Chapter 1
Fatigue Behaviour of Stainless Steels: A Multi-parametric Approach

R. De Finis, D. Palumbo, F. Ancona, and U. Galietti

Abstract In recent years different experimental methods have been experienced to enhance the fatigue characterisation of materials with the aim to overcome the Standard long-lasting tests, i.e. Wohler curve determination. Standard fatigue treatment requires at least 15 specimens being tested to get an estimation of material fatigue limit and it is worth noting that this kind of tests do not provide any information on damage phenomena occurring in the material. Thus, topic to be addressed in this research have to do with development of lock-in infrared measurement based thermal method for rapid evaluation of fatigue limit. By performing a single test , the adopted method leads to match different parameter information. The Assessed parameters are in number more than the ones provided by TSA, as well. Moreover, the adopted technique points to study damage by analysing the different phenomena involved in fatigue and in this regard, the aim of this paper is to show how a thermal technique can attain an early assessment of the failure processes during a cyclically loading test. The author is, also, focused on to illustrate the strong points of a method based on infrared measurements for assessing endurance limit for both austenitic and martensitic stainless steels while considering, as reference, the Standard Test methods.

Keywords Lock-in thermography • Fatigue • Austenitic/martensitic stainless steels

1.1 Introduction

Infrared thermography has been successfully exploited as an experimental, non-destructive, real-time and non-contact technique to observe physical processes of: damage, fatigue, and failure. The strong points of the technique concern the mechanical characterisation of metallic, composites and structural components [1–3]. Different works was meant to show that the surface temperature monitoring is a reliable technique to detect the damage phenomena and thus, the material intrinsic dissipation are evaluated. Following from the work of Luong [1] in to the use of thermal sources to assess fatigue limit, in literature, different approaches have been performed to study the fatigue damage with thermography based on: the monitoring of the surface temperature[2, 4] , the evaluation of "dissipative" thermal heat sources[5], the evaluation of the phase variation in thermographic signal by using lock-in thermography [6–8]. Referring to the temperature, it is worth noting that this parameter is very sensitive to the external influences and thus, room temperature and/or loading machine grip heating can affect the measurements and have to be considered in the analysis. In this framework [2], De Finis et All propose a robust technique to thermal data analysis in order to filter out all the noisy all the heat sources compromising the adiabatic condition of the sample during the test and for early detecting the dissipation processes. Despite the direct use of thermal parameter has opened-up the possibility of mechanical fatigue characterising with less-lasting and less expensive experimental campaign, temperature measurements are affected by thermal properties of the material [6], as well, i.e. thermal conductivity. Material with high conductivity (e.g. aluminium alloys or welded joints) experience low temperature during the test due to high percentage of reflected radiation. Another issue related to the use of temperature is represented by the lattice microstructures which cause extremely low temperature increments [2, 3]. To improve the analysing experimental dataset and to avoid the appearance of the 'external' influences another approach based on lock-in thermography is proposed. The technique, moreover, provides several parameters accounting for the study of damage phenomena. By demodulating thermal signal the harmonic analysis allows for achievement of 1° phase and 2° amplitude harmonic components: two significant parameters for assessing fatigue behaviour of material [7, 8], and all external heat source influence is eliminated. In this work lock-in thermography will support the Thermoelastic Stress Analysis by studying evolution of damage phenomena despite the loss of adiabatic conditions [6, 9]. In particular the phase shift of first

---

R. De Finis (✉) • D. Palumbo • F. Ancona • U. Galietti
Department of Mechanics, Mathematics and Management (DMMM), Politecnico di Bari, Bari, Italy
e-mail: rosa.definis@poliba.it; davide.palumbo@poliba.it; francesco.ancona@poliba.it; umberto.galietti@poliba.it

S. Quinn, X. Balandraud (eds.), *Residual Stress, Thermomechanics & Infrared Imaging, Hybrid Techniques and Inverse Problems, Volume 9*, Conference Proceedings of the Society for Experimental Mechanics Series, DOI 10.1007/978-3-319-42255-8_1

component synchronous at the mechanical frequency is related to the appearance of plastic zones or cracks in the material and so it is strictly related to damage [6]. Moreover, if thermal phenomena are present a double mechanical load frequency component arises related to dissipative heat sources in the material and thus it is associated to the temperature [8]. In this paper the phase shift and double frequency harmonic amplitude are jointly used to carry out a fatigue damage study for assessing endurance limit of both austenitic and martensitic stainless steels.

