Application of Active Thermography for Detecting Material Defects in the Building Envelope

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ABSTRACT

The thermal non-destructive evaluation technique of 'active thermography' integrates infrared imaging with external heating to access subsurface defects via the thermal response of the sample. This paper presents a measurement methodology based on active thermography in the transmission mode for the detection of defects in the building envelope of unknown structure. The construction of several building wall models built with materials of varying thermal properties was examined. The essence of the experiment was to study the thermal response of the walls, over time as they were stimulated by an external heat radiator. This data was recorded sequentially, at regular intervals, using an infrared camera, allowing us to record the dynamic value changes of wall temperature and structure. The temperatures of these defects were different from the temperature of the rest of the test area. On the basis of these thermograms showing the distribution of the surface temperature, it was possible to locate subsurface defects.

INTRODUCTION

Thermal imaging used for building examination is a very accurate and fast method of qualitative evaluation which has been used for a number of years, primarily to locate defects in the thermal envelope of buildings. Thermal imaging can identify thermal bridges, contamination of walls by moisture, and local cold air blow downs. Infrared thermography is capable of extensive qualitative evaluation of heat losses in buildings of various types and may be successfully used to find comprehensive solutions for energy efficiency issues.

Recently, infrared thermography has found an interesting use in the non-destructive testing of historic buildings. Most often in these structures, it is not permissible to test via opening up the structure. Hence, a non-destructive testing method is required such as infrared thermography. In such cases, t active thermography is used which allows, but is not limited to, finding various types of material inclusions inside the walls. (The classic method of testing the buildings with a thermal imager is classified as a passive method.)

In the tests described here, we used active thermography to detect material inclusions in surface layer of space-dividing elements of unknown structure. This kind of measuring method can be applied in non-destructive testing of space-dividing elements in which workmanship is subject to higher and higher quality requirements. Non-destructive testing provides information about material properties, detecting material discontinuities and obtaining dimension measurements without disrupting building performance or operation in any way.

Thermal stimulation of the building envelope is necessary to acquire information about possible defects or material inclusions in such elements. For instance, energy is delivered to the material surface as a high-power heat impulse. Then, when the heat source is turned off, the temperature of this surface will decrease. Due to heat transfer, the thermal energy moves deep into the material. If there are materials of different thermal properties (including discontinuities) within a homogenous area, the speed of this diffusion will change. Hence, while monitoring the temperature field on a sample as it cools, we can identify at what depth the discontinuities occur and their size. Such application of thermography requires external excitation (stimulation) of the surface under test through the delivery of a pulse of heat energy of sufficient power. The thermal response of the building partition to such pulse is recorded by an infrared camera, while timing the sequence of temperature distribution on the element surface as it appears, providing information about the

location of under-surface defects. Temperature distribution measurement on the element surface may be carried out both on the side that is being heated and on the back side. This technique is called active thermography. The standard technique used for building examination that requires no external thermal stimulation is referred to as passive thermography.

This paper presents results of measurements of models of external walls with material inclusions using active thermography in reflection mode. The purpose of the examinations was to identify those inclusions by their various thermal properties.

THE TRANSMISSION MODE OF ACTIVE THERMOGRAPHY

The transmission mode of active thermography is used to detect deep material inclusions, located close to the non-radiated side of the wall partition under test. The reflection mode, on the other hand, is used to find structures located near the radiated surface of the sample tested. Figure 1 illustrates two different modes of image recording in active thermography.

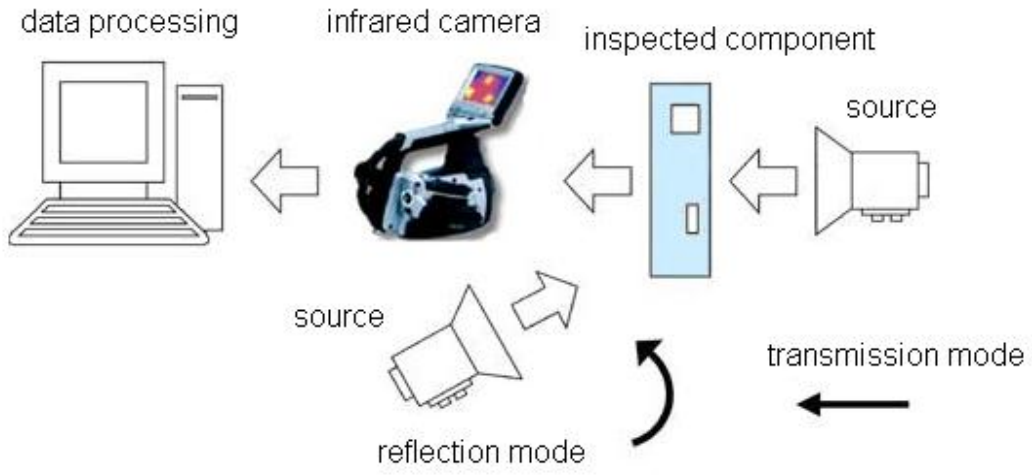


Figure 1. Example of measuring stand positions for active thermography method in the two basic modes of image recording depending on the way of exciting the structure under test, i.e. transmission and reflection modes.

