig. 2. Geometry of specimens used for tests

3. FULL TEST RESULTS

3.1. Fatigue limit

The fatigue limit was obtain by Staircase method assuming the base of 10^7 cycles. 35 specimens were tested (Fig. 3). The lowest alternating stress level S_0 was 260 MPa and the stress increment ΔS was 5 MPa. The fatigue limit obtained from Dixon & Mood relations S_e is 278.2 MPa with standard deviation S_s = 7.4 MPa.

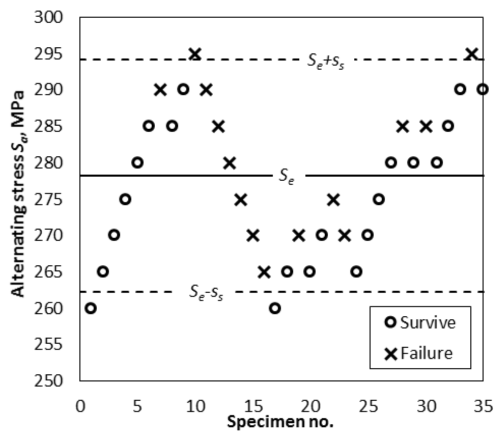

Fig. 3. The Staircase data for X5CrNi18-10 steel under reversed bending

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3.2. S-N curve

18 specimens at 6 load levels were tested for the fatigue S-N curve determination. The lowest alternating stress level S_a was 320 MPa, the highest was 495 MPa. The test results and the S-N curve with confidence interval for the significance level α = 0.05 were presented in Fig. 4.

The Basquin relationship obtained from linear regression (R^2 = 0.98) of test results is

$$S_a^m \cdot N = C, \tag{1}$$

where m = 10.38 and C = 5.12·10[31].

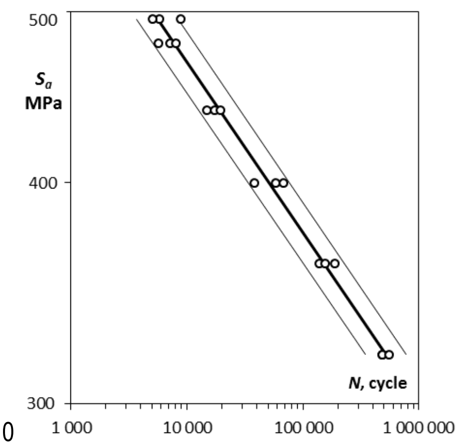

Fig. 4. The S-N curve for X5CrNi18-10 steel under reversed bending

3.3. Thermographic tests

12 specimens at 5 load levels were tested using thermographic camera in constant amplitude loading conditions. The lowest alternating stress level S_a was 320 MPa, the highest was 480 MPa. The change of the surface temperature of selected specimens during tests were presented in Fig. 5 where T = 0°C for N = 0 corresponds to initial specimen temperature of 23-25°C.

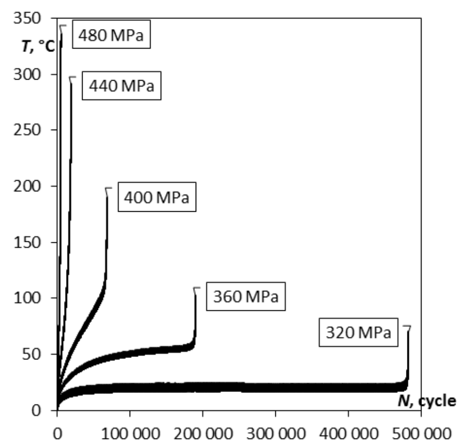

Fig. 5. Samples of the $T - N$ curves for X5CrNi18-10 steel under reversed bending

The specimen mean temperature changes presented in Fig. 5 were generated by internal energy increase which can be estimated based on the following relation:

$$\Delta I = c_v \cdot \rho \int_0^{N_{failure}} T(N) \cdot dN, \tag{2}$$

where: c_v – specific heat at constant volume; ρ – density; dN – cycle increment; $N_{failure}$ – number of loading cycles until fatigue failure. Because cv and ρ are constant for specimens from the same material the internal energy change can be taken into account as the area under $T = f(N)$ curve (Fig. 10):

$$\Phi = \int_0^{N_{failure}} T(N) \cdot dN. \tag{3}$$

The dependence of energy-related parameter Φ on load level S_a were presented in Fig. 6. The Basquin-similar relationship obtained from linear regression (R^2 = 0.93) of test results is:

$$S_a^k \cdot \Phi = B, \tag{4}$$

where k = 6.91 and B = 4.03·10[22].

