VISUALISATION OF TRANSPORT PROCESSES IN BUILDING MATERIALS BY LASER INDUCED ACTIVE THERMOGRAPHY

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Abstract
We report about laser-induced thermal excitation for the monitoring of heat and moisture transport processes in building materials such as wood and sandstone using an infrared camera.
With a Nd:YAG laser, a point, a line or other geometries are scanned along the surface of the material under investigation. During and after excitation, the absorbed heat diffuses into the material. The surface temperature is recorded by an infrared camera as a function of time.
In this paper, we present the results of two investigations. The method described above was applied to wood treated with wood preservatives in order to assess the thermal properties of the sample during the fixation process of the preservative. Different concentrations of the preservative could be detected as well as the surface moisture content. In addition, the thermal diffusivity of the wood could be determined.
The method was also proven to be suitable to investigate water transport and content in sandstone. In this case as well, the thermal diffusivity could be determined.

Keywords: active thermography, laser, local thermal excitation, thermal diffusivity, heat transport, water transport, wood, sandstone

1. Introduction

Active thermography is increasingly applied in the field of non-destructive testing of material structures and properties [1-3]. In this method, the material under investigation is thermally excited by a heat source. The heat transport depends on the thermal material properties which are given by the density, the specific heat capacity and the thermal conductivity. In most cases, active thermography is used for the investigation of the actual condition of a structural element concerning the material properties or the existence of internal faults. But as active thermography is a contactless and fast method, and as environmental influences can be controlled, it can be applied in situ as well, i.e. while the conditions of the structure under investigation are changing [4].
Comprehension of heat and moisture transport processes in building materials is essential for the prediction of durability and safety of structures. Conventional methods of testing often allow a snapshot of the scenery and have to be applied repeatedly. Apart from that, they are often not quantitative regarding position and extension of damage or moisture. Thus, the aim of our work is the development of a method for time- and space-resolved in situ measurements of heat and water transport processes for the application in industry and environment. For this purpose, active thermography is a promising tool.
In this paper, we present the results of two different investigations:
In the case of pine sap wood, the influence of treatment with a wood preservative on the thermal behavior during the fixation process of about four weeks has been analyzed. The aim of this study was to recognize the moisture content and the concentration of wood preservative and further the development of a quality control method. Our results show that the thermal answer depends on the concentration of the wood preservative and the moisture content of the wood.
The second investigation concerned water transport and content in sandstone. Two experiments have been performed. In both, the samples were locally excited by the laser. The first experiment took place during water suction, the second with different moisture contents. The aim was the

assessment of moisture distribution and transport. The thermal diffusivity could be determined for different moisture contents. Examples of the investigation of transport phenomena by IR thermography occurring at masonry can be found in the literature [5] as well. However, large-area thermal excitation is mostly used in those experiments. As we apply local laser excitation, we have the possibility to evaluate the lateral heat transport as well.
In both cases, sandstone and wood, the results are promising regarding the investigation of durability and the sustainability of materials.

2. Experimental

2.1 Experimental equipment

All experiments presented in this paper have been performed at the set-up shown in fig. 1. It consists of a sample chamber which allows experiments in different ambient conditions like air, gas or vacuum. It is equipped with a Nd:YAG laser having a wavelength of 1064 nm, a spot size of about 1 mm and an output power range from 10 to 1000 W. The laser allows local thermal excitation in a square area of 24 mm x 24 mm. The heating as well as the cooling process is then recorded by an infrared (IR) camera (InSb FPA, 3 to 5 µm) with a full frame rate of about 100 Hz. Depending on the temperature range the integration time is adjusted to achieve an ideal dynamic range.

