Thermographic Crack Detection by Eddy Current Excitation

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Eddy current thermography is a new NDT-technique for the detection of cracks in electroconductive materials. It combines the well established inspection techniques eddy current testing and thermography. The advantage of this method is to use the high performance of eddy current testing without the known problem of the edge effect. Especially for components of complex geometry this is an important factor which may overcome the increased expense for inspection set-up.
The principle of this technique and an algorithm to increase the sensitivity for small defects are described. Some inspection examples on aero engines parts are presented which show the potential of eddy current thermography.

Keywords: Crack detection; Thermography; Eddy current; Induction heating

1. Introduction

In many industrial branches, especially in the production of safety critical components, the quality of the used components is of extreme importance. In this context, cracks are of special importance since they can constitute a starting point for serious damages. Therefore, primarily in the field of aerospace, crack testing has a special tradition[1]. The eddy current testing and particularly the dye penetrant inspection are common methods.
A new method for crack testing of electroconductive materials is a combination of two existing nondestructive testing methods, the depth sensitive eddy current testing and the fast and contact-free thermography: the eddy current thermography [2,3].

This method was developed over the last years at MTU Aero Engines for special cases, which can not be tested using the existing techniques or can only be carried out at high expense. These include testing of used components whose surface is no more accessible for a penetration test because of disruption (fretting), testing of coated components where cracks can occur under the surface and testing of geometrically complex components with internal cavities where hidden cracks can initiate, beginning in the cavities.

In the following, the effectiveness of this method is described as well as the algorithm in order to derive significant and automatically evaluable test results from the small differences in the measured temperature profiles. Finally some examples should indicate the potential of this technology concerning the testing of complex component geometry and automation.

2. Functional principle of the eddy current thermography

The eddy current thermography is a new method for the detection of cracks in electroconductive materials. In this context the parts to be tested are heated up by an inductively generated current flow and the temperature profile generated thereby on the surface of the component is recorded with a thermographic camera. Cracks disturb the flow of the current in the component and thus change the temperature distribution as well. This changed temperature distribution can be detected thermographically with a very high resolution [4,5].

This method has also a high application potential for closed cracks and cracks close under the surface where the dye penetrant inspection can not be used. Figure 1 shows the cross section of a round test part around whose circumference a coil is arranged. If this coil is excited with an alternating current of high frequency, a current is induced in a certain depth position normal to the surface and in dependence of the excitation frequency. The current lines run concentrically and are directed around the disturbance, e.g. when a crack occurs. By doing this the current density increases at the crack tip and decreases at the crack flanks. The resulting local temperature change can be made visible with an appropriate thermographic camera. This phenomenon is also illustrated in fig. 2. The areas of low heating at the crack flanks and the temperature rising at the crack tips can be seen in the calculated temperature profile of a metallic specimen.

The frequency of the eddy current is a determining factor for inductive processes because the current penetration depth is influenced hereof. The greater the alternating current frequency, the lower is the penetration depth of the induced eddy currents in the material. This skin depth is calculated as follows:

Penetration depth
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

Angular frequency $\omega = 2\pi f$

Permeability $\mu = \mu_0\mu_r$

Spec. resistance ρ

The influence of the permeability μ_r which leads to very low penetration depths in case of ferromagnetic materials ($\mu_r = 50 - 80000$) compared to paramagnetic or diamagnetic materials (($\mu_r \sim 1$) has to be considered as well. Fig. 3 exemplifies the skin depth for ferromagnetic steel and a non-ferromagnetic Nickel alloy (Ni).
A low penetration depth is important for the detection of small cracks in the surface of the workpiece since a very high percentage of the induced current flows around the crack and the changes of the current density and therefore the differences in temperature are at maximum. In case of cracks under the surface it has to be considered that the penetration depth is high enough, so that the defects to be detected can still be reached. Fig. 4 clarifies this relation.

Standard induction devices provide frequencies of approx. 3 kHz to approx. 3 MHz, so that the suitable frequency for practically all metallic materials can be selected for the detection of cracks on or close under the surface. In modern turbines Ni alloys and Ti materials are mainly used. For the detection of surface cracks in these non-ferromagnetic materials HF systems with frequencies of 200 kHz to 500 kHz have proved themselves in practice.

