ACTIVE THERMOGRAPHY IN MATERIALS FATIGUE TESTING

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Abstract

Active thermography is an advanced experimental procedure, which uses a non-contact measurement of tested materials thermal response after their external excitation. The material can be excited by a direct heating or using thermo-physical effects. Information regarding surface inhomogeneities, defects or material properties can be obtained by an evaluation of the measurement. Thermo-mechanical testing is one of the active thermography methods. It uses a cyclic mechanical loading for the tested material excitation. Material thermal response can differ based on intensity and mechanism of the loading and depending on effects, which can the loading accompany. Results of a thermographic measurement during a mechanical-cyclic tension test are presented and discussed in this contribution. Possibilities, methods and limitations of thermographic measurement during mechanical tests are discussed. A standard fatigue test results and a thermographic fatigue evaluation results were compared. The performed experiments showed that thermo-mechanical effects could be usable for materials fatigue properties evaluation.

Keywords: Thermography, active thermography, material, fatigue, mechanical testing

1. INTRODUCTION

Infrared thermography [1] is an analytical technique, which is based on detection of objects radiation in the infra-red range. The amount of the radiation emitted by the objects is related to temperature and optical properties of the radiating surfaces. The temperature can be therefore evaluated by the infrared radiation measurement if the optical properties of the analyzed surfaces are known. Devices, which detect the infrared radiation and form images corresponding to temperature distribution of analyzed objects (thermograms), are generally called infrared or thermographic cameras.

The infrared thermography has a lot of advantages. It is a non-contact method and thus, it does not influence the measured objects. It can record temperature fields of moving or rotating objects and it can measure a very high temperature as well. A disadvantage of this method is that the radiation detected is influenced by the measured surface thermo-optical properties (emissivity, transmissivity and reflectivity), ambient temperature or atmosphere properties (temperature, transmissivity). Especially the object optical properties can influence the measurement significantly [2]. Knowledge of the measured object optical properties and other measurement conditions is therefore fundamental, namely for an accurate quantitative thermographic temperature measurement.

The thermography can be classified as qualitative or quantitative and passive or active. The qualitative thermography evaluates the temperature differences or infrared radiation contrasts between different positions. The contrast can be caused by real temperature differences, but also by thermo-optical properties differences. There are many important applications of qualitative thermography, for example heat leaks diagnostics, electrical components inspections, surveillance of people or medical applications. The goal of quantitative thermography is to evaluate the accurate numerical value of an object temperature. It is useful in many technological applications, for example heat treatment control and identification of thermal-boundary conditions for numerical simulations. Both the qualitative or quantitative thermography can be passive or active. In the case of the passive thermography, the temperature contrast or the temperature changes are of natural origin. An external source excitation of the analyzed object is used in the case of the active thermography. The contrast is connected with thermal properties differences, optical properties differences, material non-homogeneities or local heat sources concentration. The active thermography is the basic technique in defects detection, i.e. material infrared non-destructive testing (IRNDT).

The infrared non-destructive testing is based on changes of heat transfer conditions in the material due to defects, material inhomogeneities or local heat sources. The tested material can be excited directly by a thermal source, for example by hot air, flash lamps, halogen lamps and other heat sources. The heat flux in the material is then affected by a presence of defects or material inhomogeneities. A different approach is based on an excitation of the tested sample by internal thermo-physical processes. Magnetic, ultrasound, electrical or mechanical sources are used in this case for example. Such a loading of the material causes formation of local heat sources at positions of cracks or other defects. The both excitation principles result in thermal response, which can be detected by an infrared camera on the tested material surface.

The IRNDT is a very complex analytical technique, which has a number of modifications [3]. There are different excitation sources, which can be used. The possible sources are for example laser heating, flash lamps heating, halogen lamps heating, electric heating, ultrasound excitation, eddy current excitation, microwaves, hot air etc. The sources can operate continuously, by one pulse or periodically. Different infrared cameras and recording parameters can be used for the excided material response recording. The high-sensitivity and high-speed cooled cameras or un-cooled bolometric cameras are generally applicable. The material response is visible on a raw thermogram in the simplest case only, therefore, an advanced evaluation methods should be used in the most cases. The most used evaluation methods are pulse thermography, Lock-In thermography and Transient (step) thermography [3]. The pulse thermography is based on a very short pulse excitation (length about a few milliseconds) generated by flash lamps for example. The Lock-In thermography is based on modulated-periodical excitation generated by halogen lamps, ultrasound or mechanical excitation for example. The Transient thermography is similar to the pulse thermography, however, the excitation time is longer.

