On Folding of Coated Papers

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Abstract

The mechanical behaviour of coated papers during folding has been investigated. This problem has been studied with experimental techniques and numerical analyses in order to give a better understanding of the folding properties of coated papers pertinent to the mechanical behaviour in general, and particularly cracking along the fold.

A microscopy investigation has been performed. The surface of the folded paper has been carefully examined to study the event of fracture and related issues. The influence of the grammage on the cracking event has been studied and it was shown that the coating material would not fail if the paper sample was sufficiently thin. It was found that a stress or strain based criterion is sufficient to describe the cracking of the coating layers and that the anisotropy of paper should be taken into account when studying the folding process.

The finite element method has been used for the numerical analyses remembering that the geometry of the problem is rather complicated, excluding a solution in analytical form. Using different constitutive models for the base stock, it has been shown that the deformation of the coated paper during folding is much governed by the paper substrate. The numerical results also suggested that particular forms of plastic anisotropy can substantially reduce the maximum strain levels in the coating. Furthermore, it has also been shown that delamination buckling, in the present circumstances, has a very small influence on the strain levels in the coating layer subjected to high tensile loading.

Dynamic effects have also been studied and it has been shown that a quasi-static analysis of the problem is sufficient in order to describe many of the important features related to cracking. An attempt to model strong anisotropy of paper has been presented and the results indicate that the large anisotropy in the thickness direction of coated papers needs to be taken into account in order to fully understand the mechanics of folding.

Finally, an experimental investigation has been presented in order to study if important mechanical properties of the coating material could be determined by microindentation techniques. The results presented indicate that microindentation can be a powerful tool for characterization of these materials, but only if careful efforts are made in order to account for the influence from plasticity as well as from boundary effects.

KEYWORDS: folding, coated papers, finite element method, cracking, indentation, anisotropy, plasticity.
Dissertation

This dissertation contains a summary and the following appended papers:

Paper I


Paper II


Paper III


Paper IV


Paper V

On Folding of Coated Papers

1. Basic concepts of folding

The aim of printing is the reproduction of an original with the best quality and price available. The choice of paper is a crucial step in the long production chain. The requirements of higher and higher print quality often lead to the choice of coated paper, which offers a better surface quality and can reproduce a larger colour space than uncoated paper. Nevertheless, the choice of a high quality printing surface can also introduce problems at the end of the production chain, during finishing and especially during the folding process.

The objective of the folding step is to convert a sheet of printed paper into a form that can be handled directly, or accumulated, to undergo a further finishing process. The finished product can be a brochure presenting a revolutionary product, an instruction manual for a technical device or even a city map. In all cases, the product must have an appealing appearance for the customer. This can be done during the folding process by using different fold types. The most common ones are presented in Fig. 1.

Modern folding machines use two different methods for the finishing of printed products; these are called knife folding and pocket folding. Nowadays, combination folders are also used, enabling the advantages of each method. The main difference between the two methods is how the paper is fed between two rotating rolls, see Fig. 2. Knife folders are popular for the folding of papers with higher basis weights. Pocket folders can handle sheets more rapidly as their speed is not bounded to the mechanical movement of a knife. Pocket folding is also quiet popular when several folds are required for the same sheet.
The folding machines available today combine in a smart way the advantages of each method. Several pockets are used for the same sheet, allowing multiple parallel folds, and an optional knife unit can be coupled to the pocket unit to also cross-fold the product in one pass.

![Knife and pocket folding](image)

Depending on the paper quality and also the folder, cracks at the folding line may occur, as shown in Fig. 3. Coloured areas are often printed over the fold, and make the cracked area more visible.