Thermal images of the surface under test are collected at constant time intervals to allow dynamic changes of temperature to reveal the structure of the sample. (Heterogeneities in the building envelope are visible as thermal areas where the temperature differs from that of the remaining part of the element tested.) If a material defect is located at such depth that thermal waves would be totally suppressed before they reach it, or they decay after reflection, then detecting such defect by reflection active thermography is very difficult. Hence, active thermography in reflection mode is effective only in detecting defects that are close to the surface of the sample. The thickness of this layer is dependent, among other things, on the type of material of which it is composed and the amount of thermal energy applied to the surface.

MEASUREMENT (TESTING)

For this test, we examined two models of multi-layer chipboard walls of identical heat capacity with inclusions added of two materials of very different thermal properties, i.e. steel (λ=58 W/mK) and foamed polystyrene (λ=0,04 W/mK). These plates were tested with active thermography in reflection mode. The goal of the test was to determine the size of the material inclusions and their thermal properties.

Figure 2 is a diagram of the experiment set-up for active thermography, while Figure 3 illustrated the placement of the inclusions in the material under testing and the view of the measuring stand.

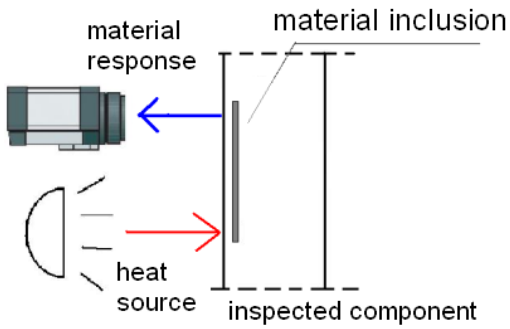


Figure 2. Diagram of testing stand using active thermography in reflection mode.

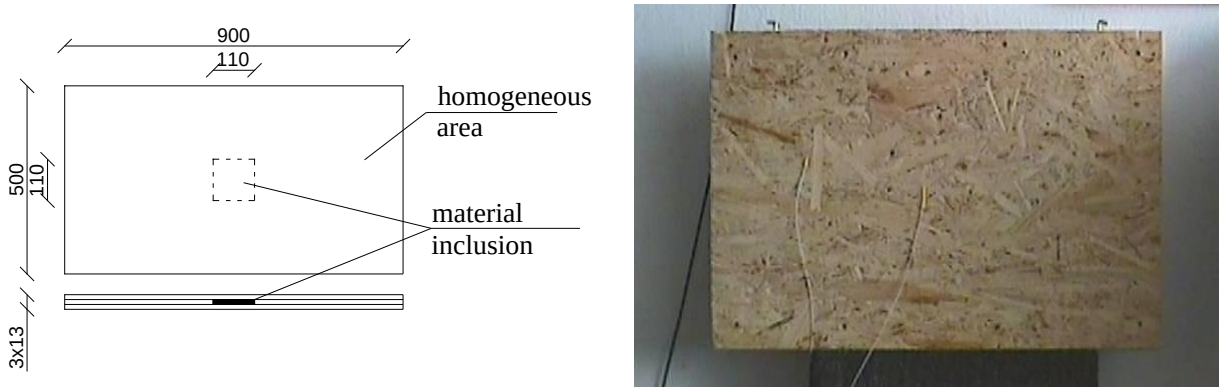


Figure 3. Diagram of wall models under test and photo of measuring stand.

Two infrared radiators (type FOBO EP 102) with total power of 2 kW were used to heat the plate with inclusions. A thermal camera (ThermaCAM P65) was used to record sequences of thermal images of the surface as it cooled [Fig.4].

Figure 4. Equipment used in examinations: infrared radiators type FOBO EP 102 and FLIR ThermaCAM P65 thermal camera.

