ONLINE EVALUATION OF MATERIAL FATIGUE LIMIT USING INFRARED THERMOGRAPHY

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Abstract

Mechanical testing and cyclic fatigue testing belong to the important material examinations. Standard fatigue testing is mostly time-consuming and needs a number of identical samples that makes the testing expensive. Infrared thermography as a noncontact method of temperature measurement is used in many industrial applications. As the mechanical energy is changed to thermal energy during the cyclic loading, the infrared thermography can be used for fatigue testing. Most of the research regarding fatigue limit evaluation by infrared thermography has been focused on a measured data post-processing. An online evaluation of infrared thermography measurement during a sample cyclic loading is introduced in this contribution.

Keywords: Cyclic fatigue, infrared thermography, online evaluation

1. INTRODUCTION

The material fatigue is a degradation process induced by a cyclic mechanical, thermal or thermo-mechanical loading. It has a cumulative character. Fatigue fractures can occur in the material during its long-time cyclic loading, even if the load is below its yield strength. A determination of the material fatigue properties is more complicated compared to standard mechanical properties tests. The fatigue lifetime depends on a loading force, frequency and time (i.e. number of cycles). It is also significantly influenced by other factors, which are not so important in the case of static loading (surface treatment for example). Knowledge of materials fatigue limits is very important in some applications. However, standard fatigue experiments are very time consuming and expensive with regard to its long-time character [1].

Infrared thermography is an analytic method based on detection of objects radiation in the infrared (IR) range [2]. Intensity of the radiation emitted by an object correlates to temperature and optical properties of its surfaces. The temperature can be therefore evaluated by the infrared radiation measurement if the optical properties of the analyzed surfaces are known. Devices, which detect the infrared radiation and create images corresponding to temperature distribution of analyzed objects (thermograms), are generally called infrared or thermographic cameras. The infrared thermography has a lot of advantages: it is a non-contact method; it does not influence the measured objects; it can be used for monitoring of temperature fields of moving or rotating objects and it can measure a very high temperature. A disadvantage of this method is that the evaluated temperature is, except of a measured object surface temperature, influenced by its thermo-optical properties (emissivity, transmissivity and reflectivity), ambient temperature (surroundings temperature or environment temperature, often so called “reflected temperature”) and atmosphere properties (temperature, transmissivity) [3]. Especially the knowledge of the object optical properties is fundamental for an accurate quantitative thermographic temperature measurement.

2. THERMOGRAPHIC METHODS OF FATIGUE TESTING

Thermographic methods have ambitions to shorten the fatigue testing time. Good spatial resolution, framerate, detectors thermal sensitivity enable their usage for indication of temperature changes in reduced area as a consequence of thermo-mechanical processes during cyclic testing [4]. The first contribution about temperature measurement during fatigue tests originates from Italy in 1990's by A. L. Geracy, G. La Rosa and A. Risitano [5]. They showed that the temperature of specimens, subjected to cyclic loads, increases at a rate determined by the applied load and number of cycles. The temperature in the first stage of its life increases linearly with number of cycles, and load in excess of fatigue limit. The temperature stabilizes in a second stage, and increases rapidly in the third stage, just before fracture.

According to previous research in Italy two main methods were developed [6, 7]. The Method 1 [6] consists of making various constant amplitude fatigue tests with stresses higher than fatigue limit. Each test is considered completed when the quasi-isothermal phase is reached. If temperature difference values are plotted as a function of the stress amplitude it is possible to assess the fatigue limit value by linear extrapolation [6]. The method 1 was used in [8] or [9] for standard flat AISI 304 stainless steel specimen and welded/heat treated tubular specimens of carbon steel 1018 testing. A different approach of the method is based on a stepped loading procedure in which specimen is successively loaded, uninterruptedly, at different stress levels that are higher than the presumed fatigue limit values. One specimen only is used in this case.

