Deformation Characteristics on Creasing of Paperboard Under Shallow Indentation

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Abstract

This paper reports on a fundamental deformation behavior and fracture modes of coated paperboard creased. The creasing condition was a shallow and loose indentation and the transition region on the occurrence of surface cracks under a folding test was revealed by observing the nominal shearing strain as initial crease. By reviewing the bending moment resistance, the initial gradient of bending moment as rigidity and the saturated bending moment at the crease, the correlation between the occurrence of surface cracks and the bending moment characteristics were founded.

Keywords: die creasing, paperboard, fracture mechanics, composite material, shear deformation

1. Introduction

Paperboard die cutting, which includes creasing, is wide spread in many fields such as foods, stationery packaging. For the improvement of productivity or the improvement of quality on die cutting[1,2], the estimation of endurance on die tools and the estimation of material properties on paperboard are required[3]. Creasing is one of most important mechanical behavior or processing technique for paperboard die cutting[4]. However, the working ability and the deformability of paperboard are different from isotropical elasto-plasticity such as many ductile metals and their work characteristics are complicated. Because the creasing work of paperboard includes deformation of laminates, fracture mechanics of fibers and non-linear contact forming with elasto-plasticity as anisotropy. In the past, since the creasing work was based on empirical knowledge of experts, any optimal condition of the work and the fracture mechanics in paper fibers are not almost revealed.

In this study, the uniaxial round-edge creaser and the square channel on the counter die plate was applied to determine the creasing property of a coated paperboard. The range of possible creasing states of a specified paperboard was investigated by varying the channel width of counter die and by varying the clearance between the creaser edge and the channel bottom under shallow indentation.

Mechanical properties of paperboard creased was compared in macroscopic with the strength of plain paperboard, by seeing the bending resistance of creased part. While the status of cracks at the crease was observed, the correlation between the generation frequency of surface cracks and the stroke of creasing rule was discussed by varying the channel width.

2. Experimental condition

2.1 Creasing model and working condition

When paperboard is creased, it results in a partial internal change of the material, and the permanent deformation is generated so as to obey the profile of creasing rule. The stiffness of the paperboard at the crease is substantially reduced and a hinge is created. **Figure 1** illustrates the geometrical relationship between a creasing rule, a paperboard creased, and a channel die. Since the crease part is altered mechanically by folding the paperboard, we call the first crease produced by the creasing rule as the "initial crease" for identifying the first one and the altered one, here. Although there are usually rubber fixtures adjoining to each creasing rule in commercial products, any rubber fixtures were not implemented in this experimental apparatus.

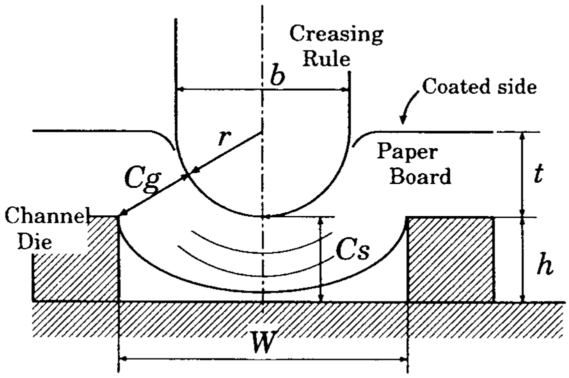


Fig.1 Creasing model and geometrical parameters

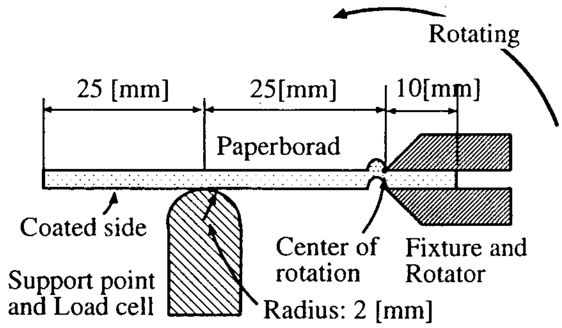


Fig.2 Schematic diagram of bending test

Nomenclature

- b: thickness of creasing rule
- r: tip radius of creasing rule
- W: width of channel die
- h: depth of channel die
- t: thickness of paperboard
- C_s: clearance on stroke direction
- C_g: groove clearance between channel edge and creasing rule $(C_g = \sqrt{(W/2)^2 + (C_s - h + r)^2} - r)$