1.2 Theoretical Framework

The thermoelastic stress analysis is a full-filed, well-established and non-contacting technique for evaluating surface stresses related to the small temperature increments when during the fatigue experiment adiabatic conditions are achieved [6, 10, 11]. Under the hypothesis of a linear elastic, isotropic and homogeneous material the temperature change occurs isoentropically: the so called thermoelastic effect [12]. The classical thermoelastic equation (1.1) states:

$$\Delta T = -T_0 K \Delta\sigma_I \tag{1.1}$$

where K is the thermoelastic constant, ΔσI is the change in the stress invariant and T0 is the specimen environmental temperature. If thermoelastic effect is present the reversible conversion between mechanical and thermal energy is feasible [10, 11]. During the cyclically loading test, when the intrinsic stress level in the material exceed the yield strength, high stress gradients and local plasticity appear caused by dissipative heat sources. In these conditions the classical thermoelastic equation (1.1) lose validity and TSA cannot be used for assessing surface stress field of material [10]. Despite this limitation in applying TSA, the phase of thermoelastic signal still represents an important parameter to evaluate fatigue behaviour of material [6].

Considering a reference signal of load cell installed on loading machine, the thermoelastic signal and reference signal are considered as two vectors rotating at the same speed (the same mechanical frequency). Time after time the shift in phase values is constant and it varies only in case of loss of adiabatic condition. Hence, for studying the fatigue behaviour another parameter can be used in place of the TSA provided parameters, it is represented by phase shift between thermoelastic signal with respect reference signal and its amplitude [6]. By using a lock-in amplifier, the signal can be reported to reference signal and a suitable signal demodulation must be realized to obtain the parameters. The adopted mathematics model describing temperature change during the test, is [8, 13]:

$$T_m(t) = a + bt + \Delta T_1 \sin(\omega t + \varphi_1) + \Delta T_2 \sin(2\omega t + \varphi_2) \tag{1.2}$$

Where “a” coefficient is proportional to the environmental temperature, “b” coefficient depends on mechanical load frequency and time, “f” is the mechanical load frequency, T1,2 and φ1,2 are coefficient proportional to, respectively amplitude and phase shift of first and second harmonic component of Fourier Fast Transform [8, 9]. In this paper the assessment of fatigue behaviour of martensitic and austenitic stainless steel is shown by evaluating φ1 and T2 parameters of thermal signal demodulation.

1.3 Experimental Setup

A typical setup for assessing signal is drawn in and Fig. 1.1.

The tested materials are the austenitic AISI 316 and martensitic X4 Cr Ni 16-4 stainless steels used in Oil&Gas Industry.

Martensitic stainless steels have a higher mechanical strength obtained by a quenching heat treatment but limited corrosion resistance. The AISI 316 material is a well-known austenitic stainless steel while X4 Cr Ni Mo 16-4 deal with the addition of Chromium in the lattice (11–16 % in weight) that allows for [14]:

- improvement of corrosion resistance through the formation of oxides,
- avoidance of the depleting of Chromium from lattice.

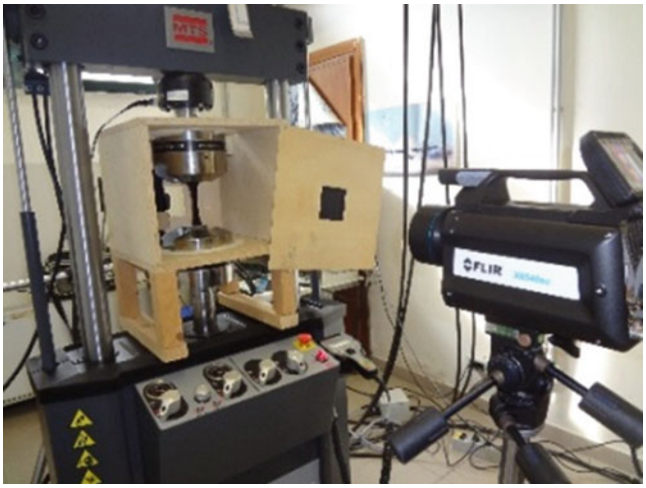

Fig. 1.1 Loading machine and IR detector

During the fatigue tests the procedure is stepwise with incremental stress amplitude and mean stresses. Three 'dog bone' shaped specimen for both material have been tested in an insulated chamber covering the clamping area and minimizing environmental heat change. During fatigue testing, a thin sub-micron matt black coating was applied on the specimen gage-length section to decrease the surface-heat reflections.

Low-cycle fatigue experiments were performed on both steels at 17 Hz on a MTS (Material Test System) machine with a R-ratio of 0.5. A load-control mode was used. Maximum stress levels ranging from 80 to 440 MPa and 440 to 830 MPa, respectively for AISI 316 and X4 Cr Ni 16-4 were applied. Note that all of the stresses were applied in a sinusoidal waveform.

