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Experimental study of the crack growth in stainless steels using thermal methods

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Abstract

Martensitic steels are used in the engineering fields where high temperatures, corrosive environments and high mechanical stress are required. In this work, the Thermoelastic Stress Analysis (TSA) technique was used to characterize the fracture mechanics behaviour of two martensitic stainless steels.

TSA technique is proposed both for the monitoring in continuous way the crack position and for evaluating the stress intensity factor (SIF). An automatic procedure was developed capable to process very quickly the thermoelastic data acquired during the test. In this way, the Paris' Law can be assessed reducing significantly the testing time.

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

1. Introduction

Martensitic steels are used in engineering applications where corrosive and cryogenic environments are present in addition to high mechanical stresses. However, in literature there is a data lack concerning the study of fatigue behaviour of these materials.

The aim of this work concerns the analysis of fatigue crack propagation in two martensitic stainless steel with a new procedure based on the Thermoelastic Stress Analysis (TSA) technique [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.

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TSA technique was already used for the determination of the stress intensity factor during fracture mechanics tests [5-10]. In fact, 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]. At the same time, it's possible to determine the crack growth analyzing the phase data obtained from TSA [8, 9]. In particular, the works of Diaz *et al.* [5-7] and Tomlinson *et al*. [8, 9], show that both amplitude and phase data can be used to evaluate respectively the SIF and crack tip growth.

In this work, the Paris' law was assessed through an automatic procedure based on the analysis of TSA data. The proposed procedure is capable to process very quickly, amplitude and phase thermoelastic data and allows to correlate SIF value with crack tip position in continuous way.

The tested stainless steel were ASTM A 182 F6NM and AISI 422 and three CT steel specimens were used for each material according to ASTM E 647 [11]. TSA data were acquired by means of two cooled infrared cameras placed on opposite side of the specimen.

2. Theory

The thermoelastic effect was reported the first time in the work of Lord Kelvin [12]. 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 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.

$$SA = \Delta\sigma \tag{1}$$

where A is the calibration factor depending on: material, kind of instrument used and environmental conditions of the test. Calibration of thermoelastic signal is needed to determine A and then to evaluate $\Delta\sigma$ and it is performed usually by means of three different approaches [4, 13, [14].

The following important relationship is obtained for thermoelastic signal obtained from a point (r, θ) in a crack-tip stress field resulting from any combination of mode I and mode II loading [4]:

$$SA = \frac{2K_I}{\sqrt{2\pi r}}\cos(\theta/2) - \frac{2K_{II}}{\sqrt{2\pi r}}\sin(\theta/2) \tag{2}$$

Considering a series of signal line plots taken parallel to the line of the crack (*y=constant*), eq. 2 is developed by putting $K_{II}=0$ and by replacing r in the K_I term by $y/\sin\theta$.

The partial derivative of S with respect to θ is zero when $\theta=60°$ and then it follows that maximum signal (S_{max}) in a line plot taken parallel to the crack occurs at $\theta=60°$. By substituting this value of θ [4]:

$$y = \left(\frac{3\sqrt{3}\Delta K_I^2}{4\pi A^2}\right)\frac{1}{S_{maz}^2} \tag{3}$$

From eq. 3 is evident as y and $1/S^2_{max}$ are linearly related and that, provided the constant A is known. K_I can be obtained directly from the gradient of a graph of y versus $1/S^2_{max}$.

In the same way, the analysis for mode I loading can be based on signal plots along lines perpendicular to the crack and ahead of the crack tip (*x=constant*), [4].

As example, in Fig. 1. (b) is plotted the maximum signal S_{max} around the crack tip versus the vertical distance y from the crack tip growth direction. The angular coefficient of the best fit line of collected data provides the SIF value.