The Method 2 [7] consists of a stepped loading procedure which starts from loading levels lower than fatigue limit. If the temperature value reached at the beginning (or at the half or at the end) of a generic step is plotted as a function of an alternate load, it is possible to obtain the fatigue limit of material by a linear approximation of the first and second stage of the temperature increase and finding of an intersection [7]. A disadvantage of this method is that it is based on absolute rather than relative temperature values. For this reason, it is very sensitive to various disturbing phenomena, such as: variation of room conditions, heat transfer by the grips, etc. The Method 2 was used for cast iron testing [10] and XC55 steel testing in [11, 12].

A lot of modified thermographic methods based on the previous original methods were developed. An accelerated method for simultaneous determination of the fatigue limit and a stress-cycle (S-N) curve, which is based on a constant rate of temperature rise occurring in the phase 2, was presented in [4]. The measurement is performed in one gradually increasing loading test and the results obtained fit inside the 95 % confidence interval for the S-N curve based on a full test. An iteration method for the thermographic determination of fatigue limit in steels was presented in [13], where also a usage of a thin opaque black paint layer for an increasing and homogenizing of measured surface emissivity was described. Lock-in method was applied to determine fatigue limit in martensitic and austenitic stainless steels in [14]. The comparison between fatigue analysis by acoustic emission and thermographic techniques was published in [15]. The thermographic technique was used to monitor the temperature evolution of the magnesium alloy and its welding joint specimen during a high-cycle fatigue testing in [16]. Robust thermographic data analysis to fatigue limit evaluation of various martensitic stainless steels was performed in [17]. On-line detection of fretting fatigue crack initiation by lock-in thermography is introduced in [18]. The authors in [19] used the "stepped loading procedure" for two different ductile iron specimens to determine thermal variations and calculate Wöhler curve. Fatigue limit of steel welded joint specimen was evaluated in [20] using lock-in method. Thermography together with a synchronous demodulation was used for a determination of the fatigue behavior of steel and aluminum alloys in [21].

3. EXPERIMENTAL SETUP

Standardized cylindrical-shaped specimens of 10 mm diameter from 15Ch2NMFA steel were used for fatigue measurement experiments. High emissivity paint Dupli-Color Supertherm black 800 °C [1] was applied on surfaces measured by a thermographic camera. The application of the paint made homogeneous and high emissivity surfaces, which enhanced the thermographic measurement accuracy [3].

Cyclic loading with thermographic measurement experiments were performed in Research and Testing Institute laboratories in Plzeň (Czech Republic). A standard fatigue testing device SCHENCK 250 kN was used for a cyclic loading of samples. A hydraulic cylinder of the device produces the maximum force 250 kN with displacement up to ± 125 mm. The device is fully controlled by a computer, which enables to set the shape of load (sinusoidal, step, rectangular), frequency, offset of the load etc. The loading force has asymmetric sinusoidal shape with minimal value of 10 % of the maximal value of the set force with frequency of 10 Hz. The load amplitude starts with force of 10 kN (load of 127.3 MPa) with equidistant step of 2 kN (25.5 MPa) up to the rupture. Each step of load takes approximately 10 minutes, when the temperature is measured after stabilization by a thermographic camera.

IR camera Optris PI400 was used for the temperature thermographic measurement. It is an uncooled micro-bolometric camera with a focal plane array detector with resolution of 382 x 288 pixels, which measures in the wavelength range from 7.5 μm to 13 μm. The camera measurement temperature range is from -20 °C to 1500 °C; the subrange from -20 °C to 100 °C was used for the measurement. A telescopic lens with the field of view 13° x 10° and the minimum focus distance 50 cm was used. A temperature sensitivity of the camera with telescopic lens is 0.1 K and its accuracy is ± 2 °C or ± 2 %. The maximum camera framerate is 80 Hz, recording framerate 1 Hz was used for this measurement.

The IR camera was placed on a tripod in front of the fatigue test machine in distance of 0.5 m. A tested sample was strengthened into the clamp jaws of the machine. A polystyrene slab was put down behind the sample to avoid reflections from the surroundings. The experimental arrangement is shown in **Figure 1**.

