# Experimental Detection of Entropy Elasticity Within the Plasic Deformation of Paper

## INTRODUCTION

Thermodynamics is one of the basic studies examining the deformation behavior of materials. However, not many thermodynamic studies of deformation have been published yet, because of a lack of the proper experimental method to determine thermal behavior during deformation. In the case of paper materials, Ebeling introduced a calorimetry for thermodynamic study[1] and found that an initial straining of paper accompanied the cooling of it, which was in accordance with Kelvin's thermoelastic theory. These experimental findings and interpretation were confirmed by Dumbleton et al. using an infrared camera[2] and by the authors using infrared thermography.[3,4] On the other hand, the heating of paper during the plastic region elongation was interpreted as an irreversible intrafiber deformation,[1] though the mechanism of paper heating is still not clear.

The present article is the first report of the thermodynamics of plastic deformation of paper by the use of infrared thermography. The thermal behavior of paper during the unloading after tensile loading and successive stress-relaxation periods was examined to suggest the cause of the paper heating.

## EXPERIMENTAL

### Materials

A commercial dry bleached softwood kraft pulp was beaten to CSF 350 mL with a PFI mill under standard conditions. Handsheets were made from the pulp in accordance with Tappi standard T 205. A commercially available rubber mat was used as a standard material showing entropy elasticity.

### Instrumentation

The experimental arrangement used here for tensile testing and concurrent temperature determination is shown in Figure 1. The specimen, carefully cut to 15 mm in width by about 70 mm in length, was clamped to an Instron-type testing machine (Shimadzu Autograph AGS-100) with a span distance of 50 mm and was strained at a crosshead speed of 30 mm/min for paper and 500 mm/min for rubber.

The infrared thermal imaging system used here for temperature determination was an Infrared Thermo-Tracer 6T62 (NEC San-ei Instruments, Ltd.). The temperature distribution within the specimen was obtained at a frame rate of 4 frames $s^{-1}$ and a temperature difference sensitivity of 0.1°C (Fig. 2). Temperature averaging over the whole surface of the specimen was carried out using the image processing system included in the instrument and caused a remarkable improvement of the sensivity. More details of thermography were described in the previous reports.[4,5] All measurements were carried out in a testing room that was carefully conditioned at 22°C and 65% RH without air circulation.

## RESULTS AND DISCUSSION

The paper specimen was first strained up to about 80% of the breaking load, followed by being held at the constant elongation for 1 h (stress-relaxation period) and then was destrained to zero load within 6 s. The changes of load and the average temperature of the specimen during the above-mentioned process are shown in Figure 3.

Following the start of the tensile test, the specimen temperature began to fall and reached a minimum at a point somewhat after the end point of the elastic region. After that, during the plastic region deformation, the temperature rose almost linearly. These thermal behaviors on straining are essentially the same as those described in the previous papers.[3,4]

During the period of stress relaxation, the specimen temperature becomes the surrounding temperature. The relaxation period of 1 h may be long enough for reaching temperature equilibrium.

On destraining the specimen, the temperature gradually falls, although the extent of the temperature drop is smaller than that of the temperature increase during the straining. The cooling phenomenon on destaining is well known as a characteristic behavior of rubber.[6,7] The changes of load and the average temperature of the rubber

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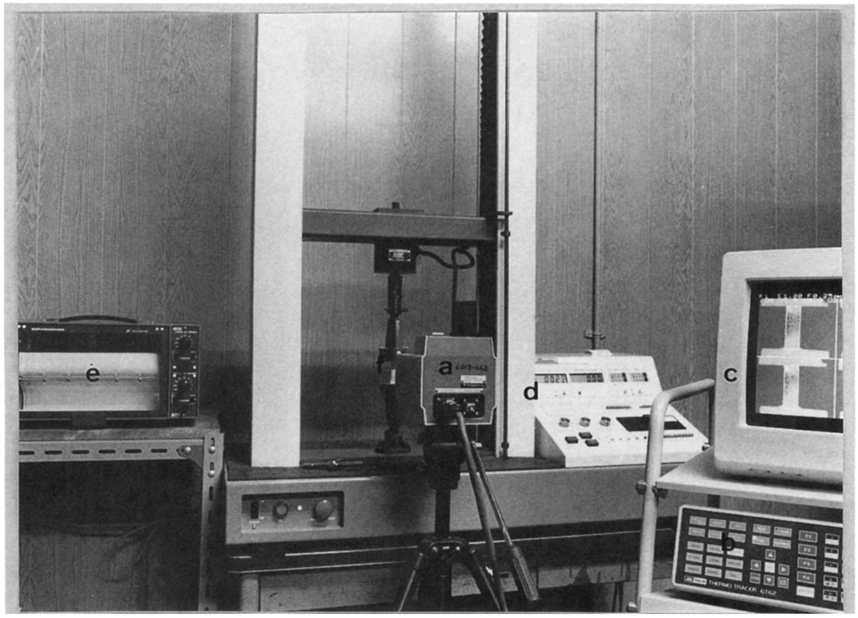


