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CONTROL OF WRINKLING IN PAPER COATING

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ABSTRACT

Muhammad Hassan Ammar: Control of wrinkling during dispersion coating of paper
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Keywords: Dispersion coating, spreading of web, wrinkles, paper web.

Paper and paperboard are essential packaging materials these days. Coated paper and paperboard material is a potential and effective substitute for non-biodegradable plastic material for cups. Extrusion and dispersion coating are widely used coating techniques to make paper a non-permeable material for liquid containment. Dispersion coating has an edge over conventional extrusion coating due to lower coating weight and recyclability. Paper is less stiff than paperboard which makes it difficult and more challenging to process it through dispersion coating. Along with other challenges and problems encountered during the dispersion coating of paper, wrinkling during coating process is a common problem which is hindering the commercial success of this technique. The aim of this study is to find out the possible causes and reasons of wrinkling of paper web during dispersion coating of paper. Furthermore, the study aims to suggest and test different settings and sets of parameters to minimize and prevent the wrinkling problem of paper web during its dispersion coating.

The study included the theoretical study of possible causes and reasons behind wrinkling phenomenon of paper web. Additionally, it involves the experimental testing and trials on pilot line to evaluate the effect of proposed settings and sets of parameters to encounter the wrinkling problem during processing and to find the optimal settings and parameters for dispersion coating of paper.

The originality of this thesis has been checked using the Turnitin Originality Check Service.

PREFACE

The thesis and the process behind this thesis gave me significant knowledge about paper and paperboard manufacturing industry and process. I came to know and study about new things related to paper industry of which I was not very much aware about before this thesis. I hope the knowledge earned from Tampere University will help me to progress in my career in future.

First and foremost, I would like to thank to Almighty God for giving me such a precious life and all that I have, then to my parents and family members for their support.

I want to express my gratitude to my supervisors and lab instructors for their sincere support and help throughout the process. I want to thank to Sanna Auvinen and Jurkka Kuusipalo for their support and guidance at each step of this process. Their comments and feedback helped me a lot in making this happen.

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Tampere, February 26, 2023

Muhammad Hassan Ammar

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LIST OF SYMBOLS AND ABBREVIATIONS

Gsm	grams per square meter
MD	machine direction
CD	cross direction
PET	polyethylene terephthalate
PP	polypropylene
PLA	polylactic acid
PE	polyethylene
EVOH	ethylene vinyl alcohol
µm	micrometer
IR	Infrared
mPa.s	Unit of viscosity, milli-pascal.second
Tg	Glass transition temperature
DSC	Differential Scanning Calorimeter
g/m^2	grams per square meter
dm^2	deci-square meter
g/cm^3	grams per cubic centimeter
m/min	meter per minute

1. INTRODUCTION

The invention of paper served as a landmark in the evolution and development of knowledge and information, as it became the main source of recording and saving the data and information. Since its invention, almost entire printing is done on the paper. However, since late 20th century, paper has been replaced by electronic devices for the storage of information, but still paper and paperboard are widely utilized in packaging applications.[1]

Paper and paperboard can be defined as a sheet generally comprises of natural fibers extracted from trees, plants or recycled from paper and paperboard waste. Paper and paperboard are differentiated based on packaging application where they are going to be used. For example, paperboard is referred to the material which is used to make cartons and boards whereas paper is the material used to make paper sacks. This differentiation was a bit confusing, as both the materials are widely available with varying thicknesses and weights, so International Standards Organization (ISO) separated the two based on their thickness and weights.[2]

ISO suggested that paper is now classified as a substrate material composed of natural fibers with grammage (basis weight) of less than 250 gsm (grammes per square meter) whereas paperboard is defined as substrate material having grammage of 250 gsm or more, however this difference based on grammage is not widely used in industry.[19]

The importance of paper and paperboard in modern day life cannot be neglected. Paper and paperboard are used in several applications from printing and writing such as newspapers, advertisements etc., packaging applications such as corrugated cartons for secondary packaging, cupboards, boxboards etc., and other healthcare and hygienic products such as tissue paper, toilet rolls etc. Initially printing and writing applications served as the major share of total paper and paperboard market, but since last two three decades, major share of total market switched to packaging applications.[1]

The use of paper and paperboard in packaging applications is constantly growing. Sustainability and recyclability of paper and paperboard are the main factors behind this growth as increase in pollution due to packaging waste material has been one of the important concerns for researchers and developers during recent years. Paper and paperboard packages are environment friendly as well as more conveniently recyclable as compared to their conventional counterparts such as plastic packaging.[1]