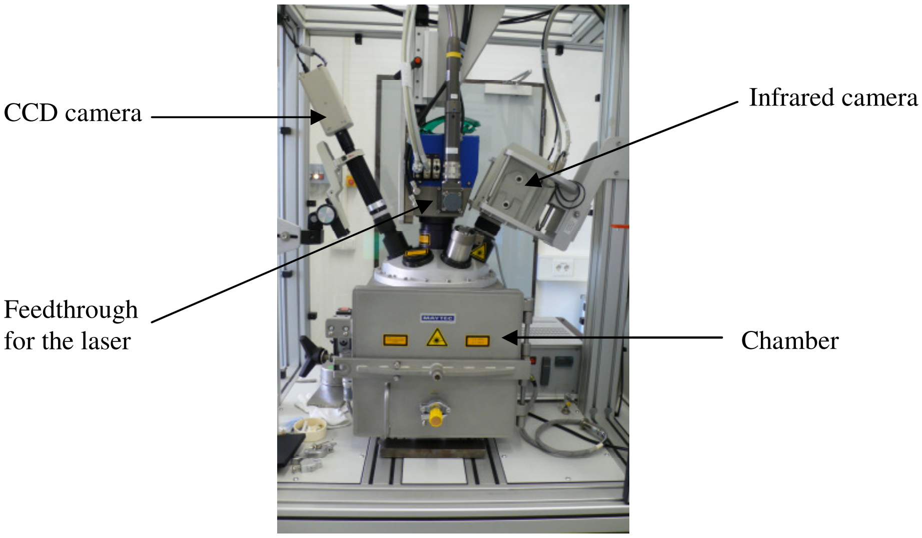

Figure 1. The sample chamber equipped with laser, infrared and CCD camera.

2.2 Investigation of wood treatment

Cuboidal pieces of pine sap wood with a size of 5 cm x 2.5 cm x 1.5 cm, cf. fig. 2, have been treated with differently concentrated wood preservatives according to [6], section 7.2. The protecting agent consisted of copper sulphate (50 %), potassium dichromate (48 %) and chromium trioxide (2 %). In the following, it will be referred to as CC.

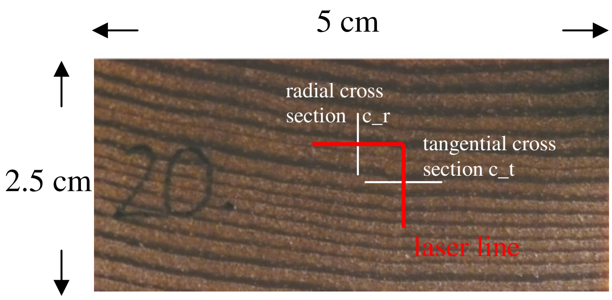

Figure 2. Pine sap wood sample treated with a copper and chromium solution.

The influence of the concentration of the wood preservative on the thermal behavior of the sample has been investigated as well as its dependence on time after treatment. For this purpose, a series of measurement was carried out for each CC concentration applied. Five different concentrations of CC were chosen: water (0 %) as reference sample, 0.6 %, 1.5 %, 2.2 %, and 4 %. For each concentration, six samples were investigated for a statistical evaluation. 16 measurements, at different positions on the sample, were performed during one month after treatment. Before each measurement, the samples were weighed to determine their moisture content. In the time between two measurements, they were stored in a conditioning chamber enwrapped in foil in order to retard the drying process. The samples were thermally excited by the Nd:YAG laser which was scanned L-shaped over the sample surface in order to perform thermal excitation parallel as well as orthogonal to the tree rings, see figs. 2 and 4. The most important parameters of the experiment can be found in table 1.

2.3 Investigation of water transport and determination of thermal diffusivity in sandstone

In a first experiment, a sample of Postaer sandstone with a total porosity of 15.5 % and a density of 1.8 g/cm^3 was put into a sponge which served as a water reservoir. During the following process of water suction, the laser was scanned linearly along the surface orthogonal to the direction of water suction. The parameters of the experiment are summarized in table 1 (Sandstone_1). The setup can be seen in fig. 3.

