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ScienceDirect
Mechanics of Materials 39 (2007) 643–663
MECHANICS OF MATERIALS
www.elsevier.com/locate/mechmat

Basic mechanisms of fluting formation and retention in paper

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Received 18 April 2006; received in revised form 20 October 2006

Abstract

Out-of-plane deformations of paper, such as fluting, significantly deteriorate the quality of a printed product. There are several explanations of fluting presented in the literature but there is no unanimously accepted theory regarding fluting formation and retention which is consistent with all field observations. This paper first reviews the existing theories and proposes a mechanism that might give an answer to most of the questions regarding fluting. The fluting formation has been considered as a post-buckling phenomenon which has been analysed with the help of the finite element method. Fluting retention has been modelled by introducing an ink layer over the paper surface with the ink stiffness estimated from experimental results. The impact of fast drying on fluting has been assessed numerically and experimentally. The result of the study suggests that fluting occurs due to small-scale hygro-strain variations, which in turn are caused by the moisture variations created during fast convection (through-air) drying. The result also showed that ink stiffening alone cannot explain the fluting amplitudes observed in practice, but that high drying temperatures promote inelastic (irreversible) deformations in paper and this may itself preserve fluting.

Keywords: Fluting; Cockling; Moisture variations; Fibre orientation

1. Introduction

Fluting of paper is a phenomenon occurring during the heatset offset printing process. It manifests itself through wavy wrinkles oriented in the length direction (machine direction, MD) of the web. It often appears on paper in connection with printing operations involving two-sided, heavy ink coverage (Fig. 1).

Fluting occurs only in web-fed, heatset offset printing. This type of printing covers most of the *higher quality* printing market. Fluting usually appears in the final product with the wavelength of 1–2 cm. Because of its appearance it seriously deteriorates the perceived printing quality.

1.1. Literature survey

Most of the articles regarding fluting were reviewed by MacPhee et al. (2000) and more recently by Kulachenko et al. (2006). Typically several topics are discussed in relations to fluting such as tension, drying temperature, presence of ink,

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0167-6636/$ - see front matter
doi:10.1016/j.mechmat.2006.10.002

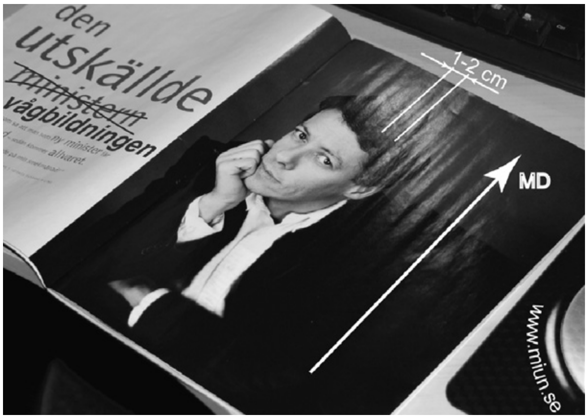

Fig. 1. A typical fluting appearance.

etc. We will present the relevant literature findings according to these topics.

1.1.1. Tension and heat

In the web-fed heatset offset printing process, the paper web is subjected to tension. Ink and sometimes water is applied onto the paper web in the printing stations and then dried in the dryer. It is unanimously supported that both tension and heat are required to create fluting (MacPhee et al., 2000). Paper may wrinkle by tension only but it was noted that applying heat, in addition to tension, creates a sharper and narrower fluting pattern than tension alone (Hung, 1984). On the other hand, upon applying heat only, the out-of-plane distortions of paper do not have the wavy fluting appearance (Strong, 1984a,b).

The web tension in the dryer usually varies from 250 to 500 N/m (Falter and Schmitt, 1987). Hung (1984) showed that a thin web may experience fluting upon high intensity drying even at a low tension (100 N/m and less). Falter and Schmitt (1987) reported that the web tension could not practically be decreased to the level where the fluting is acceptable.

The effects of web tension on fluting are not clear from the literature. Higher tension is often found to worsen fluting but for some papers, application of very high tension (900 N/m) produced less fluting (Strong, 1984a). Within a limited range of change in tension (a 17% decrease) no discernible effect was observed on fluting amplitude (MacPhee et al., 2000).

Fluting appears in the final product if web is heated to a certain high temperature (Mochizuki and Aoyama, 1981; MacPhee et al., 2000) or when air impingement velocity reaches a threshold limit (Mochizuki and Aoyama, 1981). However the effects of dryer configuration reported in the literature are not consistent. Strong (1984b) reported that press dryer configuration does not affect fluting (three manufactures, all lengths, including direct flame and high velocity hot air, were tested). Contrarily, MacPhee et al. (2000) found that open flame (impingement) dryers generally did not have a fluting problem. It may be interpreted that printing presses equipped with such open flame dryers are usually run at lower speeds and with moderate drying rates. However, Strong (1984b) did not find the web velocity to be a fluting factor. MacPhee et al. (2000) reported that longer residence time in the dryer resulted in an increase in fluting amplitudes.

Summarizing this subsection, we may say that the effect of tension and the drying method on fluting has not been clarified in the literature.

1.1.2. Moisture

Paper may take up and lose moisture during the printing process causing considerable hygro-expansion or shrinkage in paper.

During *printing*, MacPhee et al. (2000) found that the amount of moisture applied has negligible effect on fluting amplitudes. Printing with waterless plates and inks still caused fluting, in some cases even worse fluting.

During *drying*, Strong (1984a,b) did not find any relation between moisture loss and fluting. The moisture after printing varied from 0.1% to 5.4%. Measurements done by Falter and Schmitt (1987) showed that moisture can be completely lost from the paper during convection drying. The measured moisture content after the dryer was as low as 0.3%.

Contrary to what is shown in Strong's study (1984a,b), MacPhee et al. (2000) showed that fluting amplitudes *decreased* by one third as the level of moisture in the paper before printing was reduced from 5% to 2.5%. Mochizuki and Aoyama (1982) reported that increasing recycling of air used in the convection dryer gave an improvement. It was attributed to decreased water evaporation from the paper.

Waech and Sze (1996) found that the fluting tendency is largely a function of the paper coating formulation: less absorbent coating flutes less. (However, it was noted that in spite of decreasing ink absorption, calendering (smoothing the paper surface by compression) increased fluting tendency,