High-speed Blade Coating

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HIGH-SPEED BLADE COATING

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TABLE OF CONTENTS

12.4.1 Introduction .................................................. 1

12.4.2 Blade Coater Designs .......................................... 7
   Puddle-type Coaters .................................................. 9
   Roll Coaters .......................................................... 10
   Jet Coaters ............................................................ 11
   Pressurized Pond Coaters ........................................... 13

12.4.3 Blade Metering Process ........................................ 15

12.4.4 Hydrodynamic Instability in Blade Coating .................. 30

12.4.5 Air Entrainment ................................................ 35

12.4.6 Non-Newtonian Rheology in Blade Coating .................. 39

12.4.7 Blade Coating Defects ......................................... 47

12.4.8 Conclusion ..................................................... 57
Blade coating is a popular method among the many techniques used to continuously apply a uniformly thin film of liquid onto moving webs. Although still a self-metered, as opposed to a pre-metered process, blade coating falls within the class of processes where the coating layer is metered prior to the meniscus. In that sense, the blade acts as a precise smoothing device which removes excess coating - applied onto the web upstream with some kind of a mechanical feeding system or puddle - and lets a thin coating film pass through the narrow channel formed between the blade and the moving substrate (Fig. 12.4-1). The flow is primarily due to the shear stress induced by the substrate motion which is dragging coating in the channel formed between the substrate and the blade, the so-called blade nip. In contrast to the meniscus-metered class of coating processes, such as dip coating (see Chapter 13), where the coating thickness is determined by the shape of the meniscus, parameters independent of the meniscus control the coating film thickness of blade-metered coating systems. Generally, the film thickness, its uniformity and overall quality, depend on the characteristic blade nip geometry, the rheology of the coating, and properties of the web. Difficulties encountered in understanding, predicting, and controlling the blade-metering process arise from interactions of complex phenomena, which will be discussed in more detail in the following sections.

Blade coating refers to the broad family of processes where a liquid layer emanates from the shallow channel formed between a stationary blade and a moving substrate supported against a roll. The liquid may be a dispersion or suspension of solid particles; the blade can be rigid or flexible; and the supporting roll can be hard or soft. The subject of rigid knife coating is covered in Chapter 12.1. Here we focus on flexible blade coating, where
the blade can be loaded with a mechanical member or an inflatable pressure hose located at some distance from the edge of the blade - the blade tip (Fig. 12.4-1). The blade may also be loaded by rotating the blade holding assembly, so that the blade bends against the substrate and the supporting (packing) roll. Industrial applications of this process include addition of adhesives and coating to paper, paperboard, and films, as well as oxide coatings onto magnetic recording tapes.

Although flexible blades are commonly used to apply liquid films onto smooth and incompressible polymeric substrates (e.g., in magnetic suspension technology), they are most popular in surface application of coatings for publication papers and paperboard. The reason for surface treatment of paper and paperboard is to develop a uniformly smooth surface for printing and superior appearance. Blade coating generates a smooth surface with improved optical properties, gloss, and printed ink density, while capturing halftone dot highlights during printing. However, these substrates are rough, porous and compressible, properties which make the physics of this blade coating process particularly challenging.

Blade metering is the coating process of choice for paper and paperboard applications because it is conducive to relatively high machine speeds and coating viscosities. Blade coaters for paper run at speeds above 5 m/sec, while the steady-shear viscosity of mineral dispersions for paper coatings varies from several hundreds to over a thousand mPa sec. The discussion in this Chapter concentrates on the high-speed blade coating process for paper webs.

Similar to many other coating techniques, blade coating technology has evolved from simple and basic applications. Many day to day applications are, in principle, forms of blade coating. A simple process of spreading butter by knife over a piece of toast is a
simple example. In fact, Booth (1970) uses this example to describe the effect of coat weight in relation to the angle formed between the blade tip and the tangent to the substrate, i.e., the so-called blade angle. The original coating apparatus appeared in two forms (Trist 1945). In one form, a coating head or trough was used to contain the coating, hence the flexible blade formed the boundary at the leading edge of the trough. This is a "puddle" type of coater, which was common during the early development and use of the blade coating process (Fig. 12.4-2). In a second form, excess coating was applied onto the moving web with an applicator roll and metered downstream with the blade. The excess coating was then recycled back into the pad feeding the applicator roll. This configuration was termed the "inverted" blade coater. In both cases the substrate was drawn around a rubber covered supporting roll, also called the backing roll, which drives and supports the substrate.

Continual upgrading of the blade coater process, however, was needed as machine speeds increased for productivity and film thicknesses decreased due to rising mailing costs. Nowadays, there is a whole family of newer blade coaters where differences exist on: (a) the application of excess coating (or pre-metering) with roll applicators or jets, (b) variability in the dwell time between application and metering, (c) pre-metering with one blade first before final metering with a second blade, or (d) utilization of a short (2.5-5.0 cm in length) pressurized pond for application of the coating before metering, hence the flexible blade itself acts as a boundary that keeps the coating in contact with the substrate and as a metering device. This latter design is the popular type of blade coater known in the paper industry as the "short-dwell coater." These and other blade coater designs are discussed in detail in the section 12.4.2.

Blade coaters for paper are also classified into two categories, depending on their operational mode. In the first configuration the tip of the blade remains nearly tangent to
the web surface and the backing roll at the area of contact between the blade and the web. This is the so-called straight, trailing, or bevelled blade (Fig. 12.4-1). The blade angle, formed between the blade and the tangent to the backing roll (Fig. 12.4-3), is comparatively large, typically varying between 25° and 50°. In practice, blades are prehoned to nominal bevel angles - typically 45°, 40°, 35°, etc., so that one needs to set the blade angle to the bevel angle of the blade in order to run the blade on its bevelled mode. However, metallic blades wear out over time during normal operation and the bevel angle changes. When this occurs, the blade is not running anymore on its bevel, resulting in to configurations (b) and (c), as illustrated in Fig. 12.4-3. In cases (b) and (c) the blade runs on its trailing (heel) or leading (toe) edge, respectively, something which may lead to coating defects. Therefore, the exact blade geometry is a critical issue in bevelled blade coating, as it will be discussed in more detail in section 12.4.7.

In the second configuration the underside surface of the blade is parallel the web over a finite area (Fig. 12.4-1). This is the so-called flexed, low-angle or bent blade mode. The blade angle in this case varies from almost 0° to 25°. The main difference between these two blade modes is the operational window of the process, i.e., the range of machine speed and film thickness, or coat weight, for which satisfactory coating is feasible. (The papermakers use coat weight to express coating film thickness in grams per unit area, in square meters of paper.) The bent mode is preferred for comparatively high film thicknesses and low coating speeds (e.g., paperboard coating), while the bevelled blade is selected for applying thin films at relatively high speeds (e.g., light-weight coated publication papers).

There are several process parameters in high-speed blade coating systems which influence the surface quantity and quality of coating applied onto a substrate. Generally, the coating film thickness, or coat weight, depends on the interaction between the various
operating parameters; namely, the coater geometry, coating rheology, and properties of the substrate. Usually the mechanical or pneumatic load on the blade is adjusted to control the final coating film thickness of coat weight. The blade thickness is typically between 0.1 to 1.0 mm and the blade length (i.e., the distance between the edge of the blade, or blade tip, and the location where the blade load is being applied) is about 2 to 10 cm. A typical time scale of the metering process at the blade nip is 0.01 milliseconds for 17 m/sec coater speed (Gane, Watters, and McGenuity 1992). Although most of the commercially utilized blades are made out of stainless steel, newer blades are manufactured with ceramic tips which resist wear and provide a better control of coating film thickness in the long run. The manner by which these parameters influence, and therefore can be manipulated to predict, the coating film thickness are discussed in section 12.4-3.

Blade metering is a simple and rather primitive process flow, but presents a complex hydrodynamic system which has been under investigation since its original recognition as a superior coating system, as early as the 1950's. Originally blade coaters for paper operated at relatively low speeds, i.e., 5 to 10 m/sec, but modern blade coating systems operate at speeds in excess of 20 m/sec. The coating fluid (or dispersion) is forced from one extreme of flow conditions to another, while the fluid and dispersed particles experience changes in the shear rate from almost zero upstream of the blade to nearly $10^5$ 1/sec inside the passage under the blade tip in a period of time less than 0.01 millisecond. In the convergent flow through the blade nip, regions with high pressure gradients are adjacent to nearly constant pressure areas (or pressure plateau). Furthermore, the coating materials are non-Newtonian, exhibiting complex rheological behavior including dilatancy, yield stress, anisotropic recovery, and viscoelasticity. Paper coatings, for example, comprise highly concentrated dispersions (i.e., 30-40% by volume) of
anisometric, orientable particles suspended in an aqueous phase containing polymeric additives. Therefore, the ability to predict and control the coating process many times becomes a formidable task.

In addition to the above complications, one could hardly design a process which, with respect to modeling, involves more complex boundaries. The blade is flexible, the substrate is generally deformable and permeable, and there are free-surfaces with static and dynamic contact lines. On the other hand, the requirements for a successful coating process are also extreme. The flow needs to remain steady and two-dimensional at high machine speeds for maintaining a uniformly thin coating film. Uniformity needs to be sustained in both the machine line and the cross machine directions, since film thickness nonuniformities would not be acceptable from the standpoint of both visual appearance and physical attributes. Furthermore, anomalies occurring at the bounding walls, as well as the bulk of the process flow, would cause coating film defects and deposits appearing at the blade surfaces. In practice, consistent and sustained productivity requires adequate knowledge of the physics of the blade coating flows, as well as the characteristics of both the substrate and the coating material.

The focus in this Chapter is on high-speed blade coating of paper webs. Section 12.4.2 describes the various designs and their evolution over the years to the high-speed precision coaters of today. The following section, 12.4.3, discusses how the different process parameters interact to determine the film thickness, or coat weight. It also includes a review of analyses and experimental studies on the physics of blade-metering. Although the emphasis is on blade-metering on rough, porous and compressible substrates, limited reference is made to rigid knife coating of smooth, incompressible substrates to illustrate qualitative differences between the two processes. Sections 12.4.4 through 12.4.5 deal with hydrodynamic and other phenomena which influence the
process and the uniformity of the film thickness. Finally, sections 12.4.6 and 12.4.7 cover respectively aspects of paper coating rheology and blade coating defects, their appearance and origins.

12.4.2 BLADE COATER DESIGNS

The first blade metering on a continuous coating machine is credited to the system designed by Trist (1945) which was primarily used for coating an oil phase emulsion on bread wrapping paper. The superior potential of this technique was recognized in the 1950's when a growing number of applications started to adopt the blade coating system. A wide variety of blade coating equipment has been invented since then. Richardson (1957) and Booth (1970) review the earlier blade coaters and their designs.

There are in general three important regions in an application system. (i) The wetting or the dynamic contact line (see section 12.4.5) where the fluid first comes into contact with the substrate, (ii) the dwell region where the coating liquid remains usually undisturbed adjacent to the solid surface, and (iii) close to the metering region where the fluid layer approaches the blade.

The flow in an ideal application process should be steady state and two-dimensional. If the coated layer approaching the blade has uniform thickness and if the blade has no defects, then the resulting coated film would have a constant thickness. However, nonuniformities or unsteadiness upstream of the blade may result in coating defects. The mechanisms whereby flow nonuniformities upstream of the blade could result in coating defects have been analyzed by Miura and Aidun (1992).
The maximum coating speed is determined primarily by limitations set by the application unit. The fundamental limit on the coating speed depends on the maximum speed at which the air adjacent to the solid surface can be replaced by liquid at the wetting region. This is sometimes referred to as the maximum wetting speed and depends on the flow field in the vicinity of the dynamic contact line. Above the maximum wetting speed, small air bubbles entrain into the liquid and result in coating defects, as explained in section 12.4.5. Flow instabilities in the application unit upstream of the blade sometimes impose more severe limitations on the coating speed than air entrainment. These instabilities, as discussed in sections 12.4.4 and 12.4.5, result in operational difficulties and coating defects. Therefore, air entrainment and flow instabilities are the main issues of concern in the development of modern high speed coating systems.