Specification of creasing rule was as follows: thickness $b = 0.72$ [mm], height of rule = 23.1 [mm], tip radius $r = 0.364$[mm], length of rule = 40[mm]. The material of creasing rule was a steel of which the hardness was 175[HV]. The depth h and the width W of channel die were chosen as 0.5×1.5, 0.5×1.7, 0.5×1.9, 0.6×2.1, 0.6×2.3, 0.8×2.5, 0.8×2.7, and 0.8×3.0[mm], respectively. They were made by a polyester resin tip(the hardness: 120[HRC]) that was attached to a steel counter plate. The depth h is considered as $h > t$, and the width W is empirically chosen as $W \approx b + 2t$. The average thickness of specified paperboard t was 0.438[mm], while the basis weight ρ_S was 364.0 [g/m^2]. The nominal tensile strength σ_B of paperboard in the machine direction(MD) and the nominal strain corresponded ε_B were 38.14[MPa] $\times$ 2.05[%], while σ_B and ε_B in the cross direction(CD) were 15.80[MPa] $\times$ 4.72[%] (as average of five specimens, based on JIS-P8113, the cross head speed: 1 [mm/min.]). The side length and the width of paperboard specimen were 60.0[mm]$\times$40.0[mm] for the creasing test in MD and CD respectively. In this paper, when the crease line is transverse to MD, the material of paperboard is symbolized as "Transverse", and when the crease line is parallel to MD, it is symbolized as "Parallel". Here, all the specimens of paperboard were pre-processed: being kept for more than 24 hours at the room temperature 23[degree], the humidity 50[%]. The creasing test was carried out at the room temperature 20.5~22.5[degree], the humidity 39~40[%], and the cross head speed 1 [mm/min.].

2.2 Measured targets and evaluation method

The minimum stroke clearance C_s is empirically chosen as $C_s \approx h$. In this work, the variable C_s was varied from $C_s = t + h$ down to $C_s = h$, while the channel width was chosen as 1.5, 1.7, 1.9, 2.1, 2.3, 2.5, 2.7, and 3.0[mm] for the purpose of investigating the effect of groove clearance C_g and the effect of shearing deformation onto the creasing characteristics. This condition is shallow and loose indentation at the aspects of shearing deformation. By using the paperboard creased at an arbitrary C_s, the bending moment resistance M [Nm/m] of initial crease was firstly measured as shown in **Figure 2**. The hinge root of paperboard creased was cramped by the fixture and the paperboard was bended to 90 [degree] by the fixture, where the support point of the paperboard was at 25.0[mm] from the rotation center. Here, the concave surface of crease was considered to be an outside corner. From the response curve of M and the rotation angle θ, since there is usually a local maximum resistance, we have focused on the local maximum moment M_{max} and also on the initial gradient(rigidity) $dM/d\theta(= G_i)$. Three specimens were inspected for each clearance C_s.