Thermography detection was conducted using a state-of the-art FLIR X 6540SC thermographic-IR-imaging system with a 640 × 512 pixels focal-plane-array cooled detector that is sensitive to a radiation wavelength of 1.5–5.1 μm. The temperature sensitivity is less than 25 mK. The system has a highest-speed data-acquisition capability of 125 Hz at a full frame of 640 × 512 pixels.

The procedure for processing phase data does not consider any external heat influences and consists in applying a Gaussian filter to all data matrix for each loading step, first. In the data matrix the pixel is a single value of phase shift or 2° order amplitude component, only the pixels referring to the gauge length of specimen are considered in the analysis and thus a windowing is needed. Moreover, a reference data matrix has been subtracted from the leftovers to eliminate the noise of early load steps (Fig. 1.2). For specimen 1 of AISI 316 the reference load step has been fixed to 35 MPa while for X4 Cr Ni 16-4 material the subtracted image refers to 167.50 MPa. For the T2 parameter during the data processing any subtraction has been made. In the next paragraph are shown the results for both materials.

1.4 Results

In this paper a comparison between temperature phase shift φ, and second harmonic amplitude parameter T_2 data is shown. Parameters maps, parameters curves and fatigue limit found, are compared with the value of Standard Statistical Dixon method.

The adopted processing procedure leads to obtain statistical data for assessing fatigue limits, by analyzing the parameter values in the gauge length of the specimen (data matrix 40 × 140 pixels for AISI 316, and 60 × 160 pixels for X4 CR NI 16-4).

The data series considered in the processing were: difference percentiles $98° - 2°$ for temperature phase shift parameter and max value for second order harmonic amplitude parameter.

The experimental data set considered for phase shift analysis was the difference of 98° and 2° percentiles of phase series : due to large scattering of phase data this procedure sets the results free of outliers points.

The $98° - 2°$ percentiles difference is applied pixel by pixel of the matrix representing the gauge length of specimen, for all the loading steps.

To eliminate any external influence, e.g. the thickness of matt black coating layer, a residual analysis is made on $98° - 2°$ percentile data series according to similar procedure proposed by the author [2].