3. Defect resolution limit

An essential parameter for the applicability of a nondestructive testing method is the defect resolution limit. This means that the eddy current thermography method must reach the same limit as conventional methods. An approximate value is the half "technical incipient crack size" which constitutes a surface crack with a length of 0.8 mm and a depth of 0.4 mm. Therefore, a test body made of a titanium alloy (IMI 834) with an eroded slit, length 0.4 mm, depth 0.2 mm, was produced for the detection. Fig. 5 shows the result of this test specimen.

The white coloring in the middle of the crack is caused by the width of the eroded notch and is not to be considered as a crack signal.

In the phase image the typical appearance of an open crack between crack flank and crack tip as a result of the phase shift in the opposite direction can be recognized. The temporal temperature sequence of these areas is shown in fig. 5 on the right. The maximum difference in temperature between flank and tip is approx. 1 K. Because of the mostly inhomogeneous heating in case of inductive heating and the low emission coefficient of the metallic surface, a crack of this size can not be recognized in the temperature image. A very efficient analysis tool for the eddy current thermography with pulse-like excitation is the phase algorithm described below. A special characteristic is that the time window for the calculation is freely selectable.

Parameters for the inspection of specimen with crack length / depth = 0.4 / 0.2 mm:
      Thermographic camera Radiance HS InSb, Ti=2ms
      HF system: Huettinger Axio, Frequency=350 kHz, Generator capacity=10kW
      Heating duration: 50 ms
      Phase calculation: 10 – 100 ms

4. The phase algorithm

The Fourier-transformation shows how to synthesize a function with harmonic functions (sines and cosines). Usually one looks at the amplitude spectrum to find the "most interesting part" of the function. In the phase algorithm described below a direct access is used. Only a finite window (a section) of the function is put into consideration and analyzed with harmonic functions. Since the window is deliberately set in a region where the function has interesting features the first harmonic carries usually almost all important information, one of these is the phase [6,7].

The phase algorithm uses a stack of thermal images. This stack is made successively with an infrared camera. To each pixel (i, j) we can associate a function (a T-t plot), called pixel trail, made of all temperature data lying behind the pixel (i, j) in the image stack.

In the following steps it is shown, how the phase algorithm works. In the stack of thermal images time regions exist which have a varying amount of information. For example the asymptotic part is usually not very interesting in contrast to the starting section.

In the first step of the algorithm one has to determine which time interval of the pixel trail has to be handled. As a result the starting and the end point (a, b) of the time interval is defined. Until now a pixel trail has not many points, but we know it represents a continuous function. Therefore a spline interpolation is employed to make the pixel trail continuous. Such a pixel trail is regarded as a periodic function with a period b-a.
Therefore we can write a Fourier series for the pixel trail p(i, j, t):

p (i, j, t)is the pixel trail

i, j are the pixel coordinates at the image

t is time

we can represent p (i, j, t) as

$$p(i, j, t) = a_0(i, j) + a_1(i, j)\cos(2\pi \frac{a-t}{a-b}) + b_1(i, j)\sin(2\pi \frac{a-t}{a-b}) + \dots$$

or equivalently

$$p(i, j, t) = a_0(i, j) + c_1(i, j)\sin(2\pi \frac{a-t}{a-b} + \varphi_1(i, j)) + \dots$$

with
$$C_1 = \sqrt{a_1^2 + b_1^2}$$

and

$$\varphi_1(i, j) = \arctan(\frac{a_1(i, j)}{b_1(i, j)}) = \arctan\left(\frac{\int_a^b p(i, j, t)\cos(2\pi \frac{a-t}{a-b})dt}{\int_a^b p(i, j, t)\sin(2\pi \frac{a-t}{a-b})dt} \right)$$

For each pixel (i,j) such a phase is calculated and all such phases form the phase image. The phase of higher harmonics can be calculated with (n an integer):

$$\varphi_n(i,j) = \arctan\left(\frac{a_n(i,j)}{b_n(i,j)}\right) = \arctan\left(\frac{\int_a^b p(i,j,t)\cos(2n\pi\frac{a-t}{a-b})dt}{\int_a^b p(i,j,t)\sin(2n\pi\frac{a-t}{a-b})dt}\right)$$

Compared to the procedure of pulse-phase thermography or burst-phase thermography, this algorithm calculates the phase of a single harmonic from an adjustable window in the T-t-function. Normally the first harmonic is executed. The idea is to use only the interesting region with the most significant information of the T-t function to get best results in crack detection and crack visualization. This procedure has proven itself in practice at various components with different induction systems. The adjustable time window is important, because the transient effect of the induction system and therefore the temporal temperature-signal is affected by coil design, component-geometry and generator capacity.

