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Comparison between thermal energy and acoustic emission for the fatigue behavior of steels

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Abstract

The paper is focused on the study of fatigue materials, using an energy approach, with the support of two different non-destructive techniques. Indeed, the analysis of the energy behavior was conducted by the simultaneous application of Acoustic Emission (AE) and Thermography (TH). The purpose of the paper was to compare and integrate the results obtained by the two methodologies to assess the fatigue behavior of materials. The experimental tests were carried out on flat steel specimens of steels commonly used for metal carpentry either under static loading or under sequences of increasing cyclic loading. The results allow to define the fatigue limit either by the thermography or by the acoustic emission and they are encouraging to continue the comparison and the integration between the two energetic methodologies.

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Keywords: Thermal Energy; Acoustic emission; Fatigue behaviour; Steels.

1. Introduction

The energetic approach is largely used to forecast structure failure often preceded by different kinds of energy emission in terms of heat, sounds or vibrations. They are often very noticeable in the last part of the fatigue life, indicating the approaching collapse but they could also be detected during the fatigue life, following the crack

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nucleation and propagation.

Since the first studies performed by Kaiser (1950, 1953), the Acoustic Emission (AE) was proposed as a control methodology, becoming one of the more effective Non-Destructive Techniques in the industrial field. The information derived by this technique can connect the crack propagation and the number, intensity and energy of acoustic events. One of the main advantages of the AE technique is the possibility to operate in field, directly on the mechanical component while working and to identify the crack position and the degree of fatigue reached by the system itself (Roberts and Talebzadeh (2003), Biancolini et al. (2006), Singh et al. (2007), Ould Amer et al. (2013), Nani Babu et al. (2013)).

The acoustic energy is not the only one occurring during the process of material damage. Then, other techniques allow monitoring the crack nucleation and propagation making possible to detect it long before the failure happens. Under fatigue loading, in fact, the microplasticity induced by the crack causes thermal increments that can be measured on the specimen surface, as higher as the load exceeds the fatigue limit, highlighting how a phase of micro yielding started. Under cyclic loading, the temperature increases following three subsequent phases: a quick increment in the first phase (normally a small fraction of the lifetime), a second phase of thermal equilibrium and a stabilization of the temperature (along most of the entire life) and, finally, a third phase of quick and large thermal increment just before failure. (Delorme et al. (1968), Dengel and Harig (1980), Curti et al. (1986), Botny et al. (1986), Luong (1998), La Rosa and Risitano (2000), Atzori and Meneghetti (2003), Klingbeil (2003), Curà et al. (2005), Meneghetti (2007), Plekhov et al. (2007), Maquin and Pierron (2009), Vergani et al. (2014), Fargione et al. (2017), Risitano et al. (2015)).

The thermographic (TH) methodology can be also applied on specimens and mechanical components while working offering the advantages of a remote sensing technique. Several procedures were defined to assess the fatigue and fracture parameters: fatigue limit, fatigue endurance, crack nucleation and propagation. Among the above-mentioned procedures, studies were carried forward on the fatigue limit using a procedure applying a sequence of incremental loading steps. The procedure allows assessing the fatigue life (Fargione et al. (2002)) and the cumulative damage (Risitano and Risitano (2013)) and, finally, the fatigue limit under the application of simple static loading ((Geraci et al. (1995), Risitano et al. (2010, 2011), La Rosa and Risitano, (2014), Risitano and. Risitano (2013)). The latter method is based on the limit of the perfectly linear thermoelasticity as the crack nucleation and, then, the beginning of the fatigue process.

Basing on the great affinity between the two NDT techniques, even if related to different phenomena: acoustic-energy for AE, thermal-energy for TH, and following some recent studies demonstrating the possibility of detecting fatigue parameters by coupling the two techniques (Naderi et al.(2012), Kordatos, et al. (2012, 2013)), aim of the present paper is the definition of the setup and the procedure to acquire and compare the information about the fatigue parameters and the crack growing in dynamic testing. In particular, the paper describes the evaluation of the fatigue limit using both the methodologies and the comparison among them.

2. Description of the investigation

Purpose of the study was the simultaneous application of the two NDT methodologies to two different steel specimens and the comparison among the data detected.

2.1. Experimental setup

The tests were conducted on thin specimens made of Fe360 steel. All the series of specimens were preventively subjected to static tests, in order to verify the elastic range and to program the loading fatigue steps. The series were tested under static loading in displacement control with 1 mm/min cross-head speed. Either the static or the dynamic tests were carried out by an Instron 8501 testing machine with a 100 kN load cell always under loading control. Due to the slenderness of the specimens, the cyclic tests were performed at R=0.