Different excitation sources and methods can be combined with different evaluation methods for specific applications. The complexity of the IRNDT method brings some problems from - sometimes it is difficult to find a suitable parameters combination set-up. On the other hand, it brings possibilities to use the method for very different applications. The IRNDT systems are modular in the most cases. Therefore a customized configuration can be designed for a universal high-flexibility scientific measurement system, for a single purpose production integrated systems or for a mobile inspection systems. The IRNDT can be therefore used in many scientific or industrial applications [4, 5], for example for solar cells inspection, aircraft components inspection, wind turbine blades inspection etc.

2. THERMOGRAPHY ANALYSIS IN FATIGUE TESTING

The special case of component indirect excitation is a mechanical loading. This method is based on a thermo-mechanical coupling effect, where the mechanical loading causes material temperature changes. These changes are reversible in the case of elastic loading and the temperature rises permanently in the case of plastic loading. If the inspected object is periodically mechanically stimulated and the stress concentrators occur due to the defects or cracks in the material then a local heating occurs at the stress concentrators positions. The defects can be thus determined by the component thermal response analysis as it is demonstrated in **Fig. 1**.

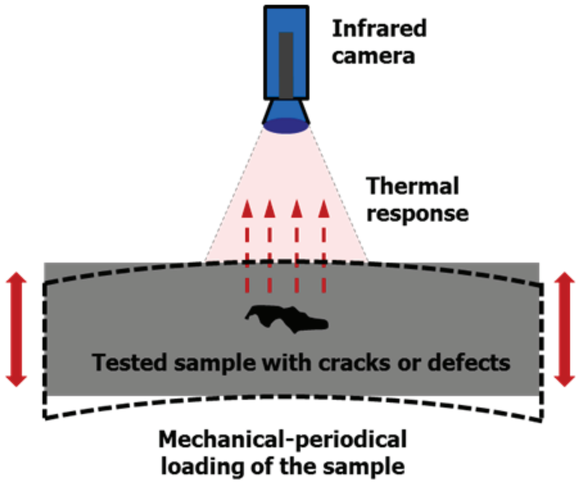

Fig. 1 Illustration of the thermal stress infrared analysis (TSA)

The thermal stress infrared analysis has to be evaluated using advanced techniques mostly based on Lock-In analysis. However, published results [6, 7] and performed experiments show, that the temperature of experimental samples can increase in the case of cyclic loading even if it is in the elastic region. The temperature changes are dependent on a load force, frequency, number of cycles and other experiment conditions. If the temperature growth is expressed in dependence on the maximum load of the periodical excitation, it can be used for the tested material fatigue limit determination.

The material fatigue is a degradation process induced by a cyclic mechanical, thermal or thermo-mechanical loading. It has a cumulative character. Fatigue fractures can occur in the material during its long-time cyclic loading, even if the load is below its yield strength. A determination of the material fatigue properties is more complicated compared to standard mechanical properties tests. The fatigue lifetime depends on a loading force, frequency and time (i.e. number of cycles). It is also influenced by other factors, which are not so important in the case of static loading (surface treatment for example). Fatigue tests are therefore very important, however, they are also very expensive and time-consuming with regard to its long-time character. Thermographic methods have ambitions to shorten the testing time, that could bring significant time and costs savings.

2.1. Experiment description

The thermography fatigue analysis experiments were performed on a standard tensile fatigue testing device. Standardized cylindrical specimens of 10 mm diameter from 17123 equivalent steel were used. The loading frequency was 10 Hz and the maximum load force was increased in subsequent steps from about 640 to 780 MPa. The temperature was measured by a standard bolometric infrared camera during the whole loading process. The specimen was painted by a high-emissivity thermographic coating, which was previously tested for optical properties and mechanical stability during a cyclic loading.

2.2. Thermography fatigue analysis results

The temperature growth of the tested sample in dependence on load and number of cycles is shown in **Fig. 2**. The temperature rises immediately after each load-increase step. Thus, the individual temperature steps in the figure correspond to the load-increase steps. The sample heating process can be divided into three regions according to the temperature rise at individual load steps. A linear and very weak temperature increase can be observed in the region "A". The temperature changes are small or the temperature remains constant after a load-increase step. A linear or very weakly non-linear temperature growth is observed in the region "B". The temperature increase in individual steps is higher compared to the region "A". This is caused by more expressive thermo-mechanical effects, which occur above the material fatigue limit. The transition between the "A" and "B" regions is therefore fundamental for the fatigue limit determination by the thermographic techniques. However, the transition is generally not clearly evident using the temperature vs. the cycles count data representation. More detailed methods should be therefore used for the data evaluation. A rapid temperature increase with a subsequent sample fracture occurs in the region "C". This process takes place at a constant load in the time interval of a few seconds.