There are four different categories of blade coating systems that depend on the coating application method before metering. These comprise the puddle, roll, jet (slot), and contact application systems. The common process involved in all of these systems is that they supply the blade with excess coating fluid which is, subsequently, metered by the blade. Typically, fifteen to twenty parts of the applied coating are removed by the blade for every part applied on the moving web. Each one of these application systems can be combined with any blade mode, i.e., bevelled or bent. A list of the different commercially available types of blade coaters are listed in table 12.4-1. Figure 12.4-4 presents schematics of the different blade coating equipment for paper.

Currently, many of the high speed blade coating systems operate with a roll applicator where a thick layer of coating fluid is transferred to the surface of the substrate. The coating layer, which is typically between 100 μm to 1 mm thick, is metered downstream by the blade to provide a final film thickness in the range of 10 to 50 μm. This operation is commonly referred to as the inverted blade coater; also known as flooded-nip™ blade
coater. Although this is a quite common blade coating system, it is now clear that other techniques such as jet and pond application systems are superior. In particular, the so-called short dwell coaters have recently found wide acceptance by the paper industry due to their compactness, ease of operation, and capability to keep the equipment clean, as well as their ability to apply comparatively thin coating films at high machine speeds (i.e., greater than 25 m/sec). The main advantage of the short dwell coater is that it can provide the same coat weight onto a paper web as a system with an applicator roll but at substantially lower blade pressures, something which significantly improves productivity since it minimizes the possibility for web breaks. The different application systems, presented schematically in Fig. 12.4-4, are discussed in the following paragraphs.

Puddle-type Coaters

There are a variety of coating application systems in this class. The two principal categories are one-sided and two-sided coating systems (Fig. 12.4-4 and 12.4-5) where both sides of the substrate are coated and dried simultaneously. In principle, these coaters cannot operate at high speed because of air entrainment at the wetting line which results in foaming of the puddle and, in extreme cases, prevents contact of the fluid with the substrate.

These coaters are commonly used today in various application, such as paper and board coating. The pond level in normal operation is between 150 to 170 mm high and the backing roll has a soft rubber cover (~70 P&J). The two-sided puddle coaters (Fig. 12.4-5), such as, the Billingsfors-Langed, better known as the Billblade™ system (Holton and Klass 1986), have remained in operation despite their limitations in speed and film thickness control. In addition to air entrainment, misting is also a problem with these
coaters. At high speed, coating droplets form a mist of coating fluid, usually at the
diverging region between the substrate and the roll where a meniscus forms. Misting
occurs because of meniscus instability and breakup (film split), similar to the spraying
mechanism in roll applicators. It is reported (Holton and Klass 1986) that by running the
backing roll 3-5% faster than the web and forming a ‘take-off’ angle of the web away
from the roll completely eliminates film split and the misting problems on the roll side.

Roll Coaters

Roll applicators are perhaps the most popular and traditional form of coating systems.
The transfer or applicator roll picks up the coating fluid from a supply pan or reservoir,
as shown in Fig. 12.4-4a, and transfers the fluid to the substrate being carried by the
backing roll. The clearance between the surface of the two rolls can vary from 100 μm
to 1 mm depending on the particular operation. The roll coating modes can be forward
where the two rolls rotate counter to each other, or reverse, were the rolls rotate in the
same direction. The amount of coating fluid transferred to the substrate by the applicator
roll depends on the fluid properties, the gap, and the relative speed between the substrate
and the roll.

There are a number of roll applicator systems with multi-roll metering units which have
been developed by various companies. For examples of these systems, the reader is
couraged to see the review by Booth (1970). For a more extensive analysis of the
mechanics and instabilities in roll applicators, see section 12.4.4 and chapter 12.1.

Roll applicators with blade metering units, in general, provide a good quality coated
surface. However, because of flow instabilities and ribbing, roll applicators have limited
use in high-speed blade coating. Also, as speed increases, the meniscus splits forming droplets. This spraying action causes difficulties in maintaining a clean and smooth layer of coating fluid prior to the blade. As indicated above, it is important that the coating layer remain smooth and uniform, since a nonuniform layer approaching the blade results in coated film thickness nonuniformities and other defects. In addition to this problem, from a practical point of view, roll applicators are difficult to operate, clean, and maintain. Manufacturing lightweight coated paper and film requires metering most of the applied coating from the surface by exerting a relatively large pressure on the blade. This causes frequent web breaks with an enormous waste in coating fluid and substrate material. Because of these difficulties with roll applicator systems, a number of more advanced application systems are being developed. These fall within the class of jet and pressurized application systems.

Jet Coaters

These systems, as the name implies, consist of a rectangular liquid jet which comes into direct contact with the substrate, as shown in Fig. 12.4-4b. We confine the term ‘jet coaters’ to those systems in which a liquid jet emanating from the nozzle directly impacts the substrate. Some in the industry refer to the pressurized pond system of Fig. 12.4-4c as jet coaters, as well. However, the fluid flow characteristics and the coating features between the two systems presented in Figures 12.4-4b and 12.4-4c are substantially different. With a jet coating system, the entire fluid leaving the nozzle is transferred to the substrate and supplied to the doctor blade. In contrast, in pressurized pond application systems some of the fluid is always rejected from the pond. Also, jet coaters are usually used for thicker liquid film application on the surface. Thinner film
applications can better be achieved with short-dwell time or other pressurized pond application coaters.

To ensure a uniform coated surface, the jet must have uniform constant momentum across the coater. This is achieved, in practice, by injecting the coating fluid from a large reservoir into a long channel before forming a two-dimensional free-surface jet. Since the volume of the reservoir is relatively large, the pressure inside will be essentially static and uniform across the nozzle (see chapter 10 for a more detailed discussion of manifold design). A long slightly converging nozzle will allow the flow to fully develop and stay attached to the wall. In other words, a converging nozzle ensures that pressure drops in the flow direction and therefore, the shear stress retarding the flow near the walls will not cause flow separation or flow reversal at the wall.

The control parameters are the opening gap of the jet, \( d \), the jet angle relative to the substrate, \( \alpha \), the velocity of the substrate, \( U \), and the jet Reynolds number, \( \text{Re} = \frac{dU}{\mu} \), the capillary number, \( \text{Ca} = \frac{\mu V}{\sigma} \) where \( \rho \), \( \mu \), and \( \sigma \) are the fluid density, viscosity, and surface tension, respectively. The jet velocity scale, \( V \), is defined as the mass flux divided by the jet’s cross-sectional area. The jet could swell or contract depending on \( \text{Re} \) and \( \text{Ca} \). Here we are assuming that the coating liquid behaves like a Newtonian fluid, although at low shear the viscosity of coating fluids usually depend on the rate of shear.

In practice, the jet is usually from 1-1.8 mm thick at the vena contracta and extends about 12 to 25 mm in length. The coating flow rate per unit width is in the range of 1.3 to 3 l/sec/m. The relative velocity of the jet to the substrate, \( \frac{V}{U} \), varies from 0.1 to 0.5 depending on the coating thickness and other parameters.
Pressurized Pond Coaters

In this class of coating application systems, the coating fluid comes into contact with the substrate in a pressurized reservoir adjacent to a metering blade. The main purpose of increasing the pressure inside the coating reservoir is to avoid 'skip coating', that is to force the fluid to remain in contact with the substrate at high speed and avoid air entrainment at the wetting line (see section 12.4.5 for more detail).

This system of coaters has received considerable attention in the industry for several reasons. The coating head is compact and easy to operate and maintain. These pressurized pond systems are frequently used in short-dwell mode (referred to as Short-Dwell Coaters) where a very thin layer of coating is applied on the surface of a substrate without causing excessive web breaks.

With these coaters, the pond is adjacent to the blade and the coating liquid is transferred to the surface of the substrate immediately prior to the metering section. In contrast to the long-dwell time coaters where the coating layer travels adjacent to the substrate for a relatively long time before being metered off, the coating in short-dwell coaters have little time to penetrate into the substrate. These coaters are particularly used for light weight printing and publication grade of paper as well as many other products including premetered size pressing applications. These coaters have several advantaged over other coating application systems. The main advantages of these coaters as compared to roll applicators are the compactness, operational efficiency, and increased productivity of thinner coated film and, therefore, lighter weight coated layers. It is reported (Closet 1986) that with these coaters, blade pressure can be reduced by 40% resulting in a considerable reduction in web breaks. This increases productivity by reducing the loss time due to web breaks by as much as 28% as compared with blade metering systems.
with roll applicators. Furthermore, a 40% reduction in coating liquid loss is reported by the industry. The lower blade pressure results in a 60% longer blade life time.

As the coating speed is increased, problems appear in all coaters. Although the short-dwell coater can operate at speeds in excess of 20 m/sec., the coated surface quality deteriorates quickly beyond a critical speed which depends on several factors including the coating rheology. Usually these problems appear in the form of long streaks which have a coating thickness deficit of about 20 to 60 percent. Section 12.4.7 describes the various coating defects in blade coating systems. The most severe coating defect with short-dwell coaters are long streaks about 1-3 cm wide and 10 to 100 cm long. Extensive experiments (Triantafillopoulos and Aidun 1990) have shown that the parameters which have the most significant influence in generating streaks are coating speed, low shear viscosity of the coating liquid, and consequently, the concentration of the suspension. Suspensions with larger aspect ratio (thin disk-shaped) and larger shear viscosity tend to be more susceptible to coating defects, in general.

Additional problems for short-dwell and other pressurized pond application coaters are the instabilities that occur inside the pond as well as air entrainment issues at the dynamic contact line. These problems are fundamental to any pressurized pond application system. Sections 12.4.4 and 12.4.5 treat these issues in more detail.

It is also possible to simultaneously coat both sides of a moving web passing between two blades located one against the other. A Billblade™ is the configuration where the web passes through the nip of a bent blade, on one side, and a roll on the other side. Two separate puddles of coating exist, one on the roll side and the other one of the blade side. These puddles allow for application of coating onto the moving web from both sides simultaneously.
12.4.3 BLADE METERING PROCESS

The physics of high-speed flexible blade coating have been the subject of interest in many studies over the years. The motivation was to document the interaction of the various forces acting on the blade and to determine how process variables affect coat weight. Most of the work focused on development of semi-empirical relationships which can be readily used to manipulate the process and control coat weight. These relationships were based on rather simplistic analyses which incorporated only a limited number of the physical phenomena involved. Fundamental understanding of the blade metering process for paper has only recently been attained with the help of both computational models and experiments.

In the present section we review key relationships between operational variables and coat weight, with a focus on high-speed blade metering of paper webs. We will refer to previous analyses and experiments which shed light on the physics of this process. Both the bevel and bent blade operating modes are discussed. Topics covered in detail in other Chapters of the book, i.e., elastohydrodynamic coating systems covered in Chapter 12.3, are only briefly mentioned here. Differences in the operational behavior of high-speed blade metering and low-speed blade and knife coatings are also discussed in order to point out qualitative difference between the two systems.

The mechanism of low-speed blade coating has been studied by several authors (Middleman 1977; Hwang 1979; Sullivan 1986). When inertia effects are neglected, lubrication theory is an acceptable first approximation to describe the viscous forces in the gap between the blade and the web (or roller in the case of knife-over-roll coating). The lubrication model predicts both the pressure profiles and the coating thickness.
Generally, the coating film thickness for Newtonian fluids is approximately equal to one half the minimum separation between the blade and the moving web. As shown by Sullivan (1986) and Strenger, Sticco, and Stamek (1992), the final coating thickness also depends on the size, curvature, inclination and inlet conditions of the upstream (feeding) region of flow. The key characteristic of this process is that coat weight decreases with increasing viscosity and web speed. In contrast, coat weight increases with viscosity and web speed in high-speed blade metering of paper coatings with bevelled blades (Kahila and Eklund 1978b). These differences suggest that, at least for the case of high-speed bevelled blade coating, inertia effects, which are ignored in pure lubrication flows, may be important.

