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An Experimental Study on Fatigue Properties Determination by Using Quantitative Infrared Thermography

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Abstract

The paper presents an experimental study for the determination of the fatigue strength and fatigue limit of C45E steel and C35 steel widely used for mechanical construction; using both traditional methods (Wöhler curve, Locati and staircase method) and the quantitative infrared ***(IR)*** *thermographic method based on measuring the surface temperature of tested samples.*

The evaluation of fatigue behavior and fatigue properties of materials, mechanical and structural components is very important in component design to avoid fatigue failures. Among many reliable experimental techniques used for the assessment of fatigue behavior of mechanical structures, a relatively new technique is based on infrared thermography.

The fatigue damage produced by cyclic loading is characterized by heat generation as a result of dissipated strain energy, conducting to an increase of surface temperature of the component. The infrared thermography is a nondestructive contactless technique widely used for measurement of the surface temperature distribution of an operating structure or mechanical component. The temperature change during fatigue loading can characterize the fatigue behavior of a component.

The fatigue strength and fatigue limit evaluation of C45E steel and C35 steel is based on rotating bending test performed on 8 mm diameter specimens. The surface thermal increments for each sample during fatigue testing were measured by using a E50 FLIR infrared thermal camera.

The fatigue properties values that were experimentally determined by using of both traditional mechanical testing techniques and the innovative thermal technique are compared, showing that the quantitative infrared thermography provided an accurate means to evaluate the fatigue strength of metallic materials.

Key words: *high cycle fatigue, infrared thermography, fatigue strength evaluation*

Introduction

The fatigue design, the fatigue damage monitoring and proper planning of maintenance activities of dynamically loaded structural and mechanical components are based on knowledge of their fatigue behavior and fatigue properties. Different methods, both traditional and innovative, are proposed to assess the fatigue behavior and to estimate the fatigue strength and the fatigue life of materials and components.

The fatigue process determined by cyclic loading is characterized by heat generation as a result of the dissipated strain energy. So, the temperature change during fatigue loading offers a means for fatigue characteristics evaluation.

The infrared (***IR***) thermography is a nondestructive control technique widely used for measurement of the surface temperature, temperature growth and surface temperature distribution of an operating structure, mechanical components or tested samples.

In recent years a great number of scientific papers have been reported presenting the application of this experimental technique to investigate the fatigue process of materials and components as well as to evaluate the fatigue strength and fatigue life by measuring the surface temperature evolution of a specimen during cyclic loading [2, 5, 8, 12, 17, 18].

In this paper an experimental evaluation of the fatigue properties of C45E and C35 carbon steel is presented using both mechanical and thermal methods.

The fatigue behavior was experimentally evaluated by constructing the Wöhler / $S - N$ curve (S – stress, N – number of cycles to failure), using the conventional constant amplitude test method. The fatigue limit was determined by applying the Locati method, based on the results of high cycle fully reversed bending fatigue tests as well as by the staircase method [7,9].

A distinction must be made between the fatigue strength and the fatigue limit. The fatigue strength (at N cycles) is the value of stress under which the material will fail at exactly N cycles as determined from $S - N$ diagram. The fatigue limit or endurance limit is the limiting value of the fatigue strength, as the fatigue life becomes very large (for instance 10^7 cycles).

The damage evaluation for each tested sample was also monitored by measuring the increase of the surface temperature using the infrared thermography, in order to correlate the temperature evaluation with the mechanical fatigue characteristics.

The experiments show that the surface temperature of the specimen is related to the value of applied bending stress. The surface temperature of the specimen is quite stationary not depending on the stress amplitude value, as long as the stress amplitude is under the fatigue limit. For stress amplitudes exceeding the fatigue limit, the sample surface temperature exhibits an abrupt increase. As a consequence, it is proposed to estimate the fatigue limit as the maximum stress amplitude that does not produce a significant temperature increase of the specimen subjected to fatigue, showing a good agreement with other experiments. [1,14,15]

Experimental Procedure

Testing procedure

The rotating beam fatigue behavior of C45E carbon steel has been determined on eight samples using the conventional constant amplitude fully reversed test method and plotting the fatigue data in from of Wöhler / S – N Curve (S – stress vs. N – number of cycles to failure). The fatigue limit was determined by using the Locati accelerated fatigue testing technique and for C35 carbon steel by using the staircase method. All fatigue tests were carried out at a frequency of *80 Hz* using a Walter + Bai Rotary Bending Testing Machines Type UBM *0.5 - 60 Nm*. The Locati method consists in applying a stepwise increasing load for *50000* cycles for each loading step, until the failure of the sample. The fatigue limit is analytically determined based on Miner’s cumulative damage concept.

