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Examination of the onset of stable crack growth under fracture toughness testing of paper

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Abstract Successive temperature distribution images around the notch tips during fracture toughness testing of paper were obtained by means of an infrared thermography system. Analysis of the images gave the critical times when the temperature significantly rose at the notch tip and when the distance between two maximum temperature spots started to decrease during the testing. Other successive microscopic images around the notch tips showed the relation between crack opening and displacement and the transitional point of the relation. The onset of stable or unstable crack growth as indicated in these critical times and the point agree with each other. For the specimen with a small width, an unstable crack starts to grow at the maximum load point without the stable crack growth period. On the other hand, a stable crack grows before the maximum load point unless the specimen width is small.The period of the stable crack growth increases with an increase in width. Differing from the methods based on thermal images to determine the onset of crack growth, the microscopic method is applicable at a wide range of strain rates and is thus suitable for quasistatic fracture toughness testing.

Key words Fracture toughness · Crack opening displacement · J integral · Crack growth · Infrared thermography

Introduction

Fracture toughness is one of the three fundamental mechanical properties of paper together with tensile strength and elastic modulus.[1] Fracture resistance based on linear elastic fracture mechanics was first invesigated for paper by Seth and Page[2] as an estimation of fracture toughness. After that the J-integral and crack tip opening displacement (CTOD) were introduced[3,4] as the useful estimation of fracture toughness of paper. They are applicable to paper materials whose plastic deformation zone size is not small enough to satisfy the small-scale yielding condition. In particular, the J-integral has been intensively investigated and was proposed as a standardized fracture toughness estimation method for paper.[5,6]

One of the most important requirements of fracture toughness testing is that it yields a toughness parameter as a true material property and is thus independent of specimen geometry. From this point of view the J-integral and CTOD at the onset of stable crack growth (J_{Ic} and $CTOD_{Ic}$) have been recognized as the most suitable fracture toughness estimation.[7] They are often called critical J-integral and CTOD (J_c and $CTOD_c$).[8] When material with a defect is strained and reaches some level of loading, a crack gradually grows from a tip of the defect with an increasing load; then fracture rapidly proceeds from the tip of crack, without additional loading. The former crack growth is called stable crack growth, and the latter crack growth is called unstable crack growth, which is occurred at and after the maximum load point.

The onset of stable crack growth must be determined precisely for a proper estimation of J_{Ic} and $CTOD_{Ic}$, however, this is one of the principal experimental difficulties in the fracture toughness testing of paper. Direct observation of the stable crack growth in fibrous material is extremely difficult. Therefore the J-integral at the onset of unstable crack growth (i.e., the maximum load point) has instead been used as J_c.[8]

Few investigators have attempted to determine either directly or indirectly the onset of stable crack growth. The indirect method developed by Choi and Thorpe includes measuring by computer.[9] Tanaka et al. pointed out that movement of the maximum temperature spots on the temperature distribution images of a paper specimen during testing might be the growth of a crack.[10] Although

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microscopic observations on a crack tip have not revealed distinctive crack growth, we propose a method to determine the onset of crack growth by analyzing the relation between crack opening and displacement. Tanaka and Yamauchi pointed that the crack started to grow before the maximum load point in a specimen with a larger width.[11] Although the acoustic emission (AE) method is expected to be a candidate technique for detection,[12] it might be difficult to distinguish the AE sounds before and after crack growth.[13]

In the present study, temperature distribution images and microscopic direct images around the notches were observed spontaneously and successively during fracture toughness testing of a deep double-edged notched tension (DENT) paper specimen. Thermographic methods that provide temperature distribution images to determine the onset of crack growth are examined in detail and are compared with the microscopic method.

Experimental

Materials

Test specimens in this study were from commercial machine-glazed paper. The basic properties in both machine and cross-machine directions are given in