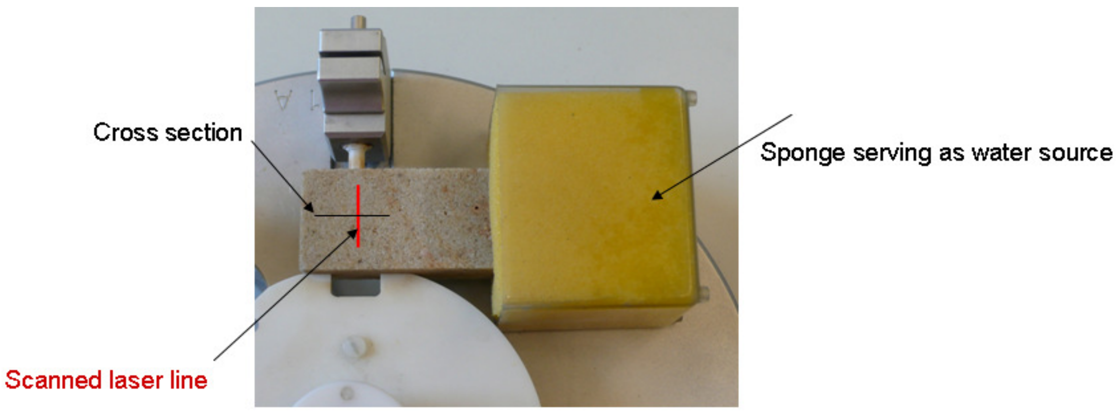

Figure 3. Experimental setup for the investigation of water content and transport in sandstone.

Sample	Laser power	Duration of laser irradiation (whole line)	Length of scanned laser line	Camera integration time
Wood	10 W	5 s	16 mm	300 µs
Sandstone_1	30 W	5 s	15 mm	300 µs
Sandstone_2	50 W	0.1 s	Point	500 µs

Table 1: Experimental parameters

In a second experiment, a dry sample of Postaer sandstone and one with a moisture content of about 4 % by weight were excited by a short laser pulse, s. table 1 (Sandstone_2). The thermal conductivity could be determined by the analysis of heat propagation.

3. Results and discussion

3.1 Investigation of the influence of wood preservatives on the thermal behaviour of pine wood

Fig. 4 shows a thermogram at the end of the laser excitation. The scan direction is from down right to top left. The intensity of the radiance is shown in digits because the calibration in order to get temperature values is quite difficult for wet samples as they are drying during the calibration process.

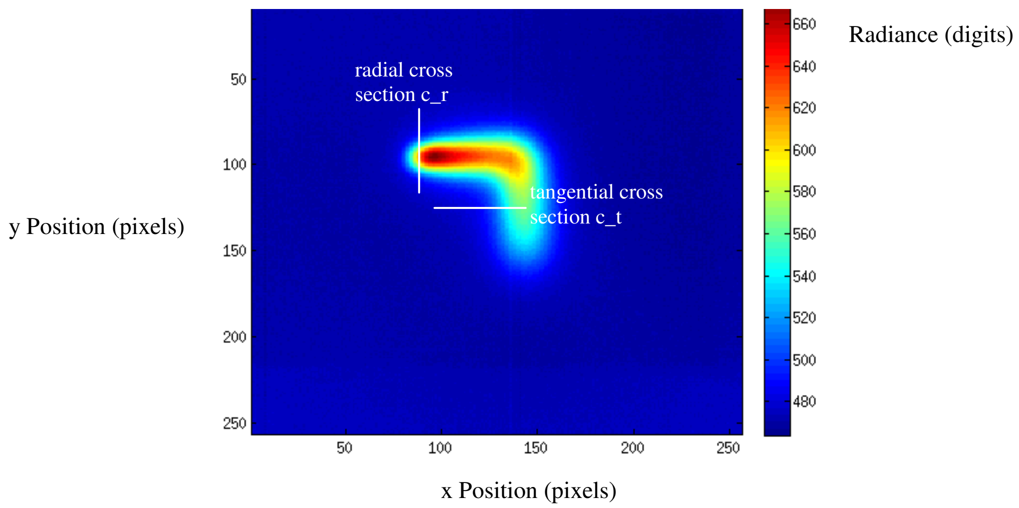

Figure 4. L-shaped excitation of the sample, 1 pixel ≈ 0.12 mm.

Fig. 5 shows the thermal radiance in the middle of the arms of the “L” 0.25 s after laser heating. “Radial” or “c_r” in the following refers to the fact that the cross section for the detection of the value of radiance was orthogonal to the annual rings of the wood, “tangential” or “c_t” means that it was parallel to the annual rings, cf. figs. 2 and 4 as well.