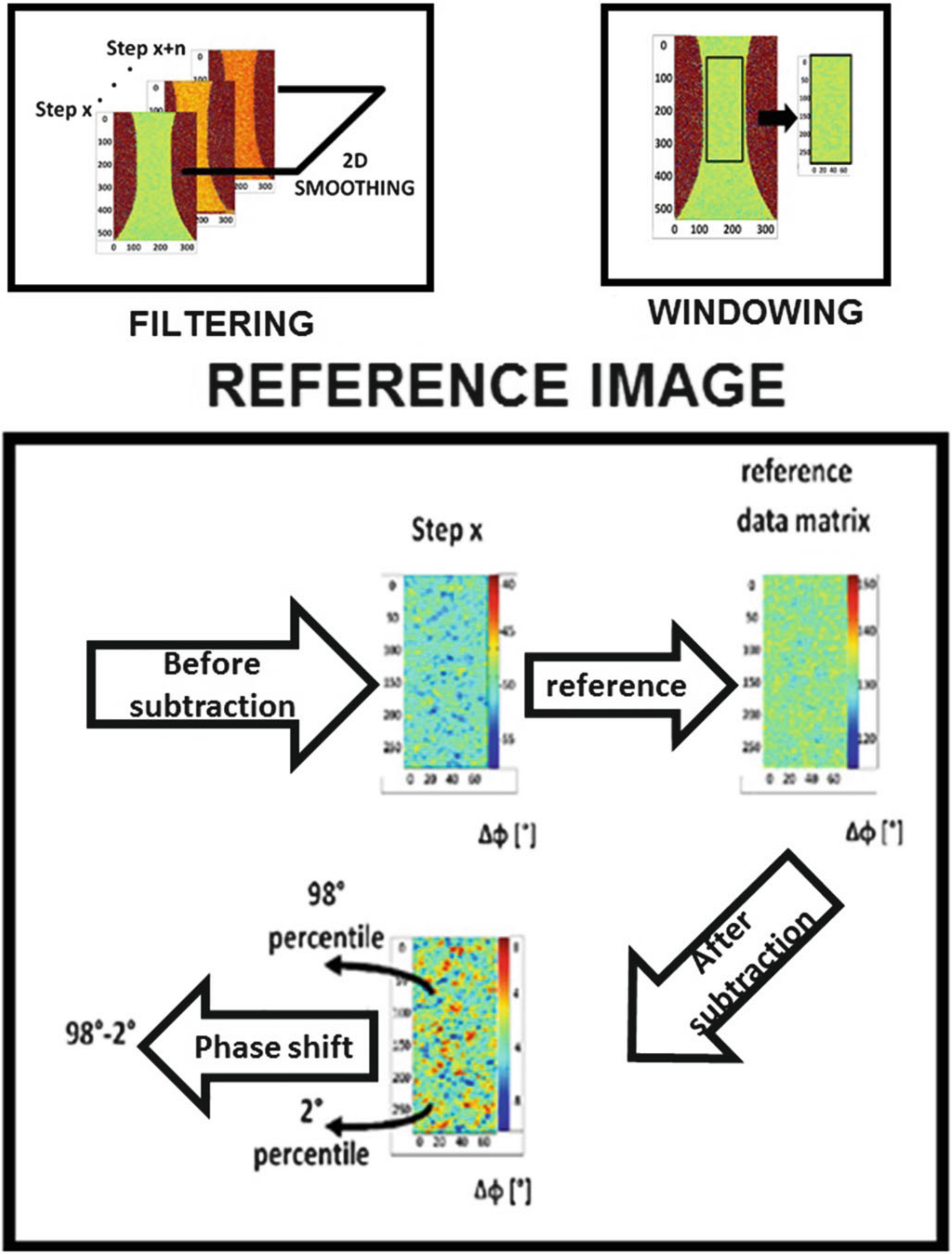

Fig. 1.2 Smoothing procedure for phase data matrix

For each sample, the residual analysis refers to phase data of the beginning three loading step levels in which any damage phenomena is present in the bulk material.

A statistical process control chart ensures fixing a threshold to early assess the occurring of damage process and thus, the fatigue limit. The threshold value is given by the mean value of the residuals data onset the test (first three points) plus three times their standard deviation. The threshold method provides a better evaluation of damage and fatigue processes referring to other methods proposed in literature, leaving the researcher their own choice of the breakpoint of data series for assessing fatigue limit [1].

The same data regression analysis was applied on second harmonic amplitude parameter and the fatigue limit found for each specimen has been evaluated by exploiting the shown procedure with another type of statistical analysis with 3σ control chart. In particular in this case, as well, the analysis consists in interpolating early three data and subtracting both the slope and offset of this straight line to the other data. A threshold value is set up to separate from data series, the value at which damage occurs. The choice of two different thresholds has been supported by results of Dixon reference method. It is worth nothing to highlight that the meaning of single threshold ($\mu + \sigma$ chart for phase shift parameter and $\mu + 3\sigma$ chart for dissipation parameter) is relied to the nature of two parameters : temperature phase shift is related to the damage occurring in the material, a significant increase of the value means that the material is experiencing fatigue phenomena. Dissipation parameter, the so called second harmonic