![Cracks observed in the upper coating layer after folding](image)

The cracks are the result of the high mechanical loading that appears during the folding process. In short, the outer layer is subjected to tensile stresses, while the inside of the fold is compressed. These cracks, that appear as a white line along the fold, result in a loss of product quality and it is most of the time unacceptable. Unfortunately, coated papers are more sensitive to this kind of problem than uncoated papers.
From the point of view of the papermaker, any paper that can be folded without cracking has a significant performance advantage because it will avoid expensive loss claims that might arise from customers. Thus, it is quite natural to investigate in detail the formation of these cracks in order to prevent their initiation, or at least to make them as small as possible, and hence invisible from a practical point of view. However, it should also be pointed out that this problem is often more an aesthetic one than a mechanical one in the digital printing industry. This is so because of the high quality papers used; the paper itself will not break, but the coating layer will and the final product will look bad!

The present study is oriented towards understanding the crack formation during the folding process of coated papers. As digital printing is of interest, the investigation below is limited to coated papers. The creasing process (which is required when grammage becomes high) is not accounted for, as this operation adds a supplementary cost that is, preferably, to be avoided, and remembering that this study is focused on (but not limited to) papers having a grammage of about 100 g/m².

2. Previous investigations

Franklin [1] was, perhaps, the first to tackle the folding problem in 1970. Furthermore, Carlsson et al. [2] studied and modelled the similar creasing process using numerical methods. Nevertheless, very little is known about this problem in relation to digital printing, although the phenomenon is so common that the most frequent and least productive remedy has, until very recently, been to fold by hand (Lindblom [3]). Failure at folding has been studied for paperboard and LWC papers. Two different mechanisms have been identified: the folding operation of paperboard relies on the ability of the board to internally delaminate in order to enable the relief of the compressive forces generated on the inside of the fold. For LWC papers, observation of the creased region (the cracked line due to the folding operation) under a microscope reveals that the coating on each side of the sheet is cracked along the line of the fold, and that the difference in quality between different papers is controlled by the state of the basepaper. In low strength paper, fibres in the creased region have been ruptured and bonds between adjacent fibres broken, but in paper of satisfactory quality fibres are intact and have merely been bent over. Guyot et al. [4] proposed a classification with four different kinds of behaviour for coated papers depending on the degree of damage after folding. It should be noted that all these analyses focus on the residual strength of the coated papers after folding. Another approach is to evaluate with subjective methods the range of the damage. The work by Eklund et al. [5] is situated between a mechanical and a subjective analysis. The damage is evaluated by scanning the outer surface and evaluating optically the range of damage.
3. Coated paper: a complex material

Coated papers can be regarded as a three-layered composite material or a sandwich structure (Hagen et al. [6]) composed of a paper sheet as the middle layer with porous outer layers of a highly mineral-filled latex polymer on both sides. A typical thickness for a coated paper used in digital printing is 0.10 to 0.15 mm with the total thickness of the coating layers accounting for approximately 10% of the sheet thickness, see Fig. 4.

![Coated paper and the simplified composite model](image)

Fig. 4. Coated paper and the simplified composite model.

A mechanical analysis of the folding of coated papers relies on an adequate representation of the process, but also on the mechanical behaviour of the material. It is therefore a necessity to characterize the coating layers and the base stock in a satisfying way to derive usable results and obtain reliable facts about the folding process.

3.1 The coating layer

Due to the fact that the coating is very thin, material characterization becomes an issue of some difficulty during a mechanical investigation of coated papers. This is especially so as uniaxial tensile testing is not a simple and reliable alternative for these types of materials, cf. e.g. Löffler [7]. As an alternative to traditional testing, indentation or hardness testing is nowadays frequently used for material characterization. In the present study, an experimental analysis using indentation technique is presented in Paper V. This study investigates if the indentation technique can be applied to determine the elastic properties of paper coatings. Indentation tests have been performed on different thin films of coating materials. The setup used is described in Fig. 5. Basically, the displacement of the indenter is measured continuously using two induction gages while the load is recorded with a load cell. From the load/displacement curve, elastic parameters can be deduced.
Indentation must be performed on single films of coating materials as otherwise the experimental results will be strongly influenced by the mechanical behaviour of the paper sheet. The microstructure of the coating materials must be investigated prior to indentation in order to ensure that isotropic material behaviour can be expected. Anisotropy will strongly reduce the accuracy of the proposed procedure. Plastic effects, as well as the influence from the finite thickness of the films, must be accounted for when interpreting the experimental results and this can be achieved by the use of numerical simulations based on the finite element method. In addition, both these effects can be reduced by using as thick films as possible in the experiments but it is then imperative to ensure that the composition of the films can, from a mechanical point of view, be considered homogeneous. Microindentation techniques can also be used to specify the plastic properties of materials. Nevertheless, it is a more difficult and tedious problem and it was not considered here. The use of indentation in order to determine the failure stress of the coating materials was also investigated, but it is a very involved procedure as it requires full knowledge of the material behaviour. In practice, such an approach can only serve as a method for verification of results from other test methods, most likely uniaxial tensile tests.

