INTERNATIONAL STANDARD

ISO 22290

First edition
2020-11

Non-destructive testing — Infrared thermographic testing — General principles for thermoelastic stress measuring method

Essais non destructifs — Examen par thermographie infrarouge — Principes généraux de la méthode de mesure des contraintes thermoélastiques

Reference number
ISO 22290:2020(E)

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Published in Switzerland

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Foreword

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This document was prepared by Technical Committee ISO/TC 135, *Non-destructive testing*, Subcommittee SC 8, *Thermographic testing*.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Thermoelastic stress measuring method, which utilizes the thermoelastic properties of materials, is a "full-field", "noncontact" technique for surface stress mapping of materials and structures. Unlike the conventional technique such as strain gauge method, the unique advantage of the method is its ability to image whole-surface stress ($\Delta(\sigma_1+\sigma_2)$) distribution in specimens easily (ISO 10878).

Industrial applications of thermoelastic stress measuring method are getting wider along with remarkable improvement of thermographic technologies. The effectiveness of any application of thermoelastic stress measuring depends upon proper and correct usage of the method. The purpose of this document is to provide general principles for the thermoelastic stress measuring method to promote correct and effective application to various industrial non-destructive testing, such as automobiles, aerospace products, electronic instruments, medical devices, industrial materials and so on.

Non-destructive testing — Infrared thermographic testing — General principles for thermoelastic stress measuring method

1 Scope

This document provides general principles for thermoelastic stress measuring method of infrared thermographic testing in the field of industrial non-destructive testing (NDT).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 10878, *Non-destructive testing — Infrared thermography — Vocabulary*

ISO 9712, *Non-destructive testing — Qualification and certification of NDT personnel*

ISO/TS 25107, *Non-destructive testing — NDT training syllabuses*

ISO 10880, *Non-destructive testing — Infrared thermographic testing — General principles*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10878 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

4 Infrared thermographic testing personnel

Personnel who are responsible for conducting infrared thermographic testing (TT) including thermoelastic stress measuring shall meet the following criteria.

a) TT personnel shall have an adequate knowledge of the testing including the basics of infrared measurement and heat-transfer engineering as required by ISO 9712 and ISO/TS 25107.

b) TT personnel's visual acuity and colour vision shall meet the requirements of ISO 9712.

5 Test Environment

5.1 Installation environment for the test equipment

Conduct the test in an environment where the temperature, humidity, and atmosphere are appropriate for the test equipment, including the infrared camera as required by ISO 10880. Be sure to avoid condensation on the surface of the test object.

In order to avoid occurrence of image blur due to fluctuation of the field of view, make sure that vibration is not applied to the infrared camera as much as possible. However, when the vibration period of the infrared camera is synchronized with the load cycle to the test object, the influence can be reduced by the position correction technique.

5.2 Avoidance of disturbances

For the avoidance of disturbances, requirements and information are given in ISO 10880.

In addition, care should be taken to minimize the surface temperature change of the test object other than based on the thermoelastic effect. For example, in order to avoid temperature change due to air currents, reduce the influence of wind as much as possible.

6 Equipment

6.1 Configuration

Schematic of an example of equipment configuration is shown in Figure 1.

In addition to the infrared camera (key 3 in Figure 1), the measuring equipment is constituted by a computer or the like which performs camera control, reference signal processing, image processing, image display and the like (key 7 in Figure 1).

