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Investigations on active thermographic testing techniques for manufacturing processes

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Abstract

Active thermographic testing techniques based on ultrasonic, inductive or optical heating were analysed and further developed. In case of ultrasonic excitation the interplay of vibration and released heat was studied by comparing thermography and 3D-vibrometry results. Damage due to ultrasound excitation can be avoided. Eddy current induced thermography is comparable in sensitivity for crack detection to ultrasound induced thermography. Analytical and numerical modelling was applied to simulate the effect of position and geometry of various heat sources and the relation of experimental parameters to the thermal contrast. Main applications comprise carbon and glass fibre reinforced polymers, aluminium components and turbine blades with thermal barrier coatings and cooling channels.

1. Introduction

The results presented originate from an ongoing joint project focussed on active dynamic thermographic techniques using various excitation techniques for application in non-destructive inspection of production processes and in materials characterisation. The techniques are further developed, scientifically assured and transferred into application oriented testing systems. They will be optimised for the different field of applications.

The recently developed variants of thermography using excitation by ultrasound, microwaves or eddy currents are partly dark-field techniques, i. e. they show defects with high contrast. There is, however, a significant lack of basic knowledge about the actual physical mechanisms, probability of defect detection, detection limits and investigations on the damage-free operation.

In this survey, a summary of the activities in the project is presented. Details will be worked out in separate publications.

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2. Mechanically excited thermography

2.1. Ultrasound excitation

In an aluminium sheet containing a fatigue crack, it could be shown, that the infrared intensity from the crack shows a quadratic dependence on the vibration velocity. Therefore, the temperature contrast in this case is proportional to the ultrasound intensity.

For a homogeneous steel sample vibrating in one of its eigenmodes, experiments reveal that maximum heating occurs at positions of a maximum gradient of displacement. Investigations on polymer plates in resonant vibration showed good coincidence of locations of high normal surface acceleration and high infrared signals.

Spatially resolved 3D vibration analyses allow to visualise the various shearing and clapping movements of cracks in components and to correlate them with the resulting thermal signatures.

In carbon fibre reinforced materials, impact damage was detectable 500 mm away from the point of insonification. Stationary as well as ultrasound gun exciters were employed with similar results.

Fatigue cracks in aluminium were generated as test defect simulating typical defects in aircraft structures.

Studying experimentally the defect contrast obtained from cracks as a function of the position of excitation and the way of clamping of the specimens, it turned out that although there are variations of the relative temperature rise, cracks remained detectable in all cases due to their large contrast. Other parameters varied were coupling pressure, excitation angle and coupling media.

For glass fibre reinforced plastic components, there was a good correlation between thermal signals and the internal structure as obtained from 3D X-ray tomography [1].

2.2. Vibrometry

In the studies reported here, non-contact and contact vibrometry were employed to obtain complementary information about the vibration state of the test object. In the case of ultrasound excited thermography the interplay of acoustic modes and the achievable defect signals as well as their reproducibility play a decisive role (figure 1). A 3D mode analyser software was developed to visualize the complicated vibration modes in the test object in a comprehensive way. The two in-plane as well as the out-of-plane vibration pattern could be measured and visualized.

Techniques like pulsed speckle interferometry and contact-free laser vibrometry were applied in addition to infrared imaging. They allowed to analyse the mode structure in typical test objects like turbine blades as well as the 3D vibration patterns around real cracks.

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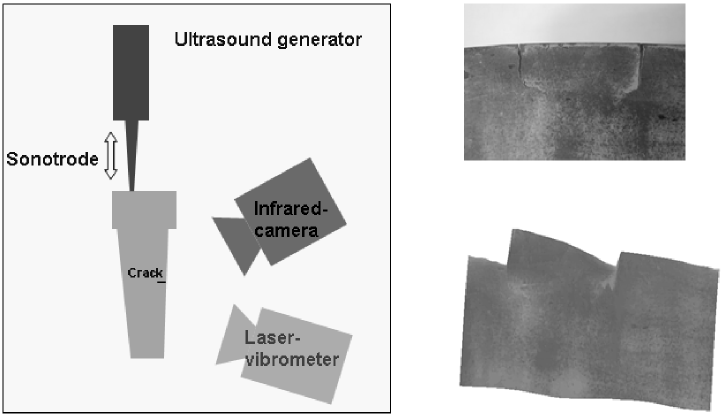

Fig. 1. *Left: Ultrasound excited thermography on turbine blades. Right: Photograph of an area with two cracks (top) and result of an experimental vibration analysis (bottom)*

2.3. Modelling of ultrasound excited thermography

Typical testing situations were modelled by finite element calculations. Based on certain friction mechanisms, these calculations allow to predict the energy dissipation as a function of external clamping of the specimen and the coupling position of the ultrasound. For carbon reinforced materials, the detectability of impact damage was studied as a function of the position of insonification. Although there is a clear variation as a function of the position, these variations were not too large to hide the defect in "dead spots". This is in agreement with experimental findings.

