25th International Conference on Fracture and Structural Integrity

Thermographic analysis during tensile tests and fatigue assessment of S355 steel

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Abstract

Structural S355 steel is widely applied in various sectors. Fatigue properties are of fundamental importance and extremely time consuming to be assessed. The aim of this research activity is to apply the Static Thermographic Method during tensile tests and correlate the temperature trend to the fatigue properties of the same steel. The Digital Image Correlation (DIC) and Infrared Thermography (IR) techniques have been used during all static tests. The Digital Image Correlation technique allowed the detection of displacements and strain, and so the evaluation of the mechanical properties of the material. Traditional fatigue tests were also performed in order to evaluate the stress-number of cycles to failure curve of the same steel. The value of the fatigue limit, obtained by the traditional procedure, was compared with the values predicted by means of the Static Thermographic Method (STM) obtained from tensile tests. The predicted values are in good agreement with the experimental values of fatigue life.

1. Introduction

Full-field measurement techniques have been applied in literature for the experimental investigation of metallic and composite materials subjected to mechanical and thermal loading [1–6].

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The Infrared Thermography was applied for the analysis of different materials subjected to different loading conditions: notched steel specimens under tensile static tests [7, 8], laminated composites under tensile static loading [9], short glass fiber-reinforced polyamide composites under static and fatigue loading [4], steels under low cycle [9], high cycle [9-14] and very high cycle [15, 16] fatigue regimes. The traditional methods of fatigue assessment of materials are extremely time consuming, so an innovative approach, based on thermographic analyses of the temperature evolution during the fatigue tests, has been proposed for a rapid prediction of the fatigue limit and the S-N curve, using a very limited number of tests: the Thermographic Method (TM) [8].

There are many studies in literature on the thermal response of composites during static tests for a prediction of the fatigue limit, as reported in [8], but only few studies [7] about the thermal response of steels during static tests, and some studies about the application to welded joints [17-19], as far as the authors are aware.

The aim of this research activity is the application of the Static Thermographic Method (STM) during static tensile tests for the fatigue assessment of S355 steel. Tensile tests were carried out and Digital Image Correlation (DIC) and infrared thermography (IR) techniques have been used during all static tests. Moreover, classic fatigue tests were performed and the S-N curve was evaluated. The predictions of the fatigue limit, obtained by the analysis of the specimen surface temperature evolution during the static tests, were compared with the predictions obtained from the fatigue tests.

2. Materials and methods

Static tensile tests and fatigue tests were carried out on specimens made of S355 steel, widely used in marine structures and shipbuilding. The specimens have a dog bone shape (Fig. 1a) with a nominal cross section of 15 mm x 10 mm. All the tests were performed with a servo-hydraulic load machine INSTRON 8854. The static tests were conducted under load control using a load rate of 183 MPa/min. Two full-field techniques were used during the static tests: Digital Image Correlation and Infrared Termography. The DIC technique is a full-field non-contact measurements method which allows the detection of displacement and strain fields. Two cameras with a resolution of 4000 x 3000 pixels, focal length of 50 mm, were used for the application of this technique. The system accuracy for the strain measurement is up to 0.01%, and the images were acquired at 1 Hz. The specimens were coated with a black-white speckle pattern and ARAMIS 3D 12 M system was used to analyze the strain pattern of the specimen surface. The infrared camera FLIR A40 was used, with a sample rate of 1 image per second, in order to monitor the specimen surface. The fatigue tests were carried out at different constant stress amplitude, ranging from 160 to 260 MPa, with a load ratio R= -1 and f= 20 Hz on specimens with the same geometry of the previously ones used for the static tests. The experimental setup is shown in Fig. 1b.
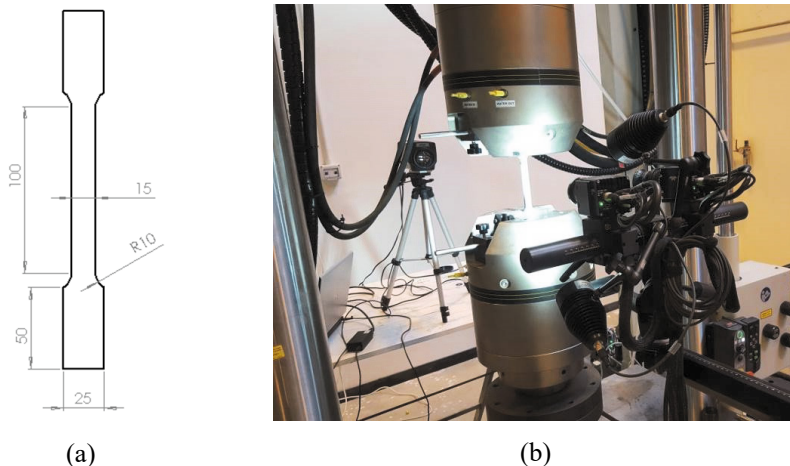

Fig. 1. (a) specimen geometry; (b) experimental setup.