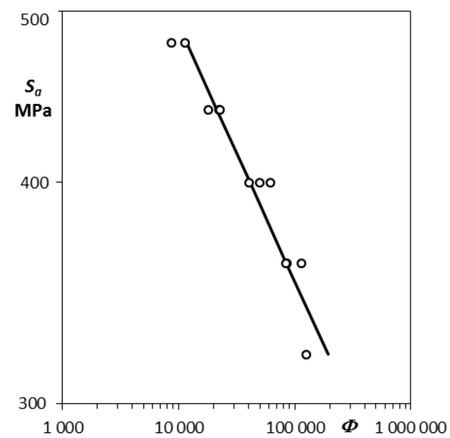

Fig. 6. The dependence of Φ parameter on load level S_a for X5CrNi18-10 steel under reversed bending

4. ACCELERATED TEST RESULTS

The fatigue limit and the S-N curve were determined in one gradually increasing loading test. The lowest alternating stress level S_{a1} was 230 MPa and the stress increment ΔS was 10 MPa. ΔN for each load level was 30 000 cycles. The test was made at the same load frequency of 77 Hz as the full test. The change of the surface temperature of selected specimen during test was presented in Fig. 7 where T = 0°C for N = 0 corresponds to initial specimen temperature 19°C.

Tab. 2. Summary of fatigue life for the individual specimens from X5CrNi18-10 steel under reversed bending in the accelerated tests

		Specimen		
		No. 1	No. 2	No. 3
Fatigue failure level	i	18	17	16
Failure stress, MPa	S_k	400	390	380
Total fatigue life, cycle	N_c	518 400	487 300	457 600

Theoretically accelerated test can be made using only one specimen, but in practice tests on three samples can increase the accuracy of estimates. Tab. 2 shows total fatigue life achieved by each sample.

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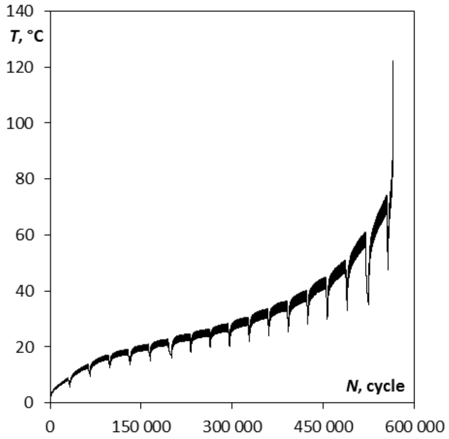

Fig. 7. Sample of the $T-N$ curve for X5CrNi18-10 steel under accelerated test

The T-N curve (Fig. 7) obtained from gradually increasing loading test was cut into individual T-N curves for the different load levels (Fig. 8). The reference level of the temperature was the initial temperature of the specimen.

5. ANALYSIS OF THE ACCELERATED TEST RESULTS

5.1. Fatigue limit

T-N curves for each load level S_a (Fig. 8) were examined for the temperature change rate $\Delta T/\Delta N$. For the period of its stabilization its average value was determined and plotted on $\Delta T/\Delta N - S_a$ plot (Fig. 9). It can be noted that these results are characterized by the minimum that can be connected with the fatigue limit. Close to the fatigue limit the other processes of material degradation significantly affect the energy balance of the whole specimen, so that less energy will raise the temperature of the specimen. Once the fatigue limit value is exceeded, there is increase of the specimen. The temperature change rate for failure level was excluded from the analysis concerning the fatigue limit.

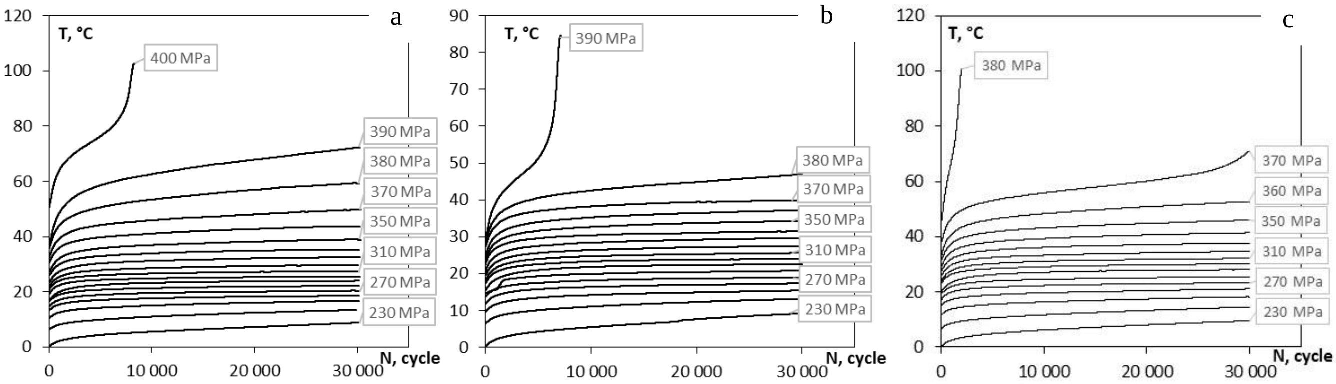

Fig. 8. Cut T-N curves for different load levels for each specimen: a) Specimen No. 1, b) Specimen No. 2, c) Specimen No. 3