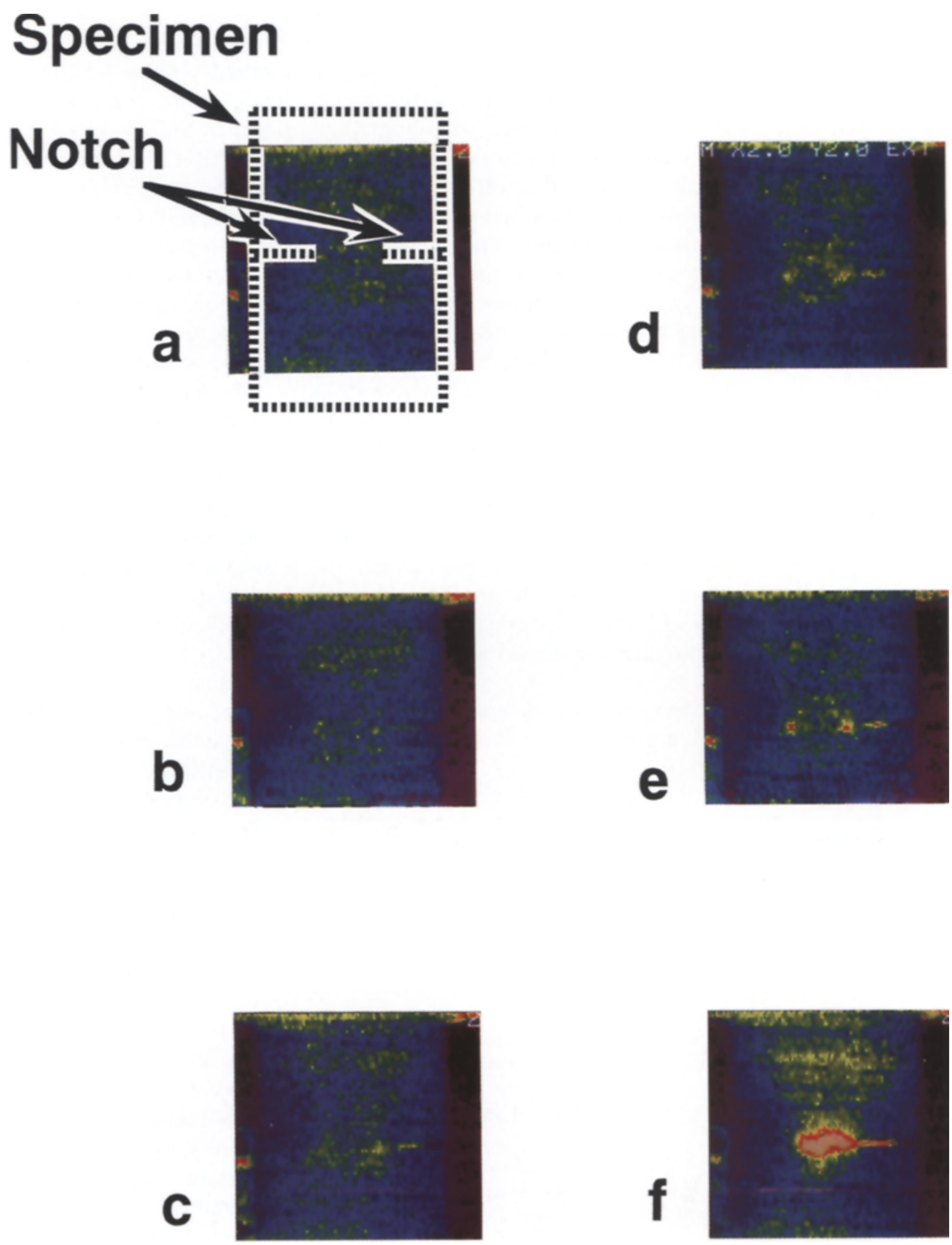

Fig. 1. Series of temperature distribution images around notch tips during the test (CD/width 63 mm); **a–f** correspond to the positions on the load-displacement curve in Fig. 2

Table 1. Basic properties of the paper sample

Property	Machine direction	Cross-machine direction
Basis weight (g/m^2)	53.7	53.7
Thickness (µm)	61.3	61.3
Sheet density (kg/m^3)	875	875
Tensile strength (MPa)	48.0	23.1
Elongation at failure (%)	1.4	2.3
0.2% Offset yield stress (MPa)	34.6	15.6
Elastic modulus (GPa)	6.9	3.3