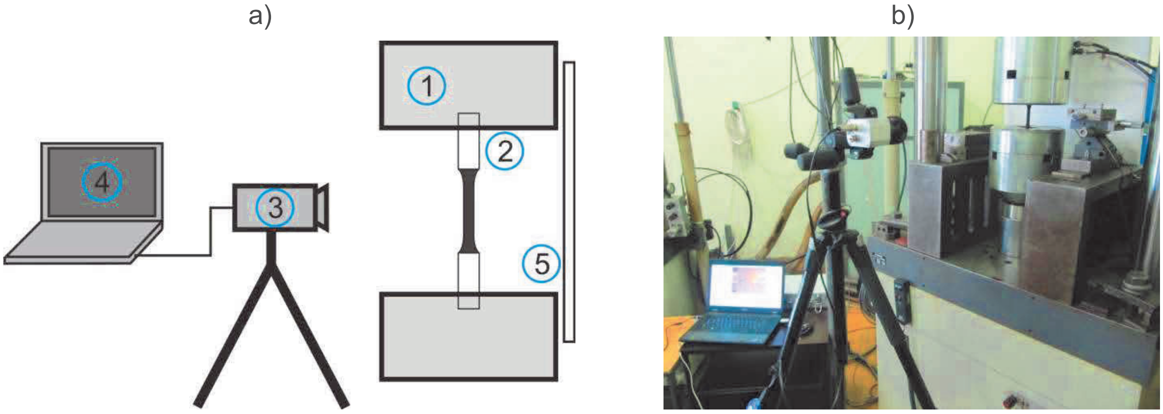
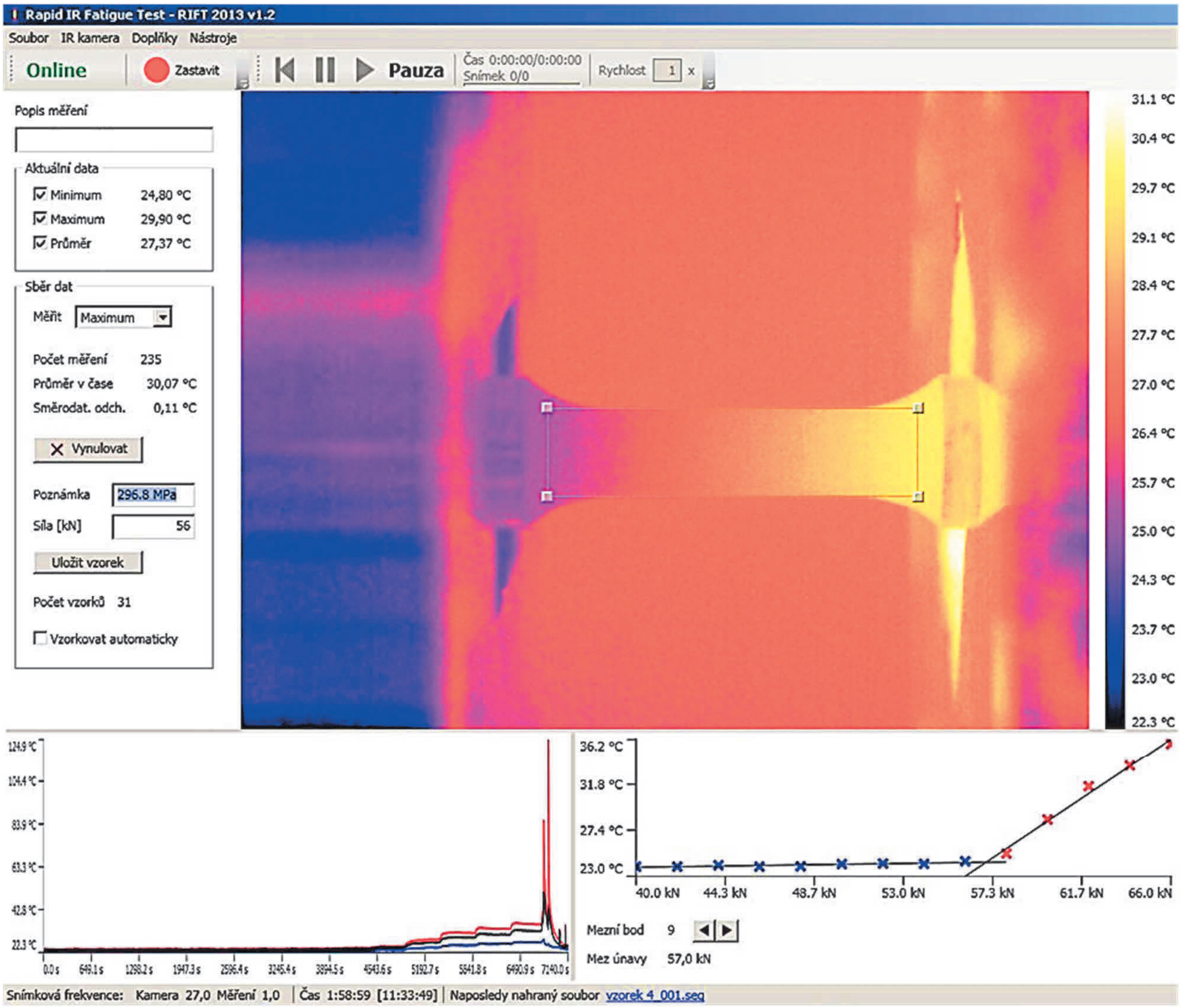