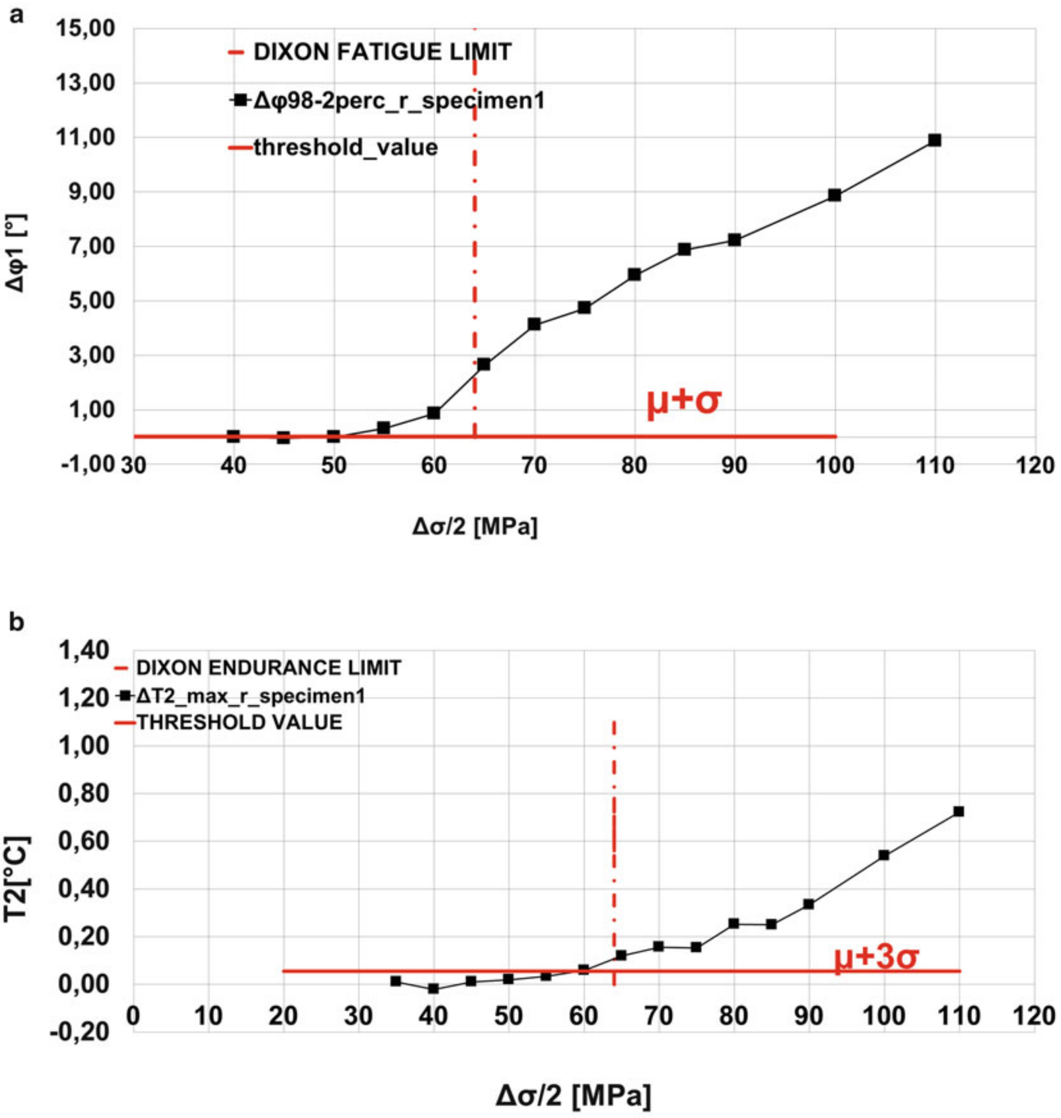

Fig. 1.3 Application of threshold method on AISI 316: phase data (**a**), dissipation data (**b**)

amplitude parameter represents the heat dissipations caused by irreversible phenomena in the material e.g. plasticity. The appearance of a dissipative phenomenon not necessarily implies damage.

Generally the range of magnitude of this parameter is lower than the magnitude of phase shift parameter i.e. 0.001–0.005 °C vs. 1–10°.

As an example, for AISI 316 specimen 1, Fig. 1.3 shows the phase parameter curve (a) and the dissipation parameter curve (b) with applied thresholds.

Figure 1.3 shows also the fatigue limit of 65 MPa (bolt red line) found with Dixon experimental tests carried out on AISI 316. The standard test method consists in run-in/run-out based procedure with infinite threshold life fixed at 2×10^{-7} cycles of loading machine. The load ratio for all the test was fixed at 0.5, and test frequency was 39 Hz.

1.5 Discussion

As drawn in Fig. 1.4 for AISI 316 austenitic material (right column in the pictures) , due to its ductile behaviour, in the phase map it is possible to observe that the damage is spread in the gauge length of specimen. In this case, for austenitic stainless steels the high yield strength allows to a global plastic work affecting homogeneously the whole material (as shown in phase and T2 matrix Figs. 1.4 and 1.5 right columns) except for some clusters appearing at the last cycles of the test phase map Fig. 1.4. Figure 1.5 shows the dissipation parameter ΔT_2 for both martensitic and austenitic steels. Referring to right column, the austenitic behaviour of AISI 316 indicates that no localized dissipations occur in the material, excepting for the final loading step. Due to the ductile beahviour the material seems easily dissipating the imposed high stress gradients without leading to some localized plasticizations. The Figs. 1.4 and 1.5 show also, a good reproducibility for all the curves of AISI 316 material.

For brittle materials, a fatigue crack could develop during the cyclically loading experiments.