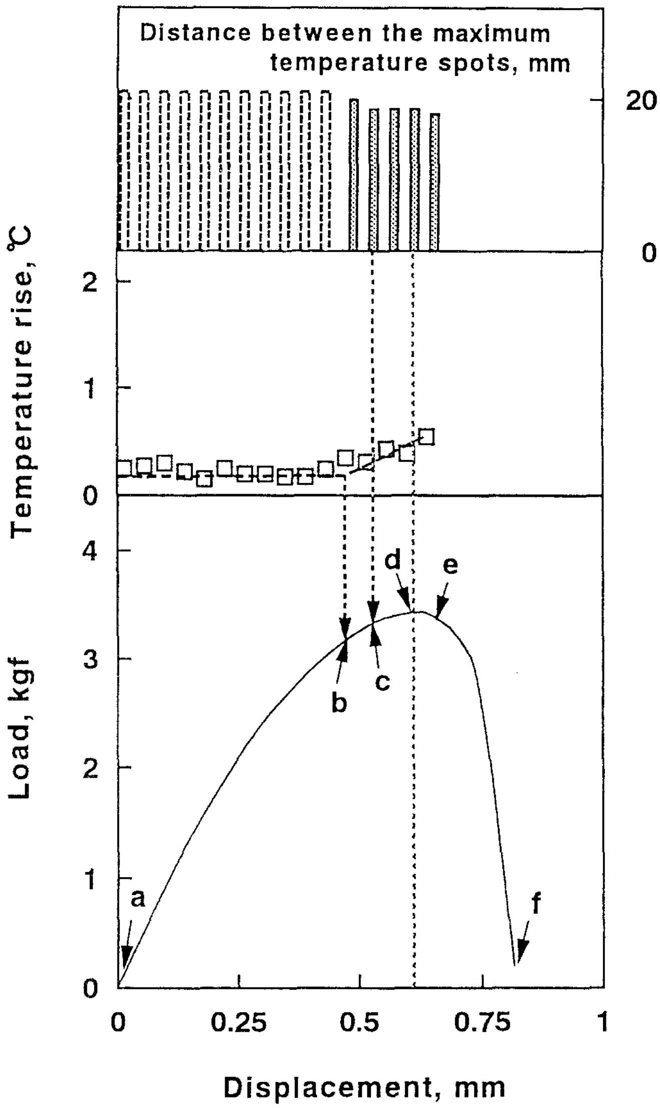

Fig. 2. Changes of temperature rise at the maximum temperature spot, the distance between two maximum temperature spots in Fig. 1, and the corresponding load-displacement curve (CD/width 63 mm)

Table 1. Extremely small spots were densely printed on the specimen for successive measurement of the crack opening displacement (COD). A series of DENT specimens with widths varying from 9 to 63 mm and with a length of 115 mm were prepared for fracture toughness testing. The notch length was one-third the specimen width for the sake of

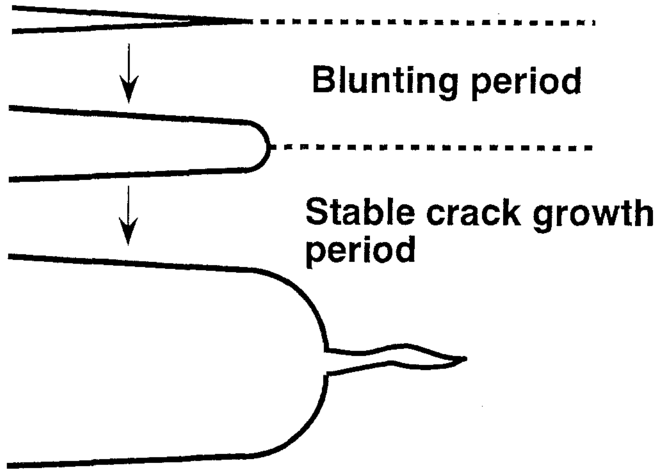

Fig. 3. Crack growth process

consistency with previous studies.[10,11] To avoid pre-stressing around the notch tips before testing, a rigid frame of thick plastic film was glued to small specimens at the top and bottom, and then the frame with the specimen was fit with testing clamps[10]

Instrumentation

The fracture toughness tests were done with a pair of line-type clamps mounted on an Instron type tensile testing machine (Shimadzu Auto-graph AGS-100) with a span distance of 100 mm and crosshead speeds of 10 and 2 mm/min. This pair of clamps were connected with guide bars, which makes plane stress loading possible.[1,10]

The thermography system (NEC-San'ei Thermo-tracer 6T62) was set up to observe the temperature distribution around the notched area. Details of the thermography system and the experimental conditions were described in previous reports.[10,14]

Direct microscopic observations of the notch tip region by means of a CCD camera with an enlarging lens system were spontaneously carried out as described in the previous report.[11]

Results and discussion

Temperature rise, inward movement of the maximum temperature spots, and application to determination of the onset of crack growth

