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Application of thermography to the deforming process of paper materials

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A method is described, in which infrared thermography is used to detect changes in the temperature image occurring in paper during a tensile test. Thermography has been found to be useful instead of calorimetry for detecting the local variations in surface temperature and the thermal energy transfer in paper under strain. The changes in temperature images during the course of tensile straining can facilitate the study of the local deformation process of paper.

1. Introduction

The deforming and fracturing processes of paper during straining are directly related to the mechanical strength of paper, and thus are very important for many of its practical uses. A great number of studies relating to the deforming and fracturing processes have been made from both experimental and theoretical points of views, especially on the tensile load/elongation behaviour of paper [1, 2]. Among those the thermodynamics of deformation is one of the basic subjects. A study on the energy transfer under straining of paper has been made by Ebeling [3] using a gas-filled calorimeter, in which the simultaneous mechanical work and heat phenomena during straining of the sheet-like materials were measured. The experimental results showed that the thermodynamic behaviour of paper was similar to that measured for other materials, such as metals and polymers [4] using thermocouples. That is, the initial straining of paper is mechanically and thermodynamically reversible and in accordance with Kelvin's thermoelastic equation.

Paper may be considered as a heterogeneous material at various levels of its structure [5]. Therefore, the energy and deformation changes within a specimen could be localized, at least in the plastic deformation region. Dumbleton *et al.* [6] employed a line-scanning type infrared thermal camera to follow temperature changes occurring in paper during a tensile test. It was found that the temperature increase was greater at the rupture point, although the energy dissipated throughout the specimen in a fairly uniform manner. However, no attempt has yet been made using thermography to obtain a two-dimensional temperature image of the paper specimens under strain. This method has been applied to the investigation of energy dissipation in composite materials (FRP) during fatigue loading, adding to the use of thermocouples to determine the temperature changes [7].

Recently, thermography (an infrared temperature imaging system) has been highly developed into two different methods with the help of advanced image processing technology. One is an experimental stress-analysing system based on Kelvin's thermoelastic effect [8]. Materials that are cyclically loaded undergo a reversible temperature change that is proportional to the sum of the principal stresses. The cyclical loading can give a high temperature sensivity of 0.001 °C with the help of computer processing, and finally provides a principal stress image of the material under strain. The other is multi-purpose conventional thermography [9]. The combination of advanced infrared sensing and image processing technologies makes thermography so versatile that it has various uses in non-destructive testing, from quality control to process monitoring in industrial production [10].

In the present work, the rather new technique of advanced thermography is applied to obtain a new aspect of the deformation process of paper through changes in the temperature image of the paper under strain. This paper reports the results from a preliminary investigation on the application of thermography for paper during tensile straining.

2. Experimental procedure

2.1. Materials

A commercial dry-bleached softwood kraft pulp was moderately beaten with a PFI mill under standard conditions. A handsheet was made from the pulp with a bonding agent, according to TAPPI standard procedure.

2.2. Instrumentation

The experimental arrangement used here is shown in Fig. 1. The paper specimen, carefully cut to 15 mm width by about 70 mm long, was clamped to an Instron-type machine (Shimadzu Autograph AGS-100) with a span distance of 50 mm, and was strained at a crosshead speed of 20 mm min^{-1}.

The infrared thermal imaging system used here was an Infrared Thermo Tracer 6T62 (NEC San-ei Instruments Ltd). This consists of an infrared camera cooled

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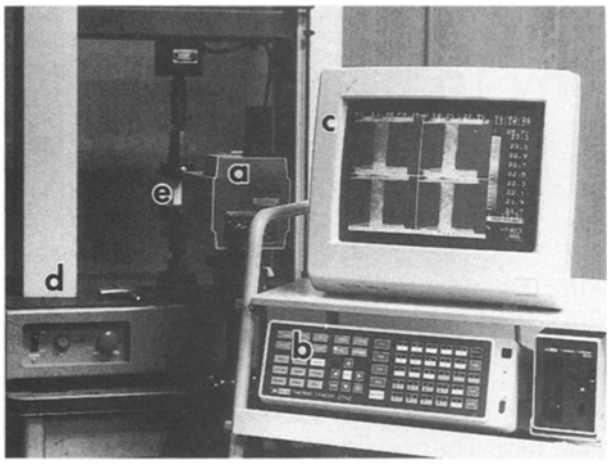