For the staircase method ten specimens were tested. The first specimen was tested at estimated fatigue strength for 10^7 cycles or until it fails prematurely. The following specimen was tested at a stress higher or lower than the stress for the first specimen, depending on whether the first specimen survived or failed and so on. The fatigue limit and the standard deviation are estimated based on statistical approach.

For each tested specimen the infrared thermography was used to record the temperature evolution from the beginning of the experiment until failure.

Material and specimens

The tests were performed on C45E normalized steel and C35 quenched steel, from two different melts and thermal treatments. One set of samples, from C45E steel, was used for Wöhler and Locati test and the sample from the C35 steel were used for fatigue limit determination applying the staircase method. The chemical compositions of the tested materials are presented in Table 1.

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

	C	Si	Mn	Ni	P	S	Cr	Mo
C45E En 10083 – 2 2006	0.42 – 0.50	Max. 0.4	0.5 – 0.8	Max. 0.4	Max. 0.03	Max. 0.035	Max. 0.4	Max. 0.1
C45E - determined with spectrograph	0.46	0.14	0.68	0.06	0.018	0.021	0.16	0.04
C35 En 10083 – 2 2006	0.32 – 0.39	Max 0.4	0.5 - 0.8	Max 0.4	Max 0.045	Max 0.045	Max 0.4	Max 0.1
C35 - determined with spectrograph	0.35	0.56	0.54	0.02	0.014	0.008	0.09	0.01

The mechanical properties of the tested steels are presented in Table 2.

Table 2. Mechanical properties of the tested steels

	Ultimate tensile strength R_m [N/mm^2]	**Yield stress R_e or 0.2% proof strength $R_{p0.2}$ [N/mm^2]**	**Min. elongation at fracture A [%]**
C45E En 10083 – 2 2006	530 - 620	340 - 455	14 – 16
C45E – determined in lab	585	438	18
C35 En 10083 – 2 2006	650 - 1000	3210 - 510	18 - 19
C35 – determined in lab	890	648	16

The round bar smooth specimens have been cut from a 19 mm diameter laminate bar. The geometry and the dimensions of the samples are presented in Figure 1, according to [20].

In order to increase the thermal emissivity of the specimen surface for infrared temperature measurements the surface of the specimen was black painted.

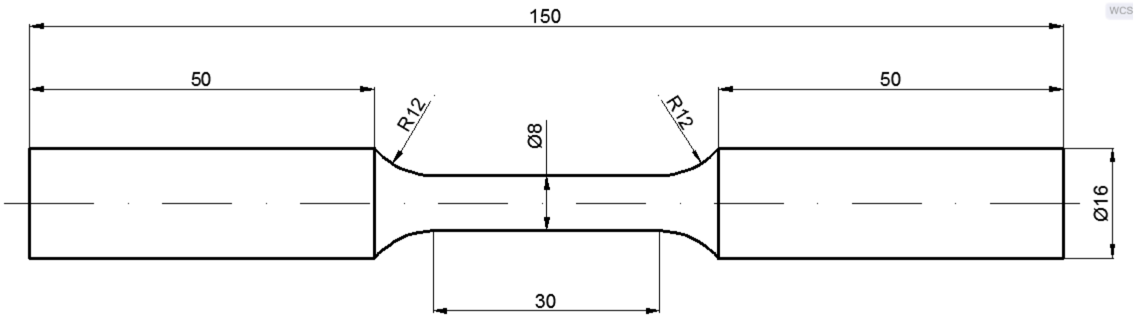

Fig. 1. Geometry and dimensions of the specimen

Application of the infrared thermographic method

The surface temperature in the mid position of each sample was acquired every *5* seconds during fatigue tests using an infrared camera type E50 FLIR, placed approximately at *1000* mm from the surface of the specimen, as is presented in Figure 2.