The Acoustic Emission data were acquired by the AMSY4-MC6 Vallen system equipped with two ASIPP acquisition boards and relative pre-amplifiers. Only two channels were used, being sufficient to detect the acoustic energy as well as the position of the crack. The signals detected by the sensors were processed by the Vallen AE-Suite software and, then, imported and processed by Microsoft Excel.

Two sensors were applied on each specimens near the clamps, on the reduced section borders, using MoS_2 silicon grease to assure the acoustic coupling and fixed by a thin tape strip, narrow enough to permit the almost complete thermal vision of the reduced section. Score-Atlanta (Dunegan/DECI) SE375-M standard AE sensor for general purpose testing, 375 kHz peak sensitivity, were used.

The thermal images were acquired using a FLIR X6540SC (Fig. 2). The thermal camera, cooled by a Stirling device, assures a thermal resolution up to 20 mK and a spatial resolution up to 320x240 pixels. After the acquisition of the whole tests, the thermal maps were processed by the FLIR ThermaCam Researcher Professional software.

2.2. Experimental procedure

The specimens were sprayed with black matt paint, to avoid all the reflections from the specimen, on the side detected by the thermal camera. The thermal maps were acquired along the whole test on the entire specimen surface. Moreover, three spots were pointed on the surface, in upper, medial and lower position, to acquire directly the behavior of the thermal variations.

The dynamic tests were carried out under cyclic loading (R=0). The loading pulse trains were applied at 10 Hz for 2500 cycles per step, with increasing steps. The values of threshold and gain were defined, for each test, defining the attenuation by the Hsu pencil lead break test broken on the specimen surface. Once set the main parameters, the following AE data were acquired: number of hits, amplitude, energy, cascade hits, source position.

The fatigue limits were evaluated using the two methodologies (AE and TH). First of all, the consolidated and established thermographic method of evaluation of the fatigue limit was used, considering the stabilization temperature reached at the end of each load step method. Then, the thermal increments are reported as a function of the applied stress. Following the method proposed by La Rosa and Risitano (2000) and, then, modified by Curà et al. (2005), the curve of the thermal variations has two phases: the first one is very low and flat, corresponding to the elastic damping; the second one rises quickly, due to the contribution of the plastic energy. The stress value corresponding to the intersection of the curve of temperature increases with the stress axis (or the intersection of the two curves) identifies the start of the crack nucleation process and, consequently, the fatigue limit.

At the same time, the fatigue limit was assessed using the value of the acoustic energy (expressed in keu=10^{-11} V^2s) and in terms of cascade hits. This parameter considers essentially the relative amount of sequences exceeding the defined threshold, starting from the loading application. Also in this case, the amount of the acoustic energy or the cascade hits can be plotted as a function of the applied stress and the curve show a first flat phase, followed by a rapid increase again. The.intersection of the curve with the stress axis (or between the two curves) represents the value for which plastic energy is not produced, hence the fatigue limit.

3. Analysis of results

The comparison among AE and TH responses are first reported as a function of the time of application. The temperature variations have a gradient increasing with the applied load, as well as the number of hits or the cumulated acoustic energy.

A better correspondence among TH and AE results can be expressed in terms of applied stress. Fig. 1 shows the good correspondence between the cumulated enegy (a) or the cascade hits (b) with the thermal increments. By applying the thermographic methodology used for the determination of the fatigue limit and widely tested by many authors, Fig. 1 demonstrates how both the AE and TH converge to the same limit, corresponding to the intersect with the stress axis or the first cyclic load producing thermal increments due to the plastic energy released, pointing out the possibility to define the fatigue limit also by the analysis of the AE energy. The convergence of both the TH and AE curves allows considering the AE methodology able to define the fatigue limit, either in terms of hits or in terms of energy, as well as the thermography in terms of initial gradient or in terms of stabilization temperature.