Properties of this phase images

A) The phase of a single pixel trail sums up efficiently the small effects of time-dependant temperature changes around the crack.

B) The phase of a pixel trail has interesting invariance properties. The phase doesn't change under following transformation:

$$p(i,j,t) \rightarrow scale\; p(i,j,t) + const$$

This means the phase image is not sensitive to the absolute heat transfer or changes of offsets.

C) If there is poor information in the first harmonic, but relevant information in: $\varphi_n(i,j)$, n >1, the window (a, b) was most probably set incorrectly. For example, if the window was set to wide by a factor of ten, there would be a useful phase image with $\varphi_{10}(i,j)$.

5. Buried cracks

Cracks under the component surface, e.g. under metallic coatings, or cracks smeared up by grinding cannot be detected with the dye penetrant inspection. The eddy current thermography has a broad field of application here. If the necessary skin depth is adjusted choosing the corresponding excitation frequency, cracks close to surface can be detected. This is clarified in the example of a titanium specimen with a crack L = 3.5 mm. Fig. 6 on the left shows the phase image of the open crack. After grinding the crack is smeared up and no more visible for dye penetrant inspection. In the phase image (fig. 6 on the right) the crack appears as a line, as the current no more passes the crack, but flows over it.

Parameters for the inspection of Ti sample with crack length =3.5 mm
       Thermographic camera Radiance HS InSb, Ti=2ms
       HF system: Huettinger Axio, Frequency=300 kHz, Generator capacity=10kW
       Heating duration: 100 ms
       Phase calculation: 20 – 160 ms

6. Examples of use

6.1 Cracks in a compressor blade

An advantage of the eddy current thermography is the possibility to automate the testing as well as the evaluation. This will be shown in the example of a compressor blade from an aircraft engine.
The blade is led to the coil by a robot (fig. 7) and an induction pulse is released. The temperature rise is recorded for the whole blade and automatically evaluated. In the temperature image (fig. 8 middle) inhomogeneities can be clearly recognized, which are suppressed only by the phase algorithm. In addition to the calculation of the phase image the actual specimen surface is determined in the analysis image (fig. 8 on the right) and cracks are marked above a threshold value. A binary image with marked defects is generated.

Parameters for the inspection of compressor blade with cracks
       Thermographic camera Radiance HS InSb, ti=2ms
       HF system: Tchernov 2, Frequency=120 kHz, Generator capacity=2kW
       Heating duration: 100 ms
       Phase calculation: 0 – 140 ms

6.2 Cracks in the dove tail root of compressor blades

Cracks can occur in the dove tail roots on the carrying flanks of compressor blade due to the centrifugal forces and vibrations. Because of the "concave" geometry this area is not accessible with normal cooled induction coils and therefore not inspectable with the eddy current thermography. Since in this testing method very short current pulses (<150 ms) are used, uncooled coils with a low wire diameter (1 mm) can be used as well. When using these wires it is possible to form respectively small radii so that unfavorable outlines on blade root become inspectable as well (fig. 9 + 10). A compressor blade with 2 cracks, crack lengths 0.8 mm and 1 mm, was tested.

Parameters for the inspection of compressor blade with cracks
       Thermographic camera Radiance HS InSb, ti=2ms
       HF system: Huettinger Axio, Frequency=340 kHz, Generator capacity=10kW
       Heating duration: 60 ms
       Phase calculation: 10 – 120 ms

6.3 Fatigue cracks expanding from inside on low pressure turbine vanes

Modern low pressure turbine vanes are produced for weight reduction using investment casting. In service cracks can occur due to fatigue, which expand from inside and are therefore recognized only very late with the dye penetrant inspection (fig. 11). Fatigue tests are carried out in the design phase of new components for the optimization of the vanes to exclude this kind of cracking in the later operation. A fast, imaging crack testing method for the detection of surface cracks and buried cracks is of great interest for the evaluation and exact documentation of fatigue tests. This is the reason why the eddy current thermography is recently used at MTU for evaluating the fatigue tests.