New methods and techniques are constantly being developed to improve the performance and functionality of paper and paperboard. Paper and paperboard coated with plastic is one of the examples of these new developments. Coated paper and paperboard have replaced conventional petroleum based plastic packaging used for variety of products in many applications. The use of these coated paperboard packaging has reduced the use of plastic in packaging applications. Besides paperboard coated with petroleum-based polymers, some biopolymers based coated paperboard are also available which is even more sustainable in nature.[1]

1.1. Problem

Interests have been increasingly developed for coating methods such as dispersion coating for paper and paperboard and these techniques are constantly being developed to find new and more sustainable packaging and consumer product applications for paper and paperboard. New methods always bring new problems and challenges. Like any other manufacturing and converting operation, dispersion coating of paper and paperboard also have some challenges, wrinkling of web during coating process is one of them, especially for paper coating. Paper being more flexible and thinner than paperboard becomes more susceptible to wrinkling due to interactions of water molecules with the fiber cellulose during dispersion coating.

1.2. Objective

The aim of this study is to find possible reasons behind wrinkling problem of paper during dispersion coating process. Moreover, the study will try to troubleshoot this wrinkling problem by optimizing set of parameters and with the help of web spreading rolls and their stationing positions. The study is a practical base investigation, which includes analyzing and observing the causes and possible reasons behind wrinkling problem during dispersion coating trials of paper on pilot line, and then trying to troubleshoot different set of parameters and process conditions such as installation of web spreading rolls to resolve this wrinkling issue.

The structure of this study comprises of several sections, first section deals with the background study of the topic, second section deals with the experimental trials, observations and suggestions related to the trials and the last section deals with the results and discussion related to the trials performed.

2. PAPER AND PAPERBOARD MANUFACTURING

2.1. Raw Material

The cellulose fiber obtained from trees and recycled waste is the main raw material used for paper and paperboard manufacturing. Several different additives are also mixed with the fiber to enhance the performance and appearance of paper. Paper and paperboard can also be coated with different coating materials to improve its functionality.[2]

There are two types of fibers used to manufacture paper and paperboard. Short hardwood fibers produced from deciduous trees and long softwood fibers produced from coniferous trees. The short hardwood fibers usually have length ranging from 1 mm to 1.5 mm whereas long softwood fibers are 3 mm to 4 mm in length. The performance of paper greatly depends on the length of the fibers used in its manufacturing. Long fiber gives strength to the paper whereas short fiber provides smoothness to the paper. Generally, the fiber comes from trees grown in managed forests, so the raw material is totally sustainable in nature having very minimal harmful effect on the environment.[2]

The second source of the fiber is recycled paper and paperboard waste. Recycled fibers have varying length and usually contaminated with different additives such as ink, wax, adhesives etc. The length of the fiber gets shortened each time they are recycled. Paper and paperboard produced from recycled fiber have low aesthetic as well strength properties as compared to the paper and paperboard manufactured from virgin fiber. However, research and development are continuously being made to improve the quality of recycled fiber.[2]

There are two main types of processes to produce virgin fiber from wood chips obtained from trees. Mechanical pulping and chemical pulping. Besides these processes, there are two intermediate methods as well, thermo-mechanical pulping and chemical thermo-mechanical pulping. These intermediated methods are used to reduce the cost of fiber production and or to enhance the properties of the fiber.[2]

In mechanical pulping process, wood chips are cleaned to remove sand particles and then grinded by using metal discs. These metal discs are known as refiner plates. Wood chips when passed through these plates break down into single fiber. The mechanical pulping process for fiber production has very high yields of up to 90 to 98 percent. Another advantage of mechanical pulping process is that it gives excellent printing properties to fiber due to high opacity and good absorption of ink which makes it suitable for printing paper production. Mechanical pulping process produces fiber with high stiffness which makes the suitable for middle layers of cardboard production. Bleaching can be done to mechanical pulp to enhance its brightness while retaining the lignin in the pulp. The drawback of mechanical pulping process is that the process is relatively less energy efficient as compared to chemical pulping process.[2]

In chemical pulping process, wood chips are fed into the digester which removes lignin and other impurities from cellulose fiber with the help of heat and some chemicals. The cellulose fibers are then bleached if white fibers are needed. Chemical pulping process is relatively expensive process with low yield when compared to mechanical pulping process but produces fibers with high strength and good aesthetic properties. The reason for low yield of chemical pulping process is that the process dissolves the lignin from the fiber which results in almost 50 percent reduction in the yield. However, the lignin removed from the fiber can be used as energy source by burning it to run the process which makes the process energy efficient as compared to mechanical pulping process. There are two types of chemical pulping processes based on the chemicals used in the process. The alkaline sulphate process and sulphite process, although sulphite process is not significantly used any more due to environmental legislations. The sulphate method uses the combination of sodium hydroxide and sodium sulphide whereas sulphite method uses metal or aluminium salts of sulphurous acid.[2]

The intermediate thermo-mechanical pulping uses hot water to softens the fibers before mechanical grinding to produce fibers having relatively higher strength. The chemical thermo-mechanical pulping uses less heat and chemicals as compared to chemical pulping which partially digest the impurities before mechanical grinding thus reducing total cost of production.[2]

The pulp is then dispersed in water by using hydrapulper which is basically a large vessel with a rotating blade for agitation. The hydrapulper mixes pulp with water to obtain required concentration to produce paper and paperboard.