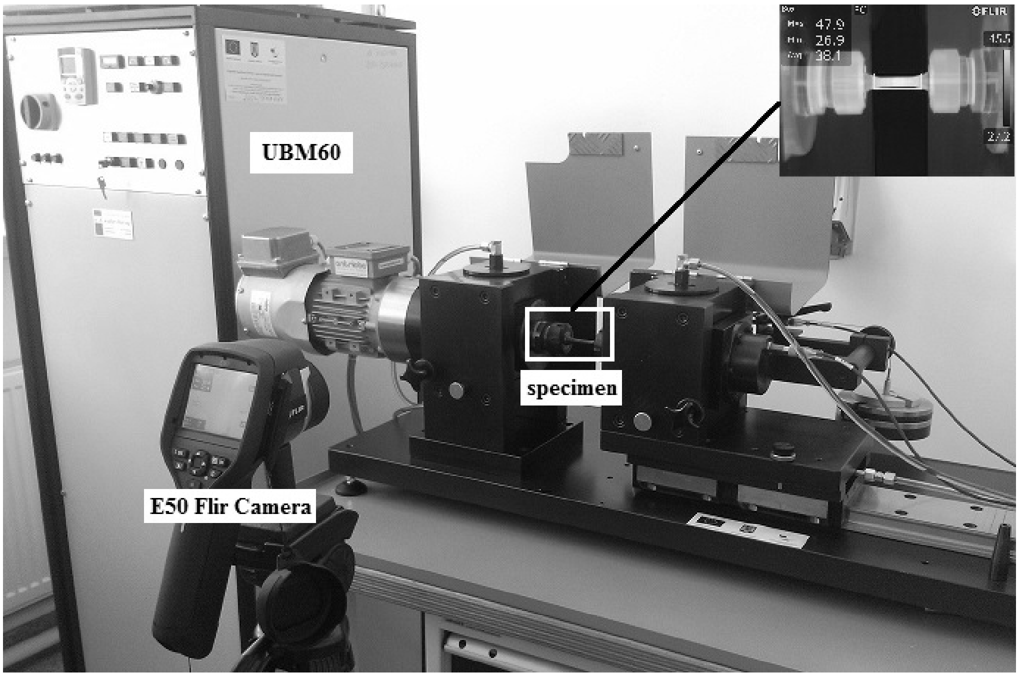

Fig. 2. Experimental setup

A dedicated software FLIR Tools Plus was used for processing the acquired data.

Results and Discussions

Based on constant amplitude fully reversed fatigue test the obtained $S-N$ curve in the finite life region is shown in Figure 3 as the curve fitted to the fatigue life values of samples tested at different load levels.

The fatigue limit of C45E steel for fully alternating bending stress was determined by using the Locati method as well as staircase method.

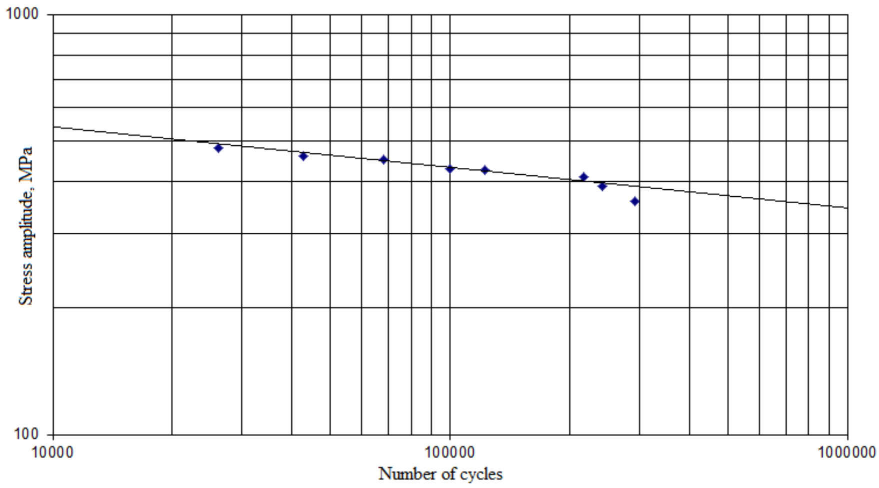

Fig. 3. Rotating beam fatigue (Wöhler) curve for C45E steel, $R = -1$

For Locati method one sample was stepwise loaded for 50000 cycles at stress increments of 20 MPa, starting with 350 MPa until 450 MPa, when the sample failed. The calculated fatigue limit values based on linear cumulative damage concept for different specified number of cycles are presented in Table 3.

