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ScienceDirect

Procedia Engineering 109 (2015) 89 – 96

Procedia Engineering

www.elsevier.com/locate/procedia

XXIII Italian Group of Fracture Meeting, IGFXXIII

Crack growth monitoring in stainless steels by means of TSA technique

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Abstract

In this work, the Thermoelastic Stress Analysis (TSA) technique was used for the monitoring of fatigue crack growth during fracture mechanics tests on stainless steel. In this regards, different methods are used in literature but most of them cannot be applied on real components since they require an off-line measurement of the crack.

An automatic procedure based on TSA technique was proposed for the continuous evaluation of the crack tip position. Advantages with respect to classical methods can be obtained in terms of reduction of testing time, experimental set-up, data processing and data report.

Peer-review under responsibility of the Gruppo Italiano Frattura (IGF)

*Keywords:*Fracture Mechanics; TSA, Crack Growth, Stress Instensity Factor

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1. Introduction

Thermoelastic Stress Analysis (TSA) is a non-contact technique that provides stress maps of a component subjected to dynamic loading [1-4]. This technique is based on the thermoelastic effect; in fact, a component subjected to dynamic loading produces a small and reversible temperature changes. In adiabatic and linear elastic conditions, these temperature changes are proportional to the first stress invariant.

TSA technique can be used for the determination of the stress intensity factor during fracture mechanics tests [5-10]. By knowing the sum of the principal stresses, it's possible to determine near the crack tip position the stress intensity factor ΔK_I [5-10] and the same time, it's possible to determine the crack growth analyzing the phase data

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Peer-review under responsibility of the Gruppo Italiano Frattura (IGF)

doi:10.1016/j.proeng.2015.06.212

[8], [9]. In particular, in the works of Diaz *et al.* [5-7] and Tomlinson *et al.* [8], [9], the amplitude of the thermoelastic signal is used for SIF evaluation while the phase signal allows the detection of the crack tip position. Phase changes are due to high stress gradients which may be ascribed to the non-adiabatic conditions and to the plastic behaviour of the crack tip. Diaz *et al.* [5-7], [10] showed that the characteristic performance of the phase signal at the crack tip contains a double reversal of sign, notably caused by the two cited effects which have the opposite sign influence. Phase signal, can be also considered as an effective parameter for the identification of local damage and for the evaluation of fatigue damage in materials [11-13].

Nowadays the principal methods used for the monitoring and the measurement of the crack growth rate are microscopy [14], ultrasound [14], X-ray [14], [15] and TSA [5], [6]. TSA and X-ray allow the on-line monitoring of the crack growth during the test against ultrasound and microscopy technique that require an off-line measurement. In addition, TSA technique allows to acquire the data by means of a simple set-up with respect to other techniques.

In this work, it is proposed an automatic procedure for the on-line monitoring of crack tip during fatigue tests based on the processing of TSA data. Three CT steel specimens were used and tested according to ASTM E 647-00 and the monitoring of the crack tip growth was performed by means of two infrared cameras.

2. Theory

The thermoelastic effect was reported the first time in the work of Lord Kelvin [16]. This effect describes the reversible variation in temperature that occurs in a solid when it is deformed in the elastic range. This effect depends on the variation in volume during the deformation of the solid. In solids the temperature change appears to be of the order of milliKelvin. Under adiabatic and reversible conditions, the temperature variations expected are proportional to the sum of principal stresses. The relation between the change in temperature due to the application of loading and the stress range of a linear elastic and homogeneous material can be written as:

$$\Delta T = -KT_0\Delta(\sigma_1 + \sigma_2) \tag{1}$$

where $K=\alpha/\rho Cp$ is the thermoelastic constant of the material, α is the coefficient of thermal expansion, Cp is the specific heat at constant pressure, ρ is the density, T_0 is the initial temperature and $\Delta(\sigma_1+\sigma_2)$ the sum of the principal stresses [17-19]. The loss of adiabatic conditions occurs with the presence of heat transfer trough the specimen, internal heat source generation due to damage phenomena and high stress gradients [20].

The infrared detector of the thermocamera is able to detect the infrared flux emitted from the surface of the stressed body and it produces a signal S related to the sum of the principal stresses.