Recycled paper and paperboard waste is deinked and then dispersed in water by using hydrapulper in the same way as virgin pulp is mixed with water. Almost 90% of the fibers are recovered through recycled waste pulping process. Recycled fibers are comparatively cost effective but having low aesthetic and strength properties.[2]

There are two main post-pulping processes, beating and refining (one process) and bleaching to be carried out after pulping to improve performance of fiber. In beating and refining process, paper pulp in suspension form is passed across a rotating surface which split the fibers into fibrils and causes them to swell. The refining of paper increases paper properties such as permeation to air, uniformity of paper surface, improve printability of surface and appearance but too much refining decreases strength, folding resistance as length of the fiber decreased with refining. Bleaching is done to remove remaining lignin from paper pulp, the process is significant to protect paper from fading and yellowing over time. Chlorine was used as bleaching agent in traditional processes but due to its safety and environmental hazards, it is now getting replaced by either of the two processes, Elemental Chlorine Free (ECF) which uses chlorine dioxide instead of chlorine gas and Totally Chlorine Free (TCF) which uses oxygen-based chemicals such as ozone or peroxides for bleaching.[2]

2.2. Additives

Fibers are not the only raw material used to manufacture paper and paperboard. Several other additives and processing aids are also used to achieve desired properties and performance of paper during manufacturing and converting processes. Fillers can be used to improve the printability of paper. Whitening agents can be used to increase whiteness, pigments can be used to achieve desired color. Sizing agents can be used to control the penetration of liquids to the surface which is significant for printing properties of paper. Resistance properties of paper against water and grease can also be increased by adding suitable additives.[2]

2.3. Production Process

There are three basic steps of paper making. Preparation of a dilute suspension of fiber and additives in water, this suspension is then formed into sheet of infused fibers, and removal of water during all stages of the process by different means to achieve required water content of the product.

The Wire or Fourdrinier method (see fig.1) is the most common method of paper/paperboard making. In this method, diluted suspension of fiber is fed into headbox from tank carrying it. Dilution of suspension depends on the weight of the paper being manufactured. Suspension is then passed through slice and got spread onto wire, which is basically a mesh, water is then drained through the mesh, drainage can be assisted by vacuuming. The movement of wire in machine direction (MD) aligns the fiber in one direction. The wire is occasionally vibrated in cross direction (CD) to achieve random distribution of fiber. Other layers of suspension can also be applied to get thicker paper/paperboard by adding similar assembly in the process.[2]

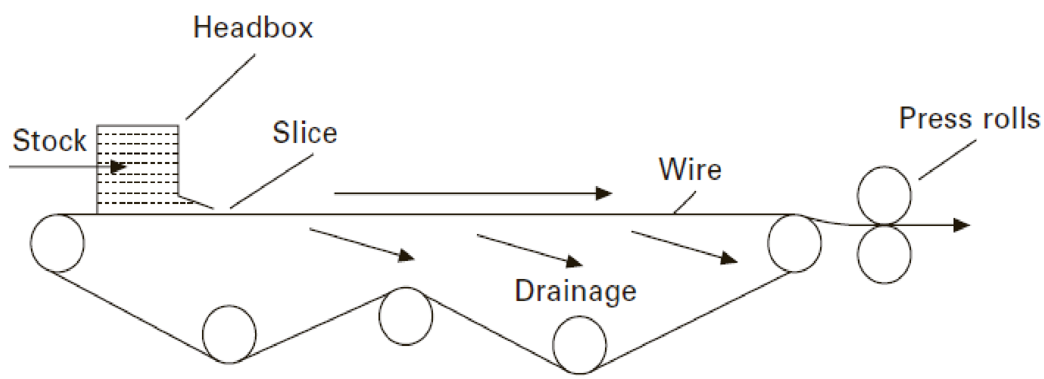


Figure. 1 The Wire or Fourdrinier Process of Papermaking [2]

The wet sheet is then passed through the press rolls where water is removed by pressing, vacuuming. The sheet is then passed through drying section where water is evaporated by using steam heated steel roll. After drying section, substrate is then sent to sizing section, surface sizing is carried out by applying starch solution to prevent fibers from shedding of the substrate surface, sizing also increase surface smoothness and strength and incorporate ease of printability. The sized substrate is then passed through cylinders which improves the smoothness of the paper as well as gives proper thickness to it, this process is known as calendaring.[2]