By analyzing Figs. 1.4 and 1.5 (left column) representing respectively the temperature phase shift and second harmonic amplitude parameter maps, the monitoring of the fatigue crack growing in the material is performed. It is worth noting the potential of this technique in detecting material failure or damage processes of real and complex shaped component during

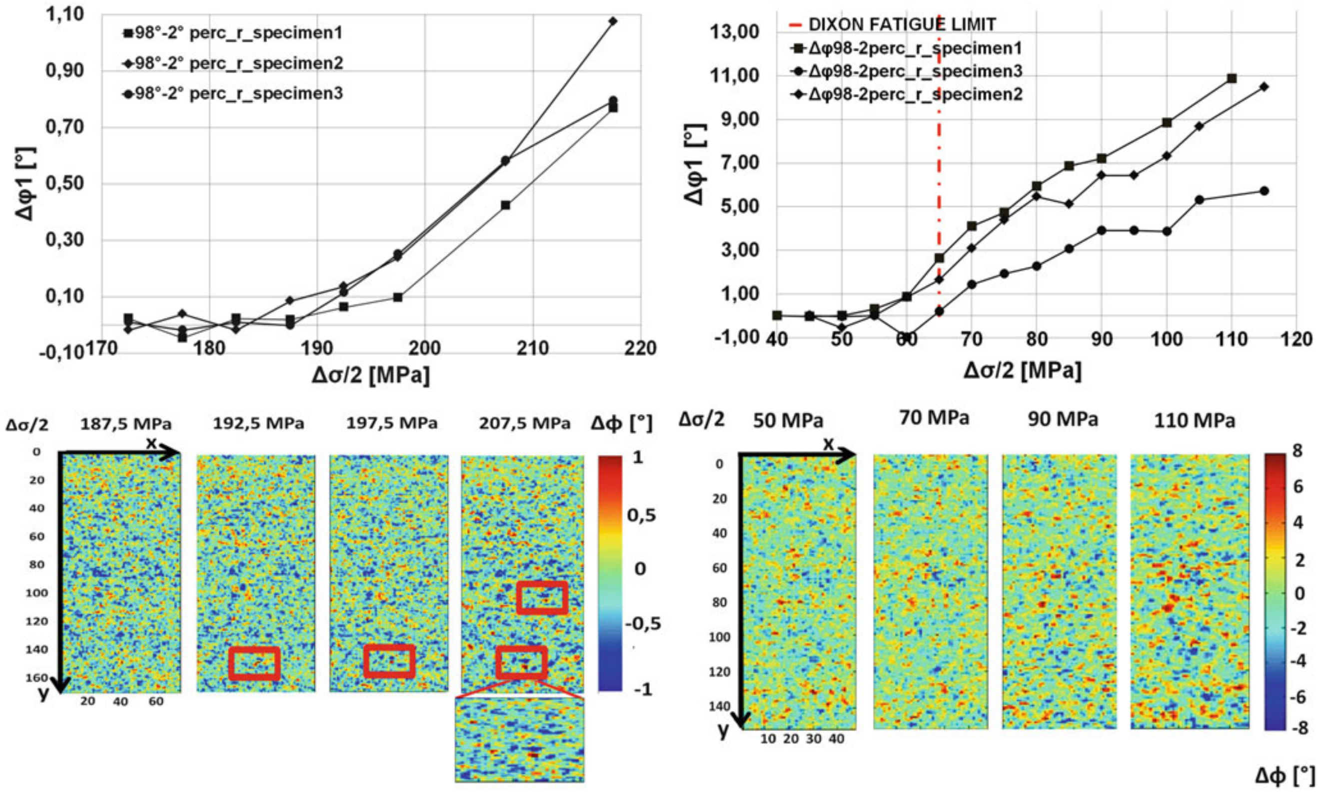

Fig. 1.4 Temperature phase residuals and maps: X4 Cr Ni 16-4 (*left column*), AISI 316 (*right column*)