Typically, the development of coat weight, of wet film thickness, as a function of blade pressure in high-speed flexible blade metering follows the behavior depicted in Figure 12.4-6. In the bevelled mode, the blade pressure lowers the coat weight (region I), up to a point where pressure changes bring a minimal change in coat weight. When the flexible blade runs on its bent or low blade angle (i.e., blade angles below 20°) mode, coat weight increases with increasing blade pressure (region III). As the blade pressure of a bent blade increases, the operating blade angle decreases and, consequently, coat weight increases. In well flexed blades, the coat weight passes through a maximum upon continual increase in blade pressure, as shown on Fig. 12.4-6. Beyond this point (region IV), coat weight decreases with rising pressure because the excessive bending on the blade causes formation of a divergent nip between the blade tip and the surface of the moving web. Under these circumstances, the final film thickness may acquire a film-splitting pattern due to instabilities developed at the free surface of the coating film emerging from the channel between the blade tip and the web (Eklund 1984). This is similar to the film-splitting phenomenon that occurs in roll coating.
The relationship between coat weight and blade pressure depicted in Fig. 12.4-6 was first reported by Eklund (1984) and it was analyzed by Saita (1984) using elastohydrodynamic principles (see Chapter 12.3). Although this relationship applies to coating any type of a web, experimental data presented by Eklund (1984) were based on a paper web. In practice, it takes a wide range of blade pressures, irrespectively of how these are applied (i.e., with an inflatable hose or a mechanical device), to generate this graph. A key observation, however, is that a certain coat weight can be achieved with the flexible blade operating at two, or even three, different conditions. To understand the behavior of this system one needs to consider the forces involved in flexible blade metering.

Several dynamic forces develop as the coating fluid is dragged by the moving web onto the converging flow under the blade (Kabila and Eklund 1978a-c; Saita and Scriven 1985). First are the shear and normal viscous stresses arising from the coating dragged into the converging region under the blade and through the blade nip. Coating fluid in these regions also develops a pressure and pressure gradient, similar to those occurring in purely lubrication flows. In turn, the viscous and pressure forces exerted on the blade cause it to deflect due to generation of elastic forces. In addition to the above, inertia forces are also present. These forces arise from the impact pressure of the upstream coating fluid layer, which contacts the blade and changes momentum to be expelled away from the blade nip. It is worth noting that other forces, such as gravity, surface tension, colloidal, etc., are present but play a minor role in high-speed blade metering.

The mechanism of blade metering is based on the balance of all the forces described above. As the moving web drags coating between it and the blade, hydrodynamic forces - in conjunction with inertial forces - stress the blade, which deforms proportionally to its flexural rigidity. Internal elastic forces and external loading (i.e., tube pressure) oppose blade deformation, so that finally the blade assumes a shape that balances all forces.
acting on it. In turn, the flow re-organizes to balance the hydrodynamic forces in the coating field of flow, while the paper web (and the backing roll) compresses under the influence of the pressure pulse under the blade. As a result, at least for the case of paper coating, the non-Newtonian rheology of the coating and the compressibility and absorptive properties of the web also influence coat weight development. Both these and the fluid dynamic phenomena occurring during blade metering of paper coatings are discussed in more detail in the following paragraphs.

Many attempts have been made over the years to analyze and understand blade coating of paper. These led to deriving models of the physics of blade coating and to developing semi-empirical relationships which connect operational parameters, coating and substrate properties to coating film thickness or coat weight. These analyses and models considered three basic kinds of fundamental phenomena: (a) the hydrodynamic and inertial phenomena at the vicinity of the blade nip which are responsible for development of the forces described above; (b) the filling of pores in the substrate, which depends on the surface roughness and compressibility of the web; and (c) the penetration of the continuous (dispensing) phase of a coating dispersion into the substrate. It should be emphasized that most paper coating applications are considered high speed, i.e., in excess of 5 m/s, and the substrates are viscoelastic networks of cellulosic fibers which can rapidly absorb water and swell.

The simplest models are based on hydrodynamic lubrication at the blade nip. This phenomenon, more or less influenced by paper absorption, is considered the principle mechanism for coating deposition (Follette and Fowells 1960; Böhmer 1969; Bliesner 1971; Turai 1971; Modrak 1973; Hayward 1973). In these analyses the blade is considered as a cantilever beam that deflects under load, while the flow through the blade nip is based on hydrodynamic lubrication. Coating in the region close to and under the
blade tip is assumed to develop a load-bearing capacity that lifts the blade in the normal direction to the web movement. The hydrodynamic lift exerted by the coating is constructed by the applied blade load. According to this model, the net force acting on the blade is that of the hydrodynamic lubrication lift which has been considered either inside the blade nip or upstream of the nip entrance on the underside boundary of the blade. This lubrication flow is similar to the one occurring in a rotating slider or a journal bearing, which has been a benchmark flow in fluid mechanics.

For the case of bevelled blade coating, the blade nip geometry has been considered as both a converging (Böhmer 1969; Bliesner 1971; Modrak 1973, Hayward 1973) and a parallel (Turai 1971) channel. In the former configuration, the hydrodynamic lubrication lift developed in the convergent flow is considered responsible for blade lifting. In the latter configuration, the blade tip is supposed to remain parallel to the paper surface at all times, so that the gap between the blade tip and the paper surface is equal to the final film thickness. Since the drag flow induced by the moving web can only account for half the coating film thickness, a pressure gradient is needed to derive the other half. That pressure gradient leads to calculating the pressure force which lifts the blade. Experimental results based on lubrication (Follette and Fowells 1960) indicated that coat weight is inversely proportional to blade load. Coating weight increases with increasing machine speed; solids concentration and steady shear viscosity of the coating; the absorbancy and roughness of the paper; and blade extension. It decreases with increasing blade load and the blade thickness, and a backing roll made out of a harder rubber.

(Extension here means the distance from the tip to the location on a blade beam where the blade load is being applied.) In addition, coast weight decreases with an increasing blade angle.
Gastaganis, Cleland, and Wairegi (1977) studied the connection between various operating parameters and coat weight in both bevelled and bent blade coating of paper. For the case of a bent blade mode, coat weight increases with increasing machine speed; blade extension; coating solids content and steady shear viscosity; the roughness and absorbancy of the web; and the backing roll radius. Coat weight decreases with increasing blade angle and decreasing blade thickness. These authors also documented the relationship between coat weight and blade load. Coat weight initially increases with blade load, up to a limiting load, thereafter decreasing as the load continues to increase. The two regimes before and after the maximum coat weight correspond to regions III and IV in Fig. 12.4-6.

Early studies demonstrated that, in both the bevelled and bent operational modes, coat weight strongly depends on properties of the substrate. Since some fibers at the paper surface cross over other underlying fibers and air voids exist between fiber crossings, paper webs have rough surfaces and are porous. Under the same blade configuration and load, more porous and compressible substrates provide comparatively high coat weights (Luciani and Galloni 1978). Among many variables, the porosity of the web depends on the papermaking furnish, mineral additives, paper formation and surface treatment. In particular, externally applied surface treatments onto paper webs are a practical way to improve their coatability. Paper compressibility, on the other hand, is primarily dependent on the papermaking furnish, formation, and consolidation of the fibrous network forming the paper web.

The simple lubrication model cannot fully explain the physics of high-speed blade coating. The blade boundary may not be parallel to the web under all possible operating conditions. The paper may deform under the pressure applied on it by the blade tip and the blade nip gap may therefore be far from parallel. The uniformity of the pressure
gradient upstream of the blade nip is questionable, so is the assumption that the blade can be analyzed as a cantilevered beam. Lubrication approximation does not take into account physical phenomena arising from the free surfaces upstream of the blade and the coating penetration into the substrate. Finally, there is no consideration of the pressure (inertial) force upstream from the blade nip where the excess coating is deflected away. Because of all these complications, more advanced models are required to describe the blade metering process of paper.

All of the previous lubrication flow analyses are based on an one-dimensional model which does not take into consideration the free surfaces, both upstream and at the terminating edge of the blade. The pressure drop across the blade nip has been considered nonexistent since both the upstream and downstream pressures are considered atmospheric. This assumption, however, may not always be valid, especially for the case of pond-type of blade coaters where a puddle is used to feed the blade nip (Fig. 12.4-4c-e). Croty and Higgins (1982) considered a nonzero pressure differential across the blade nip. These authors studied the effect of pressure differential on the load bearing capacity of the blade and found that, for the case of a negative differential, there is no bound on film thickness. When the differential however is positive, there is a limit on the final film thickness.

Drawing from elastohydrodynamic computations, which are discussed in detail in Chapter 12.3, Saita and Scriven (1985) developed a lubrication model which accounts for both the shear-driven (Couette) flow through the blade nip and the pressure-driven (Poiseuille) flow for convergent gaps. In addition to hydrodynamics, these authors considered the elastic forces of the blade, but excluded inertial effects and effects arising from free surfaces and the compressibility and permeability of the web. This model covers the operational behavior of both a low-angle stiff blade and a highly bent blade at
moderate speeds (i.e., 4.5 m/s). The coating thickness in the bevelled blade mode was found to be approximately equal to the blade nip gap, i.e., the clearance between the tip of the blade and the surface of the substrate. In the bent blade mode, the coating thickness was about one half the width of the blade nip. In addition to predicting the qualitative physics of flow (Fig. 12.4-6), this model provided quantitative results which were in agreement with measurements (Saita 1984) of relatively moderate-speed coating of Newtonian and shear-thinning fluids onto smooth, nonporous and incompressible webs. Based on this work, hydrodynamic lubrication dominates coating deposition in bent blade metering.

The above model was advanced by Pranckh and Scriven (1988, 1990) to incorporate the two-dimensional flow in high-speed (i.e., 15 m/s) bevelled blade coating. It accounted for the fluid inertia upstream of the blade nip, the viscous forces on the face and side of the blade, and the pressure force in the blade nip. Computations based on this physical model illustrated that blade load and the working blade angle influence coating deposition in bevelled blade metering, where coating fluid inertia becomes important at high speeds (Pranckh 1989). Derived qualitative relationships are in agreement with experimental results published by Kahila and Eklund (1978b,c), Eklund (1984) and Kuzmak (1986a,b). This model was further expanded to incorporate porous substrates, hence laden air is being displaced by the coating due to pressure- and capillary-driven penetration of the coating into the porous substrate (Chen and Scriven 1989). Computations illustrated that the amount of air trapped within the substrate is critical for determining the hydrodynamic pressure profile at the blade nip. More detail on the elastohydrodynamic models appear in Chapter 12.3. However, quantitative results of these models remain to be verified by controlled experiments.
Key issues in high-speed blade metering of coatings for paper are the role of inertia, from the excess coating striking the underside of the blade upstream of the blade nip, and the roughness and compressibility of the web. Windle and Beazley (1967) and Kahila and Eklund (1978a) emphasized these phenomena, instead of the viscous forces and pressure gradient at the blade nip. According to these authors, high-speed metering evolves by filling depressions (or cavities) of the web, while the blade rides almost in contact with fiber crossings at the web surface. Hydrodynamic lift develops only in the convergent flow upstream of the blade nip entrance, so that lubrication flow exists only in this region. According to these authors, the focal phenomenon involves the coating layer which comes in contact with the blade and changes direction of flow as excess coating is removed from the blade. In doing so, the coating layer transfers momentum to the rigid blade, causing it to deflect.

In the case of bevelled blades, hydrodynamic lift under the tip of the blade may exist temporally and only under unsteady conditions, i.e., when the blade tip is not exactly parallel to the web surface. Eventually, over an extended period of operation, the process attains equilibrium as the stainless steel blade wears out to assume a parallel-plate geometry under the blade tip. Thus, studies by Kahila and Eklund (1978a-c) neglect the fluid viscosity and use potential theory with a simple momentum balance over a control volume at the blade to estimate the force exerted by the coating onto the blade. The inertia generates an 'impulse' force which is similar to the stagnation pressure incorporated in the elastohydrodynamic model (Pransch and Scriven 1988, 1990). This force is significant at high-speed blade metering, i.e., the impulse force is by two orders of magnitude greater than the hydrodynamic lubrication when the blade angle is greater than 28° (Kahila and Eklund 1978b, c; Eklund 1984). Triantafillopoulos and Altug (1991) found that the inertial phenomenon is dominant for determining coat weight in...
bevelled blade coating of paper at speeds between 3 and 5 m/s. The impulse force accounted for more than 90% of the dynamic forces acting on a blade. The strong influence of the impulse force was also verified by Lyons (1993) who analyzed blade metering in a pond-type laboratory coater. Computations showed that the impulse force was by an order of magnitude greater than the hydrodynamic lubrication force. It is therefore important to realize that inertial effects are significant in high-speed bevelled blade coating of paper.