2.4. Dimensional Stability of Paper and Paperboard against Moisture

As paper and paperboard are wood and cellulose-based materials, they exhibit dimensional instability against moisture content, which can lead to serious problems during converting processes of these materials. The reason behind these dimensional changes is fiber's sensitivity against moisture and swelling of its cell wall when moisture content increases. The moisture sensitivity arises due to the cellulosic structure of fiber which makes them hydrophilic in nature. The cellulose present in fiber have hydroxyl(-OH) group, which is polar in nature and attracts water molecules. The cell wall of fiber cellulose accommodates more and more water as the water content in the surrounding increases until a saturation point is reached. The saturation point of pulped fiber is even higher than natural wood fiber which makes it more prone to moisture content. The cellulosic fiber has significant anisotropy in properties when compared between longitudinal and transverse directions. The dimensional change in cross sectional direction of fiber is 10 to 20 times higher than in longitudinal direction. The swelling of paper mainly occurs in thickness direction due to the layered structure of fibers upon one another in paper sheet. As dimensional changes occur due to swelling of cell wall, and this swelling must be transmitted from within the structure of paper, so dimensional stability greatly depends on structure of paper and fiber characteristics. [10]

There are several factors related to paper making which can contribute to making paper dimensionally more stable. Fiber furnish is the foremost factor that contribute to dimensional instability against moisture, as fibers that are bonded well in sheets have less inter-fiber spaces and upon swelling, there is no free volume within the structure of sheet and dimensional change needs to be transmitted to the external dimension of the sheet. Beating and refining of fiber increases the strength of fiber and density of sheet, but it also decreases its dimensional stability due to the reasons that freeness of the pulp decreases as a result of beating process and inter-fiber bonding improves during refining process. Fiber orientation in paper sheet also affects the dimensional stability of paper, as mentioned earlier that dimensional change in cross direction is higher than in longitudinal direction. Shrinkage during drying is opposite to swelling during wetting of paper, so if shrinkage can be restrained during drying process of paper making, it also helps in improving dimensional stability of paper. This is usually done by increasing drawing tension in drying section. Surface sizing and wet-strength agents also helps to improve dimensional stability of paper specially during short term exposure to moisture such as in converting processes. [10]

In addition to paper making factors, there are some factors related to fiber structure which contribute to dimensional stability of paper. Cross-linking of fiber wall greatly increases the dimensional stability against moisture. These cross-links can be induced either by chemical treatment or heat treatment. Hydroxyl groups in cellulose react with aldehydes and peroxides and thus securing the adsorption sites for water molecules. Crosslinking within the cell wall also provides restraints to swelling when accessed by water, thus increasing the dimensional stability of paper. [11]

3. PAPER AND PAPERBOARD COATING

Coating of paper and paperboard increases its usage in far more end use applications than normal uncoated paper and paperboard. Different types of coatings not only enhance and improves substrates surface quality such as aesthetics, printability but also incorporates some of the barrier properties to it resulting in increasing its applicability in different applications. Almost 90% of the total production of paper and paperboard are used in some of the printing matter such as magazines, brochures, catalogues, printed packages, labels etc. Printing matter is needed to be attractive on the substrate to attract buyers or end users towards the product. Pigment coating can be done to improve the sharpness and brightness of the printing matter on paper and paperboard. Nowadays, a significant portion of total paper and paperboard production is widely being used in packaging applications specially in food packaging. These packaging applications require some special properties in packaging material besides printability such as sealability, peelability for conversion processes, barrier properties against environmental factors e.g., humidity, oxygen, light, aroma, heat, grease etc. Barrier coating of different polymers such as Polyethylene (PE), Polypropylene (PP), Polyethylene Terephthalate (PET), EVOH, PLA etc. on paper and paperboard provide barrier against these environmental factors. There are two main processes to apply these barrier coatings, conventional extrusion coating and dispersion coating.

3.1. Pigment Coating

Pigment coating on paper and paperboard is applied to provide more uniformity and better surface appearance. It also helps in increasing and enhancing the receptivity of paper and paperboard towards ink for better printing quality. The coating is applied to the surface of paper and paperboard in the form of a suspension of water with pigments, colors, additives, and binders. After formation of layer of this suspension, the substrate is then dried to evaporate the water from suspension. The coating layer can be applied in single step or in multiple steps if required. The coating layer needs to be homogenous with all respects such as with respect to its porosity, topography, composition to ensure high levels of print quality on the substrate. Besides homogeneity, strength of the coating, brightness and gloss are also desired properties for paper and paperboard to be coated.[3]