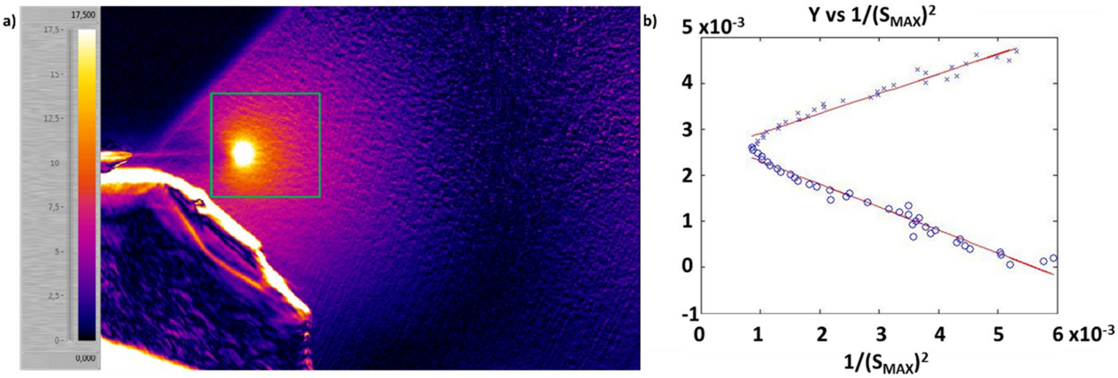

Fig. 1. Typical Amplitude signal map (a) and evaluation of the signal around the crack tip in the selected area (b)

The crack tip growth (*a*) and the stress intensity factor (ΔK_I) were used to evaluate Paris-Erdogan law:

$$\frac{da}{dN} = C\left(\Delta K_I\right)^m \tag{4}$$

where *a* is the crack length, *N* is the cycles number interval, ΔK_I is the stress intensity factor, *C* and *m* are the characteristic constants of the material.
Thermoelastic phase data can be used for identifying the crack tip and the local damage in material [15-17]. In particular, in this work, the procedure proposed by Ancona *et al.* [18] was used to evaluate the crack tip growth.

3. Experimental setup

3.1. Specimen geometry and materials

Two stainless steels were used in this work, AISI 422 and ASTM A 182 grade F6NM with martensitic lattice. Martensitic stainless steels have a higher mechanical strength obtained by a quenching heat treatment but limited corrosion resistance. In ASTM A 182 grade F6NM (σUTS=650 MPa [19]), the addition of Chromium (11-16% in weight) allows to improve corrosion resistance by formation of the oxides, and it also permits to avoid the depleting of Chrome from lattice [20]. In AISI 422 (σUTS=880 MPa [19]) 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 [21].

Compact Tension specimens (in number of three) were used with dimensions according to ASTM E 647-00 [14]. In Fig. 2. dimensions of the specimen are reported in mm. Specimens were sprayed with flat black spray for increasing emissivity to 0.92.

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 at a constant force range ΔP, fixed stress ratio (R=0.1) and frequency (f=13 Hz). The table 1 shows the range used during tests.

Table 1 Material loads

Material	ΔP [kN]
AISI 422	10.8
ASTM A 182 grade F6NM	12.4

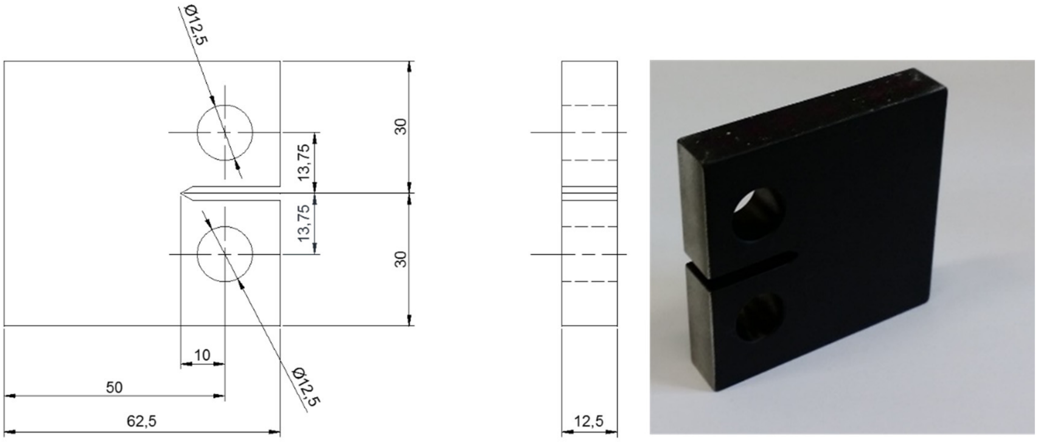

Fig. 2. Specimen dimension in mm according to ASTM E 647-00.