Thermal images were taken at constant time intervals which allowed observation of dynamic changes of surface temperature, providing the data from which we could deduce the structure of wall models under test. Heterogeneities were visible as thermal areas in which temperatures were different than those of the

surrounding areas due to the different heat transfer properties. In dense materials, heat transmission is affected by the fact that the higher the volumetric fraction of the solid substance, the greater the thermal conduction of that material will be. Interpretation of the temperature data recorded by the thermal camera as the surface cooled provided us with information about areas of discontinuous temperature. One of the formulas we used to determine the absolute temperature contrast is as follows:

$$C_a(t) = T_p(t) - T_{pj}(t), \quad (1)$$

where:
Tp(t) - temperature at any selected point on surface of the material under testing,
Tpj(t) - temperature at surface point over homogenous area.

Calculation of this contrast allows better visualization of discontinuity; however, its disadvantage is the dependence on the energy absorbed during thermal stimulation which limits the comparability of results from various experiments.

The other form of processing the data recorded by the camera is to determine standard temperature contrast:

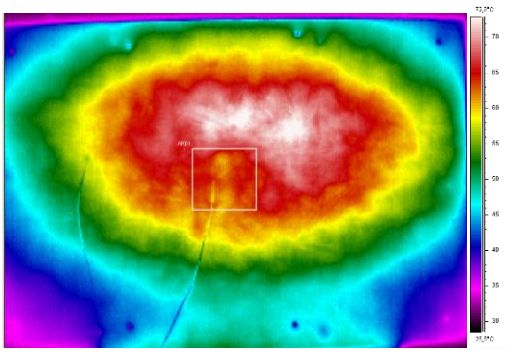
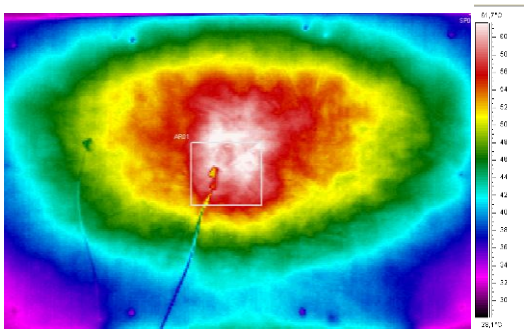
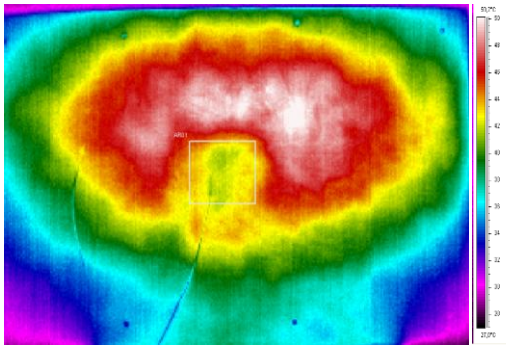
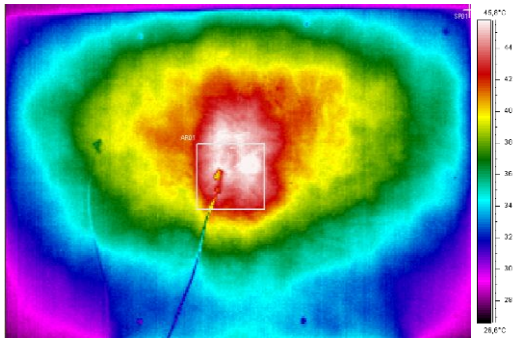
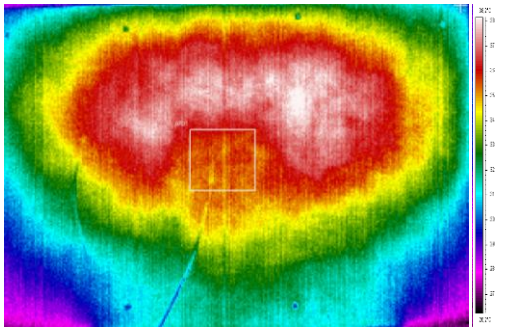
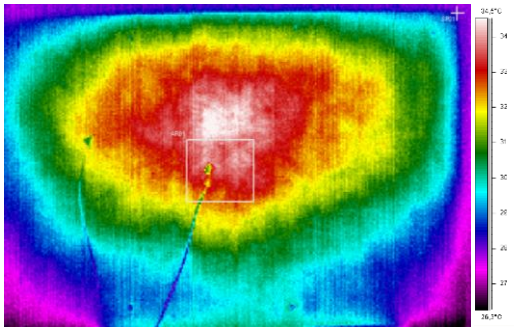
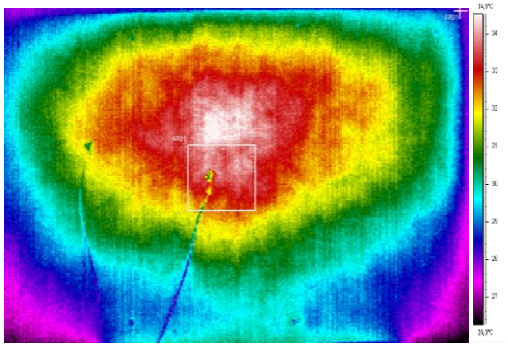
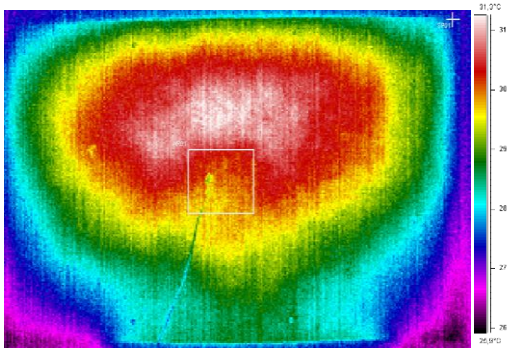
$$C_s(t) = \frac{T_p(t) - T_p(0)}{T_{pj}(t) - T_{pj}(0)}, \quad (2)$$