Pigments, binders, and additives are the raw materials for coating suspension. Pigment has the most significant effect on the properties of the final coating layer. Ground calcium carbonate and Kaolin clay shares the major portion of total market of pigments. Besides these, talc, titanium oxide and plastic pigments are also used. Particle size particle size distribution of the pigment is the most significant property of pigment. Particle size is presented as percentage<2μm. Smoothness and gloss of coating increases with the increase in percentage<2μm particle size. A broad particle size distribution results in denser packing whereas narrow distribution incorporates porosity.[3]

There are two types of binders, latex, and water soluble. The main function of binder is to bind the pigment. Water soluble binders are more widely used binder as they also serve as thickener and water retention agent. Latex binders are usually synthetic polymer dispersions mainly composed of three types of polymers, styrene-butadiene, styrene-butyl-acrylate and poly vinyl acetate. Water soluble binders are usually starch or protein-based binders. Besides pigments and binders, several additives are also used such as, dispersants to ease slurry preparation, biocides to prevent growth of bacteria, wet strength agents, optical brighteners etc. [3]

The suspension of pigment, binder, and additives is applied to the paper and paperboard substrate. There are three methods of application, roll application, jet application, and short dwell time application. A blade or air knife both can be used to meter the size of the coating. The pressure on the blade determines the coat weight of the coating. In air knife coating, an air jet is used to meter the coat weight of the coating. Blade coating results in smooth surface but non-uniform thickness of the coating whereas air-knife coating incorporates uniform thickness of coating. Blade coating is more common as compared to air knife coating due to higher machine speeds. After application of coating, substrate is the sent to the dryers for drying and evaporation of excess water. A common drying combination starts with Infrared Drying (IR) either electrically heated or gas heated, followed by hot air drying and finally with hot cylinder drying before winding into final roll. [3]

3.2. Dispersion Coating

Dispersion coating is a barrier coating type which is used to provide barrier properties to fiber-based packaging materials such as paper and paperboard. This type of coating develops a uniform, solid and non-porous film of barrier material onto the surface of substrate with required barrier properties. The reason that paper and paperboard substrate coated with dispersion barrier coating are recyclable with conventional recycling pulper as normal paper and paperboard grades increases the interests of developers. Besides its recyclability, dispersion coating of paper and paperboard does not require big assembly such as extruder unit in case of extrusion coating, which makes it easy to install and execute process. The barrier material in dispersion coating is typically used in the form of latexes and are usually different from barrier materials used in extrusion barrier coating. Latex can be defined as emulsion of small polymer particles in water. The size of particles typically ranges from 50 to 300 nm. Latex contain polymer, water, and several different additives and filler. Most common examples of polymers used in dispersion latexes are polyacrylates, polymetacrylates, polystyrene, polybutadiene, polyvinylacetate and polyolefins. Additives and fillers are used either to enhance the processability of latex, performance of coating or decrease the cost of the material.[8]

The primary function of latex is to form a non-porous film on the surface of substrate, which requires polymer particles to coalesce upon drying. Unlike extrusion coating, polymer particles do not usually melt during dispersion coating, instead when water starts to evaporate from the latex applied on the surface of substrate, the polymer particles start to coalesce and form a continuous film on the surface. Elastic nature of polymer particles helps to form non-porous continuous film of barrier material providing required barrier properties. The primary intension during dispersion coating of substrate is to coat the material with even thickness throughout the surface, which gives maximum barrier resistance, but for good printability, surface should possess an even surface. Figure 2 illustrates the difference between even surface and even thickness of coating. A good balance between even surface and even thickness is needed to achieve desired level of barrier resistance without compromising on printability characteristics of coated packaging material. Blade coaters provide even surface whereas air knife coaters provide even thickness, rod or bar coaters provide a mix of both characteristics.[8]

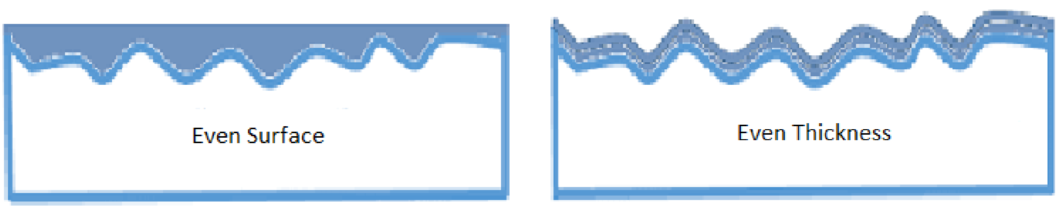


Figure. 2 Difference between even surface and even thickness of coating

The most critical phenomenon in dispersion coating is film formation upon drying of coated latex. Achievement of desired level of barrier resistance solely depends on quality of film formation. Film is formed in three steps; it starts with shrinkage of interparticle distance followed by coalescence of polymer particles and finally interdiffusion of polymer chains of adjacent particles occur. Figure 3 illustrates these steps schematically. Theoretically, several factors can affect the process of film formation supported by various theories, which are as follows:

- Particle size and particle size distribution, greater particle size increases force of attraction between particles.

