

Inline monitoring of structural quality and thermal conductivity of plastics in the hot extrusion process by means of infrared thermography

Peter Meinlschmidt, Jochen Aderhold and Friedrich Schlüter

Fraunhofer-Institute for Wood Research (WKI),
Bienroder Weg 54E, D-38108 Braunschweig

Abstract In a joint project called "Sensoren und Auswertestrategien zur autonomen Überwachung von kontinuierlichen Kunststoffprozessen" (KontiSens), the Fraunhofer Institute for Chemical Technology (ICT), the WKI, and partners from industry work on the development of sensors and evaluation strategies for the autonomous monitoring of continuous plastics production processes. The task of the WKI is to develop a monitoring technology based on infrared imaging for the production of insulating materials by hot extrusion.

Keywords: Thermography, thermal conductivity, insulating materials, image processing, hot extrusion.

1 Introduction

Hot extrusion is a widespread production process for plastics products with a cross-section which is constant lengthwise. The raw material is melted and pushed through the extrusion tool with a speed in the range of one metre per minute. Extrusion gives a very smooth surface and is able to process brittle materials such as expanded polystyrene. However, changes in the composition of the raw materials and variations in temperature and pressure can result in structural defects such as air inclusions or in an inhomogeneous distribution of material parameters such as thermal conductivity.

When the product leaves the extrusion tool, heat is dissipated by heat flows from the interior to the surfaces. The heat flow pattern in defective areas is different from that in good parts of the structure, if the defects differ in thermal conductivity and/or thermal capacity from the faultless material. This is especially true for air inclusions and density fluctuations. The different heat flows are mirrored in the temperature distribution on the product's surface. These temperature patterns and consequently the defects can be made visible with an infrared camera (thermography). Since infrared thermography is an imaging technique, many established procedures and algorithms from conventional image processing for automatic defect recognition can be adopted.

Furthermore, the thermal conductivity of the material can be characterized by means of thermography if it is subjected to a sequence of laser pulses. The laser pulses heat up the insulating material locally and generate a characteristic temperature profile. After the pulse, horizontal and vertical heat flows broaden the temperature profile and decrease its peak height.

2 Theory

The idea of thermography for structural quality control is to generate temperature differences between "good" and "bad" regions which can subsequently be detected by infrared imaging. The flow of heat in solid matter in the absence of internal heat sources is described by Fourier's law:

$$\nabla(\nabla\kappa T) = \frac{\partial T}{\partial t}$$

with the heat diffusivity κ defined by

$$\kappa = \frac{\lambda}{\rho C_{sp}}$$

where λ is the thermal conductivity, ρ the mass density, and C_{sp} the specific heat capacity. In order to have heat flows ($\nabla T \neq 0$), one needs a change of temperature in time ($\partial T/\partial t \neq 0$). A change of temperature in time can conveniently be achieved by letting cool down the material which was heated in a preceding production step (passive heat flow

thermography). The monitoring of material coming out of an extrusion machine is a typical example for this method.

For a laser beam with intensity distribution $I(x,y)$ moving in x direction at speed v with radial symmetry and diameter d , the maximum temperature in the irradiated area is given by [1]

$$T_{max} = T_0 + \frac{\epsilon}{2\lambda\pi d} \iint_A \frac{I(u,v)e^{-P_n[r-(x-u)]}}{r} du dv$$

where T_0 is the environment temperature and ϵ the absorbtivity of the material. The Peclet number P_n is defined by

$$P_n = \frac{2dv}{\kappa}$$

The dimensionless variables u and v are the coordinates x and y divided by the beam diameter. The denominator of the integrand r is given by

$$r = \sqrt{(x-u)^2 - (y-v)^2}$$

It can be easily seen that the maximum temperature is inversely proportional to the thermal conductivity. If all other parameters are kept constant, monitoring the maximum temperature is sufficient to discover any changes in thermal conductivity.

Another way to do this is to observe the evolution of temperature over time. For a Dirac pulse with specific energy Q_0 in J/m^2 , the surface temperature as a function of time is given by [2]

$$T(t) = T_0 + \frac{Q_0}{2\sqrt{\pi\kappa t}}$$

By fitting a appropriate function to the observed temporal evolution of the laser spots, κ can be obtained.