Table 3. The fatigue strength for a specified number of cycles by Locati method

Number of cycles	Fatigue limit MPa
$1 \cdot 10^6$	360
$2 \cdot 10^6$	337
$5 \cdot 10^6$	309
10^7	289

The fatigue limit at 10^7 cycles for C35 steel, σ_l, was determined by using the staircase method. The data are analyzed as shown in Figure 4.

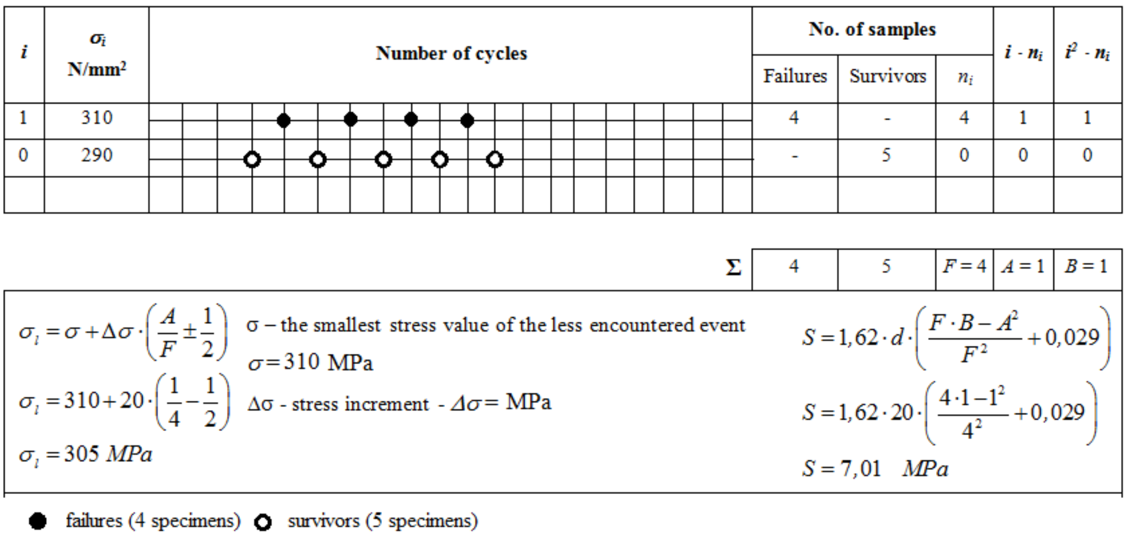

Fig. 4. Staircase test results

The experimentally determined fatigue strength is 305 MPa.

The $S - N$ curve offers the possibility to determine the fatigue strength at N cycles, σ_N, as the value of stress for failure at exactly N cycles, as defined in [19]. The determined values of fatigue strength are presented in Table 4.

Table 4. The fatigue strength for a specified number of cycles

Number of cycles N	**Fatigue strength,** σ_N **MPa**
$2 \cdot 10^6$	400
$5 \cdot 10^6$	380
10^7	340

The evaluation of cumulative damage in fatigue process was monitored by measuring the surface temperature evolution of each tested sample by means of thermographic technique. Figure 5 presents the surface temperature evaluation of steel specimens during fatigue tests. The temperature presents a rapid increase at the beginning of the test, than the temperature reaches a stabilized value, when the heat generation balances the energy dissipation. In the final stage just before the fatigue failure a sudden rise of the temperature occurs. The stationary temperature achieved during fatigue test is higher with increasing the applied stress amplitude, $\sigma_{a.}$