Figure 1 Experimental arrangement - a) schema: 1 - clamp jaw, 2 - tested sample, 3 - IR camera, 4 - measuring computer, 5 - polystyrene slab; b) photo

4. EVALUATION METHOD

The thermographic measurements were performed by the RIFT software, which was developed at the ZČU-NTC laboratories (University of West Bohemia, New Technologies - Research Centre). The software enables to set all standard thermography measurement parameters: emissivity 0.93 (high emissivity paint), distance between camera and measured object 0.5 m, reflected temperature 20 °C, atmosphere transmissivity 0.99 and atmosphere (surroundings) temperature 20 °C. As the temperature changes in observed testing steps are not fast, the recording frequency was 1 Hz. The thermographic measurement and recording of the complete data is performed during the whole test. The RIFT software evaluates the measured temperature data immediately (online) after each step is finished. The fatigue limit determination is based on the Method 2 mentioned above in Section 2.

At each step, after the load is increased and a sample temperature is stabilized, the maximum sample temperature is averaged in time interval of the length about 1 minute (start and end of this interval is set by an operator). The determined temperature value is then recorded together with the actual load and the load is then increased to a next loading step. Actual thermogram as well as temperature time-profile and the dependence of the maximum temperature on a load level are plotted in the graphical user interface of the RIFT software - see **Figure 2**. The online fatigue limit evaluation is based on the stepwise distribution of measured values to two groups - group A corresponds to loads lower then searched fatigue limit and group B corresponds to loads higher than searched fatigue limit. The temperatures in both groups are linearly approximated. The correct distribution to groups A and B is ruled by the condition that the highest load in group A is lower than fatigue limit and the lowest load in group B is higher than the fatigue limit, that is calculated as intersection of group A and B linear approximation (**Figure 2**). This procedure - dividing into groups and checking of condition fulfillment is made with the software automatically after each point addition. However, the operator has also a possibility to adjust the points in the groups manually.



Čas 0:00:00/0:00:00
Snímek 0/0
Rychlost 1 x

☑ Minimum 24,80 °C
☑ Maximum 29,90 °C
☑ Průměr 27,37 °C

Měřit Maximum
Počet měření 235
Průměr v čase 30,07 °C
Směrodat. odch. 0,11 °C
Poznámka 296.8 MPa
Síla [kN] 56
Počet vzorků 31
☐ Vzorkovat automaticky

Mezní bod 9
Mez únavy 57,0 kN

Snímková frekvence: Kamera 27,0 Měření 1,0 | Čas 1:58:59 [11:33:49] | Naposledy nahraný soubor vzorek 4_001.seq

Figure 2 RIFT software screenshot - IR image of tested sample with a selected region of interest, temperature profile and temperature-load dependence for fatigue limit determination (blue - A, red - B)

The whole thermographic sequence is recorded (raw thermographic data) during the measurement. The RIFT software enables to work in an off-line mode also. In this case, the recorded sequence can be read from a file and can be processed in the same way as when it is measured on-line (that means a measurement simulation). In such a way, the evaluation can be performed repeatedly with different parameters or for evaluation results verification.