Acquisition systems used in TSA are based on a correlation in frequency, amplitude and phase of the detected signal with a reference signal coming from the loading system.TSA provides a S signal proportional to the peak-to-peak variation in temperature during the peak-to-peak variation of the sum of principal stress. S is usually presented as a vector, where modulus is proportional to the change in temperature due to the thermoelastic effect and the phase means the angular shift between the thermoelastic and the reference signal. The phase value is normally constant unless adiabatic conditions are not achieved [9].

In fracture mechanics near the crack tip region occur two phenomena that lead to a lack of the adiabatic conditions: heat generation due to plastic work and the presence of high stress gradients [5-10]. This phenomena lead to a change in phase signal. By analyzing the phase image of the thermoelastic data, it is possible to evaluate the crack tip position. In Fig. 1. (a) is shown the typical phase map during a fracture mechanic test.

Where adiabatic conditions were achieved the phase signal should be constant, in fact thermoelastic and reference signal are set in phase. This condition is verified away from the crack tip where there are linear elastic conditions. Near the crack tip, adiabatic conditions were lost due to plasticity and high stress gradients [5-10]. The position of the crack tip can be extracted plotting the phase values along a profile taken across the crack as shown in Fig. 1. (b)

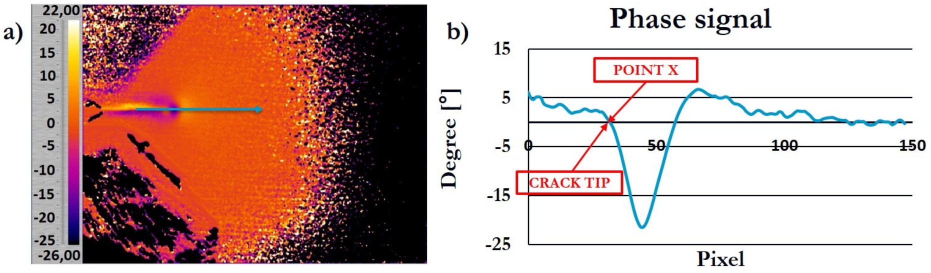

Fig. 1. Typical Phase Map (a) and Phase profile along crack tip (b).

Starting from the right Fig.1. (b), there is a region where the phase value is approximately constant and equal to zero. In all this points, the adiabatic conditions are achieved. In the proximity of the crack tip, there is a positive increment of the phase value that indicates a loss of adiabacity due to plasticity and high stress gradients. Than the phase change in value from positive to negative, that indicates the presence of a reverse plasticity (phase inverted respect the first region). The phase value returns to zero (Point X) and then it starts to assume various values positive and negative. Point X can be adopted for the estimation of the crack tip position and for the evaluation of the crack growth during the tests [9], [10].

In Fig. 2. are shown the phase maps and the phase values along the crack during the test. In Fig. 2. (a) the crack length is about of 4 mm at 30000 cycles. After 80000 cycles the crack grows to 8.5 mm (Fig. 2. b) and in proximity of the failure (140000 cycles) the crack reaches 19.5 mm (Fig. 2. c).