- Rheological characteristics of polymer, increase in viscosity makes deformation of those particles more difficult.

- Rate of water evaporation, too fast evaporation rate can hinder the performance of water as medium to bring particles closer.

- Drying temperature, drying temperature should be high enough to lower the viscosity the extent where attractive forces can deform particles.

- Chemical composition of latex, viscosity of polymer can be affected by ratio of co-monomers and percentage of plasticizers. [9]

The dispersion coating can be applied through either on-line or off-line method, but due to certain limitations in on-line method, off-line method is more widely used method of application. Most common application method of latex to the substrate is via applicator roll, where usually a steel roll covered with rubber sleeve is used to apply dispersion to the surface, then the dispersion applied to the surface is metered and smoothened by using either blade, air-knife, rod, or bar. Besides roll applicators, there are several other methods to apply dispersion which do not use rolls for application such as jet application coaters and spray coaters. As these methods are roller-less methods which makes them suitable for high-speed lines and for on-line application systems [8]

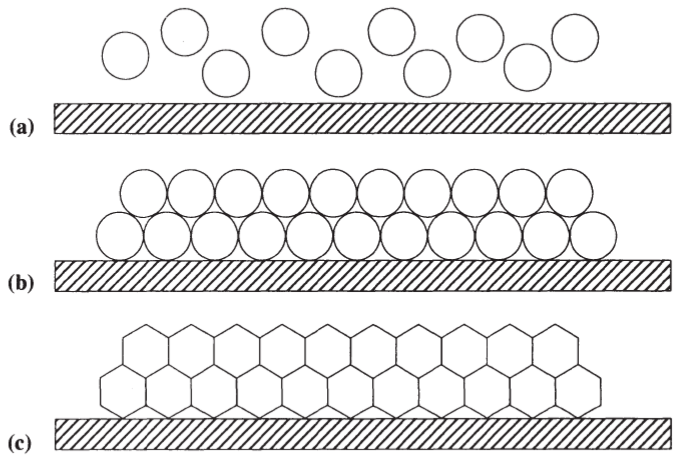
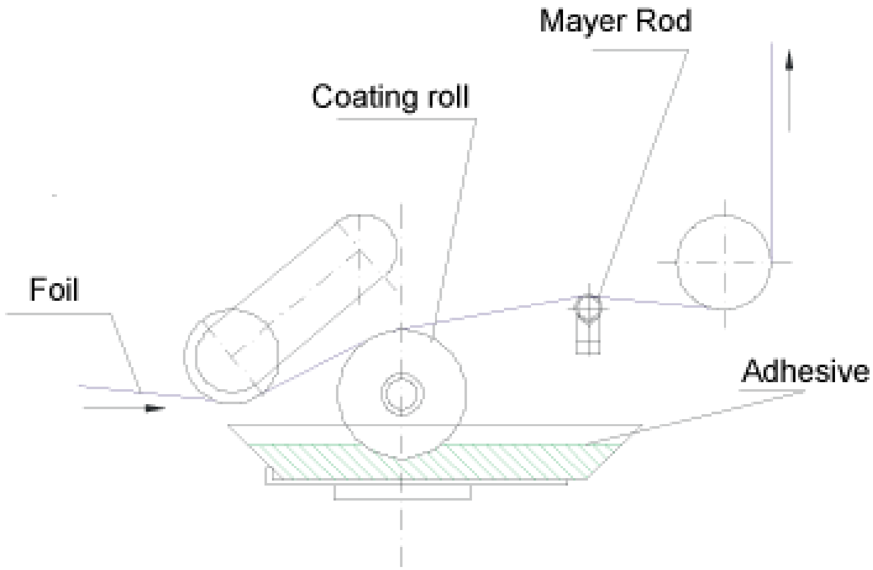


Figure. 3 Schematic Illustration of Film Formation [9]

The doctoring system used to control the thickness of the coating of dispersion is Mayer Rod Coating. This is a metering method used to control the thickness of the coating over substrate. The Mayer rod is made up of stainless-steel roll wounded with stainless steel wire of different diameters. The diameter of the wire determines the wet thickness of dispersion over substrate after doctoring. The dry thickness of the coating depends on the solid's concentration of dispersion solution. These rods are available with different wire sizes to achieve varying coating thicknesses. The table below shows the wire sizes available and the thicknesses that can be achieved using these rods. [14]