3. Experimental tests

3.1. Material properties evaluation during static tests by means of the Digital Image Correlation

Static tests were carried out under load control using a load rate of 183 MPa/min. The DIC technique allowed a complete analysis of the displacements and strains of the whole surface of the specimen, as well as the detection of local strain concentrations during the tests. The evolution of longitudinal strain during a static test versus the specimen surface evolution at different loads is reported in Fig. 2.
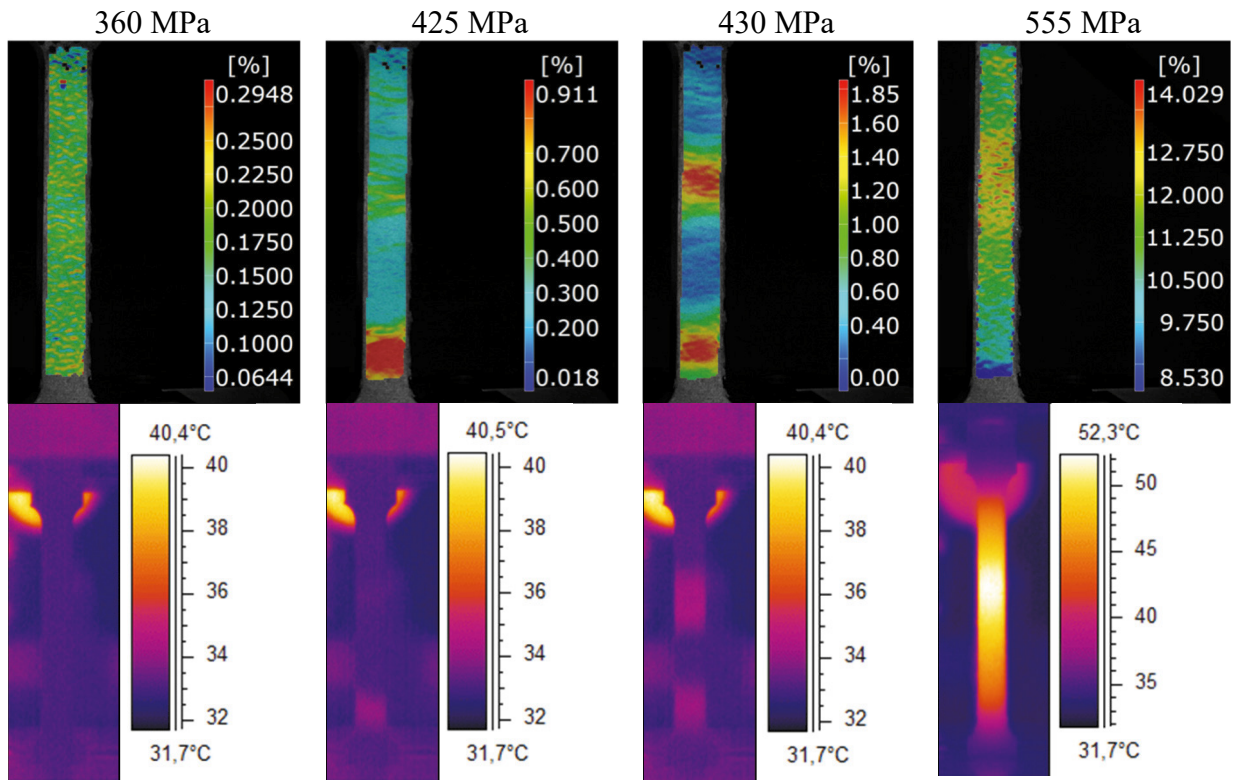

Fig. 2. Longitudinal strain vs. surface temperature evolution detected by the DIC technique and IR camera

The mechanical properties calculated with the aid of this technique are: the Young modulus (E), the work hardening exponent (n), as the exponent of the true stress - true (plastic) strain curve in the plastic field before the necking (Hollomon equation), the Poisson coefficient (ν), the yield stress (R_{p02}) as the value of the stress which, by definition, produces the 0.2% residual plastic longitudinal strain, the maximum stress (R_m) which is the stress value corresponding to the maximum load and, therefore, the maximum value of the stress - strain curve, the strain at rupture (ε_r) and the strain at the maximum load (ε_u). The obtained values are reported in Table 1. Fig. 3 shows the technical and real stress-strain curves, while Fig. 4 shows the calculation of E and R_{p02}.