where:
Tp(t) – temperature at any selected point on surface of the material under testing,
Tpj(t) - temperature at surface point over homogenous area,
Tp(t0) – temperature at any selected point on surface of the material under test prior to thermal stimulation,
Tpj(t0)- temperature at surface point over homogenous area prior to thermal stimulation.

The cool down time when the temperature contrast for surface points with defects is of the highest value provides information about the depth of defect for which we are searching. Increasing thermal contrast during initial stage of cool down is usually related to accumulation of internal energy in the discontinuity area. It leads to temperature difference and consequently, the accumulated heat propagates to the sides causing the contrast to decay. It limits the potential to detect defects located deep in the material. Hence, the reflection-mode active thermography can detect just those defects which are located in the surface layer. The depth of this layer depends on the type of material under test and on the power of thermal wave excited.

RESULTS

The sample under test was heated with an infrared radiator for 30 minutes. Then, using a thermal camera, the temperature distribution of the sample surface was recorded once a minute. The variability of temperature distribution over the area of the element under test is shown in Fig. 5.

cooling time	steel imperfection	polystyrene imperfection
0 min		
10 min		
30 min		
50 min		

90 min

120 min

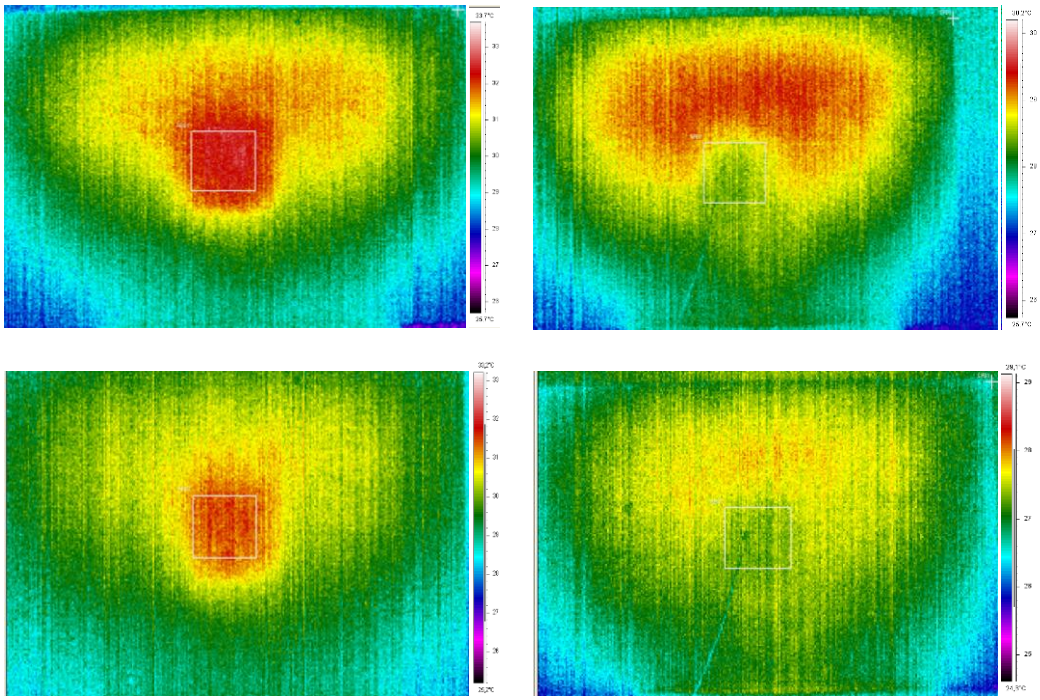


Figure 5. Variability of temperature distribution in time from starting of cool down period for steel plate defect (left) and polystyrene defect (right).