Fig. 12 exemplifies the test assembly of a vane. For inspection the component must be split in several areas. The vane is automatically driven by a linear unit and inspected by a suitable coil. The reconstructed image of a complete vane and a detailed image with crack can be seen in fig. 13. The crack has a total length of 24 mm, out of which only approx. 1.5 mm are visible on the surface. The line indication shows the crack under the surface, the spots frame the crack exit.

Parameters for low pressure turbine vane:
      Thermographic camera Radiance HS InSb, ti=2ms
      HF system: Huettinger Axio, Frequency=300 kHz, Generator capacity=10kW
      Heating duration: 80 ms
      Phase calculation: 20 – 140 ms
      Number of test positions: 7

7. Conclusion

The eddy current thermography combines the advantages of the eddy current inspection for the detection of buried cracks with the advantage of thermography, a fast, contact-free imaging technique.
The therewith involved increased expenditure of apparatuses is justified because of the robustness and the level of automation of this technology.
The eddy current thermography is an ideal tool for the monitoring of component tests, especially in case of geometrically complicated component forms. This technology has also a great potential for used components whose loaded surfaces are no more accessible for a penetration test. However, simulation calculations are necessary to generate optimum induction currents in the component.
These simulation calculations and the resulting coil designs will decisively determine the future application spectrum of the eddy current thermography.

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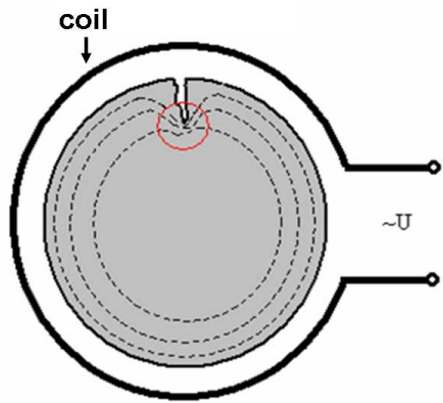
Figure 1

