

ABSTRACT

The temperature distribution of a paper sheet during fracture toughness testing was successively observed as a series of color images by means of an infrared thermography system with close-up lens. No stress concentration accompanied by plastic deformation occurs within the deep double-edge notched tension specimen except around notch tips. A uniformly and plastically deformed region develops from notch tips at the second half of the testing period and becomes a circular plastically deformed region on the ligament just before final sheet failure, irrespective of beating degree. A stable crack has started to grow from notch tips at latest at the point of maximum load.

Application:

The thermography is a good tool to examine the new testing methods for strength properties.

In-plane fracture toughness testing of paper using thermography

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(5, 6) employing deep double-edge notched tension (DENT) specimens of varying ligament lengths, as shown in **Fig. 1**. When such a specimen yields completely before fracture, a plastic deformation zone is supposed to be a circle area centered on the ligament (between double notches). The appearance of a circular plastic deformation region between double notches seems to be a prerequisite for this approach. Seth *et al.* confirmed the circular plastic deformation region as an increase of opacity on straining (5). However, the change of opacity is insensitive. It is difficult to follow the development of the shape of the plastic deformation zone on straining as the change of opacity. Recently thermography was successfully introduced to observe the plastic deformation of paper under loading as a series of temperature distribution images (7, 8).

In the present study, this technique is employed for observing how the stress concentrates within a paper specimen relative to the crack growth, especially around the notch tips, and how it affects further appearance and development of the circular plastic deformation zone during the in-plane fracture toughness testing.

EXPERIMENTAL

Material

Handsheets from a commercially available bleached kraft pulp were made following TAPPI Test Method T 205. Their basic properties are given in **Table I**.

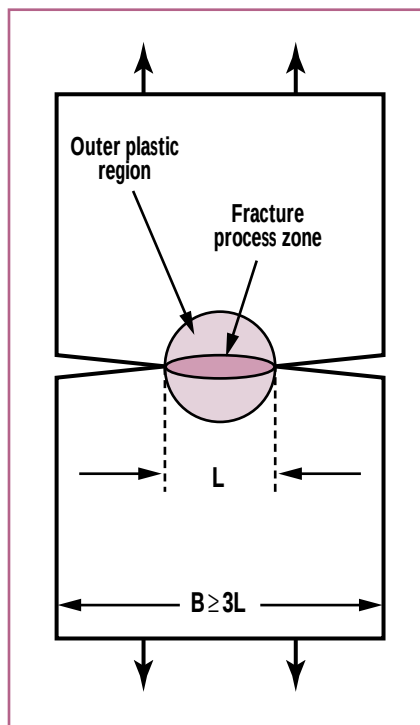
A series of DENT specimens with widths varying from 15 to 63 mm (five steps) and with length of 115 mm were prepared for the handsheets. The distance between double notches, i.e., ligament length (L), was one-third of the specimen width. Every specimen was cautiously notched with a virgin blade, using a special transparent guide bar with a scale. In order to avoid prestressing around the notch tips before testing, a rigid frame of thick plastic film was glued to the specimen at the top and bottom sides, and then the specimen and frame were set to testing clamps. The geometry of the specimen with the frame is shown in **Fig. 2a**. The right and left sides of the frame were cut by scissors just before the fracture toughness testing.

Instrumentation

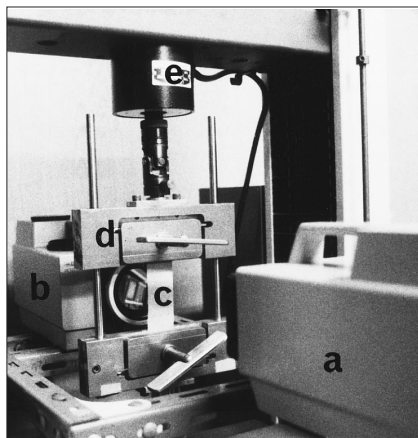
The fracture toughness testings were made with a pair of line-type clamps mounted on an Instron-type tensile testing machine (Shimadzu Autograph AGS-100) with a span distance of 100 mm and crosshead speed of 10 mm/min (5). Two sets of thermography systems were set up facing both wire and felt sides of the specimen under tension: one for observing the whole specimen and another for observing only around the notched area with a close-up lens. The experimental arrangement used here is shown in **Fig. 3**. Details of the thermography system and the experimental conditions were described in the previous reports (7-9). The minimum spot size to be detected on the temperature distrib-

THE ABILITY OF A PAPER TO RESIST cracking under tensile loading is quite important in a number of end-use situations, as well as in papermaking processes. During manufacturing, printing, and converting operations, stresses are applied in the plane of the paper sheet. In-plane fracture testing therefore is preferable to out-of-plane tearing such as the Elmen-dorf testing (1). Theories and experimental methods based on fracture mechanics have been introduced in the last two decades to understand and measure in-plane fracture toughness of paper (2). Recently "J-integral" and "essential work of fracture" approaches have been further investigated due to the elastical plasticity in the fracture of paper sheet (3, 4).