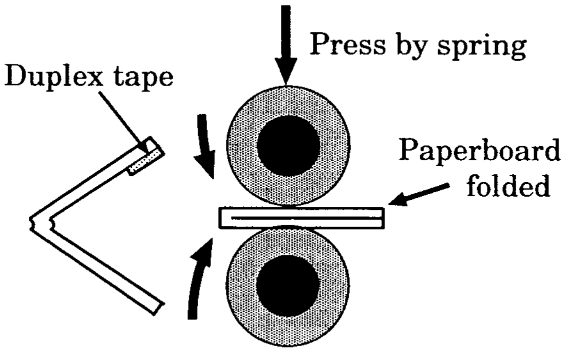


Fig.3 Schematic diagram of folding test

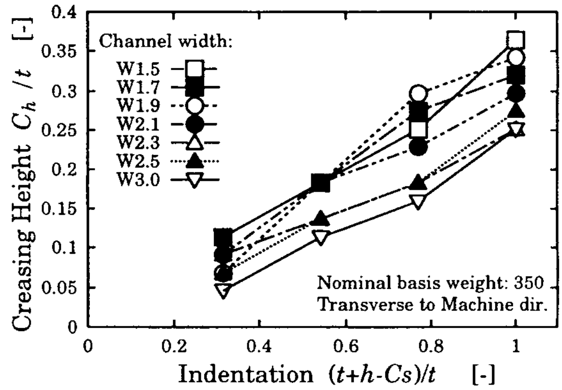


Fig.4 Creasing height and indentation of rule

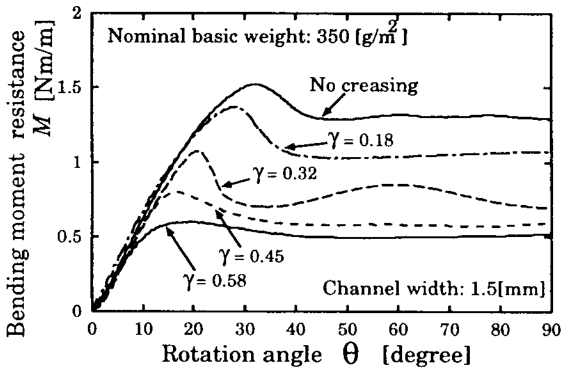


Fig.5 Relationship between rotation angle and bending moment resistance with Transverse paperboard

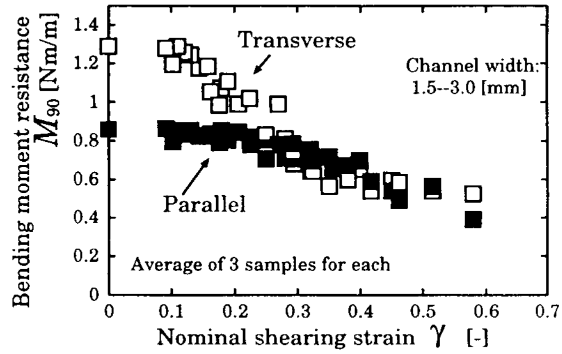


Fig.6 Effect of initial shearing strain on the saturated bending moment resistance (at θ= 90[degree])

Secondly, the paperboard was folded completely at the crease by using the two high roller shown in **Figure 3** for observing any crack generated on the surface of crease. The folding rollers were made by a hard rubber, and their diameter was 20[mm]. The pressing force 14.8[N] was applied to the folding rollers previously. After the initial creasing, the specimens were folded by hand so as to form a hinge without crushing the crease, and the both ends of paperboard were bonded by glue. By passing through the folding rollers, the crease of paperboard was crushed and a crushed hinge was completely formed. After that, the surface of crease was observed whether any cracks occur on it or not. Ten specimens were inspected for each clearance C_s respectively, and if any cracks were observed on the surface of crease, the occurrence was counted as one for each specimen. For inspecting the status of cracks, a section cut across the crease and the outer surface of the crease were observed.

3. Results of experiment

Figure 4 shows the relationship between the normalized indentation in the stroke direction $(t+h-C_s)/t$ and the normalized creasing height of initial crease C_H/t. The creasing height was measured at the convex surface, and increased with the indentation of creasing rule, almost linearly.

Figure 5 illustrates examples of the bending moment resistance at crease with Transverse paperboard. There was a local maximum M_{max} at a certain angle larger than 15[degree] and less than 30[degree] for Transverse. M_{max} becames disappeared by increasing the nominal initial shearing strain $\gamma = 2(t+h-C_s)/W$. The initial crease changes the mechanical structure and the inner state of crease. However, any cracks did not appear obviously on the outer surface of crease. For Parallel paperboard, there was also a local maximum M_{max} at a certain angle larger than 25[degree] and less than 60[degree]. The bending moment resistance with Transverse was apt to be larger than that with Parallel. This tendency is supposed to correspond to the anisotropic property of paperboard, such as the difference of σ_B. Since M is apt to be saturated at the rotation angles θ being larger than 60 [degree], the relationship between γ and M at θ= 90 [degree] was shown in **Figure 6**. The difference between Transverse and Parallel paperboard becomes disappeared as γ increasing.