Figure 2

Figure 3

camera view

surface crack frequency too low

surface crack frequency ok

subsurface crack frequency too high

subsurface crack frequency ok

Figure 4

1 cm
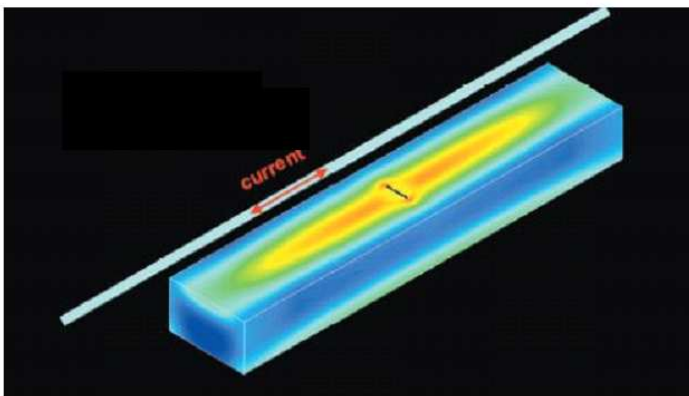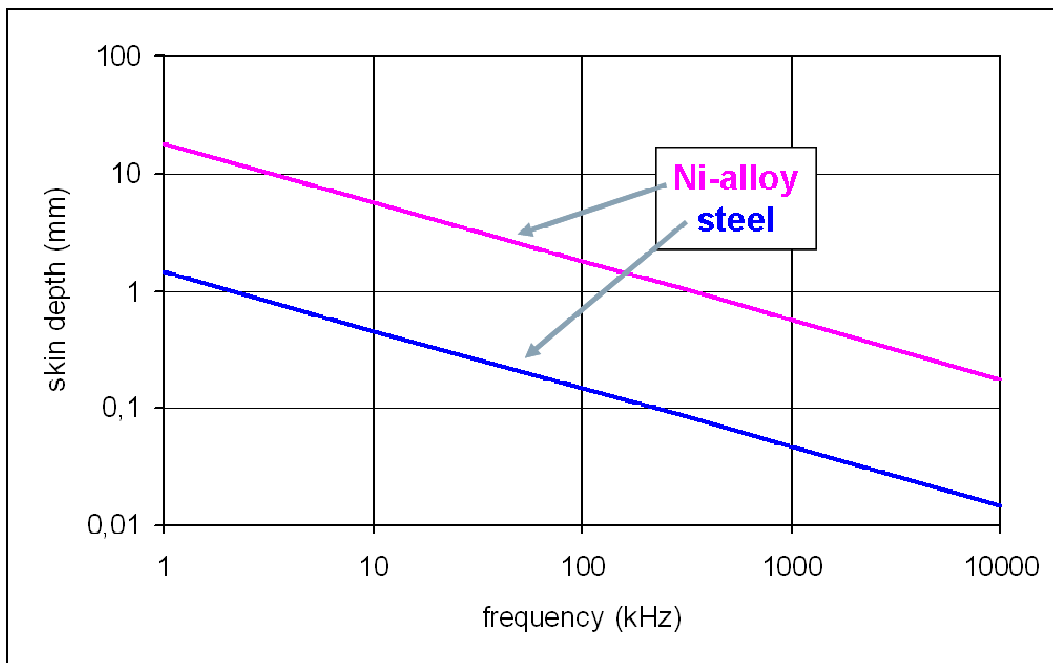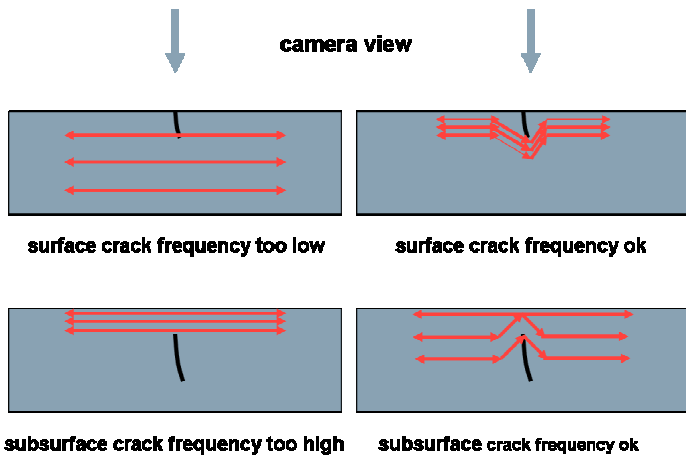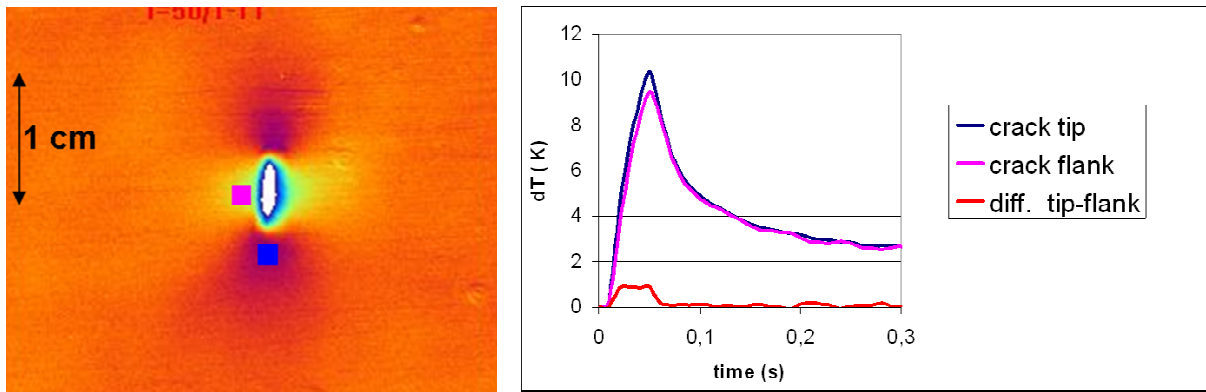
Figure 5