If the thermal pulse meets an interface between materials with different values of κ , the pulse is partially reflected with the reflection coefficient given by

$$R = \frac{1 - \sqrt{\frac{\kappa_2}{\kappa_1}}}{1 + \sqrt{\frac{\kappa_2}{\kappa_1}}}$$

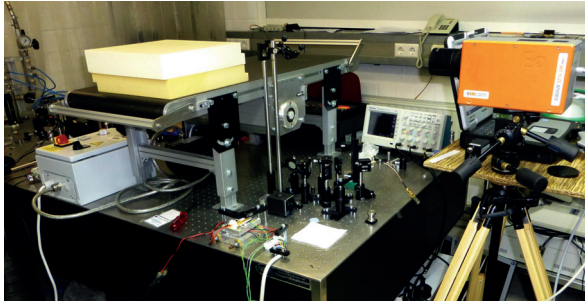


Figure 18.1: Setup used for the first experiments

This allows again for finding structural inhomogeneities in the direction of the laser beam which would change the surface temperature as a function of time in the described way.

3 Experimental

A first set of experiments was executed in co-operation with the Laser Zentrum Hannover e. V. on ready-made samples at room temperature. The aim of these experiments was to check if temperature profiles generated by laser beams can be recorded with an infrared camera and automatically extracted by image processing with sufficient precision.

In order to simulate the transport through the extrusion machine, a small conveyor belt was adjusted to have a transport velocity of 3 metres per minute. A pulsed solid state laser with a wavelength of 960 nm and a maximum power of 25 W was used to thermally excite the samples while they were moving along the laser beam on the conveyor belt. Pulse rate and spot diameter were 1 Hz and 1 cm, respectively. An infrared camera manufactured by IRCAM GmbH (Erlangen, Germany) recorded thermal images of the excited samples. In such a way, thermal signatures of up to four laser spots on the samples could be registered. The camera had an infrared detector made in InSb technology with 512 x 640 pixels with a noise equivalent detection threshold of 15 mK. It was operated at rate of 25 frames per second. The setup is illustrated in figure 18.1. The amount of heat absorbed depended strongly on the colour of the sample.



Figure 18.2: Passive thermography using the extrusion machine

A certain white material showed a temperature rise of only 2.5 K whereas some other (greenish) material was already melted in the centre of the laser spots.

A second set of experiments was carried out using the extrusion machine of Fraunhofer ICT in Pfinztal, Germany (figure 18.2). The objective was to check if structural inhomogeneities in the extruded material can be seen by passive heat flow thermography.

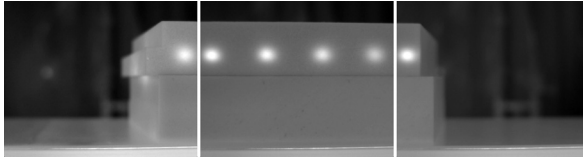


Figure 18.3: Typical infrared image from the initial, middle and final section of the series (right to left)

4 Image Processing for Data Extraction

The aim of the image processing part of the work was to write an algorithm which can extract the spatial intensity profiles of the laser spots over time automatically. This is of course necessary in the final application of the method, but even in the development stage it is not feasible to extract the information manually since every single measurement has typically more than 200 frames. For the sake of robustness, the algorithm should get as much information as possible from the image series itself. Only the following assumptions were made:

- The laser spots are brighter than their immediate surrounding, but not necessarily the brightest items in the image.
- The laser spots are moving through the field of view from left to right at constant speed and with constant distance.
- The laser spots are more or less round.

A typical infrared image series has an initial section, when the object under inspection enters the field of view, a middle section, and the final section, when the object leaves the field of view. Figure 18.3 shows one image for each section. The laser spots are clearly visible and show decreasing intensity from the left part of an image to the right part, as expected.

Of course it is much easier to identify the spots in the middle section of the series. However, in the test measurements of the development stage this section represents only a small part of the complete series. Concentrating on the middle section would thus lead to a huge loss of information. Consequently, the extraction algorithm uses the middle section in a first run to identify preliminary information of the peaks with respect to position, gray value, and size.