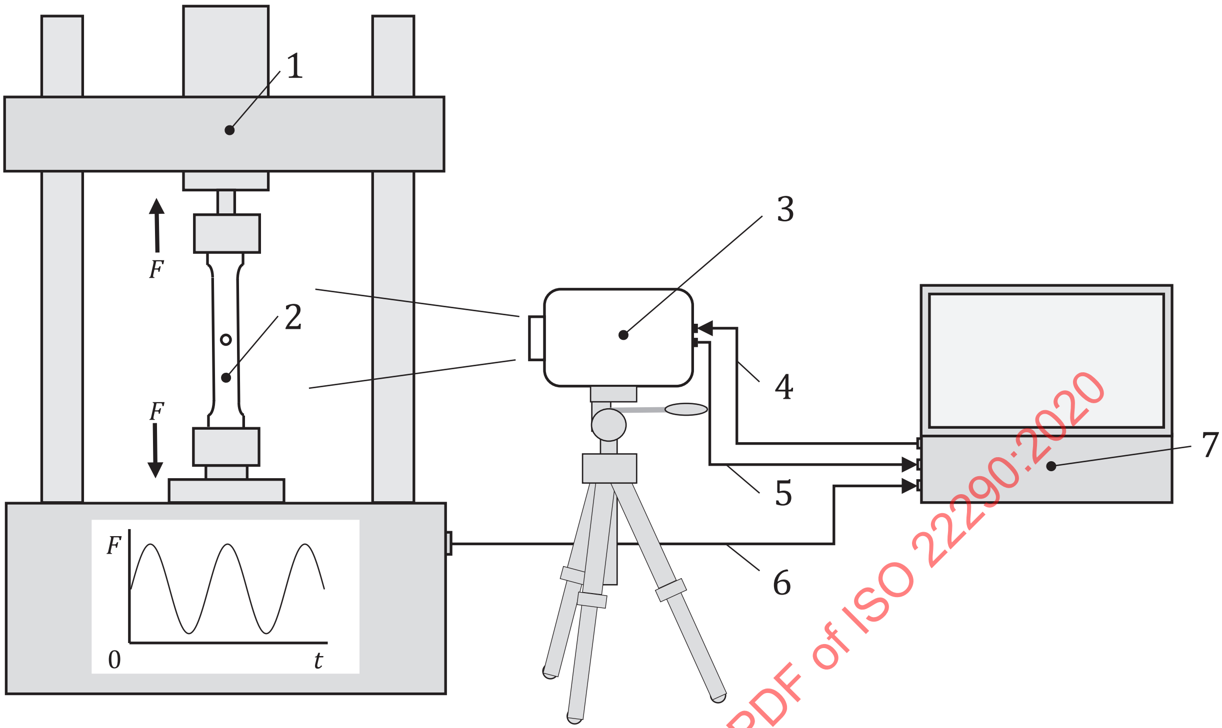
When applying cyclic load to the test object, the material testing machine is required to have the ability to load the required waveform and frequency (key 1 in Figure 1).

6.2 Infrared camera

An infrared camera shall meet the requirements of ISO 10880. In addition, an infrared camera should have an infrared measuring wavelength range about 3 µm to 5 µm or about 8 µm to 14 µm to be capable of measuring extremely small temperature changes. A camera with a frame repetition rate that provides a sufficient number of frames per cycle of load shall be used. In order to obtain the spatial resolution necessary for the test, the lens viewing angle of the infrared camera, the number of effective pixels of the camera and the distance between the camera and the test object shall be considered.

The infrared camera with appropriate temperature resolution should be used in order to obtain the required stress (the sum of surface principal stresses) resolution.

NOTE In the case of steel, a temperature resolution of about 0,001 K is necessary to obtain 1 MPa stress resolution. Generally, the temperature resolution can be enhanced by image processing such as image averaging, using an infrared camera which has about 0,03 K of noise equivalent temperature difference (NETD) value.



Key

1 material testing machine
2 test object
3 infrared camera
4 control signal to infrared camera
5 detector signal from infrared camera
6 reference load or displacement signal from material testing machine
7 computer with signal processing unit and display
F load
t time

Figure 1 — Schematic of an example of equipment configuration

6.3 Detection of temperature change by thermoelastic effect

As signal processing methods for extracting the amount of temperature change with the thermoelastic effect from the time series of temperature data, "temperature difference imaging technique" or "lock-in technique" or an equivalent method is applied.