Figure 6

Figure 7

Thermal dT-Image   Binary Phase Image
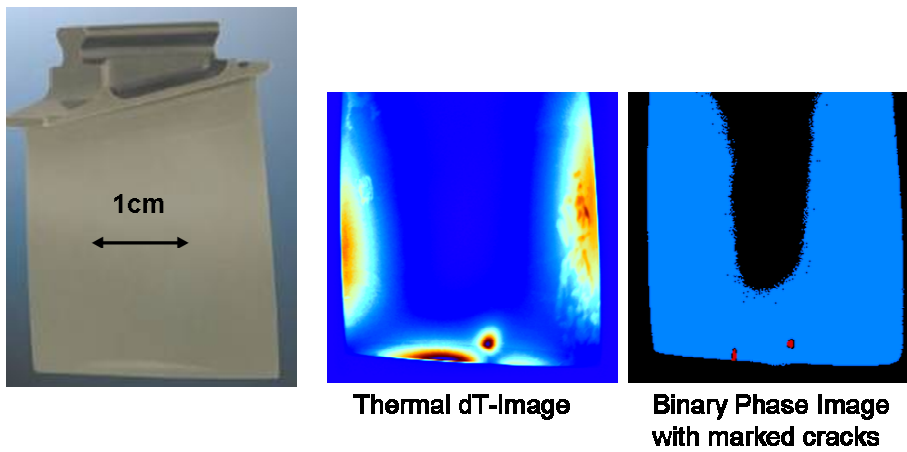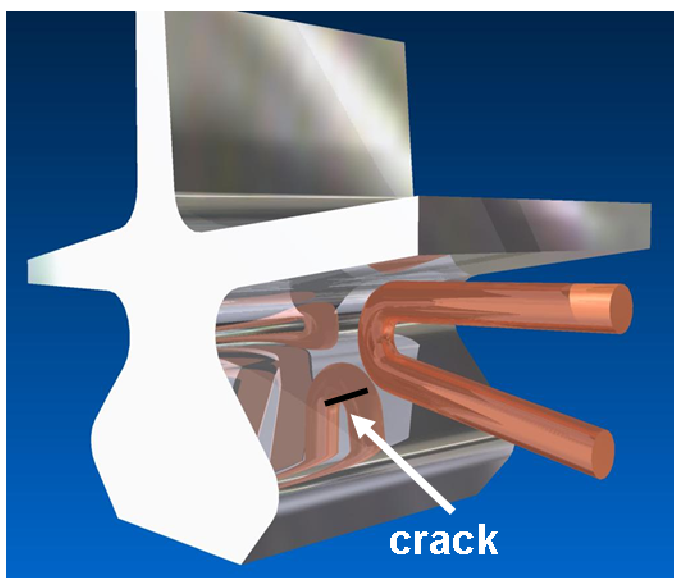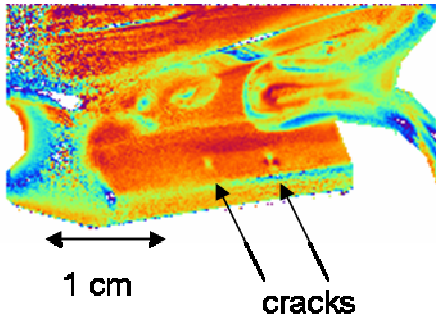   with marked cracks
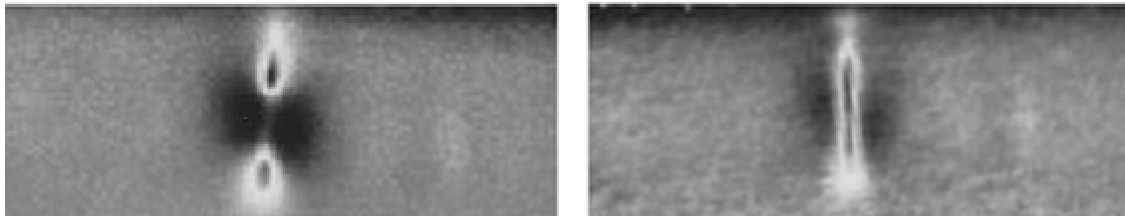
Figure 8
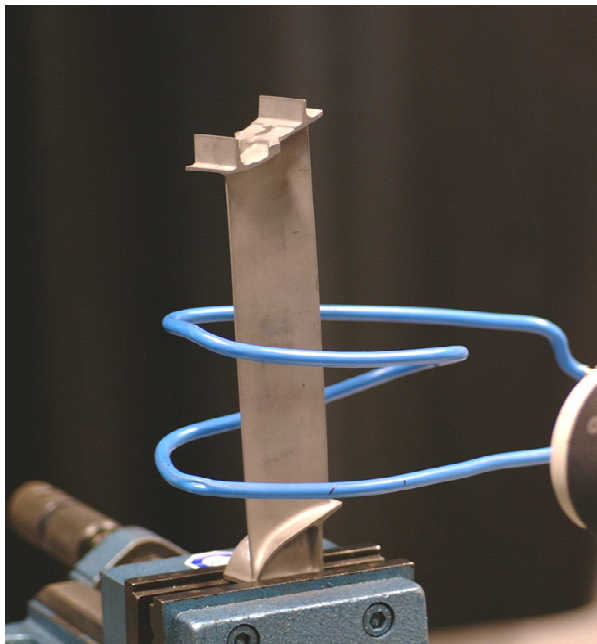