Two chipboard wall models were heated up for 30 minutes by infrared radiator, and then, after switching it off, thermal images were recorded once a minute. During the first phase, i.e. for the first 10 minutes after disconnecting the lamps, the temperature distribution waveform for both plates – steel and foamed polystyrene inserts – were quite similar. No discontinuities were visible in temperature distribution on the plate surface in both cases. After 10 minutes, however, the temperature over the heterogeneous area on the plate with the steel insert was lower than for the remaining plate area while in the plate including the foamed polystyrene insert, the situation was reversed.

During heating of the sample, the surface temperature rises. After disconnecting the infrared radiators, the surface temperature starts to decrease, mainly due to heat diffusion deep into the material. Defects existing in the surface layer can change the speed of this diffusion. Depending on thermal properties of the defect, the area over the defect will be either colder or warmer than the area outside the defect. Thermal images in Figure 5 show that when the insert is of a material of higher thermal conductivity and higher heat capacity (steel) than the surrounding material, more time is necessary to heat it up. However, it retains heat for a longer period. In the case of an inserted material with a lower thermal conductivity and lower heat capacity (foamed polystyrene) than the material it is placed in, it heats up faster, but also cools down faster than the surrounding material.

A series of thermograms can lead us to conclusions about the size of discontinuity existing under the material surface and about its thermal properties in comparison with the material under test. The thermograms clearly show the outline of the element located under the surface of the test sample.

steel imperfection

polystyrene imperfection

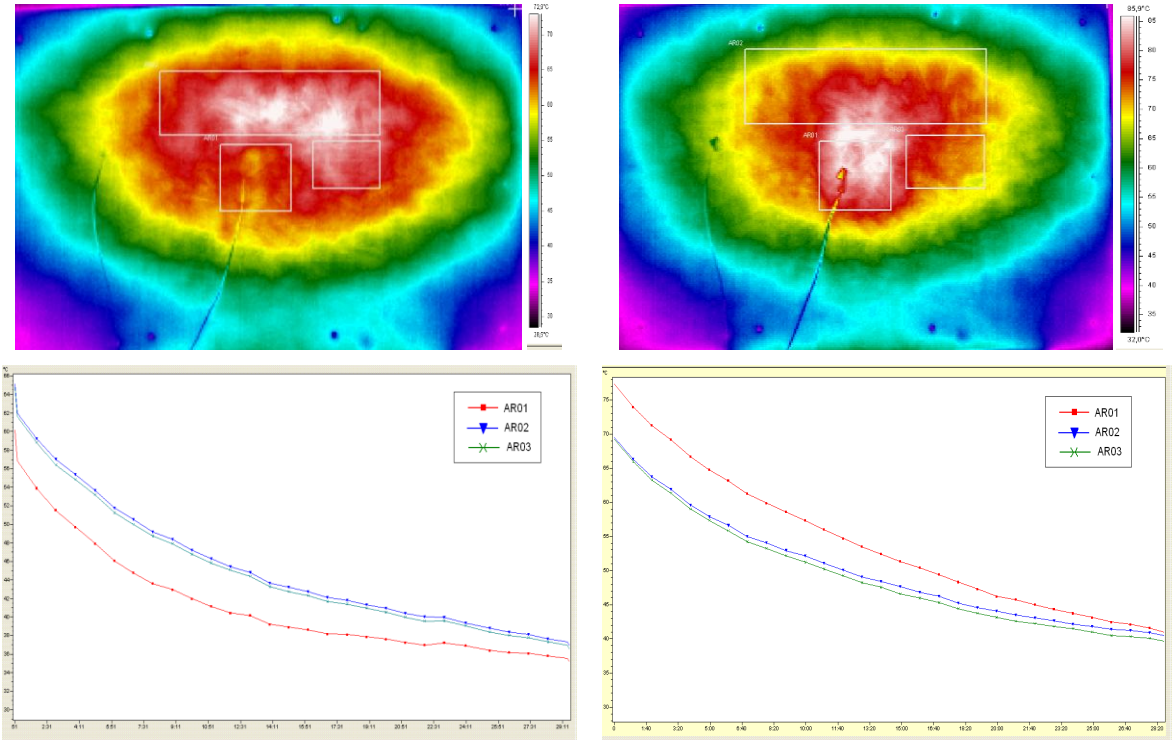


Figure 6. Variability over time of the average temperature of the area over homogenous material and average temperature of area over the material inclusions of steel and foamed polystyrene.