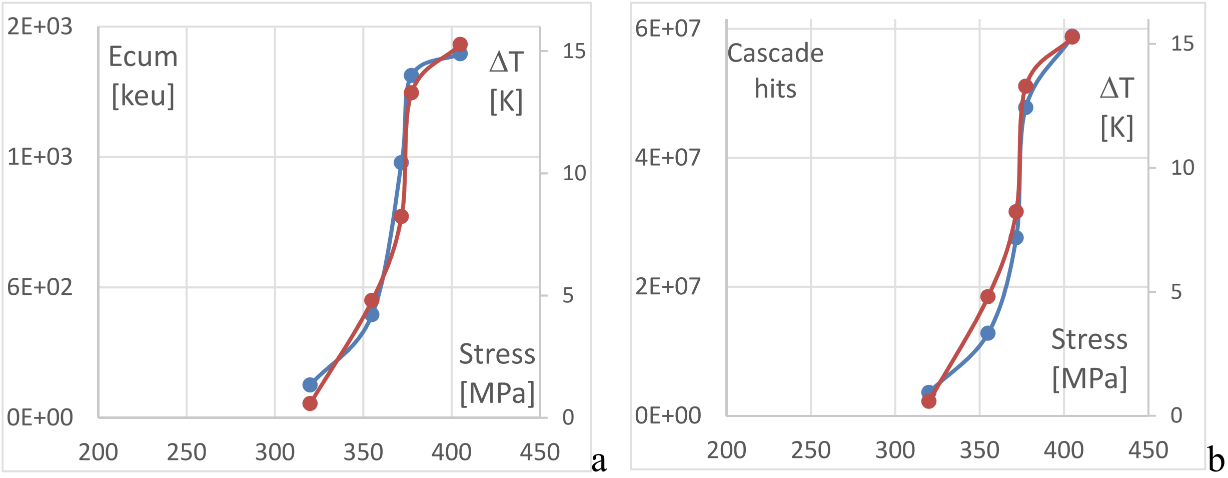

Fig. 1. Cumulated energy (a) and cascade hits (b) compared with the thermal increments (red).

4. Conclusions

Series of tests were performed on specimens in common steels, coupling the two methodologies of acoustic emission and thermography, in order to verify the possibility to detect the fatigue limit. The tests were performed under cyclic loading at R=0.

The results obtained show that the acoustic emission is able to define the fatigue limit, either in terms of cascade hits or in terms of released energy, as well as the thermographic analysis, already tested by many authors. The approach needs to be better analysed to verify if the energetic amount detected by acoustic emission could be better linked to cumulative thermal parameters. Then, the acoustic emission parameters can be used to define the fatigue limit using a methodology similar to that applied by thermography.

Following these results, the authors intend to prosecute the analysis on a larger series of specimens to better investigate on the correlation between the energy released by the two methodologies and in order to formulate a reliable procedure based on the acoustic emission data analysis able to predict the fatigue parameters.

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References

Kaiser J., Untersuchung über das Auftreten von Geräuschen beim Zugversuch, Dr.-Ing..Dissertation, Fakultät für Maschinenwesen und Elektrotechnik der Technischen Universität München (TUM) (1950).

Kaiser J., Erkenntnisse und Folgerungen aus der Messung von Geräuschen bei Zugbeanspruchung von metallischen Werkstoffen, Archiv Eisenhüttenwesen, 24 1/2 (1953) 43-45.

Roberts T.M., M. Talebzadeh, Fatigue life prediction based on crack propagation and acoustic emission count rates, J. of Constructional Steel Research 59 (2003) 679-694.

Biancolini M.E., C. Brutti, G. Paparo, A. Zanini, Fatigue cracks nucleation on steel, acoustic emission and fractal analysis, International Journal of Fatigue 28 (2006) 1820-1825.

Singh P.J., C.K. Mukhopadhyay, T. Jayakumar, S.L. Mannan, Baldev Ray, Understanding fatigue crack propagation in AISI 316(N) weld using Elber's crack closure concept: Experimental results from GCMOD and acoustic emission techniques, International Journal of Fatigue 29 (2007) 2170-2179.

Ould Amer A., A.-L. Gloanec, S. Courtin, C. Touze, Characterization of Fatigue Damage in 304L Steel by an Acoustic Emission Method Procedia Engineering, 66, (2013) 651-660.

Nani Babu M., C.K. Mukhopadhyay, G. Sasikala, B. Shashank Dutt, S. Venugopal, Shaju K. Albert, A.K. Bhaduri, T. Jayakumar, Fatigue Crack Growth Characterisation of RAFM Steel using Acoustic Emission Technique, Procedia Engineering, 55 (2013) 722-726.

Delorme J F, G Sinicki, P Gobin, Calorimetric study of the energy dissipated from a solid subjected to fatigue cycles J. Phys. D: Appl. Phys. 1 (1968) 1737-1742.

Curti G., G. La Rosa, M. Orlando, A. Risitano, Analisi tramite infrarosso termico della 'temperatura limite' in prove di fatica, XIV AIAS National Congress, Catania, Italy, (1986) 211-220.

D. Dengel, H. Harig, Estimation of the fatigue limit by progressively-increasing load tests, Fatigue Eng Mater Struct 3 (1980) 113–128.

R.S. Botny, J. Kaleta, W. Grzebień, W. Adamczewski, A method for determining the heat energy of the fatigue process in metals under uniaxial stress: Part 2. Measurement of the temperature of a fatigue specimen by means of thermovision camera-computer system International Journal of Fatigue, 8(1986) 35-38.

N.W. Klingbeil, A total dissipated energy theory of fatigue crack growth in ductile solids, Int J Fatigue 25 (2003) 117–128.