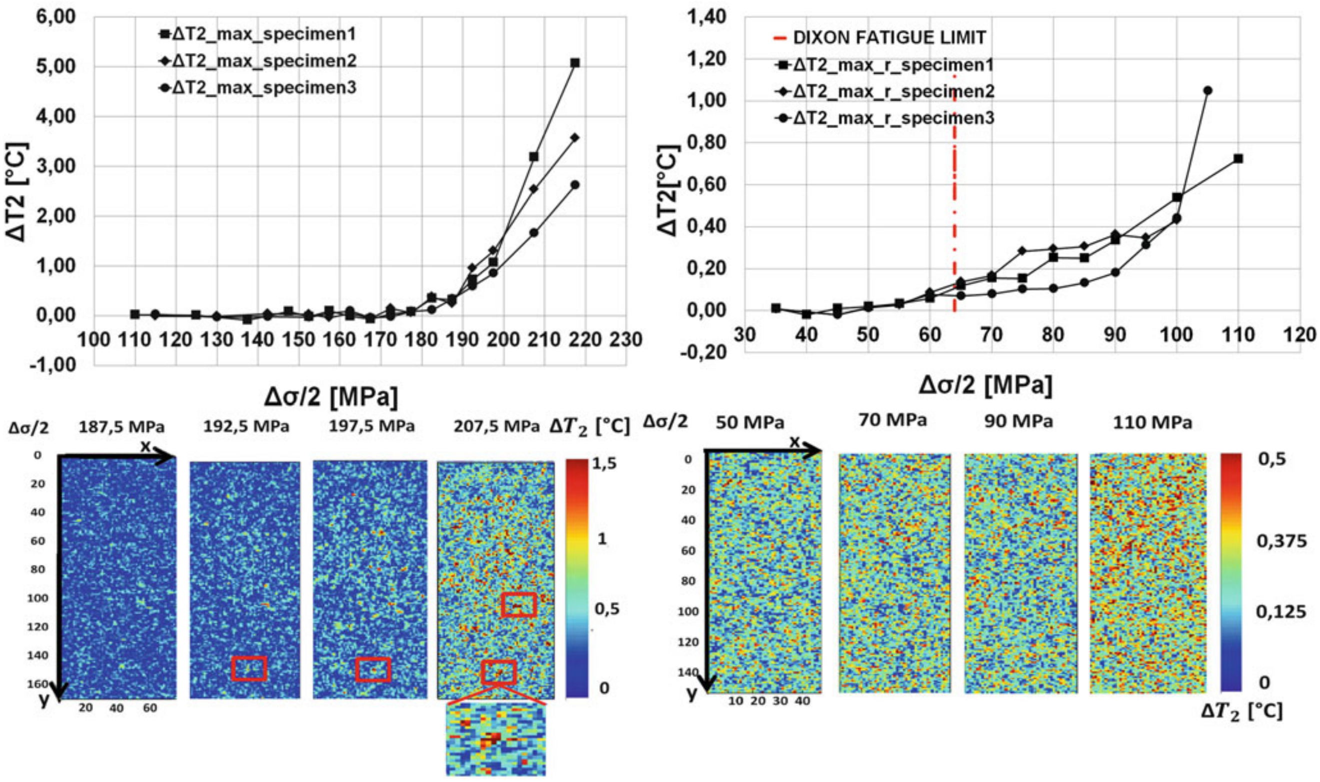

Fig. 1.5 Second order harmonic amplitude parameter T_2 residuals and maps: X4 Cr Ni 16-4 (*left column*) , AISI 316 (*right column*)

Table 1.1 AISI 316 Endurance limit results: different methods

AISI 316	Themperature phase shift parameter (MPa)	2° harmonic amplitude parameter (MPa)
AVERAGE	**60.00**	**60.00**
STD. DEV.	5.00	0.00
	FATIGUE LIMIT 'DIXON' METHOD [MPa]	
	64.58 (3.51 MPa standard deviation)	

Table 1.2 X4 Cr Ni 16-4 Endurance limit results: different methods

X4 Cr Ni 16-4	Themperature phase shift parameter (MPa)	2° harmonic amplitude parameter (MPa)
AVERAGE	**190.83**	**180.83**
STD. DEV	2.89	2.89

maintenance. As disclosed before, the appearance of dissipation phenomena could not be necessarily related to damage. In this case, by confronting Figs. 1.4 and 1.5 (left column) for X4 Cr Ni 16-4 material, a low signal dissipation appears at 187.5 MPa while the temperature phase shift map in Fig. 1.4 shows the appearance of damage at 192.5 MPa referred to the same position. By confronting the phase map (Fig. 1.4) and dissipation map (Fig. 1.5) it is possible to observe the results are in good agreement. At this regard it can be concluded that dissipations appear before the crack. The crack , as noticed in this case, develops at higher stress value in the same position. It is possible to claim that the dissipation parameter fulfil important role in detecting the inception of plastic phenomena in the material, and as confirmed by temperature phase parameter the combined use of these two parameters could help the researcher in predicting fatigue limit and failure localization.

Results regarding fatigue limits are showed in Tables 1.1 and 1.2, for both parameters for both materials.

For AISI 316 materials the results in Table 1.1 are in good agreement with the value found by means of Dixon Standard method, the phase mean values are very close to 64.58 MPa.

Referring to tested martensitic stainless steel (Table 1.2), the average value of phase result is higher than T2 average value. This phenomenon can be explained by considering the intrinsic difference in meaning between phase and second order amplitude components: the first is a manifestation of occurring damage while the second represents the dissipative heat sources due to a localized stress concentration in the material. The obtained ΔT_2 value could be lower than phase mean value because the dissipative heat sources appear before any material failure. Further studies will be focused on the comparison of found values with the reference given by standard test method.