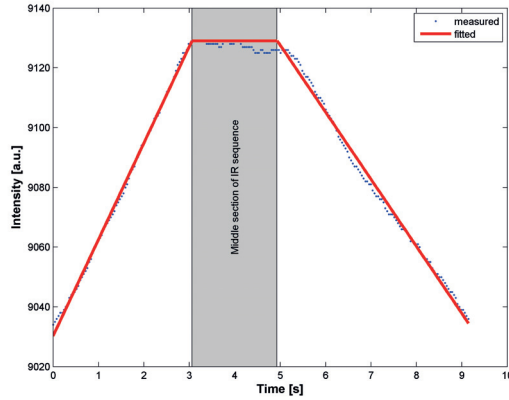


Figure 18.4: Measured and fitted mean intensities of an image series for the estimation of begin and end of the middle section

These information is then extrapolated to the complete series in order to help identifying the spots in every single image.

Thus, the first step of the work is to find the begin and the end of the middle section. For this purpose, the algorithm calculates the average intensities for the single images as a function of time. In the middle section the average intensity is more or less constant while it increases in the initial phase and decreases in the final phase. By fitting a trapezoidal function to the data, the middle section can be identified (figure 18.4). In the second step the average of the frames in the middle section over time is calculated and subtracted from the series in order to remove the background. A typical image after background removal is shown in figure 18.5. The laser spots are not averaged out completely since the number of frames is too small, but the important thing is that the intensity in the spot region oscillates over time due to the movement of the spots whereas it is constant in the rest. This can be used to identify the upper and lower boundary of the region where the spots are.

In particular, the algorithm uses the PARAFAC method to analyse the temporal behaviour of the pixels over time. PARAFAC is similar to the better known Principal Component Analysis (PCA), but calculated

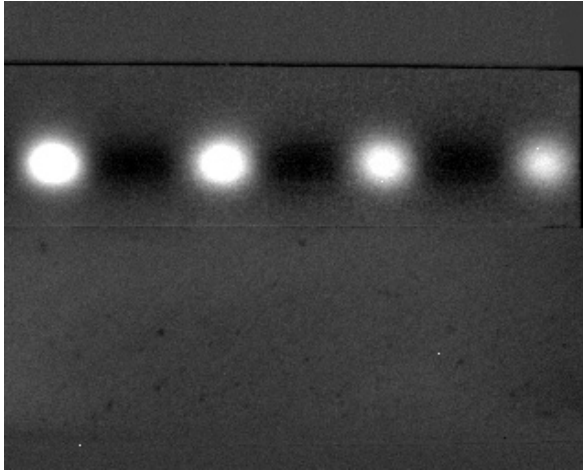


Figure 18.5: Typical image after background removal

in a different way. Whereas PCA diagonalises the covariance matrix, PARAFAC minimizes the error matrix. The result for the third component is shown in figure 18.6. The region of the moving spots is now determined by calculating the maximum of each row and fitting a Gauss profile to the result. Only this part of the image is considered in the subsequent calculations.

The next step is to segment the laser spots by a simple gray value threshold obtained by Otsu's method. In order to remove parasitic objects from the resulting binary image, elongated objects are identified and removed. After this, the image is morphologically opened, and only those objects are kept which exceed the average object size.

By this means the algorithm can find almost every peak. However, it sometimes misses a peak close to the right edge of the image and sometimes finds an object which is not a peak. This is a consequence of the decrease in spot intensity on the way through the field of view. But a simple linear fit to the estimated spot positions over time allows not only the identification of missing spots and outliers, but also calculating an individual region of interest for each single spot. Within these regions of interest, the spots can again be identified by thresholding, but with much better results due to the smaller area.

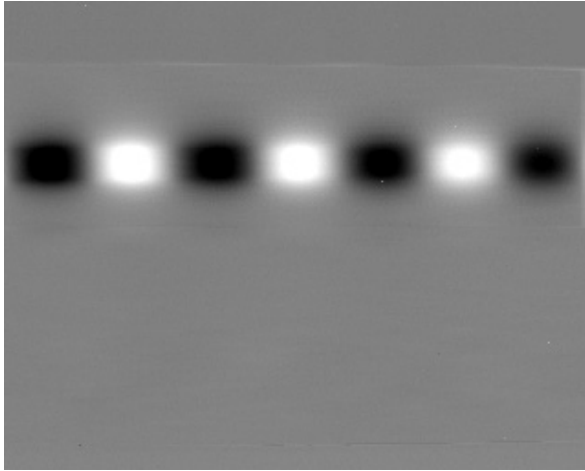


Figure 18.6: Third PARAFAC component of the time dependent intensities of each pixel

Using this methods, the spot positions within the complete series can be found and used for the final step, the extraction and storage of the two-dimensional intensity profiles around the spots.