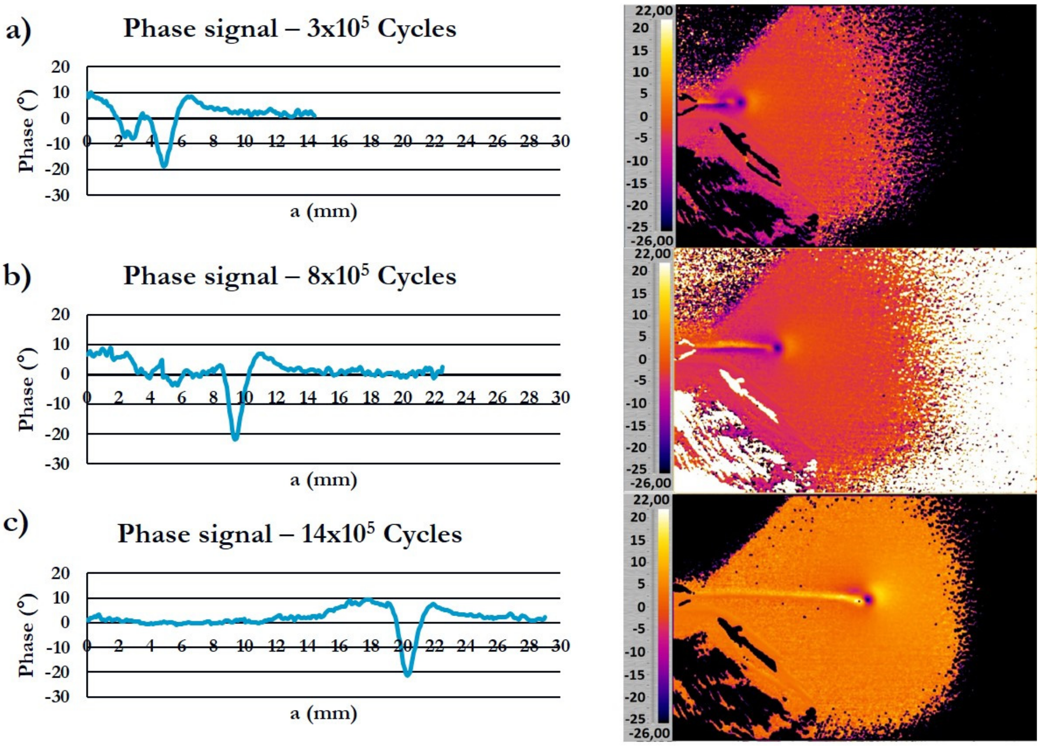

Fig. 2. Phase map (right) and Phase profile along crack tip (left) at 30000 cycles (a), 80000 cycles (b) and 140000cycles (c) for specimen 3.

3. Experimental set-up

3.1. Specimen geometry and materials

Compact Tension specimens (in number of three) were used with dimensions according to ASTM E 647 [14].

Tests were carried out on AISI 422 (σ_{UTS}=880 MPa [21]); the percentage of chromium is 11-13 % in weight, and moreover, the presence of W, V and Mo alloys in the lattice, favorites the complex carbide precipitation. So, this steel can be tempered at relative high temperature (650 °C) without having chromium depleting of the lattice. It is a standard type of martensitic stainless steel [22], [23]. In Fig. 3. dimensions of the specimen are reported in mm. Specimens were sprayed with flat black spray for increasing emissivity to 0.92.

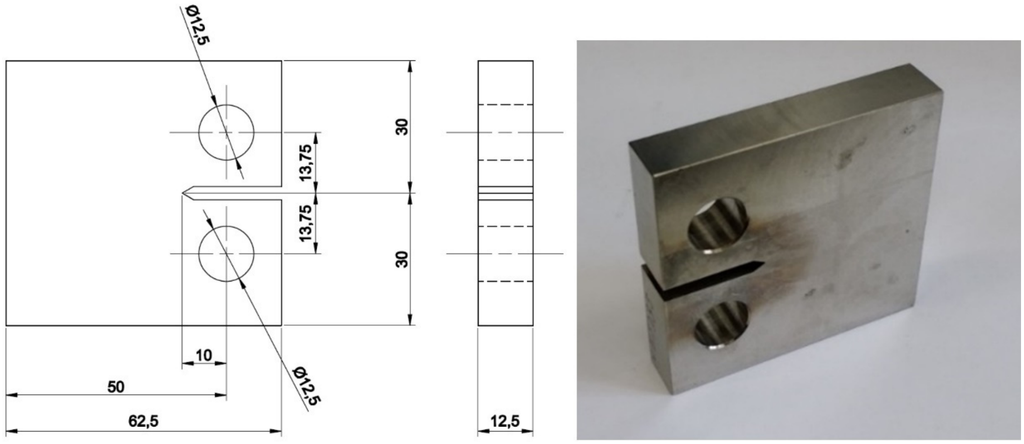

Fig. 3. Specimen dimension in mm according to ASTM E 647-00.