A series of successive temperature images around the notch tips during the testing is shown in Fig. 1, and the corresponding load-displacement curve is given in Fig. 2. Throughout the testing period a temperature rise was found only around and between the notch tips.[10] Especially the temperature at the notch tips rose markedly before the maximum load point, as indicated by the appearance of greenish yellow spots in Fig. 1c. The temperature rise at the

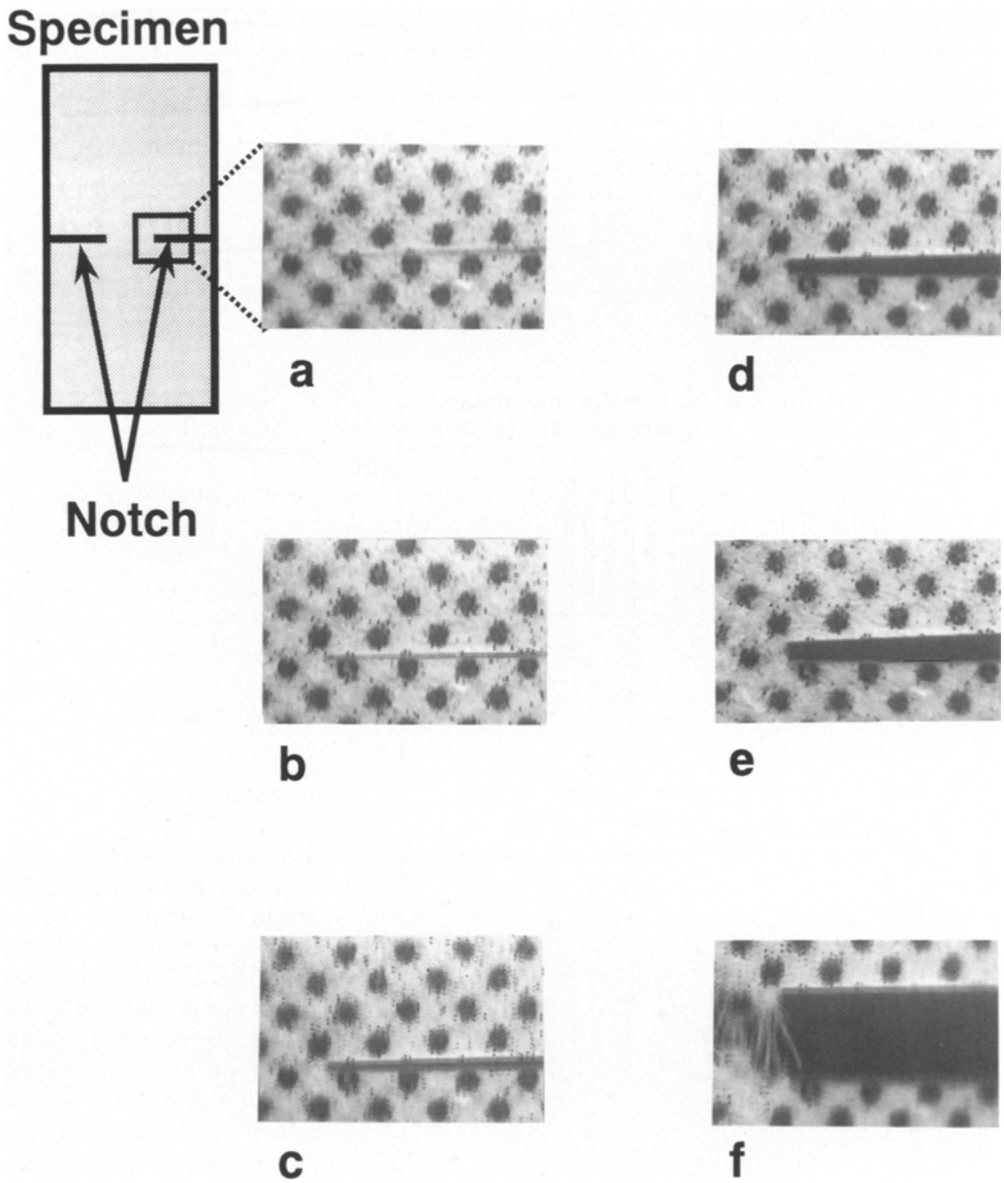

Fig. 4. Corresponding successive CCD video images during the test (CD/width 63 mm)

maximum temperature spot and the distance between two maximum temperature spots during the testing are also shown in Fig. 2. The temperature rise increases little until point "b" and then gradually increases during the testing. The start of the gradual rise at point "b" before the maximum load point ("d") could be the start of minute breakage (i.e., the onset of crack growth), as paper material shows a higher temperature rise upon breakage[14] (temperature rise method).