**Figure 1** Setup of thermography for measuring surface temperature of the paper specimen under strain: (a) infrared camara; (b) control unit; (c) monitor display; (d) Instron-type machine; (e) recorder; (f) paper specimen.

during the same loading process are shown in Figure 4. The temperature of the rubber expectedly increases on straining and falls on destraining.

Although the temperature falling behavior at the elastic deformation region shows energy elasticity in the elastic deformation of paper, the temperature falling behavior on destraining also showed entropy elasticity (rubber elasticity) in the plastic deformation of the paper material. The thermal detection of entropy elasticity in the plastic deformation may suggest that the heating of the paper during the plastic region straining partly arises from entropy elastic deformation.

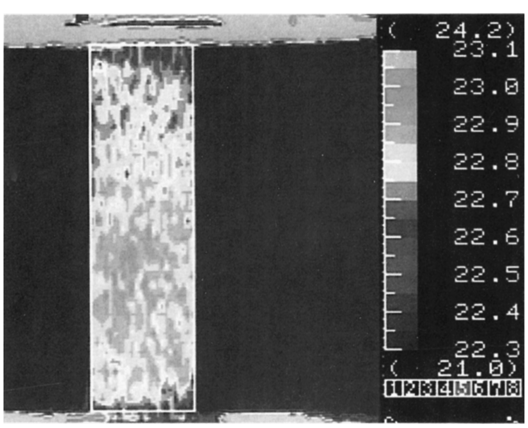


**Figure 2** An example of the temperature image of the handsheet under strain; the encircled part with the white frame shows the specimen.

## CONCLUSIONS

Thermal behavior of materials during the destraining after initial straining and stress-relaxation periods can be detected using thermography and shows whether the deformation of material tested includes entropy elasticity. The

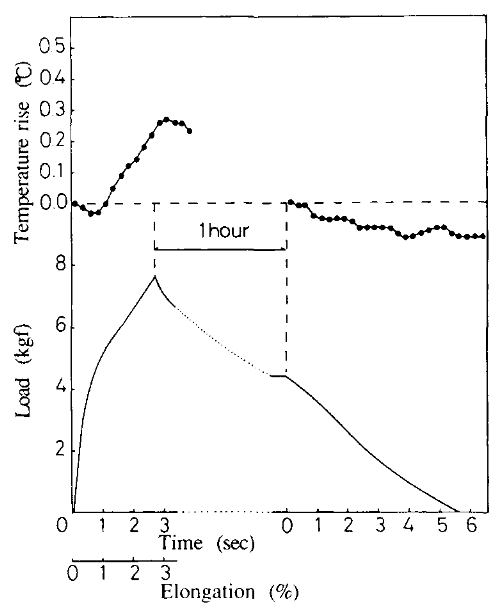


**Figure 3** Changes of load and temperature of the handsheet during the straining, stress relaxation, and destraining periods.

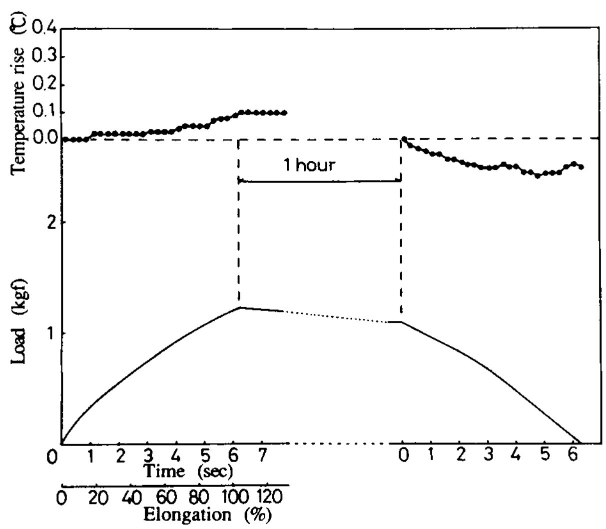


**Figure 4** Changes of load and temperature of the rubber during the straining, stress relaxation, and destraining periods.

heating accompanied by the plastic deformation of the paper sheet is partly attributed to that which came from entropy elatic deformation, although the elastic deformation is attributed to energy elastic deformation. Further experiments are currently underway to investigate the entropy elasticity in the plastic deformation of paper sheet more precisely.

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