Besides the blade forces acting in the normal direction to web travel, there is the shear force which is parallel to web movement. Kartovaara (1991) showed that the lateral shear force can be as high as thirty percent of the dynamic forces acting on the blade for coater speeds between 5 and 16 m/s. The lateral force is proportional to coater speed, coating viscosity and length of the blade tip (i.e., blade thickness).

Practical experience has shown that, for bevelled blades, coat weight is directly proportional to steady shear viscosity of paper coatings and machine speed. When viscosity increases, i.e., by raising the volumetric concentration of paper coatings, the blade load to obtain a certain coat weight also increases. Although coating viscosity does not appear in the impulse force equation, it influences the mass flow rate approaching the blade which is proportional to the impulse force. Comparatively high viscosity increases the amount of coating picked up by the web at the applicator roll nip and, consequently, raises the impulse force. Another observation from practice is that, under a constant load, coat weight increases proportionally with the coater speed (Fig. 12.4-7). This is because the impulse force is directly proportional to the momentum of the coating layer dragged by the web into the region under the blade. Both trends for coating viscosity and speed observed at high-speed blade metering of paper are the opposite of those observed in low-speed knife coating where lubrication flow is predominant.

24
The contribution of the excess coating layer carried by the web onto bevelled blade nip was also considered by Kuzmak (1986ab). In contrast to Kahila and Eklund, Kuzmak considered lubrication flow inside the blade nip, i.e., between the web surface and the blade tip. This work emphasized the effects of running the blade on its leading (toe) or trailing (heal) edge on coat weight and blade loading (Fig. 12.4-3). In particular, it is necessary to continually increase blade load over an extended period of operation when running on the heel, or decrease the load when running on the toe in order to maintain a certain coat weight. Under constant loading, an increase of the blade tip length - i.e., by using a thicker blade or running at the heel - would decrease coat weight because the effective loading force at the blade tip decreases. When the blade tip area increases, blade loading is distributed over a wider area, the force per unit area decreases and, consequently, coat weight decreases. A constant coat weight in bevelled blade coating is maintained only when the tip of the blade is running parallel to the web surface.

The sensitivity of the system to the exact geometry at the blade tip is an important issue in bevelled blade coating of paper. This issue was discussed by Ramp (1983) and Roper and Attil (1993) who pointed out that running the blade on its toe or heel may lead to web breaks and coating defects, as discussed in more detail in section 12.4.7. The parallel nip geometry is usually the physical state of operation of bevelled blades in practice. Even though sometimes the blade tip is not setup correctly, the stainless steel blade wears out to attain the parallel nip geometry. Under a certain blade load and blade angle, there is only one blade position where the blade nip is a parallel channel and the process remains in equilibrium. Changes in blade loading (i.e., tube) pressure to change coat weight lead to deviations from the parallel nip geometry, something which may increase the possibility for coating defects (Roper and Attil 1993). When the blade loading pressure increases, the blade tip shifts closer to the moving web at the toe and
reduces coat weight. However, this configuration causes the blade tip to form a converging channel with the web, as depicted in Fig. 12.4-3b. A decrease in the blade loading, on the other hand, allows the blade tip to run on its heel and apply more or less coating on the web, depending on the sharpness of the blade tip at its heel (Ramp 1983). This is illustrated in Fig. 12.4-3c. The parallel channel geometry between the blade tip and the web can be maintained only if the mechanical mounting mechanism of the flexible blade is adjusted to compensate for changes in blade loading. It is therefore important to recognize that, when one changes blade pressure to influence coat weight, he also needs to accordingly adjust the blade mounting device to maintain parallel nip geometry at the blade tip.

Although blade wear during the operation of stainless steel blades is an important subject, it has drawn little attention. Hassell (1981) illustrated that blade wear is proportional to the mass flow rate of the coating transferred under the blade and, therefore, depends mainly on coater speed and coat weight. Under a constant load, wear reduces as speed increases, the difference increasing at high blade pressures. Wear also decreases at high coat weights. However, it increases with the abrasiveness of the mineral pigment used in the coating formulation and the roughness of the web. This data indicated that blade wear is independent of the coating viscosity. As a result of wear, which changes the blade nip geometry, new stainless steel blades require readjustment of blade pressure and holder positioning after a few minutes in operation. Recently, ceramic tip blades are used for paper coatings which are free of wear. However, these blades require proper initial setting since they have tips with multiple bevels. Under normal operational conditions, ceramic tip blades have a longer life than stainless steel blades, although care is needed to avoid chipping the brittle tip of the blade.
In addition to fluid dynamics, properties of the coating fluids and the web influence coat weight development in blade metering of paper webs. One consideration is the penetration of the dispersing phase, i.e., the water with all soluble components and small colloidal particles such as latex, into the porous and absorbant paper substrate. This takes place prior to metering and when the coating contacts the moving web for the first time. This process fills the voids in the paper surface and forms a relatively immobilized layer, referred to as the "filtercake", through capillary and pressure penetration. This filtercake has much higher solids content than the bulk of the coating which is fed into the process. Pressure penetration seems to be the more important mechanism (Sandås and Salmiinen 1987) since substantial pressure pulses apply onto the web, in particular at the nip of an applicator roll. These pressures can be as high as 200 kPa in roll applicators, and about 100 kPa in fountain applicators (Eklund 1984). In contrast, the pressure in the case of a pond or short dwell coater is less than 7 kPa (Korpela, Pilsanen, Pitkanen 1986), which is the reason for the widespread preference of this application technique. The low pressure, in combination with the comparatively short coating-paper contact time period in short dwell coaters, minimizes water absorption by the paper (cellulose) fibers prior to metering. In contrast, substantial absorption occurs before the blade in the case of a coater with an applicator roll.

An indirect consequence of water leaving the coating and entering the substrate is that cellulose fibers absorb water from the coating and swell. Swelling influences both the coat weight pickup at the blade, as well as paper properties dependent on changes occurring at the paper surface. Qualitative differences which exist between papers coated with an applicator roll and a short-dwell coater have been attributed to fiber swelling and its occurrence before or after the blade metering process (Ekland 1984). For coating with an applicator roll, fiber swelling occurs prior to metering. When the fibers swell, the web
surface becomes rougher, requiring heavier blade loading to deposit a certain coat weight as the blade fills in the volume of the surface voids of the web. The blade acts as a smoothing device by covering the surface contour of paper. In contrast, fiber puffing and swelling take place after the blade metering step in the case of a short-dwell coater. This leads to a relatively rough final coated surface which adversely affects optical and printing properties. Consequently, papers coated with a short-dwell coater have inferior surface characteristics to those coated in a blade coater with an applicator roll.

In addition to substrate properties, the non-Newtonian flow behavior of paper coatings influences coat weight. Typically, higher steady shear viscosity leads to higher coat weight under a constant blade load, or higher load to obtain a targeted coat weight. A complication is that the blade metering process involves regions with a wide range of shear rates (Pranckh and Scriven 1988). Stagnation regions appear next to areas where the shear rates is substantially high. Typical paper coating dispersions are shear thinning, while they exhibit significant yield stress and thixotropic recovery. They also demonstrate viscoelastic behavior at least at low strains rates. When the volumetric concentration of the dispersion exceeds a certain level, paper coatings become dilatant. Low shear viscosity - obtained with single-point, rotating spindle type of instruments - is used to determine the ability to bring paper coatings to the metering zone, while high shear viscosity - obtained with a concentric cylinders viscometer - is used to determine the required blade load to attain a certain coat weight. Böhmer (1969) was the first to estimate that, when considering the coating film thickness at the blade nip to be about 10 μm, the shear rates in the blade nip of a coater running at speeds of practical interest can be as high 10^6 1/s. Viscometric data at these high shear rates are not readily available for paper coatings, although measurements with capillary viscometers have recently
appeared in the literature (Roper and Attal 1993). Considerations of the non-Newtonian rheology of paper coatings are discussed in more detail in section 12.4.6.

In summary, the physics of high-speed blade metering of paper webs involve complex phenomena and their interactions. Viscous forces, developing in the blade nip and at the underside of the blade, and pressure forces in the blade nip, contribute to deflecting the blade, but the inertia of the coating layer reaching the blade also plays a significant role. Although lubrication flow seems to be the dominant mechanism for bent blades, the impulse of the coating layer striking the side of the blade is an important mechanism for deflecting bevelled blades. The interaction of the blade forces under conditions of practical interest, i.e., where non-Newtonian effects of the coating fluid and the absorbancy of the web come into the picture, is still an issue for investigation. Although computational fluid dynamics shed light in the mechanisms of high-speed blade metering, there has not yet been a comprehensive model which also incorporates phenomena occurring during the application of the coating prior to metering. In addition, the influence of the paper absorbancy and compressibility to the final film thickness need to be further investigated, in particular as these properties influence formation of a filtercake prior to metering and correlate with swelling of paper fibers and roughening of the sheet. The exact mechanism of filtercake formation has not yet been studied in depth, so that the operational behavior of the process is difficult to predict and control. A point worth noting in the case of bevelled blade coating is the influence of blade nip geometry. The blade remains in equilibrium only when the geometry is a parallel channel. When the channel is convergent or divergent, coating defects appear, even though the rheology of the coating fluid has been optimized. Rheological phenomena occurring during the high-speed blade metering process and coating defects are discussed in sections 12.4.6 and 12.4.7, respectively.
12.4.4 HYDRODYNAMIC INSTABILITY IN BLADE COATING

The ideal coating flow is steady state and two-dimensional, that is, there are no temporal or cross-stream flow variations. Any instability would almost always result in a transition to a three-dimensional or unsteady state. Consequently, the film thickness becomes nonuniform. If the transition is to a two-dimensional time dependent state, there will be coating film thickness nonuniformity in the streamwise (machine) direction. Transition to three-dimensional flow will result in cross-stream variations referred to as streaks.

There are a number of regions in high speed blade coating where the flow could become unstable. The most critical modes of instability are the transitions from a two-dimensional to a three-dimensional state (i.e., a symmetry breaking bifurcation). This transition could take place at the blade nip, in the case of a diverging gap, or at other locations upstream of the blade (Aldun 1991a-c).

In pond application systems, the most serious instabilities are of a centrifugal type which occur inside the pond. In the pond, the base state consists of recirculating eddies which are almost two-dimensional over most of the coater width, except near the side walls where an Eckman-type layer forms. In actual coaters, the coater width is at least two orders of magnitude larger than the pond depth. Therefore, the effects of the sidewalls on the flow can be assumed to be a perturbation of the two-dimensional flow.

In this section, we focus on the pond of these coaters which is very similar to a lid-driven cavity, a rectangular section where the top surface moves with a constant speed. In practice, the top surface is the substrate that is being coated. Since we are interested in
the stability of the flow inside the cavity, we assume that all of the surfaces are smooth and impermeable. The substrate is usually being transported by circular rolls. However, since the radius of the roll is much larger than the streamwise length of the cavity, we assume that the top surface is flat. In the experiments outlined below, the roll diameter is 24 inches where the streamwise length of the cavity is only 2 inches long.