Table 1. Mechanical properties of the investigated S355 steel

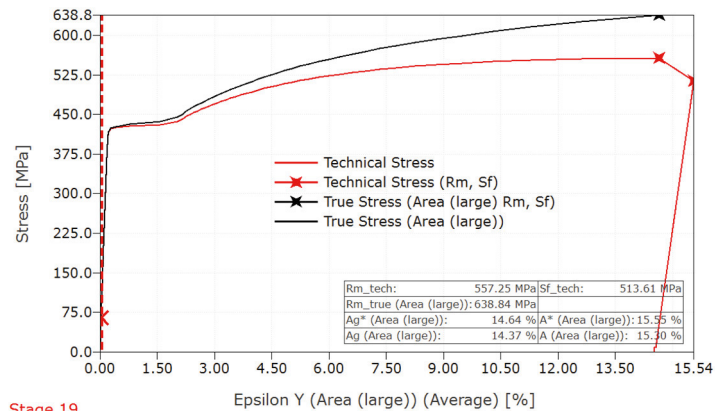| S355 steel		
Young's Modulus	E	205315 MPa
Poisson ratio	ν	0.29
Yield Stress	R_{p02}	425 MPa
Work hardening exponent	n	0.165
Maximum technical stress	$R_{m\,tech}$	557 MPa
Maximum true stress	$R_{m\,true}$	639 MPa
Strain at maximum load	ε_u	14.64 %
Stress at rupture	R_f	514 MPa
Strain at rupture	ε_r	15.55 %

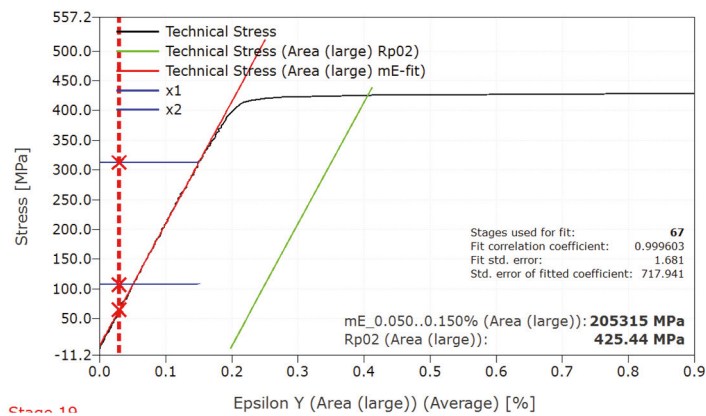Fig. 3. Technical and real stress-strain curves evaluated by the DIC technique.

Fig. 4. Evaluation of the Young modulus and yielding stress by the DIC technique.

3.2. Fatigue tests

Fatigue tests were carried out by imposing different values of the maximum stress, with a load ratio R= -1, setting the run-out (i.e. the number of cycles that have theoretically infinite life) to 5×10^6 cycles and adopting a load frequency of 20 Hz.

The value of the fatigue limit identified by the stress amplitude - number of cycles to failure (N_f) curve (Fig. 5) is close to 180 MPa. This value is in line with those present in the literature [20].
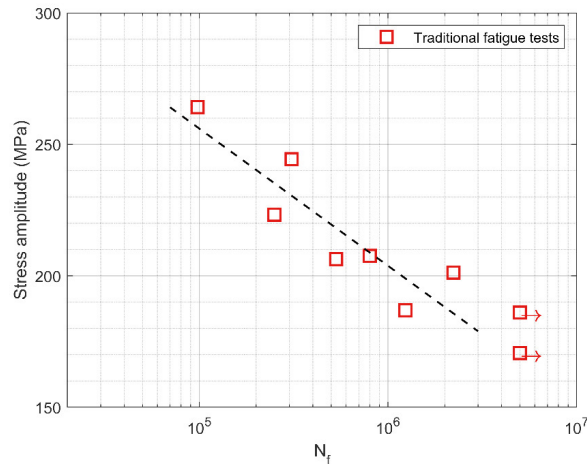

Fig. 5. Stress amplitude – number of cycles to failure curve obtained from traditional fatigue tests.