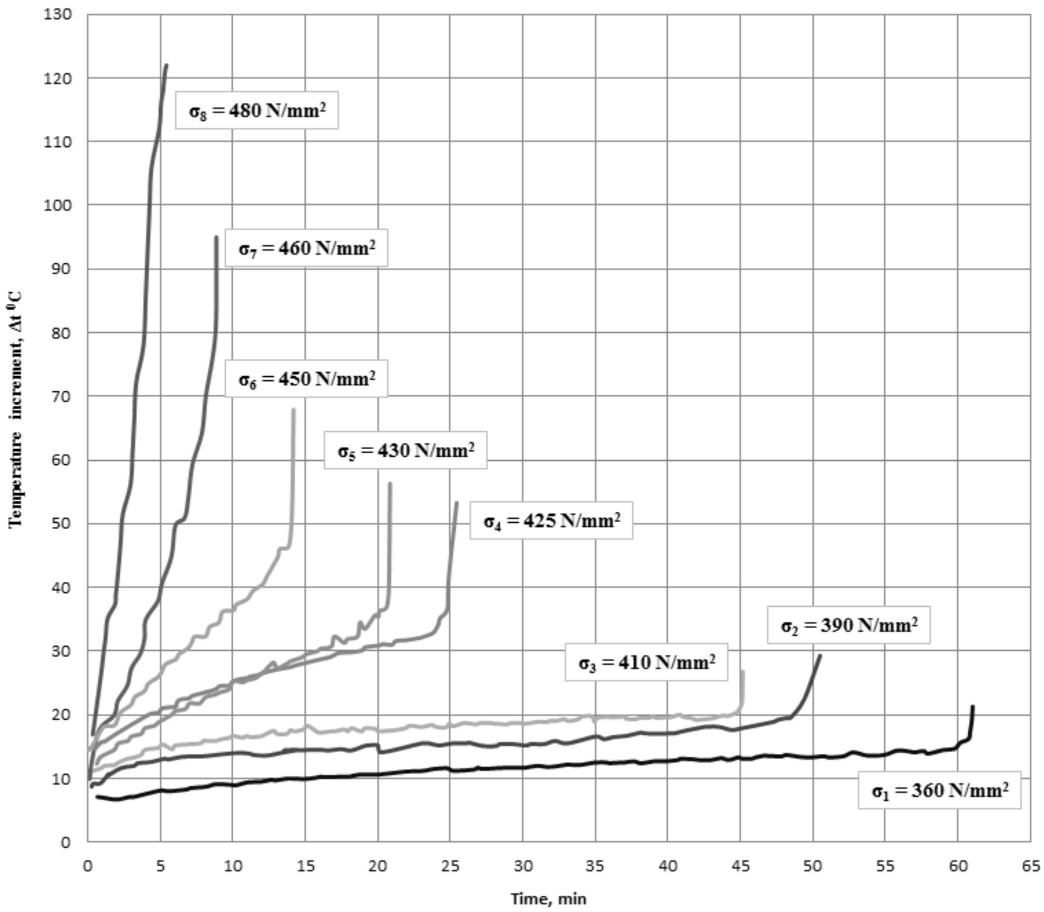

Fig. 5. Temperature increment evolution during constant amplitude fatigue tests

The temperature increment values, Δt, versus the stress amplitude are plotted in Figure 6.

Considering the fatigue limit as the maximum value of the stress amplitude that does not produce a measurable damage, expressed as temperature increase of the specimen subjected to fatigue, the criteria for fatigue limit estimation will be the abrupt increase of the specimen temperature. As shown in Figure 6, the fatigue limit will correspond to the point of intersection of the regression lines for stress levels below the fatigue limit, when the increment in temperature is practically negligible, and above the fatigue strength, with an abrupt increase of the sample temperature. The graphically determined fatigue limit in Figure 6 is 410 MPa.