5. RESULTS

Fatigue limits of two identical samples were evaluated using the thermographic fatigue testing. The results were compared with a standard fatigue testing results of the same material. The results are summarized in **Table 1.**

Table 1 Comparison between results of IR thermography fatigue limit measurement and standard test

Sample #	Fatigue limit		Tensile strength	
	RIFT	Standard test	RIFT	Standard test
1	322 ± 18 MPa	464 ± 2 MPa	735 MPa	691 MPa
2	474 ± 15 MPa		736 MPa	

The evaluation showed that the condition defined for the fatigue limit determination can be fulfilled for more combinations of distribution of load-temperature dependence points in the groups A and B. Thus, all satisfactory solutions were evaluated and an average value with a tolerance (standard deviation) were evaluated and presented in the **Table 1**. The thermographic testing brought fatigue limits 322 MPa and 474 MPa, while the standard test procedure result was 464 MPa. As the sample 1 thermographic testing result of the fatigue limit is about 100 MPa lower compared to the standard procedure, the result of the sample 2 is in a very good agreement with the standard fatigue testing results (difference about 10 MPa). The differences can be cause by other material issues and the results can be assumed as satisfactory at this stage of the thermographic fatigue testing method verification.

The thermography measurement at the cyclic loading can indicate also other material limit points except the fatigue limit. A significant thermal response during the cyclic loading has also tensile strength of the tested samples, which were evaluated in the same manner as the one used for the fatigue limit evaluation. The tensile strength of the samples 1 and 2 determined by the thermographic methods was 735 MPa and 736 MPa, respectively. Also these values are in a good accordance with the strength limit 691 MPa evaluated by a standard tensile test.

6. CONCLUSION

The method and its implementation to a software tool for online fatigue limit evaluation was introduced. The principles of thermographic fatigue limit evaluation according to the Method 2 published in [7] were adapted for the condition of fatigue limit position evaluation between groups A and B. It was shown that the method is fast enough compared to standard testing methods and can bring valuable results.

The thermographic method was used for cyclic loading test measurement and online fatigue limit evaluation of the 15Ch2NMFA steel samples. The determined fatigue limit values 322 MPa and 474 MPa as well as the tensile strength limits evaluated simultaneously at the same test are in a good agreement with results obtained by standard testing methods.

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REFERENCES

[1] ŠVANTNER, M., HONNEROVÁ, P., VOLÁK, J. Active thermography in materials fatigue testing. In *METAL 2015: 24th International Conference on Metallurgy and Materials.* Brno: Tanger, 2015, pp. 560-565.

[2] GAUSSORGUES, G., CHOMET, S. *Infrared Thermography, 1st. ed.* Amsterodam: Springer Netherlands, 2012. 508 p.

[3] TESAŘ, J., MARTAN, J., SKALA, J. The influence of emissivity on measured temperature in dependence on spectral range of IR camera detector and its approximate calculation. In *Quantitative Infrared Thermography conference, QIRT 2016,* Gdansk: PAN, 2016, pp. 89-99.

[4] Lipski, A. Accelerated determination of the fatigue limit and the S-N curve by means of the thermographic method for X5CrNi18-10 steel. *Acta Mechanica et Automatica*, 2016, vol. 10, no. 1, pp. 22-27.

[5] GERACI, A. L. , LA ROSA, G.., ANTONINO, R. Determination of the fatigue limit of an austempered ductile iron using thermal infrared imagery. In *Proc. SPIE 2646, Digital Photogrammetry and Remote Sensing '95*, 1995, vol. 2646, pp. 306-317.