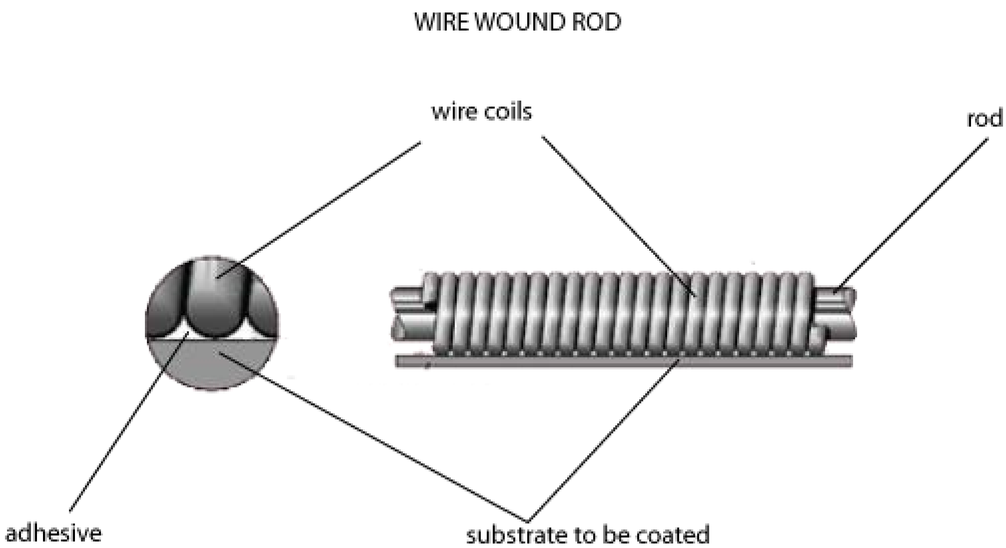


Figure.4 Mayer Rod [14]

Table 1. Theoretical coating amount depending on wire rod size (Grams Dry per Square Meter) [14]

Rod Size	Wet Mils	Thickness Microns	30% Solids	40% Solids	75% Solids	100% Solids
#3	.3	7.6	2.1	2.9	5.4	7.2
#4	.4	10.2	2.9	3.8	6.8	9.1
#5	.5	12.7	3.6	4.8	9.1	12.1
#6	.6	15.2	4.3	5.8	10.9	14.5
#7	.7	17.8	5.0	6.8	12.7	16.9
#8	.8	20.3	5.8	7.7	14.5	19.4
#9	.9	22.9	6.5	8.3	16.4	21.8
#10	1.0	25.4	7.2	9.7	18.2	24.2
#11	1.1	27.9	8.0	10.6	20.0	26.7
#12	1.2	30.5	8.7	11.6	21.8	29.1
#13	1.3	33.0	9.4	12.6	23.7	31.6
#14	1.4	35.6	10.2	13.6	25.5	34.0
#15	1.5	38.1	10.9	14.5	27.3	36.4
#16	1.6	40.6	11.6	15.5	29.1	38.8
#17	1.7	43.2	12.3	16.5	30.9	41.2
#18	1.8	45.7	13.1	17.4	32.7	43.7
#19	1.9	48.3	13.8	18.4	34.6	46.1
#20	2.0	50.8	14.5	19.4	36.4	48.5
#22	2.2	55.9	16.0	21.3	40.0	53.4
#24	2.4	61.0	17.4	23.3	43.7	58.2
#26	2.6	66.0	18.9	25.2	47.3	63.1
#28	2.8	71.1	20.4	27.2	51.0	68.0
#30	3.0	76.2	21.8	29.1	54.6	72.8
#32	3.2	81.3	23.3	31.0	58.2	77.7
#34	3.4	86.4	24.76	33.04	61.6	82.5
#36	3.6	91.4	26.23	34.96	65.5	87.4

Drying and cooling processes are essential processes of a dispersion coating unit. Drying not only removes excess water or solvent from the dispersion but it also generates the mechanism of film formation by deforming colloidal particles into continuous film. There are five major types of drying systems which includes, air impingement dryers, air flotation dryers, infrared dryers, air cap dryers and cylinder dryers. A combination of more than one drying system is usually used in an assembly to achieve maximum efficiency of drying. Air impingement dryers and air flotation dryers uses hot air for drying when web is supported by idler rollers, air flotation dryers have an advantage over air impingement dryers as web is heated from both sides. Infrared dryers are usually used before air dryers in most of the systems because heat through infrared radiation can penetrate deeper than air dryers. After drying, web is then cooled by passing over a couple of water-cooled rolls providing enough contact area to cool down it to the normal room temperature before winding. Efficient cooling before winding is essential to prevent blocking. [8]