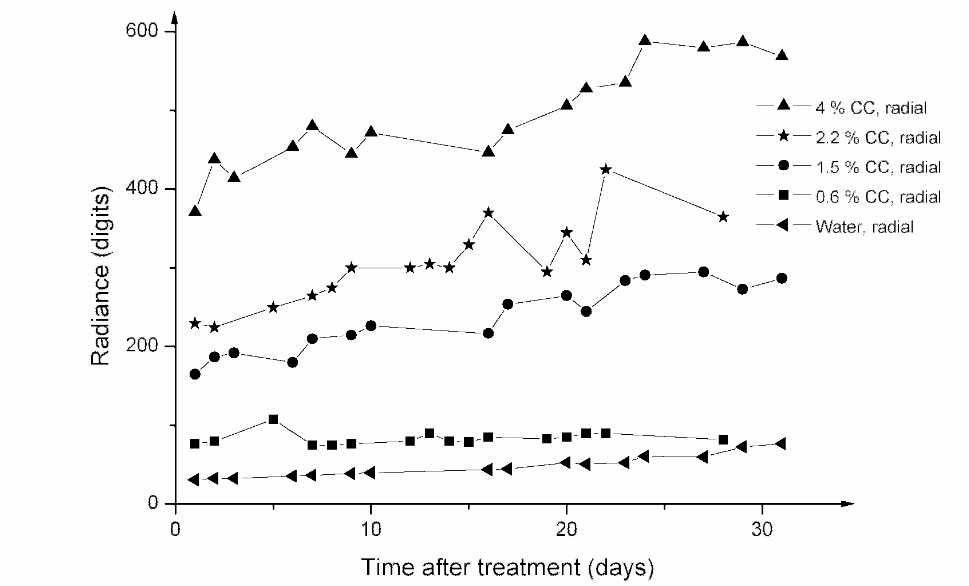

Figure 5. Thermal radiance, peak value along c_r, 0.25 s after laser heating
versus time after treatment with wood preservative for different concentrations of CC.

The following conclusions can be drawn from fig. 5:

- The higher the concentration of the wood preservative, the higher the radiance which indicates the higher absorption at the laser wavelength. The emissivity at room temperature at the camera wavelength was shown to be the same for all concentrations.
- The thermal radiance is increasing with time after the treatment. This is due to the drying of the samples during the performance of the experiment in spite of storing them in foil, cf. sec. 2.2.

Fig. 6 shows the dependence of the thermal radiance 0.25 s after laser heating on the moisture content of the sample. Here, the mean value of two thermal radiance values (c_t and c_r) is plotted.

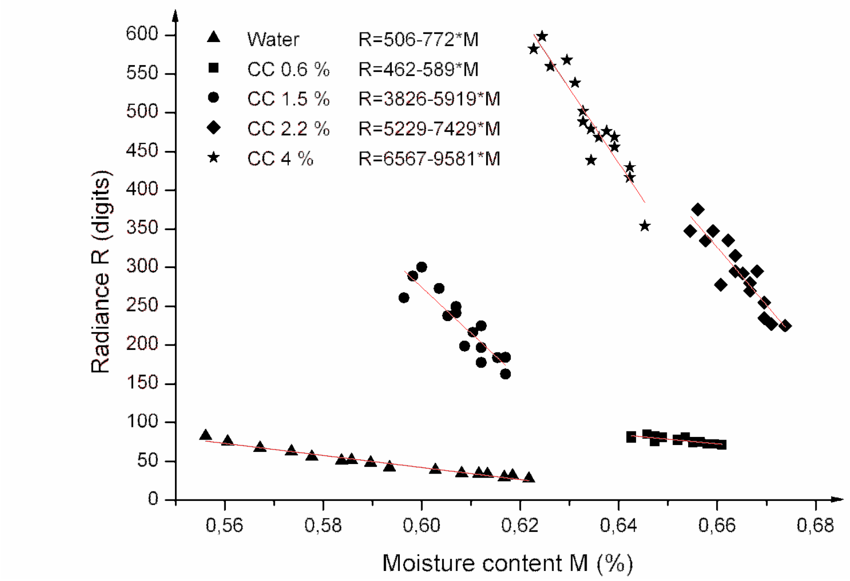

Figure 6. Thermal radiance, mean of peak values along c_r and c_t, 0.25 s after laser heating
versus moisture content for different concentrations of CC;
symbols refer to experimental data, lines to the regression analysis.