The parameters that govern the flow characteristics are the cavity aspect ratio and the cavity Reynolds number

\[ Re = \frac{\rho UD}{\mu} \]

where \( U \) is the lid velocity, \( D \) is the cavity depth, \( \mu \) and \( \rho \) are the fluid viscosity and density. Let us begin with the simplest case -- a lid-driven cavity with infinite span. The Navier-Stokes and Continuity equations given by

\[ u_t + \text{Re} \left( u \cdot \nabla u \right) = \nabla p + \nabla^2 u \quad \text{in } \Omega \]  
\[ \nabla \cdot u = 0 \quad \text{in } \Omega \]  

(1a)

(1b)

govern the flow in the cavity domain defined by \( \Omega \). The velocity vector, \( u \), pressure, \( p \), and time, \( t \), are scaled with the lid velocity, \( V \), pressure scale, \( \rho V/D \), and time scale, \( D^2/\nu \), respectively, and the cavity depth, \( D \), is used as the length scale. The boundary conditions are no slip walls, given by

\[ u_{\partial \Omega} = (V,0,0) \quad \text{and} \quad u_{\partial \Omega \setminus \partial \Omega} = (0,0,0) \]  

(2)

where \( \partial \Omega \) is the boundary of \( \Omega \) and \( \partial \Omega \) represents the top surface. At a sufficiently small value of \( Re \), the solution to this system represents a two-dimensional (2D) flow given by
The boundary integral form of this solution is available for creeping flows, and in numerical form, for a wide range of Re by many investigators (for example see Bozeman and Dalton 1973; or Nalassamy and Krishna Praasad 1977). In practice, however, this solution becomes unstable at a critical Reynolds number, $Re_C$, and most likely gives rise to a steady cellular flow (symmetry breaking pitchfork bifurcation). The value of $Re_C$ and the wavelength of the critical mode, $\lambda_C$, depend on the length, H, to depth, D, aspect ratio, H/D. The three-dimensional (3D) solution near onset can be approximated by separating variables in the linearized disturbance equation (see chapter 8 for more information on linear stability analysis) and using a trigonometric representation in the z-direction. The critical disturbance mode at onset is then given by

$$u' = [u'(x,y) \cos Z, v'(x,y) \sin Z, w'(x,y) \sin Z]$$

(4)

where $Z = 2\pi(z-\alpha)/\lambda$, $\lambda$ is the wavelength of the periodic cellular flow, and $\alpha$ represents an arbitrary phase of the disturbance structure. Since the flow close to the critical Reynolds number is a superposition of the two-dimensional base flow and the critical disturbance mode, represented in (4), then the new state is a three-dimensional flow pattern with periodicity in the spanwise direction.

Now consider a cavity with finite span, L, and free-slip end walls where the boundary conditions at the end-wall planes, $\partial \Omega_a$, are given by

$$w = 0 \quad \text{and} \quad \frac{\partial u}{\partial n} = \frac{\partial v}{\partial n} = 0 \quad \text{on} \quad \partial \Omega_a$$

(2)

Here also the steady two-dimensional solution (3) satisfies the boundary conditions (2). The bifurcating 3D solution at onset can be represented by (4) with the eigenfunction, $Z$. 

32
modified to \( n \pi z / L \), where \( n \) is the wave number of the destabilizing disturbance structure inside the container, and the phase angle, \( \alpha \), being no longer arbitrary, is set to zero.

Modes representing an even or odd number of cellular patterns can become critical and destabilize the 2D base solution as shown in Fig. 12.4-8. Here the vertical (horizontal) plane represents solutions with an odd (even) number of cellular patterns.

Since the slip condition at the end wall given by (2') is also a symmetry condition, the similarity mapping used by Aidun (1987) applies. Therefore, from the stability boundary for a single cell pattern, \( R^*_c(L) \), the entire stability boundary for the initial bifurcation point can be mapped by the transformation

\[
R^*_c(L) = R^*_c\left( \frac{L}{n} \right) \quad \text{where} \quad n=1,2,\ldots\quad (5)
\]

The expected form of the stability boundary predicted by Eq. (5) is shown in Fig. 12.4-9. This figure shows the effect of the cavity span on the critical Reynolds number for transitions from a two-dimensional flow, ideal for coating systems, to a three-dimensional flow which results in coating nonuniformities.

Let us next discuss the real driven cavity system where the no-slip condition applies to the end wall as well as any other solid boundary.

In a series of experiments, Aidun, Triantafyllopoulos, and Benson (1991) and Benson and Aidun (1992) investigated the stability of flow in a driven cavity with span to depth aspect ratio of 3 to 1. Their experimental setup consisted of a roll driving the fluid inside a rectangular cavity, as shown in Fig. 12.4-10. This is similar to the setup of Pan and Acrivos (1967), although in these experiments, the roll diameter is considerably larger than the cavity and, therefore, the penetration is about 2\% compared to 8.5\% (of the cavity width) in Pan and Acrivos’ experiments.
The cavity, placed on top of a lower compartment (Fig. 12.4-10a), makes contact with the roll and has length $H=5.08$ cm in the direction of roll motion, depth $D=5.08$ cm, and span $S=15.24$ cm transverse to the direction of roll motion. Thus, the characteristic geometric parameters are 1:1 and 3:1 for depth- and span-to-length aspect ratios, respectively. The lower compartment has the same dimensions but a depth of only $2.54$ cm and serves the purpose of feeding fluid uniformly into the cavity.

A very thin film of fluid adheres to the roll and escapes the cavity through the downstream lip EC. This layer of fluid is scraped off of the roll by a sharp blade downstream of the cavity. At the bottom of the cavity adjacent to the Gk corner, a narrow slot (3 mm opening) opens into the lower section which is connected to a pump and acts as a reservoir for replenishing the fluid that escapes the cavity.

Fluid is supplied to the lower section of the cavity via a 1.00 cm pipe tap from one side. The observed flow patterns show that the flow through the slot into the cavity is uniform over the span.

At a low Reynolds number, the flow is steady and almost two-dimensional. However, as the Reynolds number increases above 825, the steady flow destabilizes and gives rise to a time periodic state with an oscillation frequency of about $0.1U/\ell$. Flow visualization of the time periodic state shows small-amplitude time periodic waves appearing on the downstream secondary eddy starting out at the middle symmetry plane and traveling towards the side walls. As Re increases, these traveling waves become more clearly visible (see Fig. 12.4-11b) until a second incommensurate frequency, $0.0056U/\ell$, appears at Re above 990.

Benson and Aidun (1992) show that the flow remains quasiperiodic up to $Re=1055$ where many other modes are excited and a broad band of frequencies appear signaling
the existence of a low dimensional chaotic state. Figure 12.4-11d, shows the flow at Re=1900. At this state, the mushroom shaped vortices appear and disappear randomly inside the cavity. These structures are similar to Gortler-like vortices that Koseff and Street (1984a-c) have reported at higher Reynolds numbers.

The length scale of the vortices presented in Fig. 12.4-11d is comparable to a class of streaks that are observed at high speed with pond application systems such as the short-dwell coater. However, others issues such as air entrainment become important mechanisms which promote defects in coaters of this type. Recent experiments (Veverka and Aidun, 1991; Li and Burns, 1992) indicate that air entrainment is another significant cause of coating streaks.

12.4.5 AIR ENTRAINMENT

Application of a thin liquid film on a flat substrate involves displacement of air by liquid. With flexible substrates, such as paper, photographic films, or magnetic tapes, the coating is continuously applied to a moving substrate. The speed of the substrate and, therefore, the rate of coating is limited by the maximum critical speed of displacing the air. Beyond the maximum wetting speed, air cannot be effectively displaced, and some patches of air remain on the surface or entrain into the liquid.

With the increasing demand for higher production rates, air entrainment has emerged as one of the leading problems in the coating industry. By air entrainment we mean a physically isolated patch of air or bubble that enters into the liquid phase. In pond application systems, the air gradually accumulates in low pressure areas. These air
pockets interact with the substrate and generate coating defects mostly in the form of streaks on the surface (Aidun 1989).

The critical speed for onset of air entrainment has been measured by many investigators (Kennedy and Burley 1977; Burley and Kennedy 1976; Bolton and Middleman 1976; Blake and Ruchak 1979; Burley and Jolly 1984; Sullivan and Middleman 1979; see chapter 3 for more detail). Some of these measurements, however, are subjective and show inconsistent behavior. For example, some studies (Kennedy and Burley 1977; Burley and Kennedy 1976) indicate that the substrate entry angle significantly affects the critical air entrainment speed, while other studies (Bolton and Middleman 1976; Blake and Ruchak 1979) show no relation between the two. The effect of surface roughness on the critical speed for air entrainment has also remained unclear; some studies (Burley and Jolly 1984) show a strong interdependence, while others (Sullivan and Middleman 1979) indicate otherwise. It is probably the different experimental setups and substrate materials that are responsible for some of the inconsistencies.

In this section, we focus on the physical mechanism of air entrainment in blade coating systems. In particular, we investigate the sequence of events which lead to formation of air bubbles and their entrainment into the liquid. We recognize at least two regimes of air entrainment (Scriven 1982): (1) a microscopic regime, proposed by Miyamoto and Scriven (1982) and further investigated by Miyamoto (1991) and (2) a second regime at macroscopic scale where air bubbles in the order of few hundred microns and larger form at the wetting line and penetrate into the liquid.

In the microscopic regime, it is hypothesized that a thin air layer, less than a micron, forms at the dynamic contact line. Miyamoto and Scriven (1982) analyzed the two-dimensional idealization of this flow and concluded that Kelvin-Helmholtz-type
Instabilities are likely to occur for thicker gas films, while a ‘disjoining collapse’
instability of the interface will dominate for thinner air layers. Miyamoto (1991) presents
some experimental evidence of massive shear instability of the air film and formation of
_craters_.

This section focuses on the macroscopic regime of air entrainment where the entrained
bubbles are too large to dissolve in the liquid and, therefore, remain as air bubbles in the
liquid.

To study the kinetics of wetting, Deryagin and Levi (1964) used a simple slot-like
coating apparatus to reproduce the process of coating an emulsion on a flexible substrate.
They used a wetting hopper with a square cross-section with sides equal to 2.4 cm.
Using visualization techniques, they observed the deformation of the wetting line as they
increased the substrate speed. At low base velocity of a wettable liquid/solid system, the
contact angle is small, and ‘perfect wetting’ is observed. As the coating speed increases,
the meniscus deforms, and the contact angle increases to 180° as shown in Figure 12.4-12.
They report that at this critical speed, a shift in the contact line is observed by the
appearance of a triangle where contact between the liquid and the substrate is broken. As
the substrate speed increases further, the triangular area grows to a point where the brake
extends over the entire length of the contact as illustrated in Figure 12.4-12b.

The pioneering work of Deryagin and Levi (1964) reveals an important event and
limitation in the wetting of solids by liquid. A contact line, originally straight, breaks
into a sawtooth pattern at a critical speed where the contact angle reaches 180°. In the
ideal situation where the contact line is infinitely long, this behavior can be viewed as a
transition from a two-dimensional flow to a three-dimensional state.

37
Blake and Ruchak (1979) attribute this behavior to a maximum wetting speed above which the contact line has to break into a V-shaped pattern so that the effective wetting speed falls below the maximum value. A rigorous analysis of the contact line instability and formation of triangular air pockets remains to be undertaken.

Many experiments, as outlined above, show that a prerequisite for air entrainment in the wetting process of a smooth surface is the formation of these structures. The events that follow this transition and lead to air entrainment in low speed roll coating systems are discussed by Veverka and Aidun (1991) and Aidun, Veverka, and Scriven. (1992). There is some evidence that the same sequence of events also leads to air entrainment with high speed pressurized pond application blade coating systems. The difference is that with pressurized pond systems, the fluid is forced out of the cavity at the overflow baffle near the contact line (see Fig. 12.4-4e) substantially delaying air entrainment to higher speeds.

There is now direct evidence of the serious adverse effects of air entrainment in pond application systems. In a series of experiments with acetal pressurized pond coating systems, Li and Burns (1992) showed that the accumulation of air inside the coating cavity results in streaks at speeds much below the 'skip' coating regime. They used typical paper coating liquids with a small amount of fluorescent dye. The dye was added to detect the nonuniform coating thickness patterns under ultraviolet light after the coated samples were dried. The substrate used was paper and the coating speed was varied from 15 to a maximum of 25 m/sec. To examine the effect of air accumulation in the pond, Li and Burns (1992) placed a ventilation tube inside the pond. A series of experiments was completed with the ventilation tube extracting air from the pond. A second set of experiments was conducted under the same conditions with the ventilation tube blocked so that no air could be extracted from the pond. In their experiments Li and Burns (1992)
clearly document that in every case, extraction of air significantly reduced the coating thickness nonuniformity and streaks on the surface.