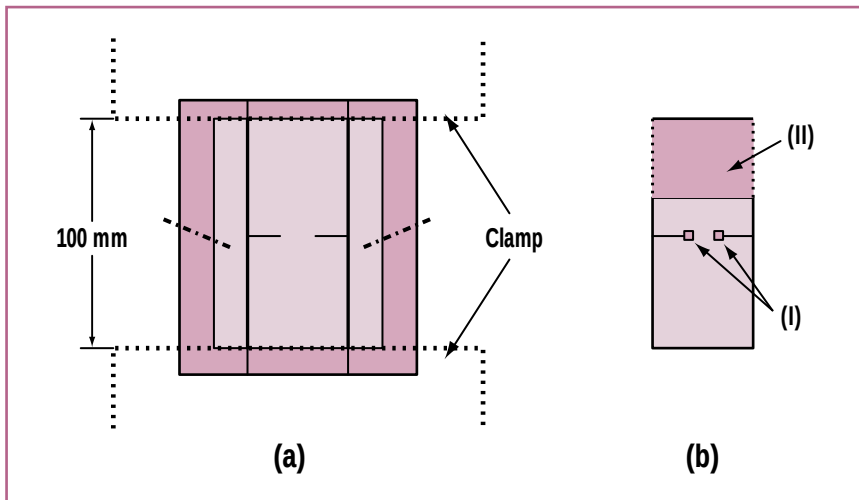
Considering the elastic-plastic fracture of paper, Seth *et al.* introduced a measurement of the "essential work of fracture" to paper sheet



1. Deep double-edge notched tension specimen for the in-plane fracture toughness testing, showing the fracture process zone and the outer plastic deformation region



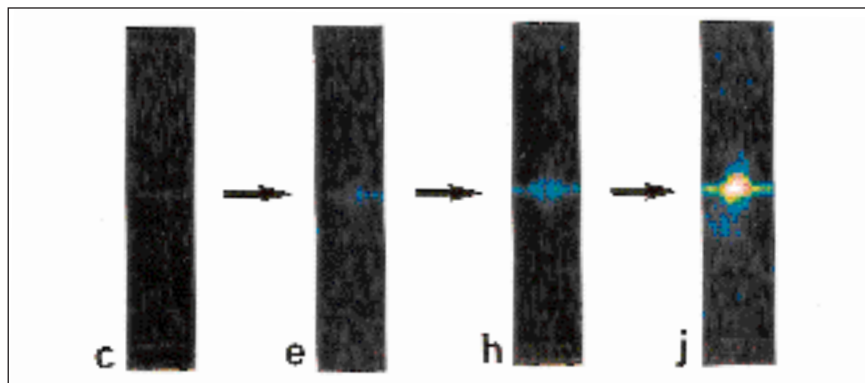
3. Experimental arrangement for the testing: (a) infrared camera for observing whole specimen (with normal lens); (b) infrared camera for observing only around notch tips (with close-up lens); (c) specimen; (d) special clamp by PAPRI-CAN; (e) Instron-type machine