Thermoelastic data were acquired by means of two infrared cameras placed 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. 3. The distances from the specimen were respectively 17 cm and 8 cm in order to obtain 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.

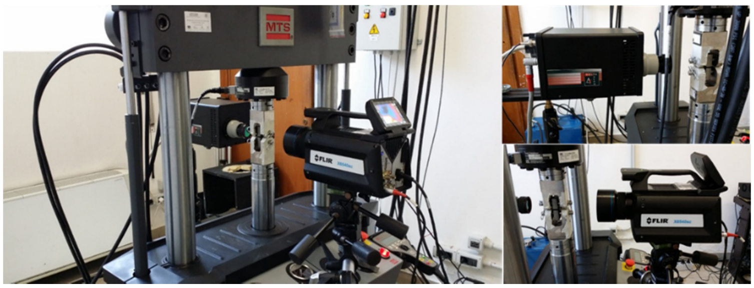

Fig. 3. Experimental set-up used for testing.

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 to evaluate the Paris-Erdogan law; the new procedure trough the on-line monitoring of the crack tip growth and the evaluation of the stress intensity factor is capable to determine the characteristic constant of the material (*m, C*).

Firstly, the calibration constant A (eq. 1) needed to be assessed. In this regard, in this work, it was used a "dog-bone" specimen made of the same material used for tests. In this way, the calibration constant *A* can be assessed measuring the average thermoelastic signal *S* on the gauge length area of "dog-bone" specimen, Fig. 4. Then, by knowing the stress field on the gauge length area of specimen, the constant *A* was obtained by means of equation 1.

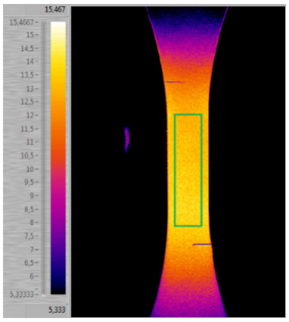

Fig. 4. Amplitude signal map of a "dog-bone" specimen and area considered for the measuring of the thermoelastic signal *S* (AISI 422).

Table 2. shows the values of the calibration constant *A* obtained for AISI 422 and ASTM 182 with the stress amplitude used for "dog-bone" specimens.

Table 2. Calibration constant *A* and stress amplitude used for "dog-bone" specimens.

Material	Load ΔP [MPa]	A [MPa/Signal]
AISI 422	275	20.95
ASTM 182 F6NM	230	10.21

The proposed procedure can be summarized as follows, Fig. 6.:
Thermographic sequence acquisition with infrared camera;

1. Thermoelastic phase and amplitude image saving;
2. Evaluation of the maximum value of thermoelastic signal from the amplitude image;
3. Automatic detection of an analysis area [A] around the maximum value of thermoelastic signal;
4. a) Evaluation of the stress intensity factor $\Delta K_{I;}$
   b) Automatic extraction of the same area [A] from phase data (phase image);
5. Normalization of the selected area in order to report the average phase data to zero [An]=[A]-mean[A];
6. Evaluation of the minimum phase signal in the selected normalized area [An] for the identification of the crack growth direction;
7. Plotting of the phase signal values along the crack growth direction.

8. Automatic assessment of the crack tip position in term of coordinates *x* and *y* in the local reference system (*0, x,* y);

9. Evaluation of the crack tip growth *da/dN*;

10. Evaluation of the constants *m* and *C* plotting *da/dN vs.* ΔK_I.

More details about the procedure for evaluating of the crack tip growth are reported in the work of Ancona *et al.* [18].