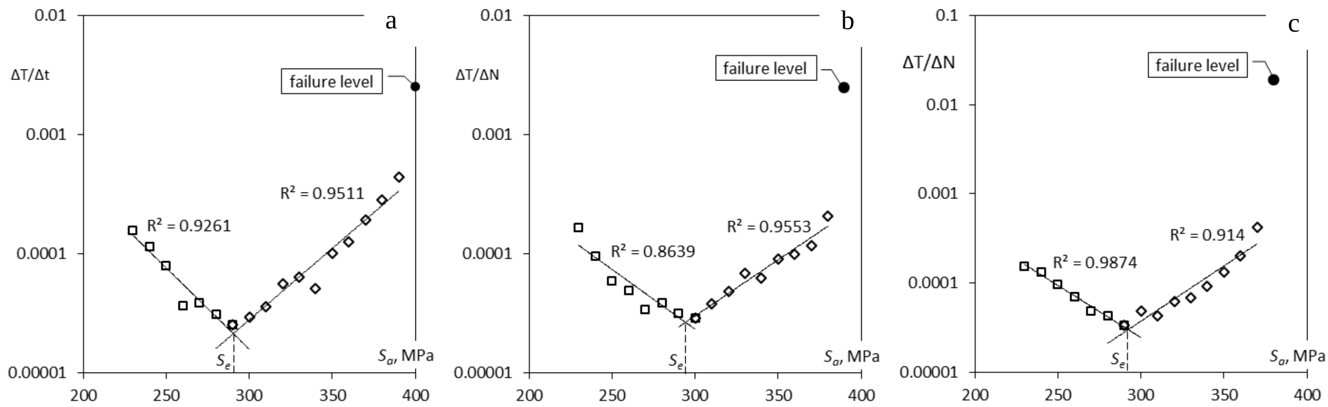

Fig. 9. The $\Delta T/\Delta N - S_a$ plots for fatigue limit S_e determination: a) Specimen No. 1, b) Specimen No. 2, c) Specimen No. 3

Tab. 3 shows the fatigue limit obtained by the thermographic method on the base of Fig. 9 for each specimen.

Value of the fatigue limit obtained from the accelerated thermographic tests in relation to the value obtained from the full test differs by 5.0 %.

Tab. 3. Fatigue limit obtained for the individual specimens of X5CrNi18-10 steel under reversed bending in the accelerated thermographic tests

		Specimen		
		No. 1	**No. 2**	**No. 3**
Fatigue limit, MPa	S_e	290.4	294.3	292.4
		292.4		

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5.2. S-N curve

The same data used for the fatigue limit determination (Fig. 8) was used for the S-N curve determination. It was assumed that under the gradually increasing loading test at each load level only part of the total internal energy represented by parameter φ was measured (Fig. 10):

$$\varphi = \int_0^{N_{step}} T(N) \cdot dN, \tag{5}$$

where: N_{step} = ΔN = 30 000 cycles.

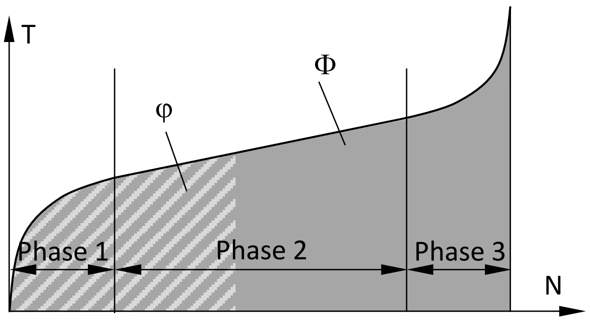

Fig. 10. Schematic representation of energy-related parameter Φ and φ

The Palmgren-Miner's hypothesis in its energy-related version can assume the following form (Kaleta, 1998):

$$\sum_{i=1}^{q} \frac{\varphi_i}{\Phi_i} = 1 \quad \text{for} \quad S_{ai} \geq S_e. \tag{6}$$