3.2. Test procedure

The tests were carried out with the MTS model 370 servo hydraulic fatigue machine with a 100 kN capacity. In according to ASTM E 647 – 00 the constant-force-amplitude procedure was used with a constant force range ΔP=10.8kN, fixed stress ratio (R=0.1) and frequency (f=13 Hz).

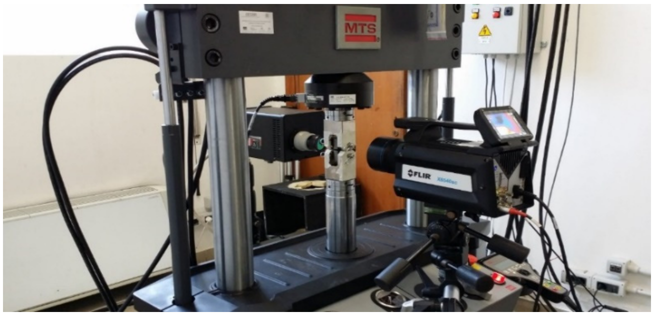

Fig. 4. Experimental set-up used for testing

For the acquisition of the thermoelastic signal two thermal cameras were used on opposite sides of the specimen in order to monitoring the crack growth on both surfaces as required by ASTM E-647. In particular, it was used a

cooled FLIR IR X6540 SC infrared camera with a indium-antimonium detector (640x512 pixel and acquisition rate of 123 Hz) and the DeltaTherm 1560 developed by Stress Photonics with an indium-antimonium detector (320x256) and acquisition rate of 105 Hz. Fig. 4. The distances from the specimen were respectively 17 cm and 8 cm with a mm/pixel ratio of 0.067 for the first infrared camera and 0.11 for the second one. All specimens were pre-cracked until to 2.5 mm according to ASTM E-647.
Thermoelastic data were acquired with a constant interval of 2000 cycles with both infrared cameras.

4. Data analysis

During fatigue tests a series of thermographic sequences were acquired with infrared cameras. Amplitude and phase data were obtained for each sequence performing the data processing by means of a suitable software. In particular the StressPhotonics™ software was used for data acquired by DeltaTherm system while IRTA™ software was used for the Flir X6540sc.

A new procedure is proposed able to perform the on-line monitoring of the crack growth in automatic way with the aim to reduce the testing time and the data processing.

The procedure can be summarized as follows:

1. Thermographic sequence acquisition with infrared camera;
   Thermal sequences of about 10 seconds must be acquired at regular intervals during the test.

2. Thermoelastic phase and amplitude image saving;
   About 2 minutes are needed to obtain the TSA data (phase and amplitude images) from the thermal sequence.

3. Evaluation of the maximum value of thermoelastic signal from the amplitude image;
   This value represents the maximum stress amplitude reached in proximity of the crack tip.

4. Automatic detection of an analysis area [A] around the maximum value of thermoelastic signal;
   [A] represents the area of interest for the following analysis.

5. Automatic extraction of the same area [A] from phase data (phase image);

6. Normalization of the selected area in order to report the average phase data to zero [An]=[A]-mean[A];
   Normalized area [An] is obtained subtracting the average value of phase signal of the selected area [A].

7. Evaluation of the minimum phase signal in the selected normalized area [An] for the identification of the crack growth direction;
   The main hypothesis is that the crack growth occurs always in the same direction that joining the minimum value of phase signal and the crack tip position obtained at the end of the pre-crack procedure.

8. Plotting of the phase signal values along the crack growth direction;
9. Automatic assessment of the crack tip position in term of coordinates *x* and *y* in the local reference system (*0, x,* y);

10. Evaluation of the crack tip growth;
    Plotting of the crack tip position in main reference system (*0, X, Y*) versus number of cycles.

The procedure is shown in Fig. 5. in the flow-chart form.