3.2 The base stock

Describing the mechanical behaviour of paper has been in focus for the paper mechanics society for years. Paper is a fibrous material made from self-binding cellulose fibres. These fibres come from different plants, but the most common papers are made of wood-fibres. The fibres can be separated from each other mechanically (mechanical pulp) or the lignin binding the fibres together can be removed in a chemical process (chemical pulp). Paper is formed by drying the fibre suspension (the pulp). During the process, the fibres tend to orient themselves in the plane and in the machine (rolling) direction. Due to this particular orientation, paper exhibits strong anisotropy. It is common to define three material directions, and denote them MD for the machine direction, CD for the cross machine
direction and ZD for the thickness direction, according to Fig. 6.

Fig. 6. Paper sheet with the common definition of the principal directions.

3.3 The toner layer
As discussed before, the folding process occurs after the printing process. In the digital printing industry, that means that very dry papers with an extra layer of melt toner particles come out of the printing presses. To handle the toner layer in a mechanical analysis is a difficult task, as very little is known of the mechanical properties of this material. Nevertheless, some results presented by Barbier et al. [8] indicate that the toner layer has very little influence on the mechanics of the process and can be neglected in a numerical analysis. In the present thesis, the influence of the ink or toner layer is not considered.

3.4 Modelling paper
Paper as an engineering material can be described using a network or a continuum model. The models available today for paper and paperboard has been well summarized by Xia et al. [9]. The anisotropic elastic constants have been measured (Mann et al. [10]), and the in-plane properties of paper are now well known. The work by Stenberg et al. [11] also presents interesting results on the out-of-plane mechanical behaviour of paper. The stiffness in MD is usually 1–5 times greater than that in CD, and typically 100 times greater than that in ZD. The yield stress is also significantly lower in ZD than in MD.

Anisotropic plasticity modelling of paper has also been studied by Mäkelä and Östlund [12]. Nevertheless, it remains difficult to use these results directly in a numerical analysis when paper is subjected to large deformations since this model is formulated assuming small strain theory to prevail. The constitutive model presented by Xia et al. [9] is an important step forward, but the authors admit that the model works best for in-plane loading of paper, due to the assumption of elastic out-of-plane behaviour. A preliminary out-of-plane modelling has been presented by Stenberg [13,14], but it is still not easily accessible in commercial finite element programs.

In paper IV of this thesis, an attempt to model numerically, in a simple way, the anisotropy of paper, taking into account the large difference between the in-plane and the out-of-
plane properties, is presented. A continuum model is adopted here, but the continuum is reinforced in suitable directions (presently the MD) with stiffening elements. A numerical analysis coupled to this mechanical model shows that the large anisotropy of coated papers must be taken into account in problems where the thickness direction is solicited.

4. Experimental findings

Features such as strain levels, relevant failure criteria and anisotropic effects, all important for a much needed theoretical/numerical investigation of paper folding, were not addressed in the studies discussed above. It should also be emphasized that the bulk of the experimental results presented in the literature concerns LWC paper and paperboard while the main interest in the investigation presented in paper I concerned paper used in digital printing applications. Accordingly, the goal of this study was to obtain a better understanding of the folding properties of coated papers pertinent to the mechanical behaviour. To achieve this, a microscopy investigation was performed of, in particular, the surface of the folded paper in order to study the event of fracture and related issues. The effect of the base stock as well as the coating was examined. Other physical parameters such as the grammage (thickness) of the paper, humidity and strain levels at cracking were also studied. A simple experimental device was constructed in order to perform these investigations, see Fig. 7. The advantages of this device are its small size, which allows the use of an optical microscope to observe deformation of the samples, and the screw mechanism allowing the folding process to be stopped if necessary for observations. It can be argued that this device does not allow the investigation of high-speed folding, as in an industrial situation, but this point will be addressed later in this thesis.