Figure 1 Infrared thermography apparatus for measuring the surface temperature of paper under strain. (a) Infrared camera, (b) control unit, (c) monitor display, (d) Instron-type machine, (e) specimen.

with liquid nitrogen, a monitoring display and a control unit with image processing function. The camera itself was positioned on a tripod about 20 cm from the specimen face. The camera contains a HgCdTe dector which is sensitive to infrared radiation in the wavelength range 8–13 μm. This device optically scans the specimen in the horizontal and vertical directions to detect infrared energy emitted from the surface of the specimen and then displays the surface temperature distribution as a colour image at a framing rate of 4 frames s^{-1}. It has a temperature difference sensivity of 0.1 °C over a scanned area of about 7 cm × 7 cm using a 2× zooming system. The temperature-imaging data were first recorded on floppy disk and then image processing of the data, such as temperature averaging in a given area and subtracting one temperature image from another temperature image, was carried out.

The temperature determination was made, assuming that the specimen was a perfect black body, namely, its emissivity was 1.0. In practice, that of paper material is considered to be about 0.9 [11]. The errors arising from this are small for the temperature differences considered and are generally less than the errors in the measurement system. They have therefore been neglected in this work.

All measurements were carried out in a testing room which was carefully conditioned at 22 °C and 65% RH.

3. Results and discussion

3.1. Temperature distribution and average temperature

Fig. 2 shows a temperature image of a handsheet under strain. Owing to the high sensitivity of the temperature difference, the thermograpy can detect a temperature difference through the handsheet tested and displays it in different hues. By means of an image processing system, an area was defined within the strained specimen and then a histogram of the temperature within the defined area and its average temperature were also provided, as shown in Fig. 2.

Changes in the average temperature of the handsheet during straining were plotted in Fig. 3 along with the load–elongation relationship. Following the start of the tensile test, the handsheet temperature began to decrease and reached a minimum at a point somewhat after the end point of the elastic region. This cooling effect is in agreement with the theory for elastic deformation of materials which has been mentioned previously [3]. After that, during the plastic deformation up to the point immediately after failure, the temperature rose quite uniformly, and then the temperature decreased.

It was impossible to perform an accurate energy balance on the system used in this study, because of some indeterminate energy transfer effects such as convection and radiation. However, it was of interest to examine the relationship between mechanical work and temperature rise to see if the observed temperature changes were reasonable. Assuming a heat capacity of 1.7 $kJ\,kg^{-1}\,°C^{-1}$ for paper of about 7% moisture content at 22 °C [12], the thermal energy involved ($kJ\,kg^{-1}$) can be calculated from the temperature rise, as shown at the right-hand side ordinate of Fig. 3. The measured thermal energy should arise from the mechanical work done during straining. In paper science, tensile energy absorption (TEA) is defined as the area under the load–elongation curve up to failure. TEA is often normalized by basis weight and is named tensile energy absorption index. The unit for this quantity is $kJ\,kg^{-1}$, which can be compared with the thermal energy measured by thermography.

The initial decrease and following increase in temperature with elongation are generally similar to the result determined with a line-scanning type infrared camera [6], and further the temperature change is essentially the same as the results measured by calorimetry [3]. However, the increase in thermal energy at the time of failure (0.8 $kJ\,kg^{-1}$) is about 55% of the mechanical energy loss during straining which was calculated as TEA index (1.4 $kJ\,kg^{-1}$). According to the experimental results of Dumbleton *et al.* [6], there is a linear relationship between the mechanical energy loss and the thermal energy determined with the line scanning type infrared camera and they are in the ratio of about 50%. Therefore, the temperature change measured by thermograpy can be used for the thermodynamic examination, although the measured temperatures are the surface temperatures of the specimen. The calorimeter for this kind of experiment was made in a laboratory [13]. On the other hand, the thermography system is commercially available, and is quite handy and convenient for measuring the temperature changes generally and locally, at least for the less thermally conductive materials such as papers and plastics.