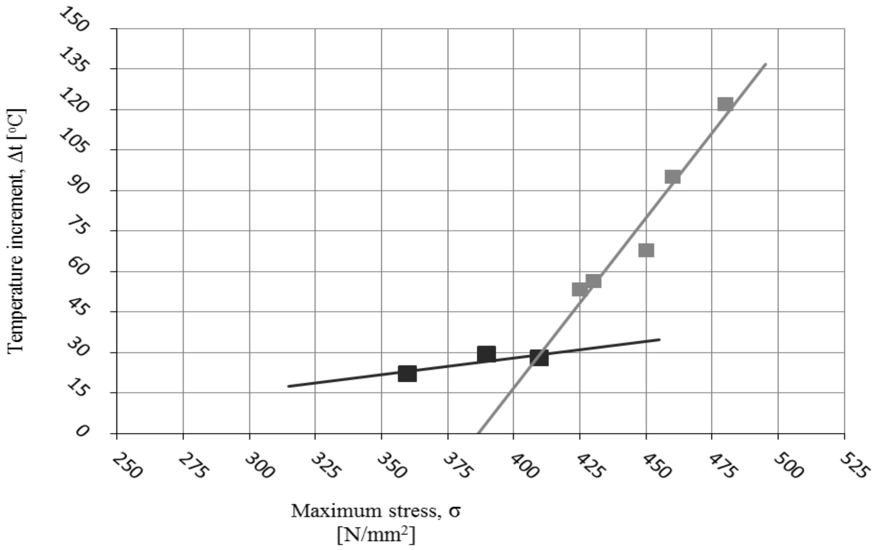

Fig. 6. Fatigue limit prediction based on linear interpolation of the temperature increment data

In literature is also proposed to graphically determine the fatigue limit as the point of intersection of the regression line representing the abrupt increase of the temperature to abscissa / zero temperature increase [14]. The estimated fatigue limit based on the proposed procedure is 385 MPa.

The temperature evolution of the specimen tested according to the Locati method is shown in Figure 7.

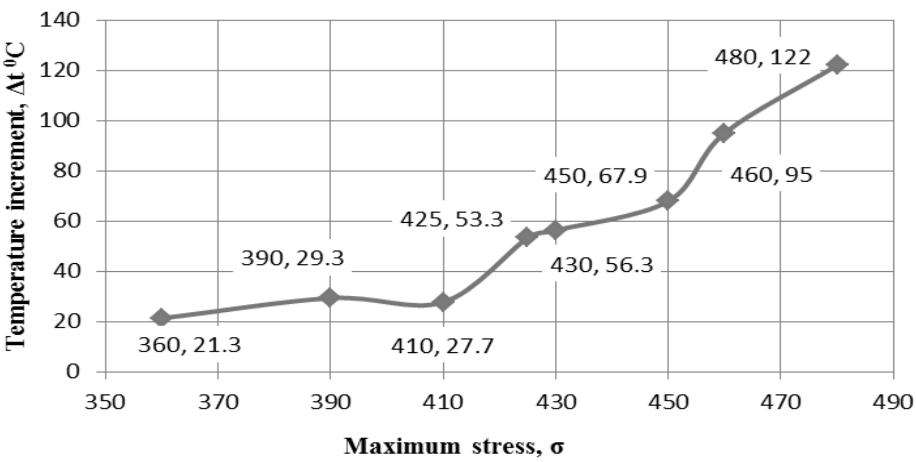

Fig. 7. Temperature increment vs. stress amplitude for Locati method

The experimental data show that starting with approximate 390 MPa, the sample temperature presents an abrupt increase, indicating the initiation of the fatigue failure process. Thus, the estimated fatigue limit is 390 MPa. The Locati method offers the possibility to estimate the fatigue limit by measuring the temperature increment of only one stepwise loaded tested specimen.

Figure 8 shows the evolution of temperature increment vs. time for specimen tested in the staircase experiment for C35 steel. There exists a significant difference between the surface temperature increment of about 35^{0}C reached by all failed specimens at 310 MPa stress amplitude and the temperature increment less than 20^{0}C for all not failed (survivors) specimens tested under 310 MPa stress amplitude. Thus, based on infrared thermographic technique the fatigue limit can be estimated at a value slight smaller than 310 MPa, which corresponds to a sudden increase of the dissipated thermal energy. This technique offers a rapid means to estimate the fatigue limit, because the temperature increment reaches its stabilized value after a few numbers of cycles (10 – 15 minutes).