The distance between the two maximum temperature spots on the images cannot be determined owing to an undetectable temperature rise during the first half of testing, but the distance might be the same as the original ligament length. An inward movement of the two maximum temperature spots, which is shown as the decrease of distance even before the maximum load point in Fig. 2, also may be the crack growth.[10] In general, there is a blunting period of the notch tip, and the notch slightly proceeds prior to the start of stable crack growth (Fig. 3),[15] but the length of the blunting period is unknown. If the period is fairly long across the time when the distance starts to decrease (b in Fig. 2) (i.e., "b" point is assumed to be in the blunting period), the second point after the start of distance decrease ("c" point) is designated the onset of crack growth (distance method).

COD and its application to determining the onset of crack growth

A series of successive video images observed simultaneously with the temperature images (Fig. 1) is shown in Fig. 4, and the corresponding COD displacement relation is given in Fig. 5. According to the previous study,[11] the COD displacement relation up to the maximum load point can usually be divided into three parts: elastic deformation process, plastic deformation process without crack growth, and plastic deformation process with crack growth. The transitional point between the second and third processes, "d," is identified as the onset of crack growth (COD method).

Comparison of the methods determining the onset of crack growth

The onset of crack growth may be indicated as the load ratio (load at the onset of crack growth versus the maximum load) and is plotted against the width in Fig. 6 for all specimens. Each data point in this figure is a mean of three tests. For each method determination of the transitional point in temperature rise, distance, or COD is somewhat arbitrary. However, the variation of each point in Fig. 6 is within 1%–2%, and they are in fair agreement among three methods. Thermography methods, especially the distance method, tend to indicate a somewhat higher value. However, if the blunting period is completed by "b" point in Fig. 2, "b" point is assigned to be the onset of crack growth with the distance method, and the agreement among three methods is thus improved.

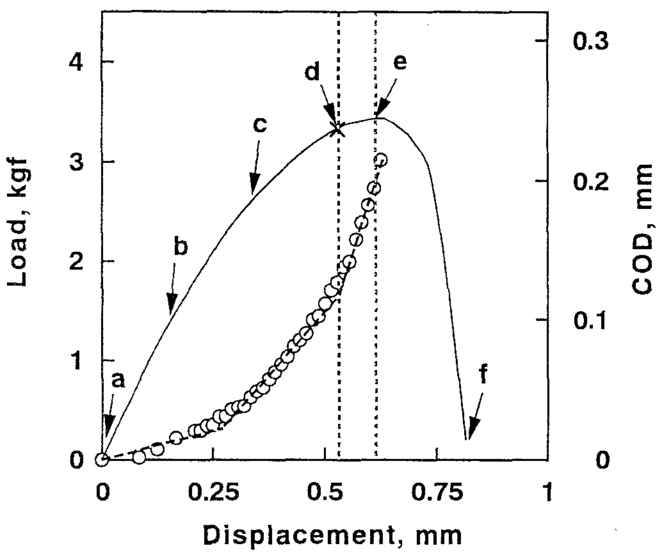

Fig. 5. Corresponding COD displacement relation with the load-displacement curve (CD/width 63 mm)

The stable crack starts to grow earlier than the maximum load point unless the width is small. Furthermore, the load ratio decreases with an increase in width, i.e., the period of the stable crack growth increases. For specimens with a small width, on the other hand, the unstable crack growth starts at the maximum load point without the stable crack growth.

Effect of strain rate on the onset of crack growth

The load ratio for all specimens was also determined using a strain rate of 2 mm/min, and the results are plotted against the width in Fig. 7. Because the temperature rise was too low to detect any difference, neither thermography method was applicable. The results using the COD method are shown in Fig. 7. For the thermography methods a higher strain rate (e.g., 10 mm/min) should be used to detect the change of temperature rise during the test, although the lowest detectable strain rate depends on the paper sample and the thermography system including the sensitivity. In contrast, the COD method is applicable at a wide range of strain rates. It can be seen that the strain rate has little