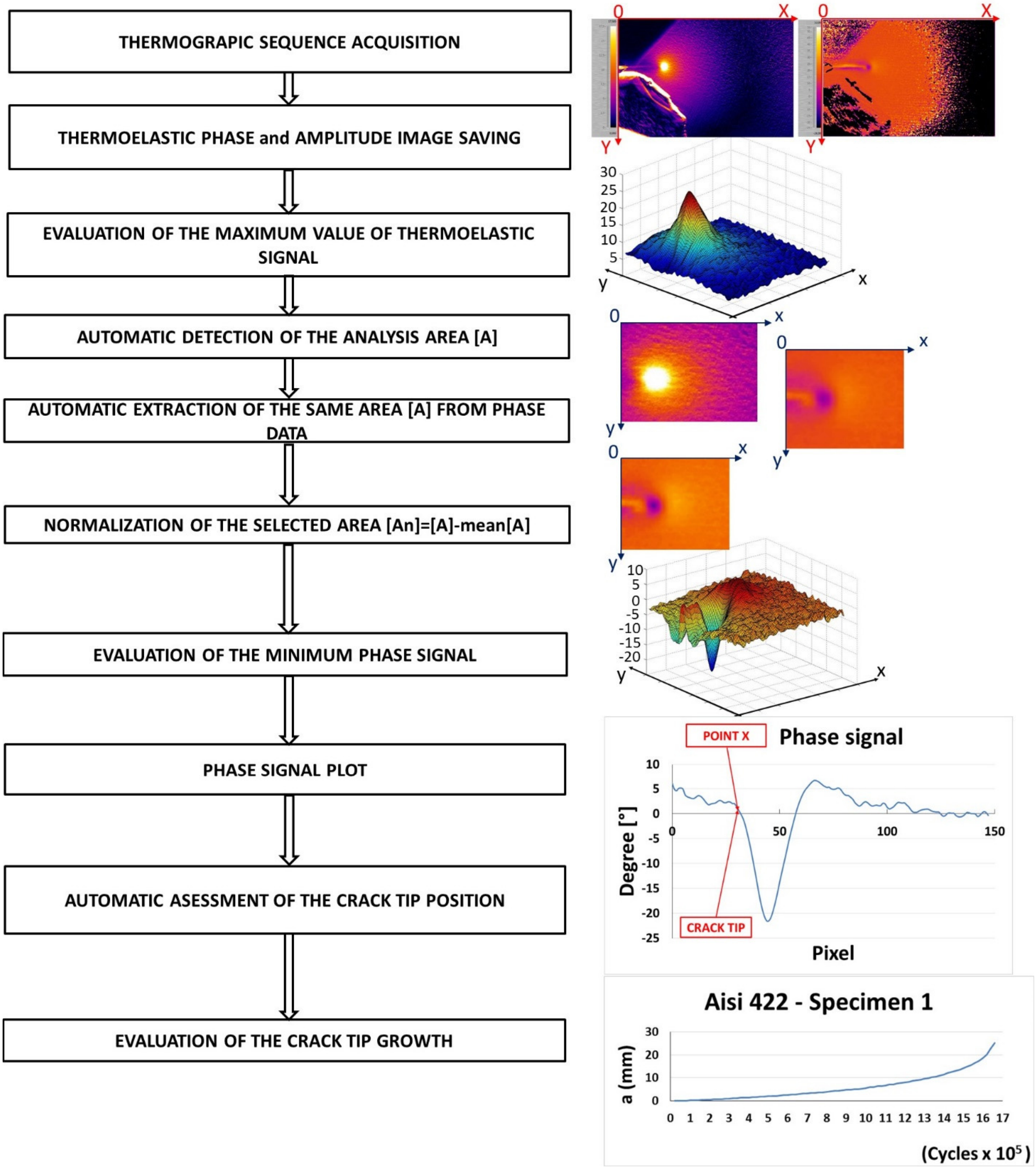

Fig. 5. Schematic representation of the proposed procedure for the crack tip growth evaluation.

5. Results

In this paragraph the results obtained with the new procedure will be shown for the analyzed specimens. Results are

referred to data acquired by the FLIR IR X6540 SC infrared camera.
In Fig. 6. it is shown the evaluation of the crack tip growth for each specimen and the fracture surfaces. Table 1. shows the constant load amplitude used for tests and number of cycles performed until to failure of specimen.