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.
All the crack tip growth and SIF values obtained from proposed algorithm were used to obtain the Paris-Erdogan law, Fig. 5., for AISI 422 and ASTM A182 F6NM.

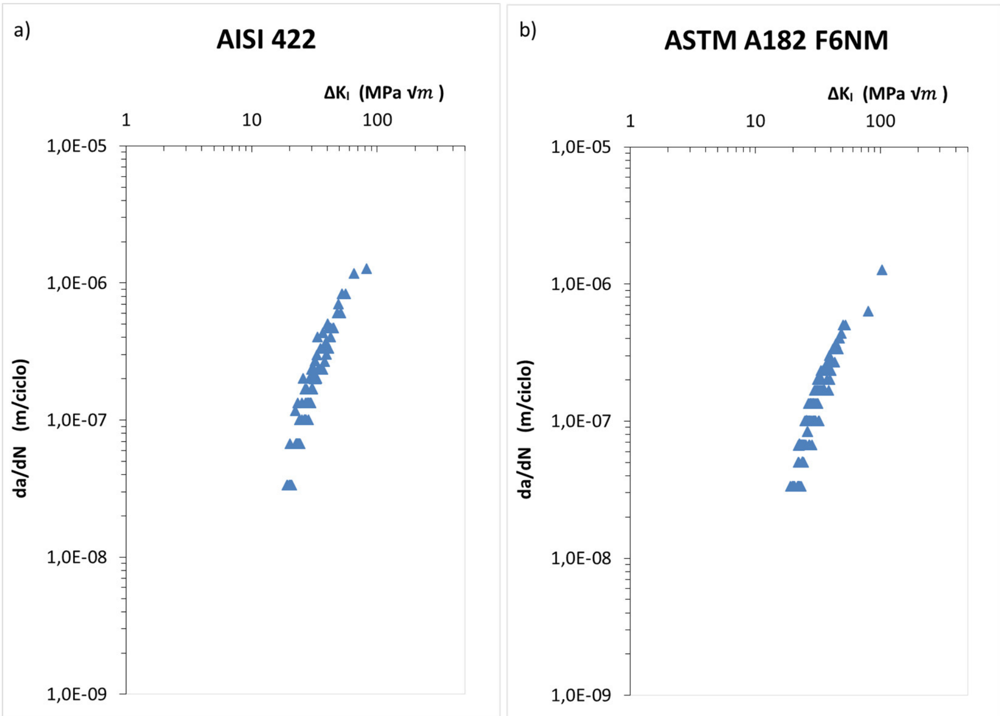

Fig. 5. Crack tip growth vs. SIF for AISI 422 (a) and ASTM A 182 F6NM (b)

Tables 3. and 4. show the constant load amplitude used for tests and number of cycles performed until to failure of specimen while, in Table 5, are shown the characteristic constants, *m* and *C,* for the two tested materials.

Table 3. Load 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

Table 4. Load and number of cycles performed for ASTM A 182 F6NM

ASTM A 182 F6NM - Specimen	Load ΔP [kN]	Cycles
1	12.4	146000
2	12.4	142000
3	12.4	138000

Table 5. Material constants obtained with the new procedure for AISI 422 and ASTM A 182 F6NM

Material	m	C
AISI 422	2.89	$1.14 \cdot 10^{-11}$
ASTM A 182 F6NM	2.44	$3.31 \cdot 10^{-10}$

6. Conclusions

In this work, the fracture mechanics behavior of two martensitic steels was studied using Thermoelastic Stress Analysis (TSA) technique. In particular, a new procedure has been proposed for evaluating the Paris law of two materials. The proposed procedure allows to assess the crack tip growth and the SIF value continuously and in automatic way.

Three fatigue crack tests for each material were carried out on CT specimens according to standard ASTM E 647 and the crack growth was monitored by means of a cooled infrared camera.

The proposed procedure allows to determine the Paris-Erdogan law of material very quickly (about 5 minutes) and presents different advantages with respect to traditional methods:

- a simpler data processing,
- TSA data are simple to monitor ,
- can be used for the monitoring of damage of real and more complex structures subjected to the loading operating conditions.

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