Assuming that the relationship between energy related parameter Φ_i for full test and load S_{ai} on level i is described by formula (4):

$$S_{ai}^k \cdot \Phi_i = B \quad \Rightarrow \quad \Phi_i = \frac{B}{S_{ai}^k} \tag{7}$$

and putting (7) into (6):

$$\sum_{i=1}^{q} \frac{\varphi_i}{\frac{B}{S_{ai}^k}} = 1 \quad \Rightarrow \quad \sum_{i=1}^{q} S_{ai}^k \cdot \varphi_i = B \tag{8}$$

is obtained:

$$\sum_{i=1}^{q} S_{ai}^{\boldsymbol{k}} \cdot \varphi_i - B = 0. \tag{9}$$

where: there are two unknown parameters B and k of the $S_a = f(\Phi)$ curve which can be determined numerically. Then it is possible to determine the values of Φ_i at the level i by using equation (7).

Fatigue life on level i can be estimated based on the following proportions:

$$\frac{\varphi_i}{\Phi_i} = \frac{n_i}{N_i} \quad \Rightarrow \quad N_i = \frac{\varphi_i}{\Phi_i} \cdot n_i. \tag{10}$$

Tab. 4 shows parameters (equations (1) and (4)) obtained by presented method.

The $S - N$ curves estimated for the individual specimens were presented in Fig. 11.

The individual estimated fatigue life data obtained from equation (10) for all three specimens has been used as a data to estimate one S-N curve (Fig. 12). It can be observed that the S-N curve obtained by the accelerated thermographic method fits inside the 95 % confidence interval for the S-N curve developed based on full test which proves good consistency of the results of presented method.

Tab. 4. Parameters obtained for the individual specimens of X5CrNi18-10 steel under reversed bending in the accelerated thermographic tests

	k	B	m	C
Full test	6.914	$4.03 \cdot 10^{22}$	10.377	$5.12 \cdot 10^{31}$
Specimen No. 1	6.408	$4.00 \cdot 10^{21}$	10.157	$2.63 \cdot 10^{31}$
Specimen No. 2	6.500	$4.10 \cdot 10^{21}$	9.196	$6.75 \cdot 10^{28}$
Specimen No. 3	6.500	$4.00 \cdot 10^{21}$	9.456	$2.30 \cdot 10^{29}$
Specimen No. 1-3	-	-	9.603	$5.87 \cdot 10^{29}$

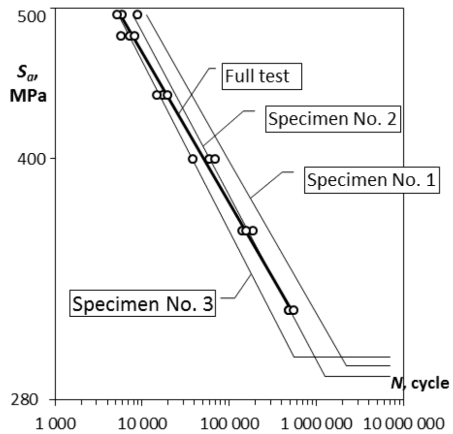

Fig. 11. The S-N curves estimated for individual specimens on the background of the full test results

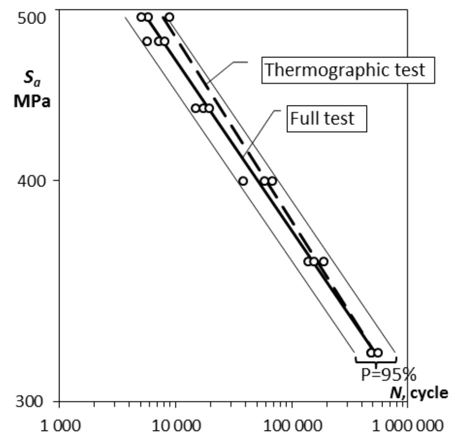

Fig. 12. Comparison of estimated S-N curve obtained by the accelerated thermographic method and the S-N curve obtained from full test

6. SUMMARY

The presented new thermographic method enables accelerated simultaneous determination of the fatigue limit and the S-N curve. The fatigue limit determination method is based on a constant rate of temperature rise occurring in phase 2 of the fatigue life. The S-N curve determination method is based on the energy-related parameter with the assumption of its dependency on the stress amplitude.

The tests made on X5CrNi18-10 steel under reversed bending revealed that the fatigue limit value obtained from the accelerated thermographic tests as compared to the value obtained from full test differs by 5.0 %. The S-N curve obtained by accelerated thermographic method fits inside the 95 % confidence interval for the S-N curve obtained from full test.

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