A mechanism that applies heat and pressure for flattening paper bills in an automated teller machine

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Abstract An efficient mechanism that uses a heat roller and a pressure roller for flattening crumpled paper was developed. The mechanical properties of creased paper bills that had been exposed to tension and a heated hot-air stream were measured, and the folds in the paper bills were observed optically by laser microscope. It was found that before flattening, the fibers in the folded papers bills showed kinks. After flattening, however, the kinks remained. It was also found that applying heat strengthened the paper. Based on these results, a mechanical model for flattening crumpled paper bills was devised and tested. The numerical results of the mechanical model for flattening paper agreed well with the experimental ones. It was found that the calculated paper height from the mechanical model agrees well with the experimentally measured height, and this agreement confirms the applicability of the model.

1 Introduction
Automated teller machines (ATMs) and laser printers need to avoid paper jamming when handling paper bills and sheets because such jamming is a serious inconvenience to users. Paper bills and paper sheets jam when they collide with or make contact with the guides in the ATM or the printer mechanism. In particular, jammed bills in ATMs are a serious problem because they are sometimes ripped or cut and cannot be used again. In addition, if the paper bills are creased or folded, the frequency of jamming significantly increases. The authors therefore, developed a mechanism to smooth creased or folded papers using a heat- and- pressure roller.

2 Mechanical properties of papers
Figure 1 shows the mechanical properties (i.e. deformation-force relationship) of paper sheets during tensile tests. In these tests, four paper conditions were used: a plane sheet of paper, one with a fold, one with three folds, one with seven folds, and a randomly crumpled sheet. The directions of the fold lines are orthogonal to the direction of extension (except that of a random crumpled one), because effect of fold line is considered most effective for the mechanical behavior similar to crack lines such a fold line is considered to have the greatest effect on the mechanical behavior of the paper (similar to the effect of crack lines). Figure 1 shows three regions, a non-linear region, shown as (a), an elastic region, shown as (b), and a plastic region, shown as (c). In non-linear region (a), the paper fibers slide at hydrogen bonds. In elastic region (b), the fibers elastically extend and compress, so the slope is linear. And in plastic region (c), the fibers extend along a plasticity path and, finally, rupture. The slope in region (c) is thus not linear (Kamata and Kato, 1984).

The results for the smooth paper and those for the papers with one or more folds show no distinct differences. However, the results for the crumpled paper considerably differ from the others. This means that crumpled paper is weaker than the others.

Figure 2 shows the results of an out plane compressive test on crumpled papers. The state of crumpling is represented as a projection area reduction ratio \( \alpha \) in the figure. When \( \alpha = 5.9\% \), the compressive relationship between reaction force \( R(x) \) and deformation \( x \) is approximately described by Eq. (1).

\[
R(x) = 6.0 - 16.77 \log x
\]  

(1)

Figure 3 shows the results of stress relaxation tests on the paper samples. In the case of line (1), a paper specimen (76 \( \times \) 150 \( \times \) 0.1 mm) was stretched to 7 N, and the paper specimen was fixed and the stress decreased. The paper
specimen represented by line (2) first went through the same deformation as that in (1). It was then exposed to an air stream at 100 °C, which increased the stress. The paper specimen represented by line (3) was stretched to 12 N, and was also exposed to a 100 °C air stream. These results show that heat increases the stress on papers.

Figure 4 shows the laser micrographs of fibers in a Japanese 1000-yen bill. The laser micrograph (with a magnification of 144) shows that the line of fibers in a creased bill is kinked. After applying heat and pressure to flatten the bill, the kinks remained, even though the bill resembled a plane bill after being flattened.

3 Mechanism for flattening paper

Figure 5 shows the mechanism of applying heat and pressure. It consists of two rollers: a heat roller and a pressure roller. The heat roller contains a heat source, a halogen lamp, and a thick rubber layer, which is stable under high temperature. A certain force applied to the heat roller pressurizes the pressure roller. A sheet of crumpled paper with an initial height $X_0$ is fed into the mechanism and compressed by the heat and pressure rollers. This compression decreases the initial height $X_0$ to $X$, which means the crumpled paper is flattened.

4 Numerical and experimental results

Figure 6 shows the mechanical model of the mechanism used in the numerical analysis to find out most effective paper flattening condition. It is a very simple mass-stiffness model. The mass is represented by the mass of the pressure roller because the heat roller is fixed and rotated by a pulse motor. The equation for flattening crumpled paper with a heat roller and a pressure roller is

$$m \ddot{x} + R(x) = F$$

(2)

where $x$ is the crease height, $m$ is the mass of the pressure roller, and $F$ is the pressure force.

Figure 7 shows the experimental apparatus namely, a laser displacement measurement sensor (Keyence LB-1000) for measuring the height of the papers. In this apparatus, a sheet is set on a flat and stable stage, and a thin, light, transparent acrylic plate is placed on it. The plate has a window through which the height of the paper is measured by the laser displacement measurement sensor.

Figures 8 and 9 show the numerical results given by Eqs. (1) and (2) together with the experimental results. $\beta$ is the force parameter shown below.

$$\beta = \frac{F}{EhW}$$

(3)

where $F$ is the force of the pressure roller applied to the sheet of paper, $h$ is the nip length, $W$ is the paper width, and $E$ is the modulus of elasticity.

In experimental data, time was calculated as below.

$$t = \frac{h}{V}$$

(4)

where $h$ is the nip length and $V$ is paper feed velocity shown in Fig. 5.