The thermal radiance for CC 4 % is 1.3 times higher than the one for CC 2.2 %, it is 1.7 times higher than the one for CC 1.5 % and about 12.5 times higher than the one for water, independent of the moisture content. The only measurement series which is not fitting too well, is the one of the CC 0.6 % treated wood.
Thus, the influence of water content is the same for all concentrations of wood preservative and the absorption at the laser wavelength does not change in the investigated range of moisture content.
Another topic investigated was the heat propagation, which can be detected by evaluating the broadening of cross section peaks.
A possibility to determine the thermal diffusivity is given by Cernuschi et al. in [7]. The temperature distribution after an instantaneous spatially Gaussian shaped heating is given by:

$$T(r,t) = f(t) \cdot \exp(-\frac{2r^2}{R^2 + 8\alpha t}), \quad (1)$$

with r being the distance from the centre of the excitation, R the radius of the excitation and α the thermal diffusivity. Fitting the temperature distribution at time t with a Gaussian function

$$g(x) = const. \cdot \exp(-\frac{x^2}{2\sigma^2})$$

results in

$$\sigma^2 = \frac{R^2 + 8\alpha t}{4}, \quad (2)$$

i.e. the thermal diffusivity is half of the slope in a σ^2-t diagram.
This is shown in fig. 7 for radial and tangential cross sections at days 6 and 20 after treatment with CC 4 %.
Note that we use intensity values instead of temperatures, thus the thermal diffusivity cannot be determined exactly. But one can clearly conclude from fig. 7 and from equation (2) that the thermal conductivity is higher in the direction orthogonal to the tree rings and that it does not change with time after the treatment. The concentration was found to be without influence on the thermal diffusivity as well.
The reason for this behavior could be the distribution of early wood (about 75 %) and latewood (about 25 %). The latter has a higher thermal conductivity. The anisotropic heat transfer is highlighted in [8].