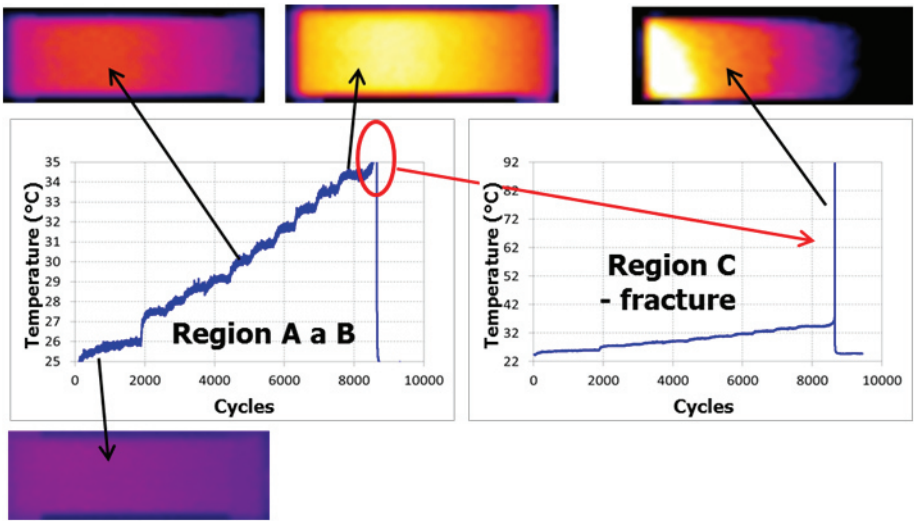

Fig. 2 Temperature progress during the sample cyclic loading with a stepwise increased load

Two identical samples were tested by the thermographic fatigue testing method. A detailed evaluation was based on load-temperature data linear regression in the "A" and "B" regions and finding an intersection of the two regions, which corresponds to the expected fatigue limit of the material. The fatigue limit of the two samples determined by the thermography fatigue analysis was 683 and 692 MPa respectively. These values are in a very good agreement with the fatigue limit value 690 MPa, which was determined by a standard fatigue test based on a Wöhler curve construction.

3. HIGH EMISSIVITY PAINTING FOR FATIGUE TESTING

Surface optical properties of objects analyzed by thermographic techniques are crucial for the measurement accuracy and reliability. The measurement quality can be significantly influenced especially in the case of low-emissivity surfaces, which are typical for most of machined metals. The problem of samples low emissivity is therefore important also for the thermography fatigue testing. A standard solution of the problem is a usage of thermographic coatings with a high emissivity and low transmissivity. However, such coatings should fulfill additional requirement for the fatigue testing applications. The coatings must be stable under long-term periodical mechanical loading from the point of view of optical properties stability, adhesion to the surface and cohesion. It also must not affect the results of the sample fatigue properties or its mechanically excited thermal response.

3.1. Experiment description

Optical properties of different coatings were analyzed by radiometric methods [8]. Four coatings were selected based on the emissivity and transmissivity measurement results: ZYP Coating CeO2, DupliColor Supertherm Black, DupliColor Color Spray Silver and Super-Spray Very Well! Black. All these coatings have a transmissivity less than 0.05 and an emissivity higher than 0.8. The coatings were applied on standardized cylindrical steel specimens for fatigue testing of 10 mm diameter. A cyclic loading on a standard fatigue testing device was applied on the specimens with the coatings and also on two identical specimens without a coating. The loading frequency was 10 Hz and the load force was above a specimen material fatigue limit. The samples were measured by an infrared camera during the entire test. The results of the cyclic loading tests (number of cycles to a fracture, visual inspection of the coatings) and the thermography measurement results were analyzed to determine a usability and suitability of individual coatings for such experiments.

3.2. High-emissivity coatings tests results

A fracture occurred after about 40-80 thousand cycles for all the samples irrespective of whether with or without a high-emissivity coating. An influence on a thermal response or fatigue properties of the experimental samples was not observed for any of the coating.