12.4.6 NON-NEWTONIAN RHEOLOGY IN BLADE COATING

Paper coatings comprise highly concentrated dispersions of mineral particles, with volumetric concentrations in excess of 40 percent by volume. Flow characteristics are generally determined by the volume fraction of the disperse phase, the magnitude of interparticle forces, and the structure of the flocculates formed. In addition, the dispersing phase of paper coatings contains polymers which may or may not be water soluble. Although these polymers are added at small amounts (typically 0.1% to 5%), they substantially affect coating rheology. Polymers function by inducing a network structure which physically bounds polymer molecules and/or dispersed particles. This structure leads to development of yield stress and viscoelasticity at low shear. At high shear rates, forces holding the network structure are disrupted leading to shear thinning. This structural breakdown is also associated with time-dependent rheological behavior, known as thixotropy. Typical coating dispersions, therefore, have high viscosity at low shear rates and low viscosity at high shear rates. At increased particle concentrations, however, paper dispersions become increasingly non-Newtonian, independent of the flow behavior of the dispersing phase.

At low stresses, coating dispersions show not only plastic behavior but also viscoelasticity. In addition to polymeric network structures, these rheological phenomena arise from three-dimensional network structures formed due to intermolecular interactions between pigment particles. When subjected to low shear stresses, these structures undergo a dynamic equilibrium between structural breakdown and

39
re-formation under the applied shear stress and exhibit primarily elastic deformation and a high viscosity. Consequently, in addition to flow curves which describe the relationship between shear rate and shear stress, rheological characterization of paper coatings requires controlled-stress and dynamic viscoelastic measurements.

The rheological behavior of paper coatings plays an important role during processing and application in a high-speed blade coater. It determines not only the coating flow at the blade nip, but also the flow feeding the application zone. Rheology influences the hydrodynamics upstream of the blade through the steady shear viscosity and plastic yield. Once at the blade nip, high-shear viscosity and, possibly, viscoelasticity affect the blade deflection and the final film thickness (or coat weight). After the blade nip, thixotropic recovery contributes to the post metering behavior of the coating layer. Although the effect of rheology on high-speed blade coating for paper is an evolving field of research, there exist some documented correlations between coating rheology and coatability. The following paragraphs point these out, while addressing the main unresolved issues. For comparison, reference is also made to rheological effects in the relatively low-speed blade (or knife) coating.

Viscoelasticity in high-speed blade coating of paper can be assessed from the Deborah number, \( D = \lambda \gamma / t \), where \( \lambda \) is the characteristic relaxation time of the coating liquid or dispersion, and \( t \) is the characteristic residence time in the process flow. Most coating materials have a very broad relaxation behavior and, therefore, exhibit a slow change of storage and loss moduli with frequency (Goodwin 1989). For example, typical values of the relaxation time for paper coatings are in the range of 0.1 to 5.0 seconds (Roper 1990; Salminen and Fors 1992). These values correspond to the time period for the shear modulus to decrease half of its value at 0.01 seconds in a dynamic rheometer. Values obtained with this method represent quantitative approximations of the characteristic
relaxation spectra. Considering that a typical residency period at the blade nip is approximately in the order of magnitude of $10^{-5}$ seconds (Kline 1985), the De is much larger than 1. Such high Deborah numbers suggest that paper coating dispersions could behave like elastic solids rather than mobile liquids during their application.

Similar or larger Deborah numbers are common in coating of polymeric liquids onto smooth and impermeable substrates. The effect of viscoelasticity on coating film thickness has been well documented for the case of lubrication flow in rigid blade coating (Middleman 1981). Prediction of the film thickness (or coat weight) requires consideration of the normal forces arising from the viscoelasticity of the polymeric liquid in addition to viscous forces (Hsu, Malone, and Laurence 1985). Theoretical and experimental studies have shown that, while the non-Newtonian shear viscosity influences the flow and pressure distributions at the nip, viscoelasticity affects blade loading (Greener and Middleman 1974; Hsu, Malone, Laurence 1985; Hsu 1986). Particularly, viscoelasticity contributes to the separating (normal) force which tends to push the bounding surfaces of the web and blade apart. The separating force increases with flow velocity, i.e., the speed of the backing roll (Hsu 1986). For relatively high flow velocities, the load capacity on a stationary blade over a moving plate can be up to 50 times greater for a non-Newtonian viscoelastic lubricant than for a Newtonian fluid (Doremus and Pian 1981). In addition, much less fluid is carried through the gap in the case of viscoelastic fluids, while both the stagnation point of the flow and the maximum normal stress absissa move closer to the gap (formed between the blade and the plate) center (Doremus and Pian 1983). Theoretical analysis (Greener and Middleman 1974) of the lubrication flow in a blade nip indicates that, as compared to a Newtonian fluid, the pressure developed under the blade decreases for a polymeric viscoelastic fluid and increases for an elastic Newtonian (Boger) fluid. Sullivan (1986) demonstrated that film
thickness increases with purely viscous shear-thinning fluids, while viscoelastic fluids, which have both viscous (shear-thinning) and elastic behavior, cause the film thickness to either increase or decrease depending on the relative contributions of shear-thinning and elastic effects. For the case of fluids with the same viscosity but different elasticity, film thickness decreases as elasticity increases. This trend is also valid for a Newtonian fluid having elastic properties, i.e., a Boger fluid. In a blade-over-roll geometry, the coating film thickness increases with both the blade angle and blade extension, although coating films of highly elastic Boger fluids are independent of blade nip configuration (Sullivan, Middleman, and Keunings 1987). Furthermore, the operability window of blade coaters shrinks with viscoelastic liquids (Stenger, Secor, and Stamek 1992). The limiting factor is the appearance of ribbing instability on the coating film. This defect is associated with converging blade geometries where inclusion of elastic normal stresses in the lubrication model predicts, for high inclinations (i.e., large blade angles), a rising pressure at the exit from the channel. Because of the complex rheology of polymeric liquids, which exhibit both viscous and elastic behavior, it is difficult to exclusively attribute their flow behavior at blade nips to viscoelasticity. Many times elastic effects compete with viscous behavior (shear thinning), making prediction and control of the final film thickness difficult to achieve.

The role of viscoelasticity in high-speed blade coating of paper is further complicated. The highly concentrated coating dispersion contain orientable particles and polymeric additives which interact with the dispersed phase in many different ways to affect rheology. In addition, paper webs are compressible, nonuniform, permeable, and filled with air. Water soluble binders and additives - such as starch, carboxymethylcellulose, hydroxyethylcellulose, polyvinyl alcohol, etc. - added to paper coatings induce viscoelasticity and increase viscosity at low shear rates. However, they also make the
coatings shear thinning at high shear rates. Therefore, it is difficult to separately assess the viscous and elastic contributions of rheology to the flow at the blade. Results by Sullivan (1966) suggest that shear thinning, characteristic of paper coatings, may offset the effect of elasticity in the case of viscoelastic coatings.

Normal forces due to viscoelasticity could influence the flow and the force balance in and around the blade nip during high-speed blade metering of paper coatings. This, in turn, could affect the final coat weight obtained under a given set of process conditions. Elasticity is expected to generate substantial normal forces perpendicular to the flow direction when the coating is flowing out from the restricted channel under the blade and the relaxation time is sufficiently long (Ginn 1974, 1977). Then, normal forces and viscoelasticity need to be taken into account when setting up the operating parameters of the process. Windle and Beazley (1967, 1968) analyzed the flow beneath a bevelled blade based on the hydrodynamic lubrication flow in a converging wedge and considered paper compressibility and roughness in determining coat weight. These authors suggested that the hydrodynamic lift acting on the blade arises, at least partially, from the normal forces of coating viscoelasticity which contributes to the total thrust of the flow through the nip. However, laboratory coater experiments with coatings containing clay, styrene butadiene latex and starch, and having the same low-shear viscosity but different low-strain elasticity did not yield significantly different coat weights. Windle and Beazley (1968) attributed their inability to document the effect of viscoelasticity to (a) failure to separate the viscous from the elastic contributions to the dynamic forces acting on the blade, and (b) the possibility that the passage of the coating through the blade nip might be viewed as fracture of a weak elastic solid rather than flow of a viscous liquid.
It is important here to recognize that characterization of coating viscoelasticity is usually based on oscillatory dynamic measurements at low deformations. These measurements are not sufficient to characterize the behavior of coatings at the very fast deformation process in the blade nip. Similar to steady-shear viscosity measurements, viscoelastic measurements cannot be extrapolated from low to high deformations. The problem is that it is difficult to measure viscoelastic properties at shear rates of the order of $10^5$ to $10^6$ s$^{-1}$ which are experienced under the blade and inside the blade nip.

Attempts to measure the normal forces exerted by paper coatings are based on viscometric measurements in capillary flows. Kurath (1965, 1974) documented that normal stresses are much larger than shear stresses for clay dispersions in a starch solution, increasing with the shear rate and volumetric concentration. However, the dependence of normal stresses on concentration was limited to clay/starch coatings and did not make any difference in a coating containing clay, calcium carbonate, and starch.

It is also worth noting that the magnitude of normal stresses depends not only on the type of mineral pigment used, but also the size and shape of the pigment. Kurath (1974) found that, when a fine particles clay was substituted with a delaminated (platey) clay in a starch formulation, both shear and normal stresses increased substantially under constant shear rate (i.e., $17.4 \times 10^4$ s$^{-1}$). For the clay/carboxymethylcellulose coatings tested by Granqvist and Sandääs (1990), normal forces increased exponentially with shear rates above $10^5$ s$^{-1}$. At constant shear rate, normal forces increase with the molecular weight of the carboxymethylcellulose and its addition level. Laun and Hirsch (1990) investigated the normal forces of two coatings (64% solids by weight), one of the coatings demonstrating absence of any normal forces, while the second one - which was dilatant at shear rates between $10^3$ and $10^5$ s$^{-1}$ - had normal stress differences which were five times greater than the corresponding shear stresses. It is possible,
therefore, for high-solids coatings which are resilient, and consequently behave like elastic solids as shear rate increases, to demonstrate substantial normal forces in shear flows when the shear rate is sufficiently high, i.e., above $10^5 \text{s}^{-1}$. The dependence of normal forces on shear rate follows the well-known relationship of normal stresses being proportional to the square of shear velocity (Granqvist and Sandás 1990).

Normal forces may also arise from shear induced structures (Brady and Bossis 1988) formed across shear planes existing between the blade and the web. Computer simulations (Bosfield 1990) illustrated that shear in the gap, formed between the paper and the blade surface, can cause an ordered arrangement of pigment particles such that "bridging" between the two boundaries occurs. Formation of bridges develops an additional normal force, which can be as much as four times the normal force occurring originally. Bridging frequency increases rapidly with increasing solids content of the coating.

The recent growth of interest in understanding the physics of blade metering and coating rheology is partly due to higher machine speeds and lower coat weights. Currently, many industrial coaters run in excess of 24 m/s and apply from 4 to 10 grams of coating per square meter of paper. When the machine speed increases, the deformation process under the blade becomes faster and the Deborah number increases, while large transient stresses develop due to the relatively high blade loadings. Such process conditions, coupled with the trend toward coatings with high volumetric concentrations, make consideration of normal forces in high-speed blade metering of paper webs more realistic.