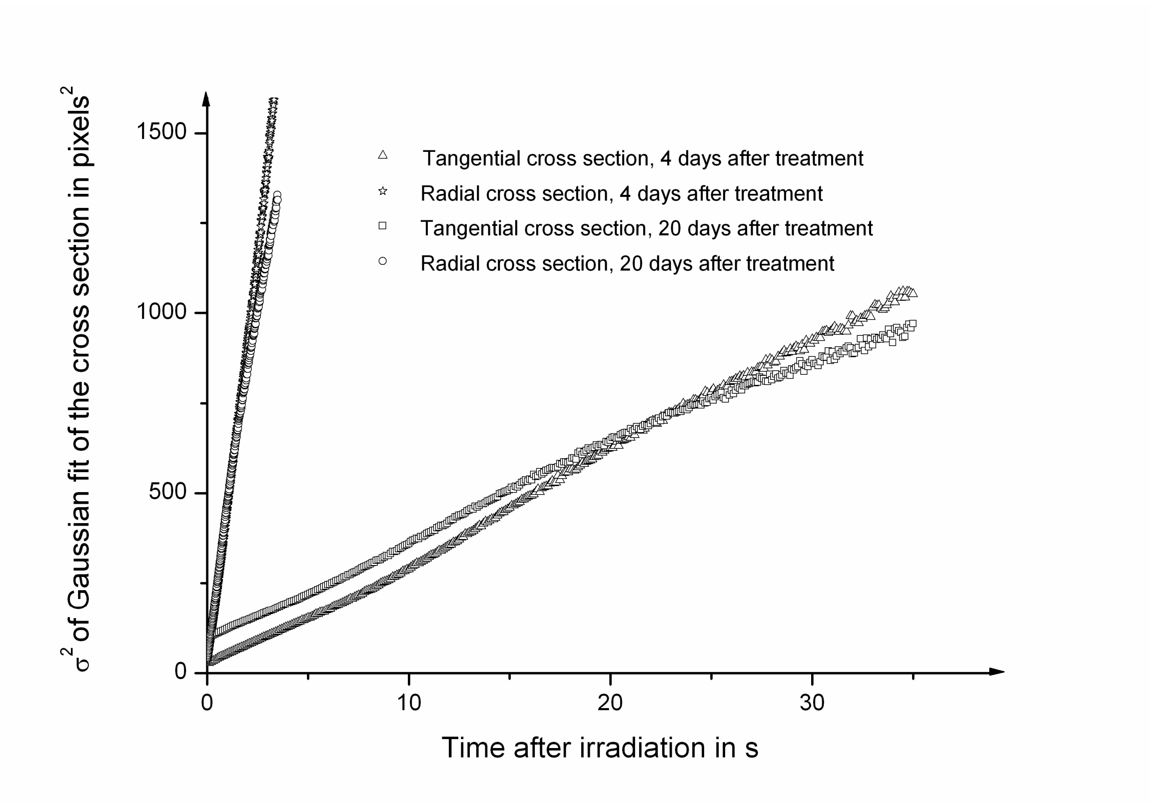

Figure 7.
σ^2-t diagram for radial and tangential cross sections at days 4 and 20 after treatment with wood preservative CC 4 %.

3.2 Investigation of water transport and determination of thermal diffusivity in sandstone

The three cross section diagrams in fig. 8 show the radiance in digits versus the position in pixels. The cross sections have been performed as indicated in fig. 2.

The parameter t in the diagrams refers with increasing index to the time of advancing water suction. At time t1, the stone was in contact with the water source for 40 s, at time t2 for 80 s and at time t3 for 140 s. The velocity of water suction was found to be approximately 0.2 mm/s. The position of the scanned laser line was reached by the water about 125 s after contact with the water source.

Diagram a) of fig. 8 shows the thermal answer of the sample 1 s before laser excitation, diagram b) during laser excitation and diagram c) shows the thermal answer of the sample 1 s after laser excitation.