The deviation of temperature change over time points out the defect under the surface of the material under test. Based on temperature readings taken over a period of time on the surface of the sample as it cooled, an average temperature versus time was found for the area over the homogenous material and for the area with the discontinuity. Temperature versus time for homogenous material is shown in Figure 6 in blue and green (two selected areas), while the area over the defect is shown in red. It is clearly shown that a defect under the surface changes the temperature-time relationship. Depending on thermal capacity of the defect, the temperature-time waveform for the heterogeneous area is above or below that for the homogenous material. Namely, for a defect in which thermal capacity is higher than the material tested (e.g. steel), the waveform for heterogeneous material is below the waveform of the homogenous area, while in the case of material with a lower thermal capacity than the sample (foamed polystyrene), the situation is reversed, i.e. with the waveform above homogenous material.

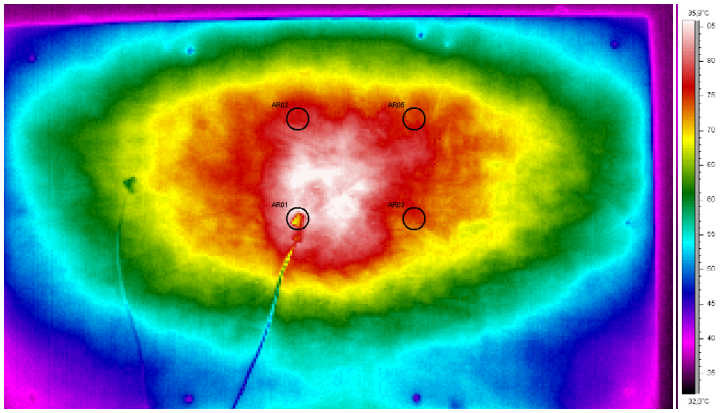


Figure 7. Diagram of the measurement points on the sample under test.

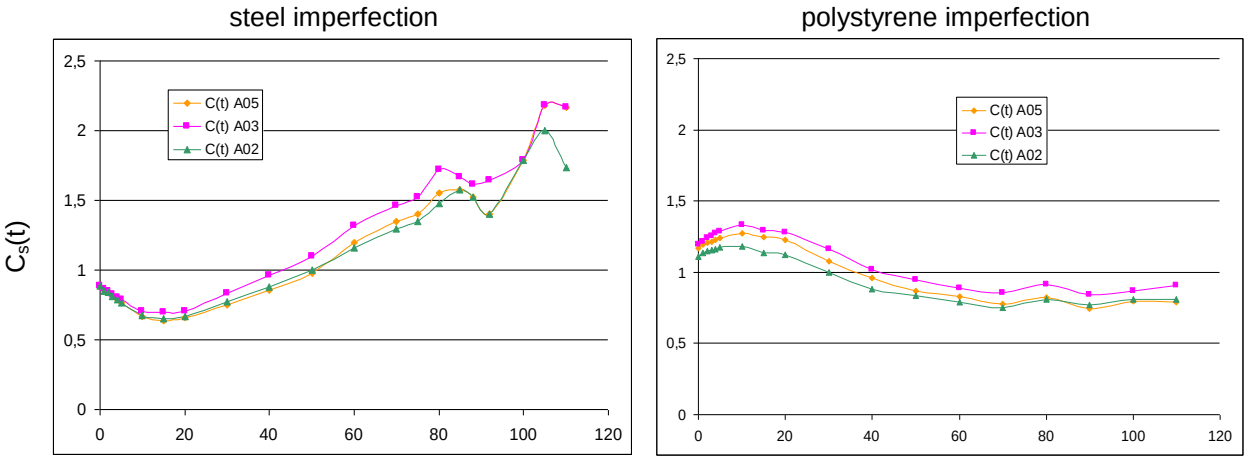


Figure 8. Diagram of standard contrast (equation 2) during cool down period for the sample tested at three measuring points, for defects of steel (left) and foamed polystyrene (right).

As shown in Figure 8, the standard contrast for the sample with the steel defect, independent of the selected point where it is calculated, reaches its extreme value after about 10 minutes and then rises significantly. The standard contrast for the sample with the foamed polystyrene defect also reaches its extreme value after about 10 minutes. Thereafter, however, it declines considerably until it stabilizes somewhere near a constant value of about 0.8. Hence, as can be seen, the tendency of this waveform formation depends on the type of subsurface defect material and its attendant thermal properties.