As a first step to an inversion of thermographic image sequences, modelling of the 2D surface thermal response from buried sources by analytical and numerical techniques was performed. Analytical results for different point, line and distributed plane heat sources were implemented and compared with experimental results.

2.4. Damage due to high ultrasound intensities

Damage due to high power ultrasound was studied on artificial cracks made from roughened steel plates. Areas of friction could be identified by changes in surface reflection and are in good local correlation to hot spots in the thermographic images [2].

For ceramic coatings on steel, possible damage due to high power ultrasound was studied by verification using other non-destructive techniques. With high-frequency ultrasound C-scans a change of the interface condition before and after high power insonification could not be proven up to now.

2.5. Excitation at low frequencies

The high sensitivity, temporal and spatial resolution of modern IR cameras allows one to take significant steps beyond classical thermal stress analysis

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techniques. Detection of higher harmonics in the temperature response during cyclic mechanical loading provides additional information about the plastic deformation processes in specimens.

3. Induction excited thermography

Another heating technique (EDDYTherm) uses eddy current excitation for thermographic crack detection (figure 2). The enhanced induction current densities occurring around crack tips show cracks in good contrast. Further improvement can be achieved by compensation for temperature gradients caused by the geometry of the test objects (turbine blades). An automated turbine blade testing equipment based on inductive heating was realized. By suitable data evaluation techniques, e. g. pulse-phase analysis of the detected image sequences, the defect representation can be clearly improved.

2.6. Modelling of induction excited thermography

The heat generation around cracks by various inductor arrangements and with different defect orientations was simulated using finite element calculations. In particular, half-penny shaped cracks were modelled (figure 2). The influence of the distance of the inductor from the specimen surface was studied. Other parameters were the orientation of the inductor with respect to the defect orientation.

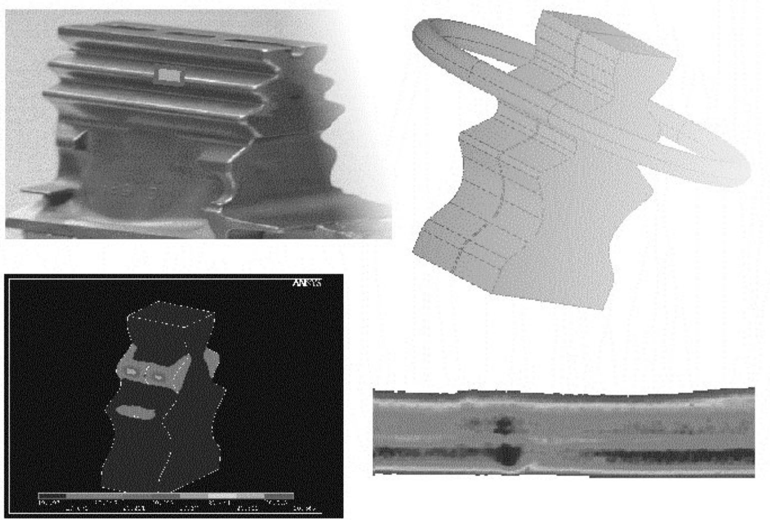

Fig. 2. *Upper left: Photograph of a turbine blade root with a 1 mm long crack in the indicated area. Upper right: Modelling of the blade root and the induction coil. Lower left: Calculated temperature distribution. Lower right: Enlarged thermographic image of the tested area. The crack becomes visible.*

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4. Flash light, laser excited and hot air thermography

Thermographic inspections of turbine blades are now at a stage where fully automated inspection systems for 100% production control are in operation [2]. Such systems are able to detect delaminations of ceramic thermal barrier coatings, their thickness and blocked cooling channels in the blades. The residual wall thickness at cooling holes as well as crack detection in metals are also of high interest. Flash heating is applied for the coating characterization and hot air heating for the cooling channel testing, respectively. Among the different evaluation schemes described in literature, those providing highest evaluation speed and robustness were selected and optimised.

Local stationary heating with laser spots was used to determine the wall thickness of metal sheets.

Flash heating was used for testing laser welds in cars as a function of the mileage under load. The increasing damage of the weld could be visualized in repetitive inspections.

Flying-spot thermography using laser sources was employed to detect defects in carbon fibre reinforced polymers in a depth of up to 20 mm.

Local optical heat input by means of Nd-YAG or diode power lasers turned out to be efficient for testing laser welds.

A particular problem for optically semi-transparent coatings not sufficiently solved is the role of scattering, the transparency for thermal infrared radiation and the absorption of the excitation light at the substrate surface.

5. Conclusion

Significant progress has been achieved in the basic mechanisms of the new variants of dynamic thermography. Applying the techniques in combination and using additional information from optical vibrometry and other non-destructive techniques was a central point in the present work. The techniques have reached a level of maturity to apply them in production environments. This has been proven for the case of the turbine blade inspection system. Powerful modelling tools are available for planning of experimental tests.

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