When the paper was sufficiently thin (90 g/m²), the loading was too small for cracking to occur in the coating. For higher grammage papers, cracking of the coating layer occurred
momentarily and a cloud of cracks was formed. This result indicates strongly that a stress or strain based fracture criterion is relevant.

The biaxiality of stresses as well as in-plane anisotropy must be taken into account when determining material properties pertinent to cracking, as different results were observed depending on the orientation of the paper during folding (MD or CD perpendicular to the folding line).

The studied samples showed that cracking of the coating does not lead to subsequent cracking of the paper substrate.

Another feature common in the creasing and folding of paperboard is delamination. It was observed that delamination always occurred in the base stock inside the fold, and not at the interface between the base paper and the coating layer. The delamination did not grow during continued loading.

Finally, high relative humidity proved to have very little influence on the load levels pertinent to cracking compared with medium relative humidity. Low moisture levels were not investigated, as it is already well known in the graphic industry that low humidity leads to a more brittle material with a tendency of developing severe cracking during finishing operations.
5. Finite element modelling of the folding process

The folding process was modelled using a simplified geometry. A paper strip fixed between two parallel metallic walls (rigid material compared to paper) was folded by reducing the distance between the two walls, as described schematically in Fig. 8. It is worth mentioning that this method simulates correctly paper folding by hand. This geometry was used in all the numerical analyses presented in this thesis, papers II, III and IV.

In paper II, the numerical analysis aimed at identifying and quantifying the influence of different parameters relevant for the folding process. As a first step, the paper was modeled as an orthotropic material and a quasi-static analysis was relied upon. The results obtained can be summed up as follows:

Elastic effects are negligible during the final and most important part of the folding process.

Particular forms of plastic anisotropy can substantially reduce the strain levels, and
thereby also the damage at folding.

Such features as delamination buckling and unloading will not significantly affect the damage levels at folding.

The deformation of the coated paper is very much governed by the paper substrate and, accordingly, the strain hardening behaviour of the coating will not influence the resulting strain levels (but certainly the corresponding stress levels) at maximum loading.

The numerical results indicate that periodic cracking of the coating, a desirable feature for mainly aesthetic reasons, is a possible event at folding.

Remembering that in an industrial process, the speed at which the products are folded can reach 200 m/min, it was found necessary to check if the quasi-static model was applicable. This was done in an analysis, parallel to the quasi-static analysis, reported in paper III. The results indicate that dynamic effects are of little importance as regards maximum strain levels in the coating but will influence the stress and strain distributions. Accordingly, a quasi-static analysis of the problem will be sufficient in order to describe many of the important features related to cracking, an exceptional case being when an analysis of periodic cracking of the coating layer is attempted, as it was observed that the locus of the maximal longitudinal strains was not situated at the symmetry line when dynamic effects were taken into account.

In paper IV, the strains were computed using the new material description described above. The main conclusion is that high anisotropy, and especially the weak behaviour of paper in the thickness direction must be taken into account in future works if a quantitative analysis is aimed at.

6. Final remarks and suggestions for future work

The aim of this thesis was to study in detail the phenomenon of cracking of coated papers during folding. Here, this problem has been studied with experimental techniques and numerical analyses. The finite element method has been used, as the geometry of the problem is rather complicated, excluding a solution in analytical form. The results presented here show trends that could be explored more deeply when an accurate description of the mechanical behaviour of paper is available.