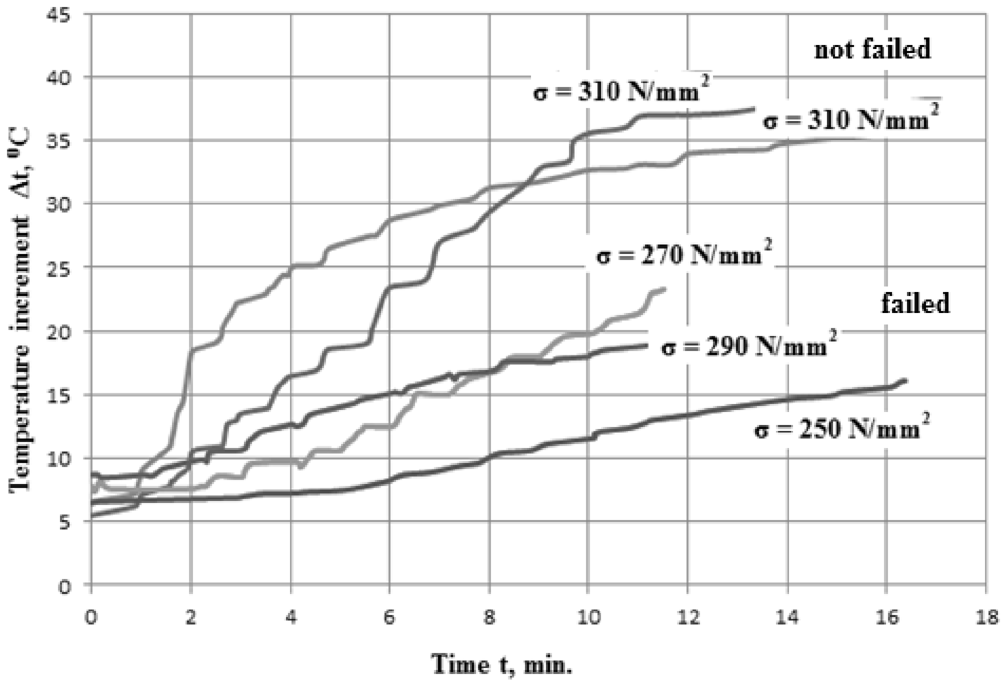

Fig. 8. Temperature increment vs. time for staircase method

The fatigue limit values estimated by means of infrared thermographic technique are compared to the values estimated by using traditional mechanical testing as shown in Table 5.

Table 5. Fatigue limit estimations

Fatigue test	**Fatigue limit, MPa**	
	Mechanical testing	*IR thermography*
S – N curve	400 for $2\cdot10^6$ 380 for $5\cdot10^6$ 340 for 10^7	410 – first procedure 385 – second procedure
Locati	360 for 10^6 337 for $2\cdot10^6$ 309 for $5\cdot10^6$ 289 for 10^7	390
Staircase	305	310

The experimental results confirm the applicability of the quantitative infrared thermographic method to predict the fatigue limit with acceptable accuracy.

Conclusions

The high cycle bending fatigue experiments were performed in order to estimate the fatigue limit of C45E and C35 steel, using both traditional mechanical fatigue tests and quantitative infrared technique. The estimated fatigue limit, based on thermal techniques, showed a very good agreement with the estimated values obtained by using the conventional Wöhler curve determination in the finite life region, the Locati stepwise loading and the staircase methods.

The infrared thermographic technique used to assess the fatigue damage by measuring the thermal increment evolution of the specimen during fatigue testing, provides a valid, nondestructive tool for rapid estimation of high cycle fatigue properties.