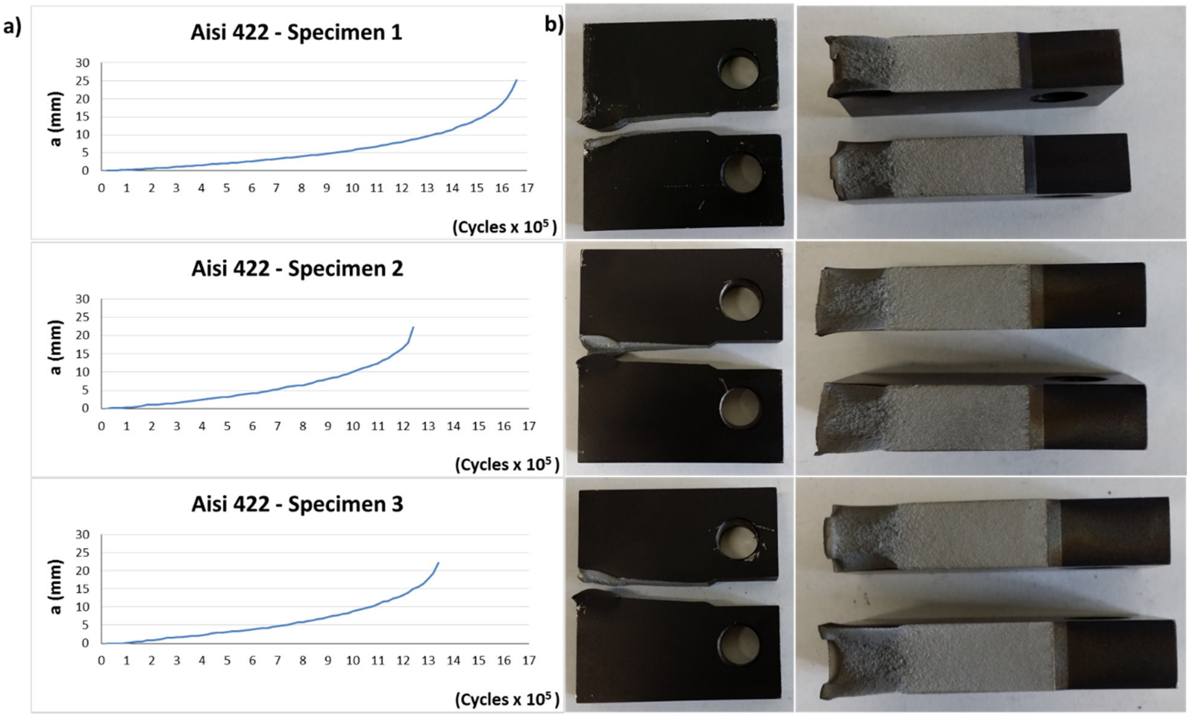

Fig. 6. Crack tip growth vs. number of cycles for AISI 422 specimens (a) and specimens after the test (b).

Table 1. Loads and number of cycles performed for AISI 422

AISI 422 - Specimen	Load ΔP [kN]	Cycles
1	10.8	166000
2	10.8	124000
3	10.8	134000

6. Conclusions

In this work, Thermoelastic Stress Analysis (TSA) has been proposed for the monitoring of the crack tip growth during fracture mechanics tests. The proposed procedure allows to assess the crack tip growth continuously and in automatic way.

Three fatigue crack tests were carried out on CT specimens made of AISI 422 according to standard ASTM E 647. Crack growth was monitored by means a cooled infrared camera capable to acquire thermographic sequences each 2000 cycles during the test.

Each thermal sequence was processed in order to obtain thermoelastic data in term of amplitude and phase data that were then used to assess the crack tip position in automatic way. The whole procedure takes about 5 minutes.

The proposed method can be also used for the monitoring of damage of real and more complex structures subjected to the loading operating conditions.

Acknowledgements

This work is part of a large-scale research project (PON-SMATI) aimed at identifying innovative steels to turbo machinery used in extreme environmental conditions. The authors would like to thank GE oil & gas (Nuovo Pignone S.r.l.) for the support and collaboration provided in the experimental tests.

References

[1] J.M. Dulieu-Barton, Introduction to thermoelastic stress analysis. Strain, Quantitative InfraRed Thermography35(1999) 35–39.