5 Results

A typical result from passive thermography using the extrusion machine is shown in figure 18.7. The structure shown in the image is most likely due to unwanted density inhomogeneities. Figure 18.8 shows a typical intensity profile of a peak. The raw data are displayed in the left part while smoothed data are shown in the right part. Smoothing was achieved again using the PRAFAC algorithm assuming a three-dimensional model (two spatial coordinates, one time coordinate).

Peak intensities as a function of frame number are exemplarily shown in figure 18.9. It can be seen that the curves for four peaks are close to each other whereas two peaks have higher intensities. It is not yet clear if this is due to changes in heat diffusivity or in laser power.

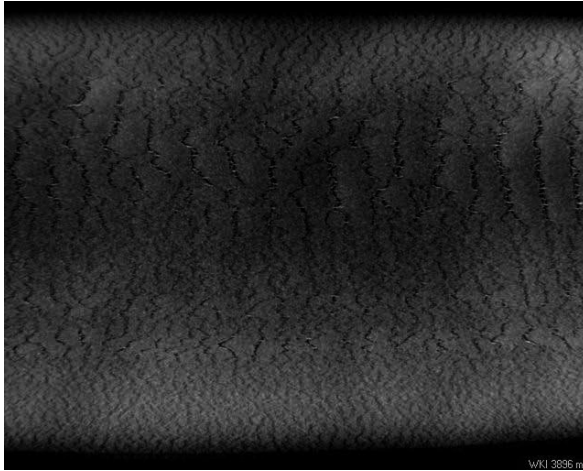


Figure 18.7: Inhomogeneities in extruded material in the infrared image

6 Summary and Conclusion

It was shown that structural inhomogeneities in extruded plastics can be found using passive heat flow thermography. Furthermore, the intensity profiles of laser induced hot spots can be recorded with infrared imaging and extracted automatically with sufficient precision. In the forthcoming phases of the project, both passive thermography and laser stimulation will be carried out inline using an extrusion machine. Furthermore, thermal properties will be measured by standard methods and compared against the results of thermal stimulation by laser.

References

1. G. R. B. E. Römer and J. Meijer, "Metal surface temperature induced by moving laser beams," *Optical and quantum electronics*, vol. 27, no. 12, pp. 1397–1406, 1994.
2. D. P. Almond and P.-M. Patel, *Photothermal Science and Techniques*. London, UK: Chapman and Hall, 1996.

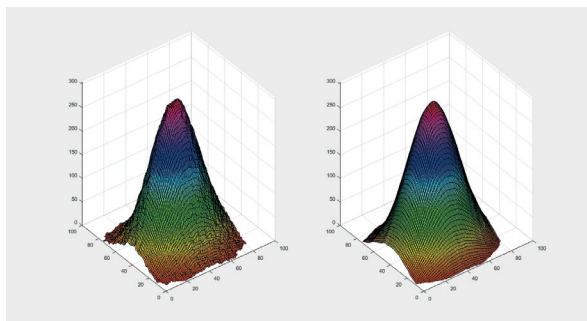


Figure 18.8: Typical peak form with raw data (left) and smoothed data (right)

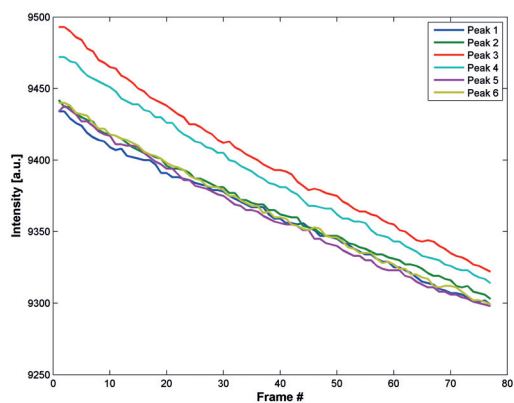


Figure 18.9: Typical peak intensities as a function of frame number