In summary, the non-Newtonian behavior of paper coating dispersions arises from interparticle interactions and the network structure of polymeric additives. Most paper
coatings are viscoelastic at low strain rates, demonstrate substantial yield stress, and are shear thinning anisotropic over a broad range of shear rates. The magnitude of the characteristic rheological parameters depends primarily on volumetric concentration and the amount and type of polymeric additives and, secondarily, on the particle size and shape of the mineral pigments used. The viscoelasticity of paper coating dispersions is substantially lower than that of polymers. Although viscoelasticity prevails at low strain rates, the elastic network structures break down with shear so that, at high shear rates, paper coatings behave like viscous suspensions. The degree of shear thinning depends on the coating formulation, i.e., coatings with soluble polymers have relatively high low-shear viscosity and low high-shear viscosity. Suspensions of coarse, highly anisometric pigment particles demonstrate comparatively high elasticity at low shear and viscosity at high shear. Although most paper coatings do not demonstrate significant elasticity at high shear rates, coatings with extremely high volumetric concentration become dilatant and behave like weakly elastic materials. The large Deborah number makes processing of these type of coatings in a high-speed blade coater problematic. However, there is not yet a clear connection between rheological properties of coatings and their processability at high-speed coaters. This is partly due to interactions between the coating dispersion and the substrate, such as formation of a filtercake on top of the web prior to metering and the swelling of cellulosic fiber of paper when they come in contact with a coating dispersion. Furthermore, it is not yet known how the coating layer rheology after metering and before drying influences the appearance of coated surface defects and the end-use properties of paper.
12.4.7 BLADE COATING DEFECTS

As with any coating operation, a defect free surface is important in maintaining consistent and sustainable productivity and product quality in high-speed blade coating. Although there are many different types of defects appearing in the various applications of the blade coating process, here we concentrate only on blade coating defects on paper webs. Furthermore, the focus is on defects arising from process flow dynamics and properties of paper coating dispersions.

Good runnability usually means coating without visual film defects on the coated surface and a uniform coat weight (or film thickness) in both the machine and cross-machine directions. In the development of a coating formulation strategy, good runnability also means being able to obtain a certain coat weight at comparatively lower blade loads. This leads to lower blade forces acting onto the web, thus minimizing the possibility for web breaks. Indeed, coater runnability becomes more important as the speed of commercial coaters increases beyond 24 m/s and the coating film thickness continually reduces.

Most of the common visual defects in blade coating appear in the form of scratches, skips or streaks on the coated surface. Scratches usually appear in the form of fine hair-like indentations (less than 3 mm in width) in the coating layer running along the machine line direction. Skips are associated with a patterned surface appearance because of areas devoid or depleted of coating. The appearance of skips is associated with air inclusion or entrapment into the coating pond or in a region upstream the metering blade. Streaks, on the other hand, appear in various forms. Narrow streaks take the form of relatively narrow indentations, 5 mm and up to a few centimeters in width. Wider streaks can be as broad as several centimeters and form bands of heavier coat weight running along the
machine direction. All of these defects are easy to observe when paper samples are viewed with transmitted ultraviolet light. Streaks appear as variation of opacity across the web, while scratches appear as thin, less opaque lines. The origin and mechanisms responsible for these defects are numerous, some of them discussed in more detail in the sections about air entrainment and hydrodynamic defects (Sections 12.4.4 and 12.4.5).

The appearance of scratches depends on properties of all three components in a blade coating operation; namely, the base paper, the coating dispersion, and process parameters or blade nip geometry. Usually this defect is a problem with bevelled but not bent blades. Huang (1984) separated scratches into mechanical and rheological based on their origin. 'Mechanical' scratches are attributed to the entrapment of foreign matter in the blade nip. These materials may be loose fibers from the web, contaminants in the coating stream, non-dispersed or aggregated mineral pigments in the coating, poorly prepared soluble binders or thickeners, etc. Additionally, hard spots on the bevel of the blade or chipping of a ceramic blade can cause scratching of the coated surface.

'Rheological' scratches are associated with properties of both the coating dispersion and the base sheet. The coating needs to have good 'water holding', also known as water retention. Water holding defines the capability of a coating dispersion to control release of its dispersing phase when it makes contact with the porous web during processing (Eklund 1981). Water and solubilized materials are released from the coating by capillary and pressure penetration, but the dominant mechanism for dewatering is pressure penetration experienced by the coating dispersion at the nip of the applicator roll and under the blade (Sandlås and Salminen 1987). Water retention is associated with the physical and chemical state of network structure present in the dispersion due to inter-particle interaction and the presence of polymeric additives. Consequently, it depends on the type of mineral pigment used, and its ability to form an array of closely
packed particles under the influence of an external pressure pulse; the low shear viscosity of the coating and the liquid phase; and the nature of structural networks due to presence of polymeric additives. Water holding additives used in paper coatings may be soluble or insoluble in water. Typical additives are carboxymethylcellulose, hydroxyethylcellulose (and their associative derivatives), alginates, polyvinyl alcohol, polyurethane associative thickeners, alkali swellable latices, etc. Soluble binders and their modification, such as starch and proteins, are also inducing some water retention in paper coatings.

Experiments by Gane, Watters, and McGinity (1992) illustrated that the coating layer, or filtercake, formed next to the web prior to metering has a higher solids concentration than the coating at the application station or feeding stream. Coatings with good water retention, however, do not loose substantial water and soluble matter into the basesheet at the applicator roll and the blade nips. Because of that, the filtercake build onto the web before metering maintains a solids content close to that at the application zone.

Associated with water retention is the term 'immobilization solids', which represents the volumetric concentration at which a coating dispersion has almost infinite shear viscosity - the coating becomes dilatant. For a coating dispersion with a certain solids content, the characteristic immobilization solids are closely connected to water retention. Ideally, coating immobilization should occur after the blade metering step of the application process (Eklund 1981). Excessive dewatering prior to metering can cause the filtercake formed onto the web to become dilatant. In turn, a dilatant filtercake reaching the blade nip can generate scratches and narrow streaks (Huang 1984, 1986).

Coating dewatering also depends on properties of the basesheet; namely its surface pore structure, compressibility, smoothness, and absorbancy. An 'open', absorbent basesheet tends to take up more water from the coating and, therefore, increases the solids content of the filtercake layer formed prior to metering next to the web. Coating immobilization
before the blade nip is responsible for the appearance of scratches or narrow streaks due to entrapment of particles or particle agglomerates at the blade nip. Furthermore, scratches and streaks can be generated from poor water retention at the stagnation line, appearing on the blade boundary, of the converging flow upstream the blade nip (Pranckh and Scriven 1988). Eventually, new coating material reaching the blade will push large agglomerates deposited at the stagnation line through the blade nip. As a result, streaks and scratches due to this mechanism are temporal in nature, disappearing over a long time of operation.

The exact mechanism of interaction between water retention and the substrate is not yet completely understood. Water leaving the coating layer on top of the traveling web is absorbed bycellulosic fibers ofthe web, thus causing them to swell and rise. Fiber rising, in turn, influences the quality of the coated surface and properties like gloss. In systems with an applicator roll, fiber swelling takes place prior to the blade nip, while in the case of a short dwell coater, swelling takes place after the blade since the fibers do not have enough time and the coating does not experience high normal pressures prior to metering. Consequently, there are differences in the final quality of papers coated with each one of these two types of coaters (Eklund 1984). Although the rise in coating solids concentration between the application and metering steps has been documented, little is known about the exact mechanism of the dewatering process. Recent computational work suggests that dewatering occurs through a filtration process (Letzelter and Eklund 1993).

The origins of visual coating defects and large scale (i.e., several centimeters in width) coat weight nonuniformities at high coater speeds are still under investigation. In addition to other blade coating variables, such as the basesheet and blade nip geometry, the coating formulation plays an important role. The major formulation variables are:
the choice of plas tic pigment particles (i.e., delaminated clays) and their size distributions, the continuous (dispersing) phase rheology, and the solids content of coatings.

Experimental evidence suggests that the ability of highly anisometric particles to orient parallel to the flow direction in the blade nip might be critical (Gane and Coggan 1987).

Among other variables, particle orientation depends on rheological and viscoelastic properties of the continuous phase. Furthermore, it seems that the rapidly accelerating flow at the converging geometry near the blade nip would generate elongation (or stretching) along the streamlines of the flow, thus introducing the elongational viscosity of the coating as an additional variable. In that sense, the flow in the blade nip can be viewed as a time-dependent extensional deformation. Usually, the elongational viscosity is at least three times greater than the steady shear viscosity. This rule may also apply for highly concentrated dispersions of paper coatings containing soluble polymers (Schurz 1984). However, recent measurements at shear rates of $5 \times 10^5 \text{ s}^{-1}$ demonstrated that paper coatings without soluble additives (i.e., starch, carboxymethyl or hydroxyethyl cellulose, associative thickeners, polyvinyl alcohol, etc.) do not have a measurable elongational viscosity (Carreau and Lavoie 1993). These coatings flow as Newtonian fluids at high shear rates. Elastic structures in suspension, which prevail at small rates of deformation, are destroyed at high shear rates, i.e., structures are sensitive to shear and disappear at high strains or shear rates.

In addition to the above defects a common problem in many blade coating operations with paper webs is the appearance of almost dried out coating extruded from under the blade at the outgoing nip. This defect is known as feathering, weeping, whiskering, or bleeding, and is more common in bevelled than the bent blade mode. Many times, bleeding leads to localized wet deposits at the exit from the blade nip which grow over time to eventually form dried out deposits, known as stalagmites, hanging onto the upper
side of the blade. Therefore, often bleeding is qualitatively classified as wet or dry, depending on its appearance. Stalagmites as long as several centimeters have been observed in practice. Their appearance is a localized phenomenon which may not adversely affect the coated paper quality until stalagmites detach from the blade and deposit on top of the paper, or grow to a size where they start scratching the surface. When this happens, wet and dry bleeding lead to visually observed coating surface defects.

There have been numerous attempts over the years to correlate coating and process variables with the occurrence of wet and dry bleeding. Generally, bleeding is promoted by high coater speeds; highly concentrated coating, i.e., the solids content of coatings; poor water retention; increased coating viscoelasticity; the type of mineral pigment particles used, i.e., clays are more susceptible to bleeding than calcium carbonates (Hofmann and von Raven 1986; Eklund and Förs 1988; Gane, Watters, and McGinity 1992, Triantafillopoulos and Granqvist 1992). Additionally, bleeding reduces with high blade angles and decreased blade thickness and blade extension in the case of bevelled blades (Engström and Rigdahl 1987). Although many of these conditions are sufficient for the occurrence of bleeding, they are not always necessary. For example, it was frequently thought before that shear thickening in the form of dilatancy under the blade tip could cause formation of aggregates and the appearance of bleeding. However, experimental work has demonstrated that this is not always a requirement (Engström 1984). Many times, shear thinning coatings are associated with the buildup of stalagmites at the blade. Gane and Coggan (1987) speculated that plug flow or slippage at the blade tip of a bevelled blade cause bleeding and stalagmites formation. Furthermore, the coating film at the exit of the nip fractures, thus causing emission of
coating droplets and aggregates. Gane and Coggan (1987) gave no explanation of the mechanism which causes the film fracture.

Recent studies with high-speed visualization and microphotography have shed light on the phenomenon of blade bleeding, or weeping. Stalagmites are initially formed by a stepwise process which involves formation of small columns of nucleation, or trunks, which then branch out (Branston et al. 1993). The appearance and disappearance of new growths is a continuous process. Two ways that weeps grow are through trunks which continually acquire coating that flows up their web sides, and crowns that acquire coating during temporary contact with the moving web. Overgrown weeps eventually are propelling away with the web. Scanning electron microphotography (Vodnicky et al. 1993) indicated that all weeps have a bulbous crown atop a comb of separate trunks which join, two-by-two, in their upper reaches. Evidence from these observations suggests that trunks and crowns grow through different mechanisms and that, at least partly, trunks grow by blockage of large pigment particle booklets or lumps trapped at the blade nip.