[2] G. Pitarresi, EA. Patterson, A review of the general theory of thermoelastic stress analysis. The Journal of Strain Analysis for Engineering Design38(5) (2003) 405–17.

[3] W.J. Wang, J.M.Dulieu-Barton, Q.Li, Assessment of non-adiabatic behaviour in thermoelastic stress analysis of small scale components. Experimental Mechanics 50 (2010) 449–61.

[4] N. Harwood, W.M. Cummings, Thermoelastic Stress Analysis, Adam Hilger, Bristol Philadelphia and New York, 1991.

[5] F.A. Diaz, E.A. Patterson, R.A. Tomlinson, R.A. Yates, Measuring stress intensity factors during fatigue crack growth using thermoelasticity. Fracture of Engineering Materials and Structures27 (2004) 571–83.

[6] F.A. Diaz, E.A. Patterson, R.A. Yates, Some improvements in the analysis of fatigue cracks using thermoelasticity. International Journal of Fatigue 26(4) (2004)365–76.

[7] F.A. Diaz, E.A. Patterson, R.A. Tomlinson, R.A. Yates, Differential Thermography Reveals Crack Tip Behaviour, Sem Org. 2005 SEM Ann. Conf. s060p1.

[8] R.A. Tomlinson, E.J. Olden, Thermoelasticity for the analysis of crack tip stress fields – a review, Strain, May 1999.

[9] R.A. Tomlinson, E.A. Patterson, Examination of Crack Tip Plasticity Using Thermoelastic Stress Analysis. Thermomechanics and Infra-Red Imaging, Volume 7, Conference Proceedings of the Society for Experimental Mechanics Series 2011, (2011) pp 123-129.

[10] F.A. Diaz, E.A. Patterson, R.A. Yates., Application of thermoelastic stress analysis for the experimental evaluation of the effective stress intensity factor, Frattura ed Integrità Strutturale, 25 (2013) 109-116.

[11] D. Palumbo, U. Galietti, Characterization Of Steel Welded Joints By Infrared Thermographic Methods. Quantitative Infrared Thermography. 29 (2014) 42-11.

[12] U. Galietti, D. Palumbo, R. De Finis,F. Ancona, Fatigue Damage Evaluation of Martensitic StainlessSteel by Means of Thermal Methods. National Conference IGF XXII (2013).

[13] U. Galietti, D. Palumbo, R. De Finis, F. Ancona, Fatigue limit evaluation of martensitic steels with thermal methods. QIRT Conference (2014).

[14] ASTM E 647-00 Standard Test Method for Measurement of Fatigue Crack Growth Rates.

[15] J. Réthore, N. Limodin, J.Y. Buffière, S. Roux, F. Hild, Three-dimensional analysis of fatigue crack propagation using X-Ray tomography, digital volume correlation and extended finite element simulations. Procedia IUTAM 4, (2012) 151-158.

[16] W. Thomson, (Lord Kelvin), On the Thermoelastic, Thermomagnetic and Pyro-electric Properties of Matters, Philosophical Magazine, 5(1878) 4-27.

[17] P. Stanley, Applications and potential of thermoelastic stress analysis. Journal of MaterialsProcessingTechnology64(1997) 359-370.

[18] S.A. Dunn, Using Nonlinearities for Improved Stress Analysis by Thermoelastic Techniques. Appl. Mech. Rev. 50(9) (1997) 499-513.

[19] S.M. Dulieu-Smith, Alternative calibration techniques for quantitative thermoelastic stress analysis. Strain. 31 (1995) 9-16.

[20] W.J. Wang, J.M. Dulieu-barton, Q. Li, Assestment of non-adiabatic behavior in Thermoelastic Stress Analysis of Small Scale Components. Experimental Mechanics. (2010) 449:461-50.

[21] Web site: http://www.Matweb.com. Matweb Material Property Data.

[22] M.F. McGuire, Martensitic Stainless Steels. StainlessSteels for Design Engineers. Asm International. (2008) 123-135.

[23] R. Tomei, Criteri di scelta degli acciai inossidabili in funzione degli impieghi. La meccanica italiana. (1981) 55.