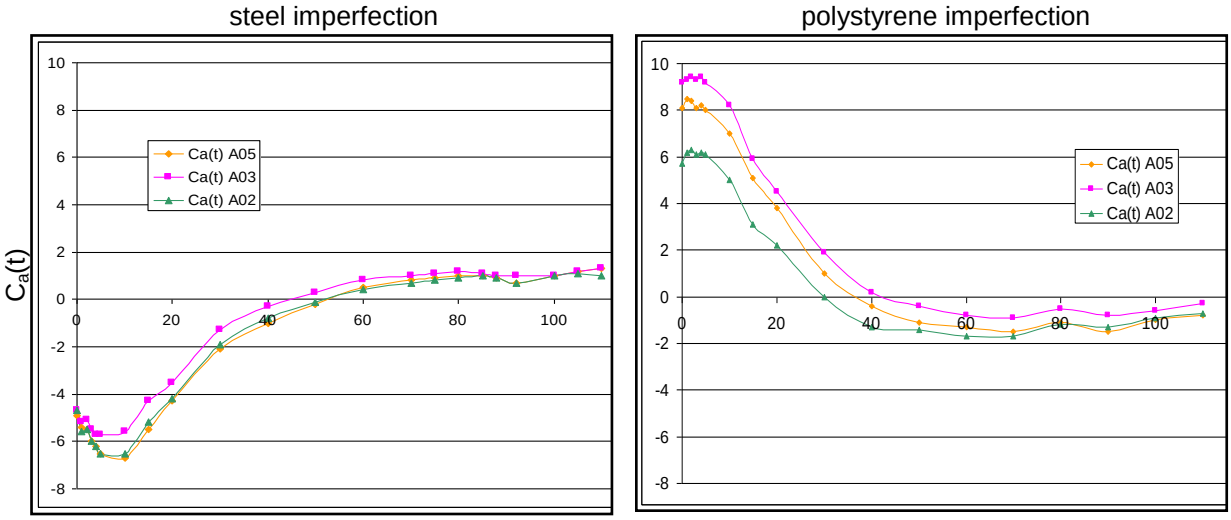


Figure 9. Time diagram of absolute contrast (equation 1) during the cool down period for the sample test at three measuring points, for defects of steel (left) and foamed polystyrene (right).

The absolute contrast for the sample with the steel defect reaches its extreme value after about 10 minutes and then rises significantly until it stabilizes at a constant value of about +1, as shown in Figure 9. The absolute contrast for the foamed polystyrene defect also reaches its extreme value in about 10 minutes, but, diminishes more and stabilizes at constant value about -1. Depending on thermal properties of the defect, the absolute contrast of the sample under test may have either positive or negative values.

The values of absolute contrast were significantly lower than zero in the surface material above discontinuities with higher thermal capacity than the sample itself (steel). In the case of a defect material with a thermal capacity lower than that of the sample (foamed polystyrene), the value of absolute contrast will be higher than zero.

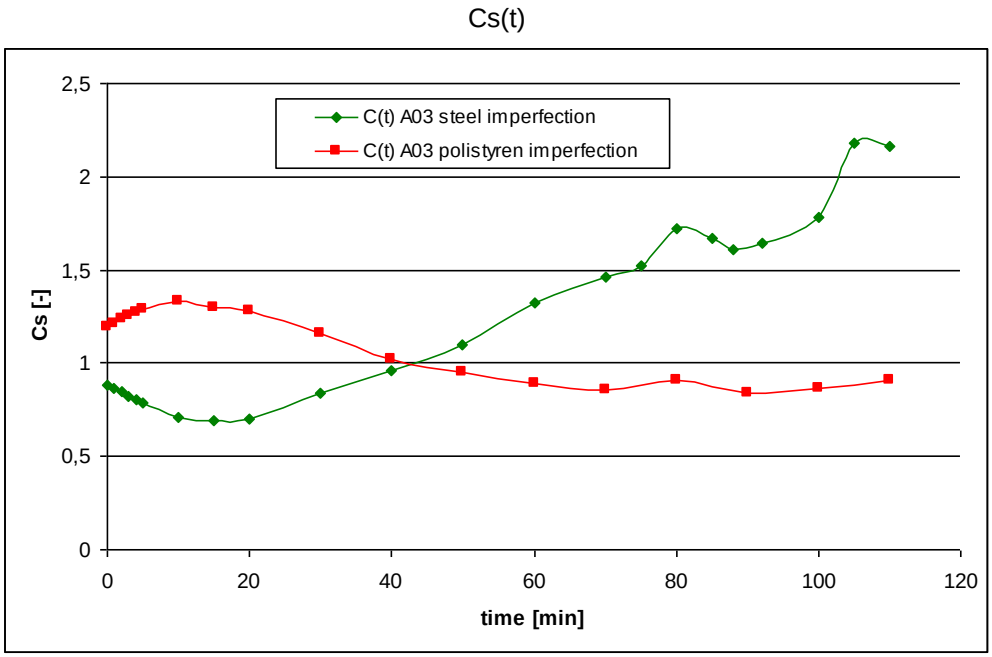


Figure. 10. Time diagram of standard contrast for defects of steel and foamed polystyrene at selected points for samples under test.