The viscoelastic character of paper coating formulations can also cause the appearance of coating surface defects. These defects in turn influence the aesthetic appearance, properties and quality of the coating layer. The 'memory' induced by viscoelasticity at low deformations can dramatically change the spreading response and consolidation of coatings after metering. Immediately upon cessation of shear stresses and other forces acting during the fast deformation at the blade nip, the stored energy in the coating begins to relax. The coating layer would then return, at least partially, to its previous state of rest. Expansion (or spreading) of the coating layer after the blade tip, due to removal of external stress, promotes coverage of the substrate. The recoverable strain may be related to coating patterns and defects, such as scratches and various types of
streaks (Engström and Rigidahl 1987). This phenomenon would be more pronounced for coatings with a more elastic character since, to some extent, levelling-out of blade induced streaks is controlled by viscoelastic properties of the coating (Adolfsson, Engström, and Rigidahl 1989). The relaxation time, which characterizes coating viscoelasticity, is often comparable with the time available before the coating layer has been immobilized due to dewatering into the substrate. This is especially true in the case of coaters which run at high speeds. When one compares the relaxation times of different coatings - determined by stress relaxation measurements - with the residual width of an initially rather broad streak deliberately induced into the wet coating layer, the longer the relaxation time the wider is the remaining streak (Adolfsson, Engström, and Rigidahl 1989). Appearance of this type of coating defect at the surface of paper can be, at least partially, attributed to the inability of the coating film to spread and level out after metering and before drying. Furthermore, at high coater speeds, viscoelastic coating formulations have a strong tendency to form stalagmites at the blade surface upstream of the blade nip exit (Engström and Rigidahl 1989). The correlation of the presence of blade defects to the characteristic relaxation time of a coating has also been illustrated recently with measurements of stress relaxation of paper coatings (Young and Fu 1990, 1991). Paper coatings containing soluble thickeners exhibit substantial viscoelasticity. These coatings which have comparatively slow relaxation would most likely exhibit formation of streaks in the final coated paper.

A few experimental studies have been made over the years to investigate the influence of the viscoelasticity on defect-free runnability and bleeding in high-speed blade coaters. Sandás and Salminen (1991) investigated the effect of starch, carboxymethylcellulose, polyvinyl alcohol and an alkali-swellable thickener on rheological properties, including viscoelasticity, and on coating performance (the pigment was an platey English china
clay). The oxidized starch, which had the lowest elastic modulus at low deformations, showed the best performance at the coater. A similar study (Triantafillopoulos and Grankvist 1992) with a variety of pigments and three different starches demonstrated that wet bleeding and scratches appear when the low-strain elasticity is relatively high. Particularly, coatings with cationic starch have high elasticity which substantially reduces at high strains and develops to excessive shear thinning. Dry bleeding, on the other hand, does not seem to depend on elasticity but rather the geometry of the blade nip.

Sustained and consistent coater runnability without defects and a uniform coat weight does not only relate to viscoelasticity. It is also a function of a combination of formulation parameters including: steady shear viscosity at low and high shear rates, water retention, and immobilization solids. In addition, the blade nip geometry in the case of a bevelled blade plays an important role. Preferably, the blade tip has to be as close as possible to parallel to the web surface (or tangent to the backing roll at the blade nip region). Under this configuration the blade is truly running on its bevel, as shown in Fig. 12.4-3a, and the coat weight is proportional to high-shear viscosity measured with a capillary viscometer (Roper and Attai 1993). When the blade is off its bevel, the system is not in equilibrium and coating defects are more likely to occur. Running on the toe of the blade (Fig. 12.4-3b) can lead to dry bleeding, formation of stalagmites at the blade surface and web breaks at high blade loading. Running on the heel (Fig. 12.4-3c), on the other hand, generates a divergent nip where film splitting at the exit from the blade induces visual defects, even though the coating rheology may be acceptable (Hofmann and von Raven 1986; Roper and Attai 1993). It is therefore important to recognize that, in addition to all the other variables discussed earlier, the blade geometry is a critical variable which needs to be monitored and controlled.

55
In summary, the appearance of surface defects in high-speed blade coating depends on all three components of the process: the paper web, coating rheology, and the metering geometry of the blade. Although the exact mechanisms leading to coating surface defects have only recently been explored, many cause-and-effect relationships have been established through practical experience. For instance, too porous and absorbent webs are detrimental to defect-free runnability because of excessive dewatering of the coating dispersion prior to metering and an increase in the solids content of the filtercake reaching the blade. Water entering the fibrous matrix of paper causes fibers to swell, a phenomenon which influences both the coat weight and end-use properties of paper. Generally, coatings with comparatively high elastic moduli at low strain rates and high plastic yield are more difficult to process up to the application zone and are associated with the appearance of visual defects, appearing both on the blade and the web. In addition, relatively high high-shear viscosity many times is associated with poor runnability because it requires higher blade pressures to obtain a certain coat weight, something which may lead to coating defects since the stresses applied onto the web also increase. Beyond the rheological parameters, the water retention property of a particular formulation plays a role in its processability. Coatings with the ability to hold water, particularly under the influence of a pressure pulse, can be processed trouble free at high coater speeds. Furthermore, the parallel channel geometry needs to be always maintained at the tip of a bevelled blade, since convergent or divergent flows at the blade nip will lead to coating defects. If this requirement is not met, coating defects may appear even though the substrate and coating rheology have been optimized for good runnability.
High-speed blade metering of paper webs is a qualitatively different process than knife coating. Blade coating of paper is a precision process where the blade is flexible, the substrate is porous and compressible, and the speeds are three to four times faster than those prevailing in knife coating. This process comprises mass transfer phenomena coupled with inertia and viscous effects, flow through porous media, nip dynamics of resilient rolls, and non-Newtonian fluid dynamics of highly concentrated dispersions. The forces at the blade nip and the interaction of the coating material with the web are the principle mechanisms for coating deposition. Because of the high speeds involved, inertia effects at the blade nip may become important, as do viscous and elastic effects. Furthermore, the quality and uniformity of the coating layer also depends on coating dewatering prior to metering and the roughening of the web at the application zone due to capillary penetration and fiber swelling. Therefore, the strong interaction between coating rheology, paper web and process variables make prediction and control of the process difficult to sustain.

In addition, there are physical differences between the operational modes of the blade (i.e., bevelled versus bent) and coating feeding systems into the metering zone. Bevelled blades are preferred for high speeds and relatively low coated film thicknesses (10-25 μ), while bent blades are commonly used at lower speeds (below 7 m/s) for heavier coat weights. However, bevelled blades are more susceptible to visual coating defects and web breaks as the blade loading pressure - and, therefore, the stress applied onto the web - continually increases. It is also important to realize that the operation of bevelled blades is very sensitive to the geometry under the blade tip. Deviations from a parallel channel geometry lead to convergent or divergent flows at the blade nip which are responsible for the appearance of coating surface defects, even when both coating
rheology and web properties have been optimized. Bent blades are generally less susceptible to coating defects.

Variations in the feeding system to the metering blade are also responsible for qualitative differences in the coating film. Systems with an applicator roll generate a substantial nip pressure which causes coating dewatering, fiber swelling, and web roughening prior to metering. The blade acts as a metering device which also compresses the web, filling in its surface voids with coating and, therefore, creating a smooth contour of coating. In contrast, pond type and short-dwell blade coaters induce little dewatering prior to metering, but fiber swelling and web roughening take place after metering. Consequently, the coating contour is more nonuniform than in the previous case, an effect which may lead to inferior surface properties. Although pressurized pond coaters are superior coaters compared to roll applicators, these coaters also have limitations in terms of hydrodynamic instabilities and air entrainment in the pond. Both of these phenomena may generate coat weight nonuniformities across the machine line direction, manifested as bands or streaks when the web is viewed with transmitted light. These nonuniformities impose limits in the processability of high-speed blade coaters for paper, with respect to both the coater speed and shear viscosity.

Non-Newtonian fluid dynamics introduce an additional complexity in the physics of high-speed metering of paper coatings. Coating formulations, comprising of highly concentrated dispersions of anisometric mineral particles and including polymeric additives, demonstrate a whole range of non-Newtonian effects under the large strains occurring during the coating process. Interparticle interactions and network structure due to the presence of polymers are responsible for plastic yield and viscoelastic behavior at low strain rates. At high shear, most coatings are shear thinning and exhibit thixotropic recovery. When the concentration of pigment particles increases, coatings
become dilatant and impose strong viscoelastic effects at high rates of shear. However, most coatings do not demonstrate viscoelasticity at high shear rates. Particle orientation and packing under the high shear flow conditions prevailing close and inside the blade nip determine the rheological behavior of paper coatings. Orientation of platey pigment particles parallel to the machine line direction reduces the effective shear viscosity in the blade nip. However, slipping phenomena at the blade tip surface may lead to coating defects as film fracture occurs at the exit from the blade nip. In addition to rheology, the dewatering properties of paper coatings influence their processability. Poor water retention is detrimental to coat runnability, since water leaving the coating layer prior to metering increase the effective solids content of the filtercake reaching the blade.

The physics of high-speed flexible blade metering remains an active field for research. Practical experience has played a significant role in establishing many of the relationships existing today between application variables and final film thickness and properties. Semi-empirical relationships, however, are not sufficient to explain the complex physics involved, since these relationships many times do not find universal application to all different types of coating formulations and paper webs. For instance, many relationships connecting coating rheology and web properties with the appearance of visual coating defects and film nonuniformities are not always accurate. A good example of this is dilatant coatings which many times have been associated with the buildup of blade deposits (stalagnites). However, many shear thinning coatings can also lead to stalagnites and surface scratches on the coated web. It is only with thorough, systematic studies based on mathematical analyses and experimentation that understanding of the process can yield useful results to predict and control the appearance of these and other coating defects.
The high-speed blade metering of paper is an area rich with opportunity for advancement. Conceptual models are needed to explain the interaction of coatings with the paper web to better describe the dewatering process and the local nonuniformity in coating coverage. The physical phenomena occurring at the blade nip are still not well understood since there are only a few experiments that have been executed under well controlled conditions. Furthermore, there needs to be a more systematic approach in establishing relationships between rheological and dewatering parameters of coatings and their processability at high-speed coating operations. These relationships should also include the influence of the various coating components. Finally, the mechanisms for hydrodynamic instabilities and air entrainment need to be investigated in depth in order to assess their contribution to process limitations and to the appearance of coating defects. However, successful contributions to part or all of these areas would require the combination of theoretical analysis with carefully designed experiments.
REFERENCES


63


64


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<table>
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<tr>
<th>Coater Type</th>
<th>Coating Application Mode</th>
<th>Blade Configuration</th>
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<tbody>
<tr>
<td>Inverted Blade</td>
<td>Roll Applicator</td>
<td>Bevelled (stiff) Blade</td>
</tr>
<tr>
<td></td>
<td>Slot Orifice</td>
<td>Bent Blade</td>
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<td></td>
<td>Jet Fountain</td>
<td>Zero-angle Blade</td>
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<td>Contact Applicator</td>
<td>Billblade™</td>
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Puddle Coater
Short-Dwell Coater
Simultaneous Two-sided Coater
Figure 12.4-1. Schematic of the flow approaching the blade in a coater with an applicator roll.
Figure 12.4-2. Schematic of a paddle coater.
Figure 12.4-3. Schematic of a bevelled blade running on (a) parallel, (b) toe, and (c) heel.
Figure 12.4.4. see next page for caption
Figure 12.4.4. Schematic of (a) roll, (b) jet, and pond application systems which include (c) paddle coater and pressurized pond application systems with (d) short-dwell time and (e) long-dwell time modes of operation.
Figure 12.4-5. Double-sided puddle or (Billingsfors-Langed) Billblade™ coater.
Figure 12.4-6. Schematic illustrating change in coating weight as a function of the blade pressure in blade coating of paper webs (Edlund 1984).
Figure 12.4-7. Coat weight increases with machine speed in a bevelled blade coater. Experiments by Trianafillopoulos and Al rug (1991).
Figure 12.4-8. The state diagram for a lid-driven cavity with free-slip end walls, an ideal representation of a pond application coater.
Figure 12.4-9. An example of the stability boundary showing the self-similarity of various cellular patterns (Aidun, Triantafyllopoulos, and Benson 1991).
Figure 12.4-10. Schematic of the experimental setup showing (a) the coordinate system x,y,z and the corresponding velocity components u, v, w, and (b) recirculating primary and secondaryeddies of the steady state primary mode.
Figure 12.4-11. Front-view photographs of flow patterns. From top to bottom: (a) two-dimensional steady flow with primary and secondary rolls at Re=500 (notice the straight separation line); (b) wavy separation line for Re=700-1000 (time-periodic flow); (c) appearance of mushroom-like structures for Re=1100; (d) unsteady state at Re=1900 (Ailun, Triantafyllou, and Benicó 1991).
Figure 12.4-12. Schematic of the boundary displacement during wetting (Deryagin and Levi 1964).