3.2. Change in the temperature image during straining

The local deformation process of paper under straining can be identified and studied by the change in temperature images.

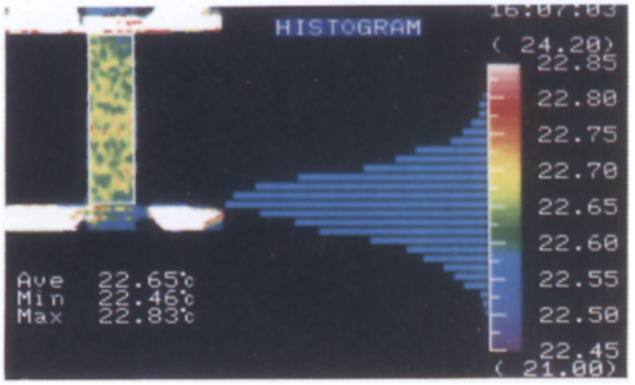

Figure 2 Temperature image of the handsheet under strain, histogram display of its temperature distribution, and calculated average temperature.

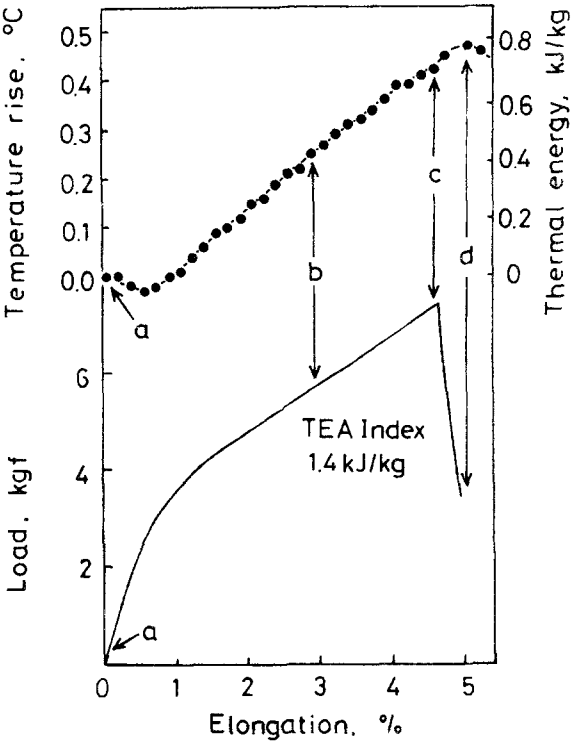

Figure 3 Change of average temperature of the handsheet under strain and the corresponding load–elongation curve.

A series of temperature images of the handsheet during straining is shown in Fig. 4a–d which correspond to positions a–d in the load/elongation relationship shown in Fig. 3. It should be carefully noted that the same hue in different figures does not mean the same temperature, thus the mid-temperature of the displayed temperature range is 22.3 °C for Fig. 4a, 22.6 °C for Fig. 4b, 22.7 °C for Fig. 4c and 22.8 °C for Fig. 4d, respectively.

Fig. 4a was recorded just after the beginning of elongation. This image was similar to that recorded before elongation. During the course of elongation the temperature image gradually changed. The temperature image at the midpoint of plastic deformation (Fig. 4b) is different from that after the beginning of elongation and is rather close to that recorded just before failure (Fig. 4c). That is, the upper part of the paper generally showed a higher temperature than the lower part (Fig. 4a) but the situation was opposite in Fig. 4b. The temperature image just after failure (Fig.