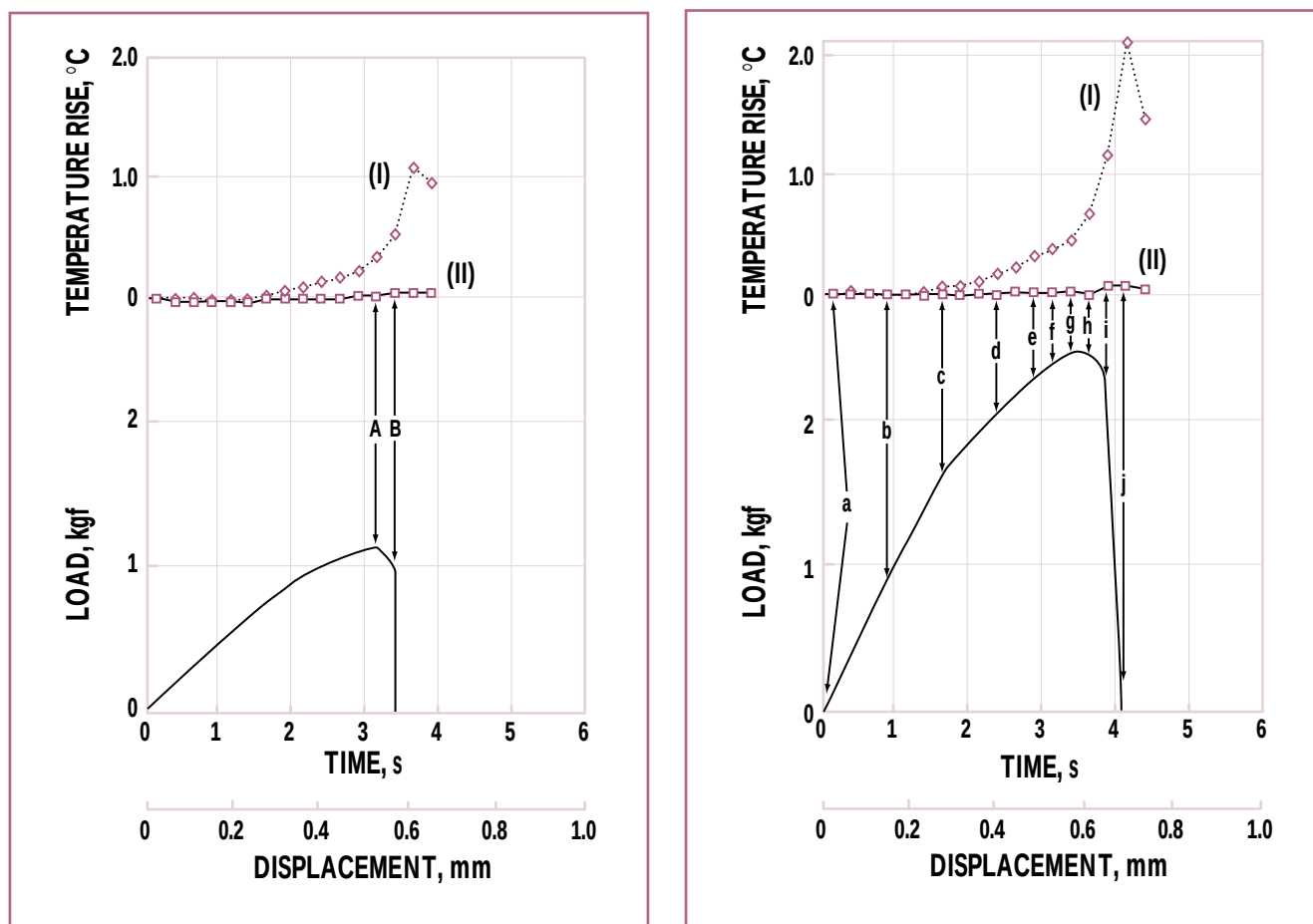
2. Specimen geometry: (a) specimen with frame; (b) two zones representing area around notch tips (I) and far from notch tips (II)

	UNBEATEN	BEATEN
PFI mill, revs.	0	3000
Freeness, ml CSF	571	516
Basis weight, g/m ²	58	59
Thickness, μm	117	84
Sheet density, kg/m ³	494	704
Tensile index, Nm/g	27.8	88.2
Elongation at failure, %	2.3	3.7
0.2% offset yield stress, Nm/g	19.2	48.6
Fracture toughness (w_e), Jm/kg	18.2	34.4

1. Basic properties of the samples



4. A series of temperature distribution images for the whole specimen during the testing for beaten pulp sheet



5. Changes of the average temperature of the zone (I) and (II) in Fig. 2b and the corresponding load-displacement curve: (a) unbeaten pulp sheet/L:5mm; (b) beaten pulp sheet/L:5mm

ution images was 0.5 mm (without close-up lens) and 0.1 mm (with close-up lens). All tests were carried out at 23°C and 50% RH after conditioning the specimens. Experimental plots between work of fracture and ligament lengths were invariably linear, as described by Seth *et al.* (5). The specific essential work of fracture (w_e) obtained was also given in Table I.