A temperature field without any abnormalities was observed in the case of DupliColor Supertherm Black and Super-Spray Very Well! Black coatings. These coatings also did not show any sign of damage out of the fracture region of the samples after the tests. Thus, these coatings seem to be usable and suitable for the thermography cyclic mechanical loading experiments. In the case of the DupliColor Color Spray Silver coating, a higher temperature data scatter shows less suitable optical properties of the coating. Thus, it is less suitable for the thermographic measurement. A number of small cracks on the coating were also detected after the cyclic loading test. Cracks and visible peeling were also observed in the case of the ZYP Coating CeO2 during the test. The ZYP coating after the test is showed in the **Fig. 3**. These two coatings are therefore not usable for the thermography measurement of cyclically mechanically loaded samples.

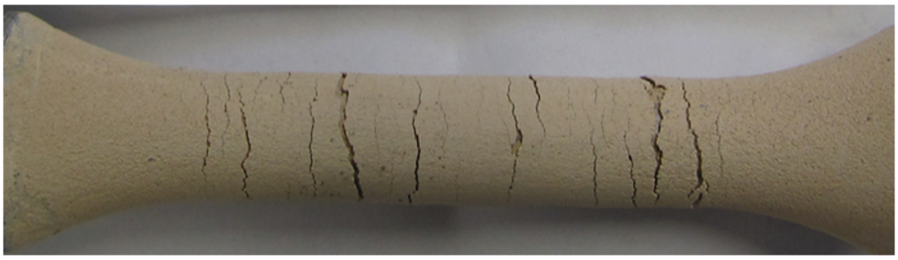

Fig. 3 The sample with the ZYP Coating CeO2 after a cyclic loading test

4. CONCLUSIONS

The fatigue limit and fatigue lifetime of components can be critical in many technical applications, where a cyclic loading takes place. Fatigue properties of materials are therefore an important material characteristic, which is often required for example in energy industry. However, the fatigue testing is very expensive and time consuming. A number samples should be used for a standard fatigue test, which takes from a few days to several moths based on used device and frequency. The thermography fatigue testing takes several hours and that means it is really a rapid testing method. The comparison of the standard fatigue limit measurement and the thermographic fatigue limit measurement showed a good agreement. The fatigue limit was 690 MPa by the standard test and 683 and 692 MPa respectively by the thermographic test. Although the thermographic method is in the development stage, the results so far are promising.

The experiments showed that a high-emissivity coating should be applied on surfaces for an infrared measurement. All the tested coatings had satisfactory optical properties, which were measured by radiographic analyses. However, the performed tests showed that the mechanical stability of the coatings is also important for thermography cyclic loading analyses. The experiments revealed that the DupliColor Supertherm Black and Super-Spray Very Well! Black coatings are suitable for such experiments. On the other hand, the DupliColor Color Spray Silver and ZYP Coating CeO2 coatings mechanical stability was insufficient. These coatings are not suitable for a measurement, where the sample is mechanically loaded.

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REFERENCES

[1] GAUSSORGUES G. Infrared Thermography. Kluwer Academic Publisher, 1994.

[2] ŠVANTNER M., VACÍKOVÁ P., HONNER M. Non-contact charge temperature measurement on industrial continuous furnaces and steel charge emissivity analysis. Infrared Physics & Technology, Vol.61, 2013, pp.20-26.

[3] ŠVANTNER M., VESELÝ Z. Active thermography for materials non-destructive testing. In METAL 2014: 23rd Int. Conf. on Metallurgy and Materials. Brno, Czech Republic, TANGER Ltd., 2014, pp.861-856.

[4] MALDAGUE X. Theory and Practice of Infrared Technology for Nondestructive Testing. Wiley-Interscience, 2001.

[5] YOLKEN H. T., MATZKANIN G. A. Thermography for Nondestructive Evaluation (NDE). Nondestructive Testing Information Analysis Center, USA, 2001.

[6] FERNÁNDEZ-CANTELI A. et al. Checking the fatigue limit from thermographic techniques by means of a probabilistic model of the epsilon-N field. International Journal of Fatigue, Vol.39, 2012, pp.109-115.

[7] HONNER M., LITOŠ P., VACÍKOVÁ P. Termografické měření meze únavy materiálu. In EAN 2007: Conf. on Experimental Stress Analysis, Plzeň: Západočeská univerzita v Plzni, 2007, pp. 1-8.

[8] MAUER M., KALENDA P., HONNER M., VACÍKOVÁ P. Composite fillers and their influence on emissivity. Journal of Physics and Chemistry of Solids, online: http://dx.doi.org/10.1016/j.jpcs.2011.11.015, 2011.