A reference signal synchronized with the stress change of the test object is utilized to perform the signal processing techniques. As the reference signal, a load or displacement signal from the material testing machine (key 6 in Figure 1), or a signal obtained from the strain gauge attached to the test object or the like, shall be used.

NOTE The temperature difference imaging technique is a signal-processing method to obtain a picture of the change of the sum of principal stresses, consisting of measuring temperature distribution images during the maximum temperature period and the minimum temperature period, and making an overall "temperature range image" from the images, as defined in ISO 10878. The lock-in technique allows for the extraction of a signal of a known carrier wave from an extremely noisy environment. This signal can be, but is not restricted to, temperature.

7 Measuring method

7.1 Test object

The test object should be made of a material that can be regarded as a homogeneous isotropic linear elastic body.

The emissivity of the test object shall meet the requirements of ISO 10880. In addition, the surface emissivity of the test object should be uniform and close to the emissivity of a black body (1,0). A coating of matte black material with an emissivity of more than 0,95 can be applied thinly and uniformly until the surface of the base material is covered. The application of matte black paint can also reduce any reflections from other infrared radiation sources on the surface of the test object and is thus effective in improving the measuring accuracy.

Care should be taken when the load frequency to the test object is high and/or when the coating is thick; the temperature change over the paint coating surface does not follow the temperature change of the test object surface.

In the case of a polymer test object, by performing a homogeneous surface finish with sandpaper, it is possible to obtain substantially the same effect as coating of matte black paint.

NOTE 1 There are differences in emissivity depending on the wavelength of infrared and specifications of the coating paint.

NOTE 2 The optimum thickness of the matte black paint coating is 20µm to 30µm. In general, when a matt black paint is uniformly coated twice with aerosol spray on a test object, it has been shown that the measurement result is not affected at load frequency of 5 Hz to 30 Hz.

7.2 Load condition

7.2.1 General load condition

After setting the testing object appropriately to the testing machine, a sinusoidal load with a constant average value, amplitude and frequency shall be applied. At this time, appropriate supporting apparatus and appropriate loading apparatus shall be used so that the sum of the principal stresses at each point on the test object changes in proportion to the load. If this is difficult, the measured results shall be evaluated, taking into account that the sum of the principal stresses of the test object does not change proportionally to the load.

EXAMPLE In the case of two objects in contact, the size of contact area often changes depending on the magnitude of the load. When the size of the contact area changes, the change in the sum of the principal stresses near the contact area is not proportional to the change in the load.

7.2.2 Average value and amplitude of load

The average value and amplitude of the load should be set appropriately in consideration of items a) through c) below.

Preliminary measurements should be performed by setting the load frequency constant and varying the average value and amplitude of the load. Then, the average value and the amplitude of the load are selected within a range in which the value obtained by normalizing the temperature change with the load amplitude is substantially constant.

a) Set the minimum load (the load obtained by subtracting the amplitude from the average) and maximum load (the load obtained by adding the amplitude from the average) in avoiding any remarkable yields, buckling or destruction on any part of the test object. If yield, buckling or destruction are unavoidable with a part of the test object, the measured results should be carefully evaluated with them taken into account.

b) Set the load amplitude to a sufficiently large value so that the temperature change caused by the thermoelastic effect can be measured with sufficiently high resolution and accuracy.

c) Set the load amplitude to a sufficiently small value so that the difference between the displacement of the sample (rigid body displacement and/or transformation) in measurement field of the test object at the minimum load and the maximum load does not become excessive. If the displacement is too large to be ignored, utilize the appropriate motion compensation technique. In that case, the measured results should be evaluated with attention paid to the applicable range of the motion compensation technique.

7.2.3 Load frequency

The load frequency should be appropriately set after taking the following a) through c) into account.

The appropriate load frequency should be decided after having performed preliminary measurements with a wide variety of load frequencies while maintaining a constant load average and amplitude. Then, select the load frequency such that the variation range of the measured temperature and/or the change of the phase with respect to the load frequency are minimal.

a) Set the load frequency sufficiently large enough so that the influence of the heat conduction of the test object on the temperature distribution is minimized and the test object is in near adiabatic status.