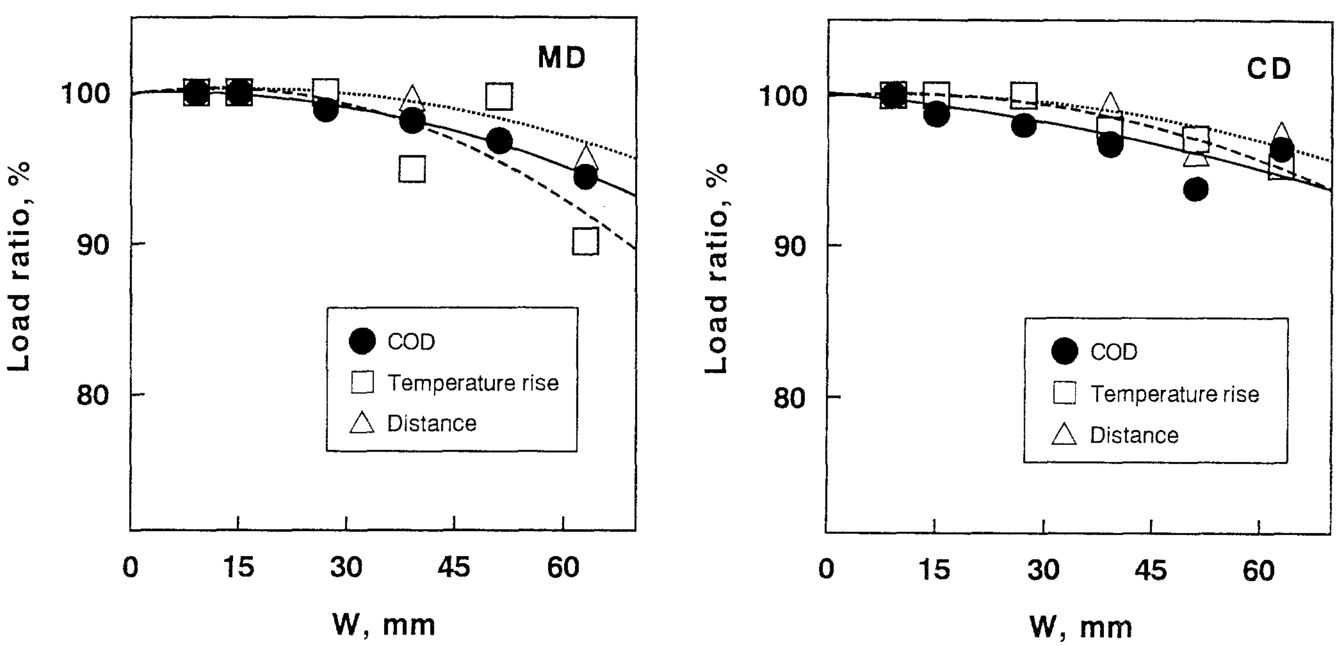

Fig. 6. Effect of specimen width on the onset of crack growth (comparison of methods)