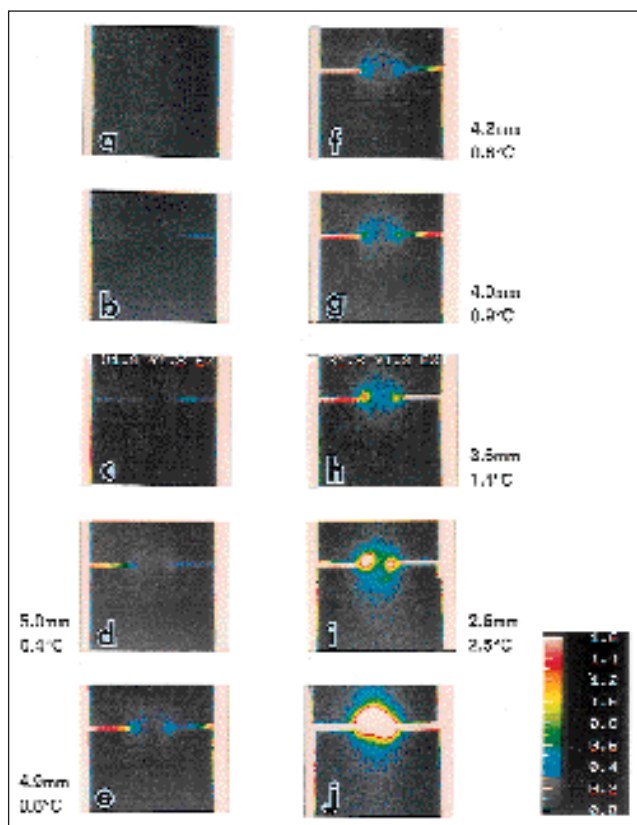
RESULTS AND DISCUSSION

Stress concentration around notch tips

For the paper sheet with notches, uneven heat generation during straining is expected, probably because of stress concentration. A series of whole temperature distribu-

tion images during the testing for beaten pulp sheet is shown in Fig. 4 and the corresponding load-displacement relations are given in Fig. 5b. All through the testing period, no thermal change was found within the sheet except around notch tips. An image processing function of the thermography, i.e., temperature averaging within a box frame, was used to determine changes in the average temperature around notch tips and far from notches during the testing. The results are shown in Fig. 5a and 5b. Two box frames, one 1.3 mm square from notch tips [zone (I) in Fig. 2b] and one 15 mm wide and 33 mm long from the upper end of the specimen [zone (II) in Fig. 2b], were chosen as representative of around

notch tips and far from notch, respectively. The temperature of zone (II) is almost constant or decreases only slightly all through the testing period except at the moment of sheet failure. On the other hand, the temperature of zone (I) increases nearly linearly during the second half of the testing period to the maximum load point and steeply increases after maximum load point. According to the previous studies on simple tensile straining, the temperature of the paper sheet decreases in the elastic deformation region and then gradually increases, with an increase of elongation in the plastic deformation region, and steeply increases further at the moment of sheet failure (7, 9).



6. A series of close-up temperature distribution images of the handsheet (beaten pulp/L:5mm); (a)–(j) correspond to the positions on the load-displacement curves in Fig. 5b. Beside each image, distances between the maximum temperature points around both notch tips are shown with temperature

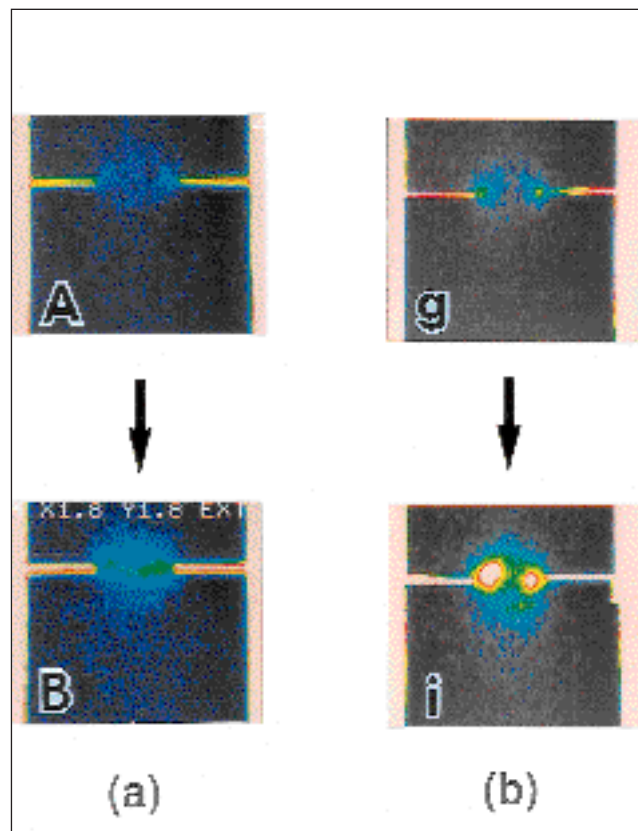
Taking into consideration these results, the constant temperature at far from notch tips implies that elastic or no deformation/loading zone occurs all over the test specimen except around notch tips during the testing, while the increase of the temperature around notch tips implies that stress concentration on these areas results in plastic deformation and crack growth. A slight movement of the maximum temperature point toward the inside during the testing is observed by the use of a close-up lens and will be discussed in the section on crack propagation.