NOTE 1 When a linear elastic body is of adiabatic status, the phase difference between the sum of principal stresses and temperature is 180° (0° when compressed). The difference in the phase in degrees being up to 180° means that the degree of the effect of the heat conduction of the test object on the temperature distribution can be roughly estimated.

NOTE 2 The extent of the effect of the heat conduction on the temperature distribution on the test object is inversely proportional to the load frequency and proportional to the temperature conductivity (thermal diffusivity) of the material of the object.

NOTE 3 If the change of the sum of principal stresses is uniform throughout the test object, the temperature change due to the thermoelastic effect also becomes uniform, so that the heat conduction can be neglected.

b) Set the load frequency value so that the infrared camera provides a sufficient number of frames per cycle of load.

c) Set the load frequency to a value corresponding to the class of the paint film and thickness if any anticorrosion paint has been applied to the surface of test object.

NOTE 4 If the coating film is thick, as the load frequency increases, the temperature change of the coating film surface hardly follows the temperature change of the test object surface.

7.3 Imaging method

The imaging method shall meet the requirements of ISO 10880. In addition, set the distance between the test object and infrared camera with the resolution required by the stress measurement field.

The surface of the test object and the infrared camera shall be facing each other as close to squarely as possible. At the same time, ensure to avoid any ghost images of the camera itself being reflected by the surface of the test object.

If the angle between the perpendicular of the surface of the test object and the optical axis of the infrared camera exceeds 45°, the infrared emitting from the surface of the object to the infrared camera will gradually drop, with an extreme decrease if it exceeds 60°. For this reason, measurements within 45° are desirable and 60°, as the maximum, shall not exceeded. An infrared reflection mirror can be used if the angle does exceed 60° or to measure the backside surface of the object, but the effect of the mirror reflectivity on the measurement accuracy should be taken into account.

7.4 Calibration of stress value

Under the adiabatic condition, the relationship between the change in the sum of principal stresses of the test object and the temperature change by thermoelastic effect is described by Formula (1):

$$\Delta\sigma = -\frac{\Delta T}{k_t T} \tag{1}$$

where

$\Delta\sigma$ is the change in the sum of principal stresses, in pascals;

ΔT is the temperature change, in kelvins;

T is the object temperature, in kelvins;

k_t is the thermoelastic coefficient, in reciprocal pascals;

$$k_t = \frac{\alpha_l}{\rho C_p}$$

where

α_l is the coefficient of linear thermal expansion, in reciprocal kelvins;

ρ is the material density, in kilograms per cubic metre;

C_p is the specific heat at constant pressure, in joules per kilogram per kelvin.

Basically, the temperature change of the surface of test object, ΔT, is converted to the change in the sum of surface principal stresses, $\Delta\sigma$ ($\Delta(\sigma_1 + \sigma_2)$) via Formula (1).

However, with temperature measurements made via infrared thermography, it can be difficult to accurately estimate all the parameters, for example, the actual emissivity of the surface of test object, any effect due to infrared absorption/scattering between the test object and the infrared camera. Therefore, a calibration coefficient, β, should be obtained for use in Formula (2), based both on the change in the sum of principal stresses measured by a strain gauge method in a flat position of the stress distribution of the object and the apparent radiant temperature measured via infrared thermography, for example.

$$\Delta\sigma' = -\frac{\beta \Delta T'}{k_t T} \tag{2}$$

where

$\Delta\sigma'$ is calibrated value of the change in the sum of principal stresses, in pascals;

β is the calibration coefficient;

$\Delta T'$ is the apparent temperature change, in kelvins.

NOTE Actual thermoelastic stress measuring equipment often displays the change of the temperature and the change of the sum of principal stresses (so-called total amplitude). However, the amplitude (so-called half amplitude) can sometimes be displayed, thus making it necessary to pay attention to the measuring equipment being used.