M.P. Luong, Fatigue limit evaluation of metals using an infrared thermo-graphic technique. Mechanics of Materials 28 (1998) 155-163.

G. La Rosa, A. Risitano, Thermographic Methodology for Rapid Determination of the Fatigue Limit of Materials and Mechanical Components, International Journal of Fatigue 22 (2000) 65-73.

G. Fargione, A. Geraci, G. La Rosa, A. Risitano, Rapid Determination of the Fatigue Curve by Thermographic Method, International Journal of Fatigue 24 (2002) 11-19.

F. Maquin, F. Pierron, Heat dissipation measurements in low stress cyclic loading of metallic materials: from internal friction to micro-plasticity, Mechanics and Materials 41 (2009) 928-942.

G. Meneghetti, Analysis of the fatigue strength of a stainless steel based on the energy dissipation, Int. Journal of Fatigue 29 (2007) 81-94.

F. Curà, G. Curti, R. Sesana, A new iteration method for the thermographic determination of fatigue limit in steels, Int. J. of Fatigue 27 (2005) 453-459.

B. Atzori, G. Meneghetti, Energy dissipation in low cycle fatigue of austempered ductile irons. LCF 5, Proceedings of the 5th International Conference on Low Cycle Fatigue, DVM, Berlin (2003), pp. 147–152.

O.A. Plekhov, N. Saintier, T. Palin-Luc, S.V. Uvarov, Naimark, Theoretical analysis, infrared and structural investigations of energy dissipation in metals under cyclic loading, Material Science and Engineering A, 462, 1-2 (2007) 367-369.

L. Vergani, C. Colombo, F. Libonati, A review of thermographic techniques for damage investigation in composites, Frattura ed Integrità Strutturale, 27 (2014) 1-12.

A. Risitano, G. Risitano, Cumulative damage evaluation in multiple cycle fatigue tests taking into account energy parameters, International Journal of Fatigue 48 (2013) 214-222.

C. Clienti, G. La Rosa, A. Risitano, R. D'Andrea, Proposta di utilizzo di metodologie termografiche per il controllo di qualità di componenti meccanici, Frattura ed Integrità Strutturale 12 (2010) 37-47.

A. Geraci, G. La Rosa, A. Risitano, Correlation between thermal variation in static test and elastic limit of material using infrared imagery, 7th International Conference on Mechanical Behaviour of Material, The Hague May 28- 2June 2, 1995.

A. Risitano, G. La Rosa, G. Fargione, C. Clienti, G. Risitano, A First Approach to the Analysis of Fatigue Parameters by Thermal Variations in Static Tests on Plastics, Eng. Fract. Mech. 77 (2010) 2158-2167.

A. Risitano, C. Clienti, G.Risitano, Determination of fatigue limit by mono-axial tensile specimens using thermal analysis, Key Engineering Materials 452-453 (2011) 361-364.

G. La Rosa, A. Risitano, Evaluation of the fatigue limit of materials in static test using thermal analysis: Effect of the cross-head speed, Key Engineering Materials 577-578 (2014) 69-72.

A. Risitano, G. Risitano, Determining fatigue limits with thermal analysis of static traction tests, Fatigue & Fracture of Engineering Materials & Structures 36 (2013) 631-639.

Fargione, G. F. Giudice, A. Risitano, The influence of the load frequency on the high cycle fatigue behaviour, Theoretical and Applied Fracture Mechanics, 88 (2017), 97-106.

Risitano, A.,Fargione, G., Giudice F., Patanè, G. Evaluation of the Relative Plastic Work Factor during the Fatigue Test, Procedia Engineering, 109 (2015) 346-355, 23rd Italian Group of Fracture National Conference, IGF 2014; Trapani; Italy.

La Rosa G., Clienti C.,Lo Savio F. Fatigue analysis by acoustic emission and thermographic techniques, Procedia Engineering, 74 (2014), 261-268, 17th International Colloquium on Mechanical Fatigue of Metals, ICMFM 2014; Verbania, Italy.

M. Naderi, A. Kahirdeh, M.M. Khonsari, Dissipated thermal energy and damage evolution of Glass/Epoxy using infrared thermography and acoustic emission, Composites Part B: Engineering 43 (2012) 1613-1620.

E.Z. Kordatos, D.G. Aggelis, T.E. Matikas, Monitoring mechanical damage in structural materials using complimentary NDE techniques based on thermography and acoustic emission, Composites Part B: Engineering 43 (2012) 2676–2686.

E.Z. Kordatos, K.G. Dassios, D.G. Aggelis, T.E. Matikas, Rapid evaluation of the fatigue limit in composites using infrared lock-in thermography and acoustic emission, Mechanics Research Communications 54 (2013) 14-20.