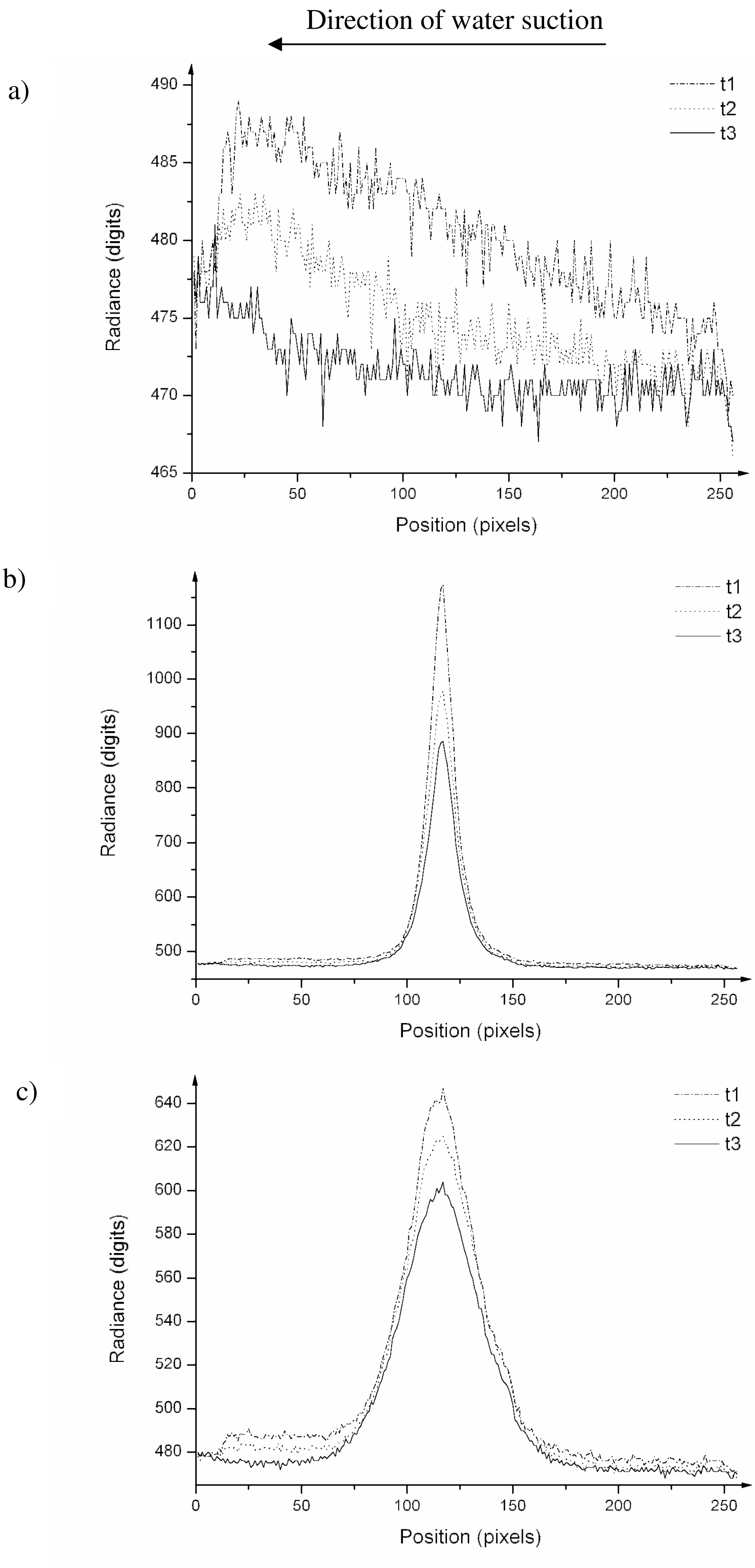

Figure 8. Results of cross sections during water suction of sandstone and laser excitation for three different times of water suction.
a) 1 s before laser heating, b) during laser heating, c) 1s after laser heating.

The following conclusions can be drawn from fig. 8:

- The lower the moisture content, the higher the radiance. This can be clearly seen in the top diagram where the line called t1 indicates the situation of beginning water suction and the t3 line the situation at advanced water suction. One reason of this behavior is certainly vaporization but different absorption could play a role as well.
- The full width at half maximum is higher for advanced moisture which indicates a higher diffusivity.

To determine the thermal diffusivity more quantitatively, a dry sample of sandstone and one with a moisture content of about 4 % by weight were excited by a short laser pulse in a second experiment. The thermal conductivity could be determined according to equations (1) and (2). Fig. 9 shows the σ^2-t diagrams for both samples

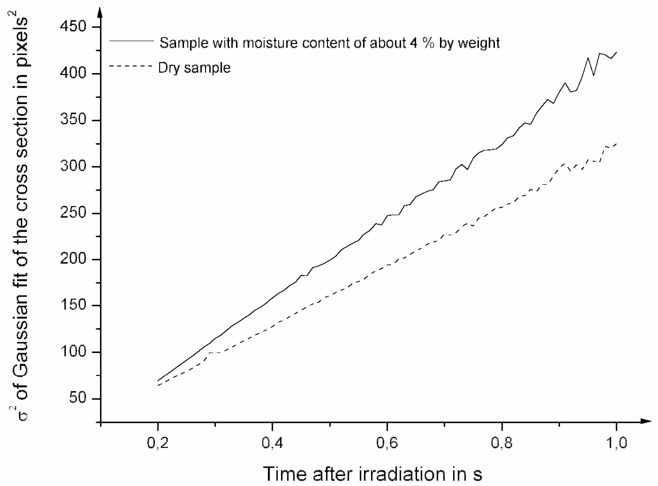

Figure 9.
σ^2-t diagram for a dry and a moist sample of Postaer sandstone.

As in the case of wood, we have used radiance values instead of temperature values for the analysis, thus the exact value of thermal diffusivity cannot be determined. However, it can be clearly seen that the thermal diffusivity is higher for the moist sample.

4. Conclusions

In this paper it has been shown that the method of laser induced active thermography is applicable to various problems concerning the assessment of building materials. We presented two different experiments:

- Pine sap wood treated with inorganic wood preservatives was investigated. Different concentrations of the preservative could be detected because of their different absorption of the laser wavelength. Moisture content had the same influence for all concentrations. Thus, if the dependence of absorption of the laser wavelength on moisture content is known for one concentration of wood preservative and the dependence of the absorption on the concentration for a certain moisture content, the presented method provides a possibility to measure the surface moisture content. Apart from that, our results show that the thermal diffusivity is higher in the radial direction of the wood sample.

- First results of laser excitation during water suction in sandstone show the applicability of the method for the investigation of water transport and content in building materials. The thermal diffusivity was shown to be higher in moist samples than in dry ones.

Acknowledgements

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