By sampling M_{max} and G_i from Figure 6 and other data, the relationship between γ and the normalized bending moment resistance M_{max}/M_0 with Transverse paperboard is shown in **Figure 7**, while the relationship between γ and the normalized initial gradient G_i/G_0 is shown in **Figure 8**. Here, M_0 is M_{max} with the paperboard that was not creased initially. Similarly, G_0 is G_i with the paperboard that was not creased initially. By applying the linear normal equation to these data approximately, the coefficients of normal equations were gotten as **Table 1**.

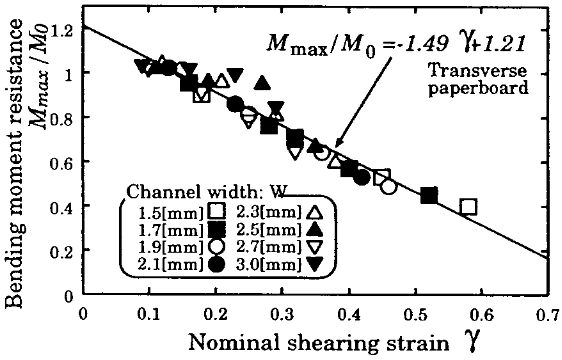


Fig.7 Effect of initial shearing strain on the bending moment resistance

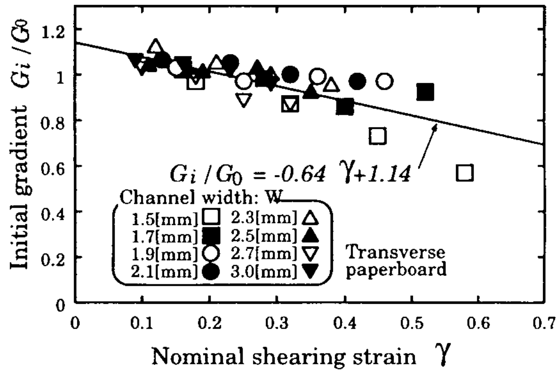


Fig.8 Effect of initial shearing strain on the rigidity of crease

$$M_{max}/M_0 = k_b\gamma + m_b \quad (1)$$
$$G_i/G_0 = k_t\gamma + g_t \quad (2)$$

Table 1 Coefficients of normal equation(1),(2)

Material	k_b	m_b	k_t	g_t
Transverse	-1.49	1.21	-0.64	1.14
Parallel	-0.71	1.08	0.14	0.91

(a) γ= 0.184 (b) γ= 0.58

Fig.9 Section of crease with Transverse paperboard after passing through folding rollers

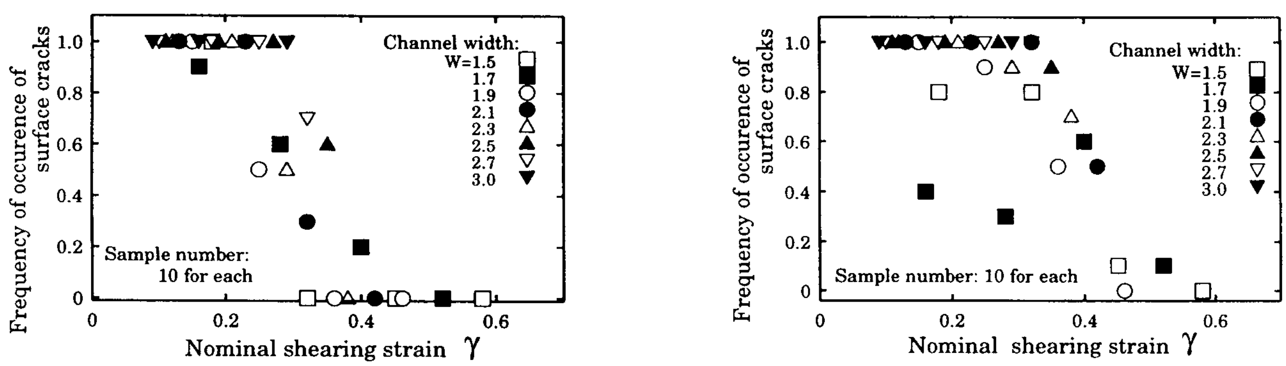
(a) γ= 0.184 (b) γ= 0.58

Fig.10 Section of crease with Parallel paperboard after passing through folding rollers