1.6 Conclusions

This work deals with the characterisation of two kind of stainless steels : AISI 316 and X4 Cr Ni 16-4. In particular as knowledge of authors, not so many works concerns the fatigue characterisation of showed martensitic stainless steel.

The fatigue limit characterisation has been made by exploiting potentialities of a thermal methods. Infrared measurements provide a signal which analysis concerns the extrapolation of two parameters related to thermoelastic signal. The experiments were meant to demonstrate that the temperature phase shift and second order harmonic amplitude represent good indicators for damage and dissipative phenomena appearance. Thus , they allow for assessing fatigue limit of both austenitic and martensitic lattice. In this framework, a method to evaluate a threshold for getting the fatigue limit has been showed. The showed method to post-process the data allows to obtain results in good agreement with theoretical assumptions and they are also very close to Dixon fatigue limit evaluation. Recent advances of the threshold method are addressed to easily and automatic implementation of the algorithm and to calibrate technique by using a Standard Test method.

Following, the research carried out the great dependence from the type of crystal network: the austenitic microstructure dissipates energy by affecting all the surrounding lattice planes, while the martensitic microstructure leads to a stress concentration only in localized zones that may become fatigue cracks. As shown by analysis, and as confirmed by results, the phase shift $\Delta\varphi$ parameter is capable to detect the damaged zone and the $\Delta T2$ analysis involves in an assessment of dissipative heat sources not-necessarily close to damage (a dissipative heat sources can be localized inside the material but these one could not cause a failure).

In this paper the fatigue test with infrared thermal methods was meant to show the thermoelastic signal processing provides different parameters describing the overall process involved in the damage behavior of material. The potential of this method is moreover, the reliability to real component monitoring during maintenance.

References

1. Luong, M.P.: Infrared thermographic scanning of fatigue in metals. Nucl. Eng. Des. **158**, 363–376 (1995)
2. De Finis, R., Palumbo, D., Ancona, F., Galietti, U.: Fatigue limit evaluation of various martensitic stainless steels with new robust thermographic data analysis. Int. J. Fatigue **74**, 88–96 (2015)
3. Freire, J.L.F., Waugh, R.C., Fruehmann, R., Dulieu-Barton, J.M.: Using thermoelastic stress analysis to detect damaged and hot spot areas in structural components. J. Mech. Eng. Autom. **5**, 623–634 (2015)
4. La Rosa, G., Risitano, A.: Thermographic methodology for rapid determination of the fatigue limit of materials and mechanical components. Int. J. Fatigue **22**, 65–73 (2000)
5. Boulanger, T., Chrysochoos, A., Mabru, C., Galtier, C.: Calorimetric analysis of dissipative and thermoelastic effects associated with the fatigue behavior of steels. Int. J. Fatigue **26**, 221–229 (2006)
6. Palumbo, D., Galietti, U.: Characterization of steel welded joints by infrared thermographic methods. Quant. Infrared Thermogr. J. **11**(1), 29–42 (2014)
7. Enke, N.F., Sandor, B.I.: Cyclic plasticity analysis by differential infrared thermography. Proceding of the VII International Congress on Experimental Mechanics, pp. 830–835, 7 June 1988
8. Krapez, J.C., Pacou, D., Gardette, G.: Lock-in thermography and fatigue limit of metals. Quantitative Infrared Thermography Conference QUIRT 2000, Reims (France), 18–21 July 2000
9. Galietti, U., Palumbo, D., De Finis, R., Ancona, F.: Fatigue damage evaluation with new thermal methods. 3rd International Workshop on Advanced Infrared Technology and Applications, Tourin (Italy), 11–14 September 2013
10. Wang, W.J., Dulieu-Barton, J.M., Li, Q.: Assessment of non-adiabatic behaviour in thermoelastic stress analysis of small scale components. Exp. Mech. **50**, 449–461 (2010)
11. Stanley, P.: Beginnings and early development of thermoelastic stress analysis. Strain **44**, 285–287 (2008)
12. Wong, A.K., Sparrow, J.G., Dunn, S.A.: On the revised theory of thermoelastic effect. J. Phys. Chem. solid. **49**(4), 395–400 (1988)
13. Galietti, U., Palumbo, D., De Finis, R., Ancona, F.: Fatigue limit evaluation of martensitic steels with thermal methods. Quantitative Infrared Thermography 12th International QIRT Conference, Bordeaux (France), 7–11 July 2014
14. McGuire, M.F.: Martensitic stainless steels. In: Stainless Steels for Design Engineers, pp. 123–135. ASM International, Materials Park (2008)