crack
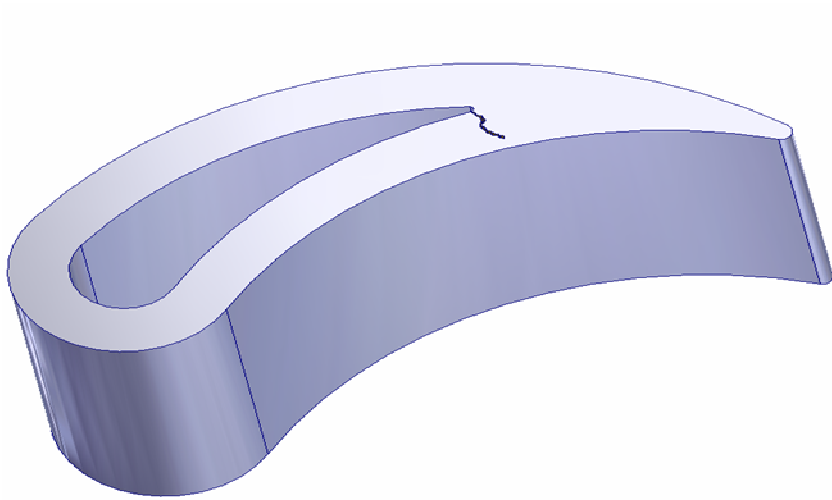
Figure 9

Figure 10
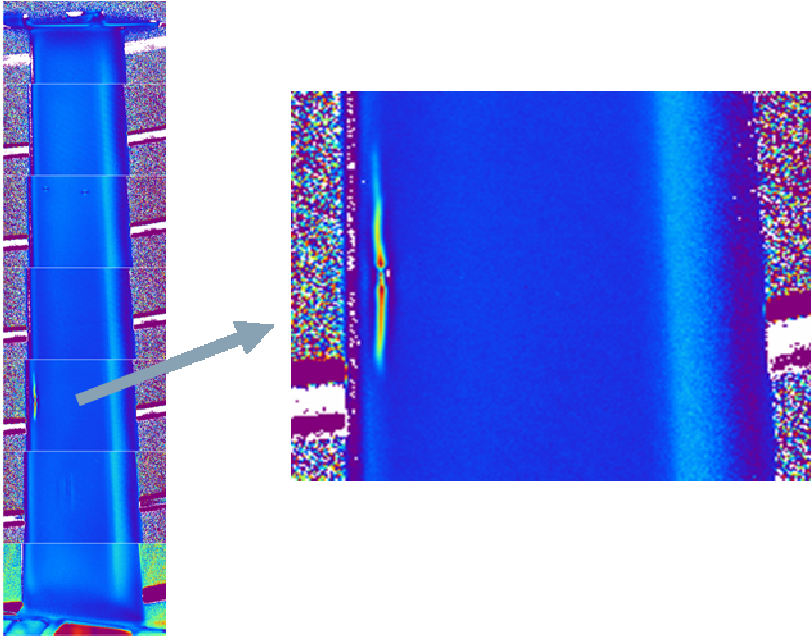

Figure 11

Figure 12

Figure 13

Fig. 1: Functional principle of the eddy current thermography

Fig. 2: Calculated temperature profile of a metallic specimen with crack

Fig.3: Skin depth dependent on alternating current frequency and material properties

Fig.4: Choice of the excitation frequency / skin depth for detection of cracks

Fig. 5: Test specimen with small crack; phase image + T-t diagram

Fig. 6: Phase image of titanium sample with crack open / smeared up

Fig. 7: Fully automatic inspection of compressor blades

Fig. 8: Test result of compressor blade

Fig. 9: Blade root with crack and adjusted coil

Fig. 10: Phase image of blade root

Fig. 11: Cut through the blade of a low pressure turbine vane with a buried crack

Fig. 12: Test assembly for low pressure turbine vane

Fig. 13: Test result: phase images of low pressure turbine vane