Since this approximation is for all the range of channel width W, it is clarified that the inner change of crease relies on the initial shearing deformation. According to the article[4], the clearance C_g is said to be important to decide the creasing characteristic. Observing M_{max}/M_0 and G_i/G_0 with C_g, as all the data were separated by W, to focus on the initial shearing strain is suitable arrangement in this work. From Figure 8 and Table 1, as the variation of $k_t\gamma$ is smaller than g_t, G_i/G_0 can be roughly simplified as a constant value when $\gamma < 0.58$. Although k_t was calculated as -0.64 for Transverse and calculated as +0.14 for Parallel, the latter can be understood that G_i/G_0 does not depend on γ and the plus of value includes the error measured, while the former shows slightly the dependency of γ to G_i/G_0. **Figure 9(a),(b)** show the section across the crease formed a hinge with Transverse paperboard (the indentation: $(t+h-C_s)/t=$ 1.0, 0.315, the channel width: $W=$ 1.5[mm]), and **Figure 10(a),(b)** show the one with Parallel paperboard. **Figure 11(a),(b)** show a top view of the outer surface at the crease after passing through the folding rollers ($(t+h-C_s)/t=$ 0.315, $W=$ 1.5[mm]). The depth of burst layer was roughly 0.1[mm].

(a) Transverse paperboard (b) Parallel paperboard

Fig.11 Outer surface of crease after passing through folding rollers ($\gamma=$ 0.184)



(a) (Transverse paperboard) (b) (Parallel paperboard)

Fig.12 Effect of shearing strain on the occurrence of surface cracks

The shapes of folded hinge were remarkably different from each other by varying γ as shown in Figure 9, and also they were different in Figure 10. When the indentation as initial crease is small relatively, since the inner delamination is little, the bulge of hinge becomes small for the both of Figure 9 and Figure 10. Here, Figure 9(a) and Figure 10(a) are quite different from each other, while Figure 9(b) and Figure 10(b) are almost similar profiles as formed hinge. This is supposed to be a reason why the anisotropy of bending moment resistance of paperboard disappeared with creasing in Figure 6. Namely, the bending moment resistance saturated depends on the geometrical profile of folded hinge. When the indentation is not sufficient for the inner delamination, the outer surface layer of crease is apt to be broken by folding the paperboard. This burst almost occurred at the first layer which delaminated with the thickness 0.1[mm] roughly. Since the tensile strength σ_B of paperboard in MD is larger than the one in CD, it is supposed that the initial bending strength of Transverse paperboard is apt to be larger than that of Parallel paperboard. Moreover, the inner delamination (local buckling of inner layer) of Transverse paperboard is apt to concentrate to a narrow region, while the inner delamination of Parallel paperboard is apt to be decentralized in the creased region. Namely, M_{max} depends on σ_B and the bending stiffness of paperboard.

Figure 12(a),(b) show the effect of shearing strain γ on the occurrence of surface cracks for Transverse and Parallel paperboard, respectively. From these figures, there is the critical shearing strain at which the surface cracks become increased remarkably for a certain transition region: $\gamma \approx 0.3 \sim 0.5$.

Comparing Figure 6 with Figure 12, it is supposed that there is a correlation between the occurrence of surface cracks at the crease and the convergency of saturated resistance. Namely, the hinge formed at the crease becomes changed so as to extrude the inner side layer delaminated and to reduce the surface tension stress at the outer side layer.

4. Conclusion

The characteristic of creasing for a coated paperboard, of which the nominal basis weight was $350[g/m^2]$, was investigated by varying the channel width of counter plate under the constant indentation of creasing rule. The results are summarized as follows:

1) The bending moment resistance at the crease has a correlation with the initial crease height, and also relies on the nominal shearing strain γ, while the initial gradient as rigidity is almost invariant when γ is less than 0.58.
2) The saturated bending moment resistance with Transverse paperboard differs remarkably from the one with Parallel paperboard when γ is less than 0.3.
3) The shapes of hinge formed are altered by the specified initial crease, namely the indentation of creasing rule affects to the mechanical inner change of crease or the state of delamination at crease.
4) The occurrence probability of surface cracks at crease has the transition region at $\gamma = 0.3 \sim 0.5$. Namely, when $\gamma > 0.3$, the surface cracks become disappeared and any surface cracks can not be almost observed under $\gamma > 0.5$.

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