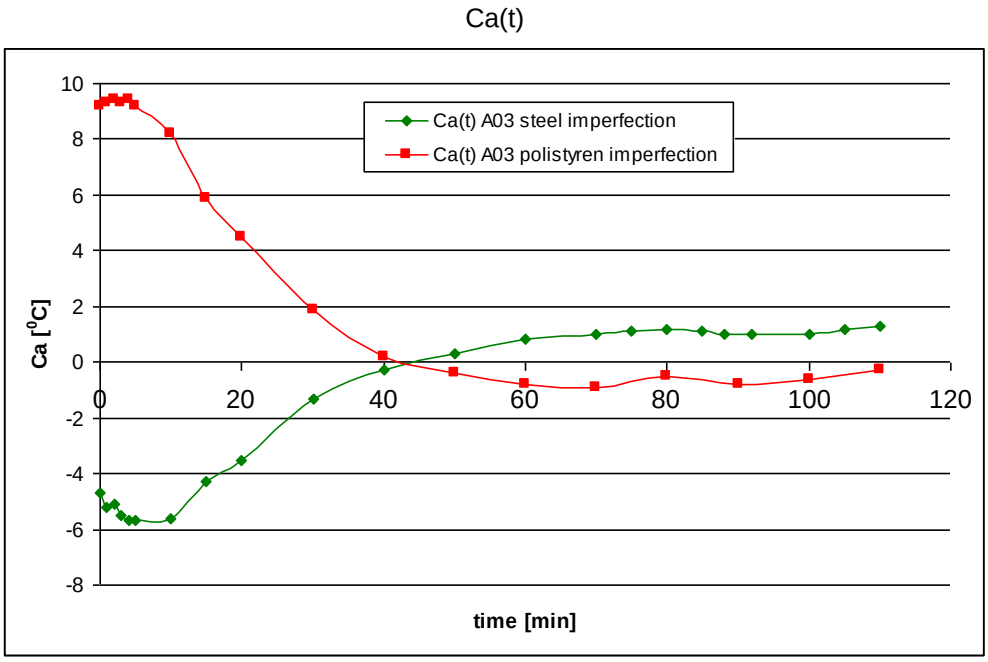


Figure. 11. Time diagram of absolute contrast for defects of steel and foamed polystyrene at selected points of sample under test.

Figures 10 and 11 show that independent of the defect material, both standard contrast and absolute contrast reach their extreme value at the same time after the cool down phase begins. This may be an indication that the defects are at the same depth. However to confirm this theory, additional testing is necessary, which is planned in further research work.

SUMMARY

Examinations confirmed that thermal properties of a defect can be concluded from sequential recording of thermograms including temperature distribution on the surface of the plate under test starting at the beginning of the cool down phase. Thermal images allowed determination of whether specific material inclusions were of higher or lower thermal capacity than the surrounding material.

The time-related temperature distribution waveform for homogenous material differs from that for the area above a defect. Depending on the type of defect, i.e. its thermal capacity, the deviation is above or below the temperature distribution waveform for the homogenous area [Fig.6].

Absolute and standard contrast at each point of defect-free areas are very close to each other as it relates to their values and waveform – they both rise or diminish in pairs depending on the defect type. In the same type of defect, they also reach their maximum and minimum temperatures in a paired state. Standard contrast is independent of the type of material tested; it is dimensionless and oscillates around a constant value of about 1, so it is possible to compare results from various experiments. Absolute contrast is the difference of temperatures, depending on the type of material and the conditions of testing. Standard contrast varies with time; absolute contrast becomes stable at some point in time.

Still to be resolved in further thermal imaging tests is the problem of reverse heat exchange, or how one can determine the size and depth of the defect on the basis of temperature distribution on the surface as it cools. Further research work will attempt to identify deep defects which are revealed later and at lower contrast. It will be necessary to prepare several samples with defects at various depths and to analyze temperature distributions on their surfaces.

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