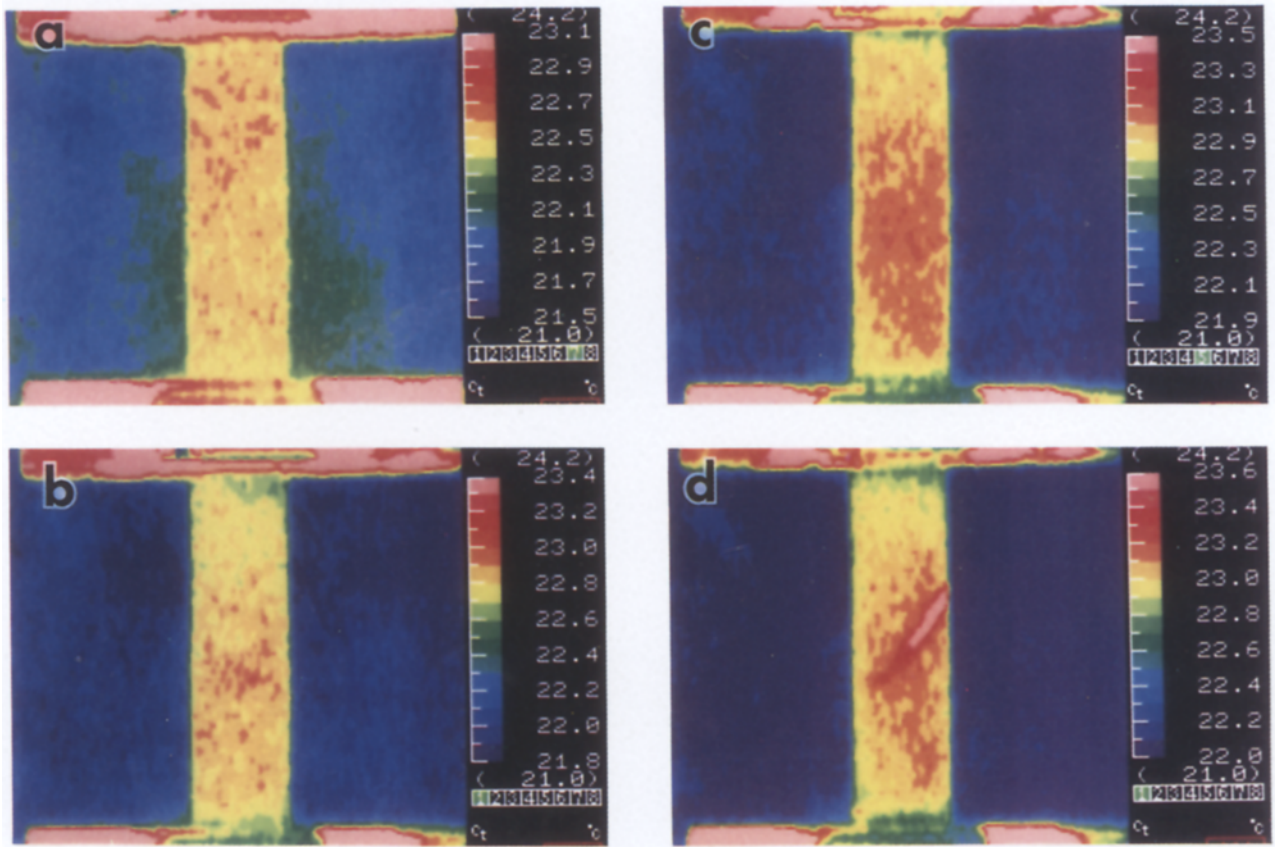

Figure 4 A series of temperature images of the handsheet under strain. (a)–(d) correspond to the positions on the load–elongation curve in Fig. 3.

4d) was similar to that just before failure (Fig. 4c) and, additionally, a high-temperature zone, which was a failure line, may be observed extending diagonally through the specimen.

In this case, the temperature image essentially changed during the early stage of plastic deformation. A great deal of further work is required to clarify whether this type of image change is common, or varies with each tensile test.

4. Conclusions

Instead of using calorimetry, thermography can be more often employed to measure the thermal energy transfer in a specimen during straining. The local deformation process of paper materials can be identified and studied through the change in temperature images during the course of elongation. The method using thermography for study of the deforming process could be applicable to other materials, such as plastics and composite materials.

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