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References

1. Amiri, M., Khonsari, M.M. – Rapid determination of fatigue failure based on temperature evolution: Fully reversed bending load, *International Journal of Fatigue*, **32**, 2010, pp. 382–389.
2. Colombo, C., Libonati, F., Pezzani, F., Salerno, A., Vergani, L. – Fatigue behaviour of a GFRP laminate by thermographic measurements, *Procedia Engineering*, **10**, 2011, pp. 3518–3527.
3. Cura, F., Curti, G., Sesana, R. – A new iteration method for the thermographic determination of fatigue limit in steels, *International Journal of Fatigue*, **27**, 2005, pp. 453–459.
4. Deubelbeiss, E.E. – Dauer fastigkeitsveisuche mit einem modifizierten treppenstufen – verfahren, *Material prufung*, **16**, n. 8, 1974, pp. 240 – 244.
5. Earls, C.J. – Stochastic inverse thermographic characterization of sub-pixel sized through cracks, *Mechanical Systems and Signal Processing*, **30**, 2012, pp. 146–156.
6. Ezanno, Doudard, C., Calloch, S., Millot, T., Heuzé, J.-L. – Fast characterization of high-cycle fatigue properties of a cast copper–aluminum alloy by self-heating measurements under cyclic loadings, *Procedia Engineering*, **2**, 2010, pp. 967–976.
7. Fan, J.L., Guo, X.L., Wu, C.W., Zhao, Y.G. – Research on fatigue behavior evaluation and fatigue fracture mechanisms of cruciform welded joints, *Materials Science and Engineering*, A 528, 2011, pp. 8417– 8427.
8. Fernández-Canteli, A., Castillo, E., Argüelles, A., Fernández, P., Canales, M. – Checking the fatigue limit from thermographic techniques by means of a probabilistic model of the epsilon–N field, *International Journal of Fatigue*, **39**, 2012, pp. 109–115.
9. Lagüela, S., González-Jorge, H., Armesto, J., Arias, P. – Calibration and verification of thermographic cameras for geometric measurements, *Infrared Physics & Technology*, **54**, 2011, pp. 92–99.
10. Li, X.D., Zhang Wu H., D.L., Liu, X., Liu, J.Y. – Adopting lock-in infrared thermography technique for rapid determination of fatigue limit of aluminum alloy riveted component and affection to determined result caused by initial stress, *International Journal of Fatigue*, **36**, 2012, pp. 18–23.
11. Meneghetti, G. – Analysis of the fatigue strength of a stainless steel based on the energy dissipation, *International Journal of Fatigue*, 29, 2007, pp. 81–94.
12. Montesano, J., Zouheir, F., Bougherara, H. – Use of infrared thermography to

investigate the fatigue behavior of a carbon fiber reinforced polymer composite, *Composite Structures*, **97**, 2013, pp. 76–83.
13. Müller-Bollenhagen, C., Zimmermann, M., Christ, H.-J. – Very high cycle fatigue behaviour of austenitic stainless steel and the effect of strain-induced martensite, *International Journal of Fatigue*, 2010, pp. 936–942.
14. Naderi, M., Khonsari, M.M. – An experimental approach to low-cycle fatigue damage based on thermodynamic entropy, *International Journal of Solids and Structures*, **47**, 2010, pp. 875–880;
15. Pastor, M.L., Balandraud, X., Grediac, M., Robert, J.L. – Applying infrared thermography to study the heating of 2024-T3 aluminium specimens under fatigue loading, *Infrared Physics & Technology*, **51**, 2008, pp. 505–515.
16. Steinberger, R., Valadas, Leitao, T.I., Ladstatter, E., Pinter, G., Billinger, W., Lang, R.W. – Infrared thermographic techniques for non-destructive damage characterization of carbon fibre reinforced polymers during tensile fatigue testing, *International Journal of Fatigue*, **28**, 2006, pp. 1340–1347.
17. Ummenhofer, Th., Medgenberg, J. – On the use of infrared thermography for the analysis of fatigue damage processes in welded joints, *International Journal of Fatigue*, **31**, 2009, pp. 130–137.
18. Wang, X.G., Crupi, V., Guo, X.L., Zhao, Y.G. – Quantitative Thermographic Methodology for fatigue assessment and stress measurement, *International Journal of Fatigue*, **32**, 2010, pp. 1970–1976.
19. * * * – ASTM E 1823-96 (reapproved 2003), *Standard terminology relating to fatigue and fracture testing.*
20. * * * – SR ISO 1143. *Materiale metalice. Încercarea la oboseală prin încovoiere rotativă a barelor*.

Cercetări experimentale privind determinarea limitei de oboseală utilizând termografia cantitativă în infraroşu

Rezumat

Lucrarea prezintă un studiu experimental pentru determinarea rezistenței şi limitei de oboseală pentru două oțeluri C45E şi C35, utilizate pe scară largă pentru construcții metalice, folosind atât metode tradiționale, precum curba Wöhler, metoda Locati şi/sau metoda treptelor, cât şi prin aplicarea termografiei cantitative in infraroşu, metodă bazată pe măsurarea temperaturii suprafeței de eşantioane testate. Evaluarea comportamentului oboseală şi proprietăților de oboseală ale materialelor diferitelor componente mecanice este foarte important în proiectarea acestora pentru evitarea apariției unor cedări datorate fenomenului de oboseală.