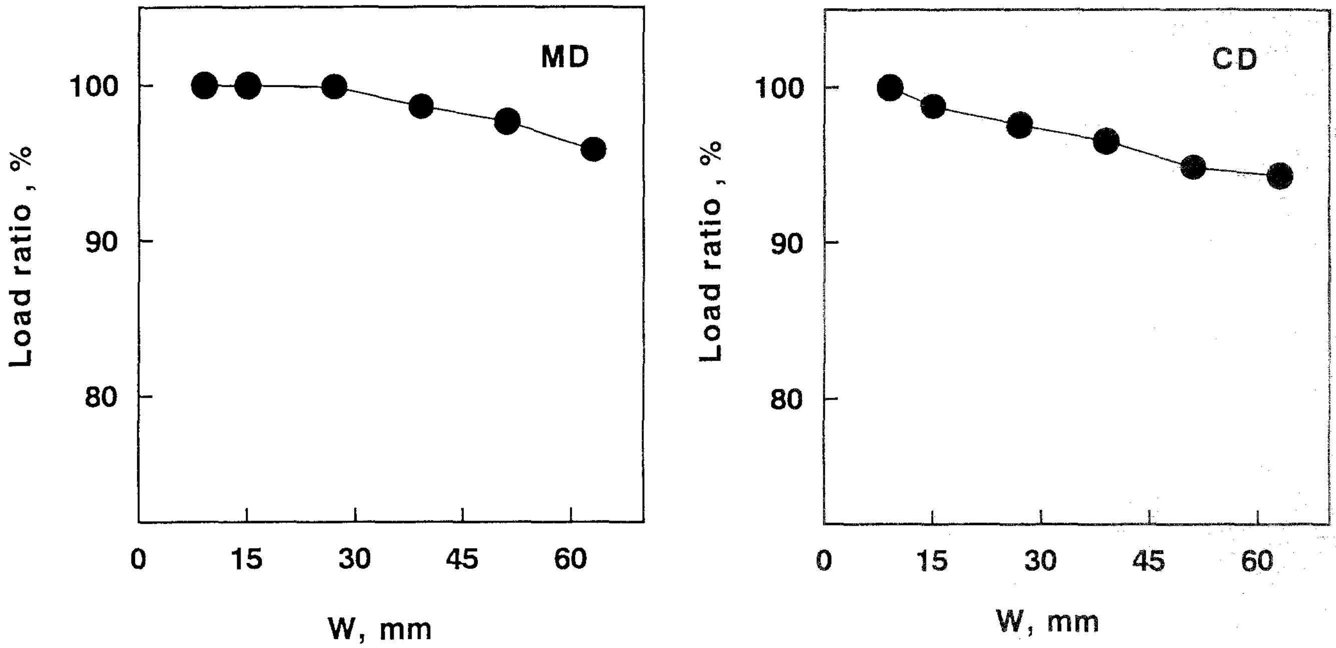

Fig. 7. Effect of specimen width on the onset of crack growth (COD method) under the strain rate of 2 mm/min. *CD*, cross-machine direction; *MD*, machine direction

influence on the onset of crack growth, at least in the range 2–10 mm/min.

Taking into consideration that fracture toughness testing should be carried out under quasistatic conditions, a strain rate of 2 mm/min is preferable to that of 10 mm/min. In the present situation the COD method is the most suitable one for determining the onset of stable or unstable crack growth under the quasistatic strain rate.

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References

1. Seth RS, Robertson AG, Mai YW, Hoffman JD (1993) Plane stress fracture toughness of paper. TAPPI J 76(2):109–116
2. Seth RS, Page DH (1975) Fracture resistance: a failure criterion for paper. TAPPI J 58(9):112–117
3. Uesaka T, Okaniwa H, Murakami K, Imamura R (1979) Tearing resistance of paper and its characterization (in Japanese). Jpn TAPPI J 33:403–409
4. Steadman R, Sloane M (1990) Fracture toughness – a paper test for the 1990's. In: Proceedings of the 44th Appita Conference, C3, pp 1–16
5. Yuhara T, Kortschot MT (1993) The J-integral as a parameter for characterising the fracture toughness of paper. In: Baker CF (ed) Transactions of the 10th Fundamental Research Symposiun held at Oxford, vol 2. PIRA International, Leatherhead, Surry, UK, pp 783/806
6. Wellmar P, Fellers C, Delhage L (1997) Fracture toughness of paper-development of a test method. Nordic Pulp Paper Res J 12(3):189–195
7. JSME Standard S-001 (1981) Standard method of test for elastic-plastic fracture toughness J_{Ic} (in Japanese). Japan Society of Mechanical Engineers
8. Yuhara T, Kortshot MT (1993) A simplified determination of the J integral for paper. J Mater Sci 28:3571–3580
9. Choi D, Thorpe JL (1992) Progressive deformation at the crack tip in paper during mode I fracture, part 1-bond paper. TAPPI J 75(10):127–134
10. Tanaka A, Otsuka Y, Yamauchi T (1997) In-plane fracture toughness testing of paper using thermography. TAPPI J 80(5): 222–226
11. Tanaka A, Yamauchi T (1997) Crack propagation of paper under fracture toughness testing. J Pack Sci Technol Jpn 6:324–332
12. Uesaka T (1983) Design for testing paper and paperboard. In: Mark RE (ed) Handbook of physical and mechanical testing of paper and paperboard, vol 1. Marcel Dekker, New York, pp 77–113
13. Yamauchi T, Okumura S, Noguchi M (1990) Acoustic emission as an aid for investigating the deformation and fracture of paper. J Pulp Paper Sci 16(2):J44–J47
14. Yamauchi T, Okumura S, Noguchi M (1993) Application of thermography to the deforming process of paper materials. J Mater Sci 28:4549–4552
15. Shiratori M, Miyoshi T, Matsushita H (1980) Computational fracture mechanics. Jitsukyo Publishing, Tokyo, p 45