Another possible research direction would be to study the phenomenon of distributed cracks. Due to the large deformation of the materials during folding, it can in many cases be an overwhelming challenge to avoid cracking of the coating layer. However, it would be easier instead to allow the coating layers to crack, but in a more controlled manner, with small distributed cracks instead of a cloud of cracks all situated at the folding line. In a numerical analysis, this phenomenon could be implemented using for example a shear lag model for the cracking of the coating layer.
7. Summary of appended papers and division of work between co-authors

Paper I: Experimental investigation of damage at folding of coated papers

An experimental investigation is presented. An experimental device, specially constructed for the investigation, was used in order to achieve close resemblance with an industrial situation. During the experiments, the influence on the damage levels in the coating from such features as delamination, humidity and paper thickness was studied using an optical microscope. The behaviour of two different paper materials was investigated. A stress or strain based fracture criterion proved to be relevant for the present problem, and biaxiality of stresses as well as in-plane anisotropy must be taken into account. It was observed that the cracking of the coating would not lead to subsequent cracking of the paper substrate, and that delamination during folding occurred in the base stock, and not at the paper/coating interface, but its quantitative influence as regards cracking could not be determined. The influence of sheet grammage was investigated and it was found that the only case when visible cracks did not appear was at low grammage. High humidity did not affect the cracking behaviour.

Christophe Barbier carried out all tests and analysis and did the main part of the writing of the paper. Per-Lennart Larsson and Sören Östlund contributed to research guidance, overall ideas and writing of the paper.

Paper II: Numerical investigation of folding of coated papers

A numerical investigation is presented, based on a quasi-static analysis. The finite element method was used, as the geometry and the material behaviour are strongly nonlinear, hence making it impossible to achieve an analytical solution of the problem. Particular emphasis was put on the behaviour of field variables relevant for cracking of the coating layers. The basepaper was modelled as an anisotropic elastic-plastic material (both elastic and plastic anisotropy was accounted for) while the constitutive behaviour of the coating layers was approximated by classical (von Mises) elastoplasticity. The numerical results suggested, among other things, that particular forms of plastic anisotropy can substantially reduce the maximum strain levels in the coating. It is also shown that delamination buckling, in the present circumstances, will have a very small influence on the strain levels in the coating layer subjected to high tensile loading.

Christophe Barbier performed most of the work and did the main part of the writing
Paper III: On dynamic effects at folding of coated papers

A similar analysis as the one in paper II was carried out, but here dynamic effects were accounted for. The results presented indicate that dynamic effects are of little importance as regards maximum strain levels in the coating but will influence the stress and strain distributions. Accordingly a quasi-static analysis of the problem will be sufficient in order to describe many of the important features related to cracking.

Christophe Barbier performed most of the work and did the main part of the writing of the paper. Per-Lennart Larsson and Sören Östlund contributed to research guidance, overall ideas and writing of the paper.

Paper IV: On the effect of high anisotropy at folding of coated papers

A finite element procedure, developed in order to account for the effect of high anisotropy at folding of coated papers, is presented. The anisotropic behaviour (with very low stiffness in the thickness direction) was modelled using stiff structural elements (trusses and beams). The numerical results presented indicate that high elastic anisotropy leads to lower strain levels at folding than reported in previous analyses where this effect was not accounted for. High plastic anisotropy, on the other hand, will contradict this result.

Christophe Barbier performed most of the work and did the main part of the writing of the paper. Per-Lennart Larsson and Sören Östlund contributed to research guidance, overall ideas and writing of the paper.

Paper V: On material characterization of paper coating materials by micro indentation testing

Microindentation as a method for determining important material properties of paper coating materials was studied experimentally and numerically. The bulk of the investigation was concentrated upon the short-lived elastic part of a spherical indentation test but determination of the failure stress of the coating was also discussed. The results indicated that microindentation can be a powerful tool for material characterization of these coating materials but only if careful efforts are made in order to account for the influence of plasticity as well as boundary effects.
Christophe Barbier performed the indentation and numerical tests, carried out the analysis and contributed the writing of the paper. Nils Hallbäck and Michael Karathanasis contributed to overall ideas and performed the tensile tests. Per-Lennart Larsson contributed to research guidance and did the main part of the writing of the paper. Sören Östlund contributed to research guidance.

8. References