Development of the plastic deformation zone during testing

A series of successive close-up temperature distribution images is

shown in Fig. 6 for the handsheet from beaten pulp. The corresponding load-displacement relationship is given in Fig. 5b.

In this case, halfway through the plastic deformation region, the blue colored spots whose temperature is higher than that of the surroundings appear around the notch tips (Fig. 6d, 6e). These spots spread out toward the inside, and then the enlarged spots join together just after the maximum load point (Fig. 6h). Finally, the whole shape of the amalgamated high-temperature zone becomes circular at just before failure (Fig. 6i). Judging from the spread and color, the circular zone seems to be rather uniformly and plastically deformed and therefore corre-



7. Temperature distribution images at the maximum load point (the upper) and just before sheet failure (the lower); (a) unbeaten pulp sheet/L:5mm, (b) beaten pulp sheet/L:5mm

sponds to the “circular plastic region” assumed in the “essential work of fracture method” (5).

Selected temperature distribution images for the handsheet from unbeaten pulp at the maximum load point and just before failure are shown in comparison to those from beaten pulp in Fig. 7. The corresponding load-displacement relation is given in Fig. 5a. A zone colored in purple to indicate slightly higher temperature has developed between notch tips. This zone is fairly uniformly and plastically deformed, and the shape of the zone is nearly circular at the maximum load point.

Crack propagation

While the temperature rise at the vast circular plastic deformation

KEYWORDS

Fracture, hand sheets, infrared radiation, kraft pulps, plastic deformation, stress concentration, test methods, thermography, toughness.

zone is not high, the temperature steeply rises at or around the notch tips from a little before maximum load point, as indicated by the yellow/red colored point in Fig. 6g, h for beaten pulp sheet or the temperature of zone (I) at g and h points in Fig. 5b. Even before the stage of maximum load, the point which gives maximum temperature has moved toward the inside by about 20% and the temperature rises nearly 1°C for beaten pulp sheet. Furthermore, after maximum load, the point which gives the maximum temperature has moved toward the inside by about 30% and the maximum temperature rise is 1.4°C at Fig. 6h and h point in Fig. 5b. The movement grows to about 50% and the maximum temperature rise is 2.5°C at Fig. 6i and i point in Fig. 5b. Taking into account the extent of the maximum temperature rise, the movement of the maximum temperature point before maximum load point might be a movement of center of stress concentration or growth of crack, but the movement after maximum load point must be an extending of the notch tips, i.e., stable crack growth. Further investigation is required to examine the crack growth in the period before and after maximum load point to sheet failure by means of direct observation of the notch using video-microscopy (10). When

the sheet fails, i.e., a crack instantaneously runs on ligament from notch tips, heat vigorously generates along the crack, and finally a pink-colored higher temperature zone, shaped in oval, emerges on ligament as shown in Fig. 6j.

The steep rise in the maximum temperature and the movement of the maximum temperature point are also observed for unbeaten pulp sheet, although the extent of the rise in the maximum temperature is fairly lower than that for beaten pulp sheet. The extending of the notches toward the inside after maximum load point must occur even in the unbeaten pulp sheet.

CONCLUSION

The results presented here for hand-sheets of softwood kraft pulp show that thermography with a close-up lens successfully allows the successive and detailed observation of heat generation around the notch tips during the course of in-plane fracture toughness testing. No stress concentration causing plastic deformation occurs within the test specimen except in the area around ligament. The two zones showing uniform and plastic deformation spread toward the inside from notch tips at the second half of the loading period and are attached to each other at about maximum load point. The amalgamated zone becomes circular in shape just before sheet failure and should correspond to the outer plastic region in the essential work of fracture method. A movement of the maximum temperature point toward the inside, suggesting a stable crack growth from notch tips, is found at the period after maximum load point to sheet failure. **TJ**

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