3.3. Thermographic method during static tests

During static tests of common engineering metals, the temperature evolution on the specimen surface, detected by means of an IR camera, is characterized by three different phases [7, 17-19] (Fig. 6): an initial approximately linear decrease due to the thermoelastic effect (phase 1), then the temperature deviates from linearity until a minimum (phase 2) and a very high further temperature increment until the failure (phase 3). The first deviation from linearity, which corresponds to the end of the phase 1, can be correlated to the damage limit, very close to traditional fatigue limit.
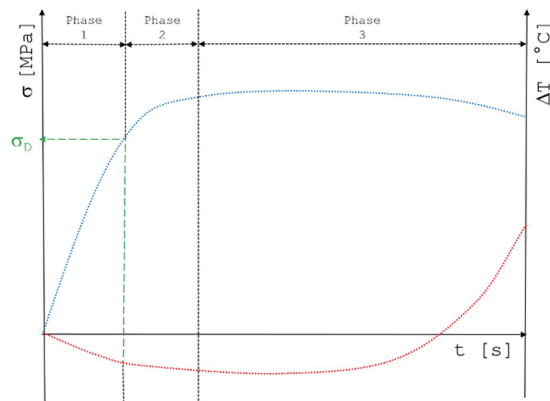

Fig. 6. Maximum temperature evolution during a tensile test.

Fig. 7 shows the trend of the applied stress and the experimental temperature increment ΔT, calculated as the difference of the actual temperature of the specimen surface minus the initial temperature of the specimen surface (ΔT

$= T_i - T_0$), during the tensile test. From the same graph it is also clearly visible that there is an initial phase in which the temperature variation has an almost constant slope (thermoelastic phase) and then tends to stabilize during a second phase. The change in the slope of the temperature increment can be easily find as the intersection between the straight line of regression of the thermoelastic region and the straight line of the zero derivative flex region. The corresponding stress value is around 169 MPa. The tests have shown that the slope change between 160 MPa and 180 MPa.
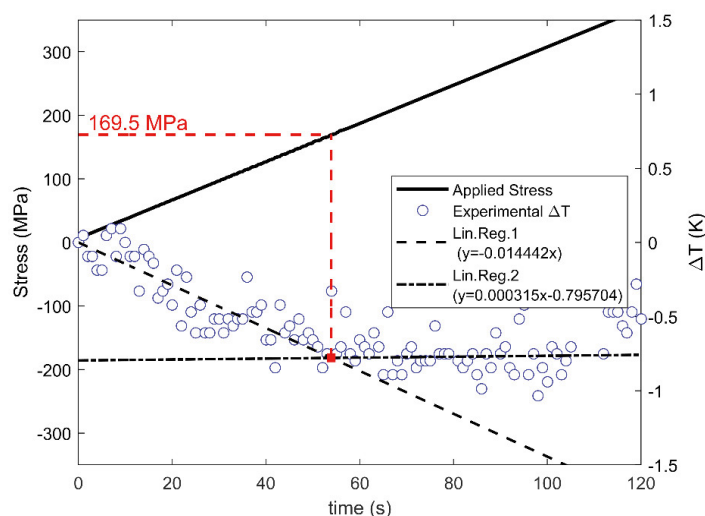

Fig. 7. Maximum temperature evolution during a tensile test.

The values obtained using the two different approaches of traditional fatigue tests and Static Thermographic Method, seem to be in good agreement, as the obtained scatter is normal for welded joints also during traditional fatigue tests.

Conclusion

Full-field techniques were applied for the study of S355 specimens. The DIC technique allowed the detection of strain field and the mechanical properties evaluation. The IR technique allowed the application of the Thermographic Method. The thermographic measurements during static tests can be used to predict the fatigue limit.

The predictions of the fatigue life, obtained by means of the thermographic method during static tensile tests, were compared with the value obtained by the traditional procedure. The predicted values are in good agreement with the experimental values of fatigue life.

The results gave interesting information for the development of prediction models for the fatigue life assessments of welded joints.

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