[6] MORABITO, A. E. , DATTOMA, V., GALIETTI, U. Energy analysis of fatigue damage by thermographic technique. *Thermosense XXIV, International Society for Optical Engineering*, 2002, vol. 4710, pp. 456-463.

[7] La ROSA, G. , RISITANO, A. Thermographic methodology for rapid determination of the fatigue limit of materials and mechanical components. *International Journal of Fatigue*, 2000, vol. 22, no. 1, pp. 65-73.

[8] GERACI, A. L. , RISITANO, A. L., ROSA, G.L.A.. Influence of frequency and cumulative damage on the determination of the fatigue limit of materials using the thermal infrared methodology. In *XV Sympozjum Mechaniki Eksperymentalnej*, Jachranka: PAN, 1992, pp. 63-66.

[9] WILLIAMS, P. , LIAKAT, M., KHONSARI, M.M., KABIR, O.M. A thermographic method for remaining fatigue life prediction of welded joints. *Materials and Design*, 2013, vol. 51, pp. 916-923.

[10] La ROSA, G., RISITANO, A. Application of a new methodology to determine the fatigue limit using thermal infrared techniques. In *17th Symposium on Experimental Mechanics of Solids*, Jachranka (Poland), 1996, vol. 19, pp. 498-503.

[11] LUONG, M. P. Fatigue limit evaluation of metals using an infrared thermographic technique. *Mechanics of Materials*, 1998, vol. 28, no. 1-4, pp. 155-163.

[12] LUONG, M. P. Infrared thermographic scanning of fatigue in metals. *Nuclear Engineering and Design*, 1995, vol. 158, no. 2-3, pp. 363-376.

[13] CURÀ, F., CURTI, G., SESANA, R. A new iteration method for the thermographic determination of fatigue limit in steels. *International Journal of Fatigue*, 2005, vol. 27, no. 4, pp. 453-459.

[14] DE FINIS, R., PALUMBO, D., ANCONA, F., GALIETTI, U., BARI, P. New thermal method to assess endurance limit of stainless steels. In *AITA2015 - Advanced Infrared Technology & Applications*, Pisa, 2015, pp. 162-166.

[15] La ROSA, G. , CLIENTI, C., Lo SAVIO, F. Fatigue analysis by acoustic emission and thermographic techniques. *Procedia Engineering*, 2014, vol. 74, pp. 261-268.

[16] XIAO-QING, L.., HONG-XIA, Z., ZHI-FENG, Y., WEN-XIAN, W., YA-GUO, Z., QIAN-MING, Z. Fatigue life prediction of AZ31B magnesium alloy and its welding joint through infrared thermography. *Theoretical and Applied Fracture Mechanics*, 2013, vol. 66-67, pp. 46-52.

[17] De FINIS, R., PALUMBO, D., ANCONA, F., GALIETTI, U. Fatigue limit evaluation of various martensitic stainless steels with new robust thermographic data analysis. *International Journal of Fatigue*, 2015, vol. 74, pp. 88-96.

[18] CHHITH, S., DE WAELE, W., DE BAETS, P., VAN HECKE, T. On-line detection of fretting fatigue crack initiation by lock-in thermography. *Tribology International*, 2017, vol. 108, no. July 2016, pp. 150-155.

[19] FARGIONE, G., GERACI, A., LA ROSA, G., RISITANO, A. Rapid determination of the fatigue curve by the thermographic method. *International Journal of Fatigue*, 2002, vol. 24, no. 1, pp. 11-19.

[20] Palumbo, D., Galietti, U. Characterisation of steel welded joints by infrared thermographic methods. *Quantitative InfraRed Thermography Journal*, 2014, vol. 11, no. 1, pp. 29-42.

[21] Krapez, J.-C. and. Pacou, P. Thermography detection of damage initiation during fatigue tests. In *Thermosense XXIV, Proc. SPIE, vol. 4710*, Orlando, ASTM, 2002, pp. 435-449.