4. WEB WRINKLES

There are several challenges and problems which can be faced during any converting operation of webs, wrinkling of web is one of them. During any converting operation, material needs to be transported through hundreds of meters of length across machine and must pass through dozens of rollers, which can easily cause wrinkles, misalignment, and several other potential issues. These wrinkles can become of even great concern when the wrinkled web is passed through a nip roll or pulling roll, where the wrinkles are converted into permanent creasing. These type of issues results in material waste and economic loss. Although web wrinkling is a common problem in both types of substrates, either paper or paperboard, but due to low stiffness and smaller thickness of paper, it becomes more significant in case of paper. [12]

4.1. Causes of Web Wrinkles

To understand the reason of formation of wrinkles in a web, web handling principle needs to be understood first. A web behaves on a simple web handling principle which states that a web will always tend to align itself perpendicular to the roll at the entry span to that roll. To behave according to this principle, the web should remain in the traction with the roll. However, if it slips over the face of the roll, then it will remain in its current alignment rather than aligning perpendicular to the roll, which eventually causes wrinkles in web. There are several conditions which can cause wrinkles, some of them are related to web characteristics while others belong to machine characteristics. [6]

- Gauge band or variation in thickness across web width which results in tension variation across web width. Due to thickness variation across web width, web encounters tensile stress in areas with higher thickness and compressive forces in areas with smaller thickness, this compression can cause wrinkles.

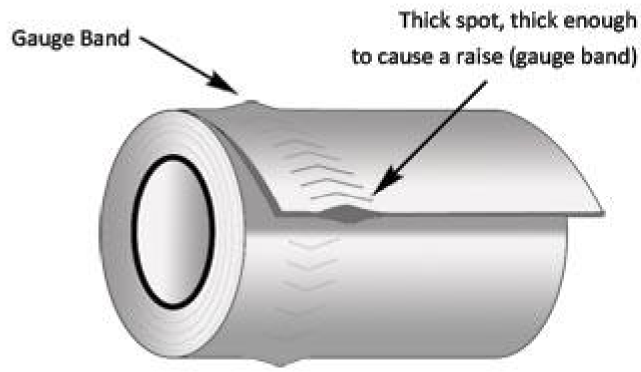


Figure.5 Gauge Band (thickness variation) [15]

- Tight side/loose side of the roll which results in tensile stress on tight side of the web. This condition arises when the web is being longer in length linearly on one side than other (if extremely long length of the web is laid flat, it would be an arc shaped instead of being straight).

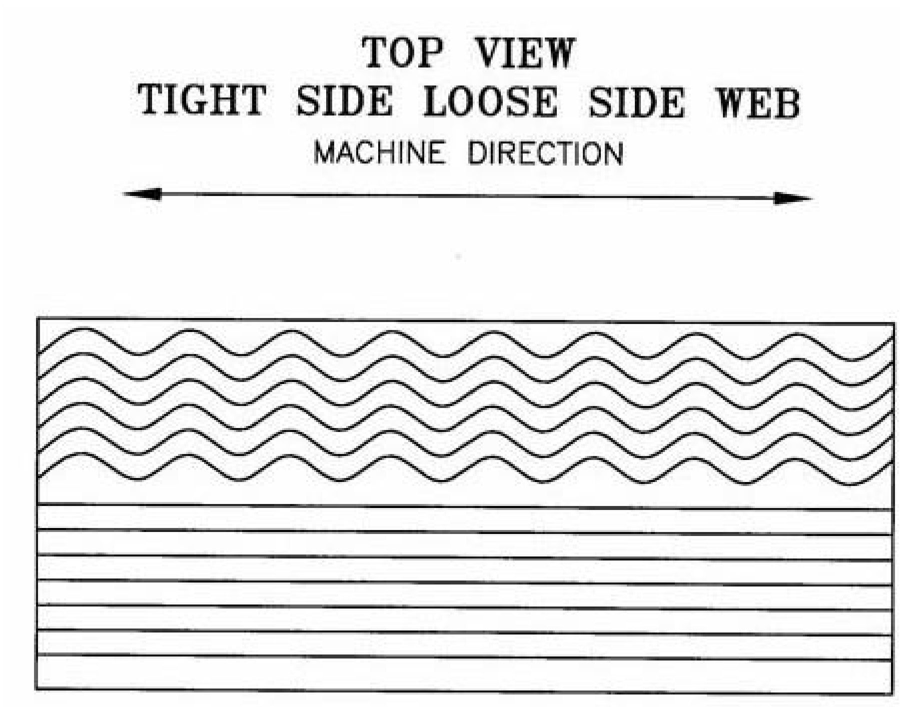


Figure.6 Tight Side / Loose Side web [16]

- Baggy center or baggy edges of the web. If a web is baggy from center and tight from edges, the tension will entirely be distributed to the edges and waviness will appear in the center of the web, eventually producing wrinkles. On the other hand, if web is baggy from edges and tight in the center, the edges will experience ripples during tension resulting in wrinkles.

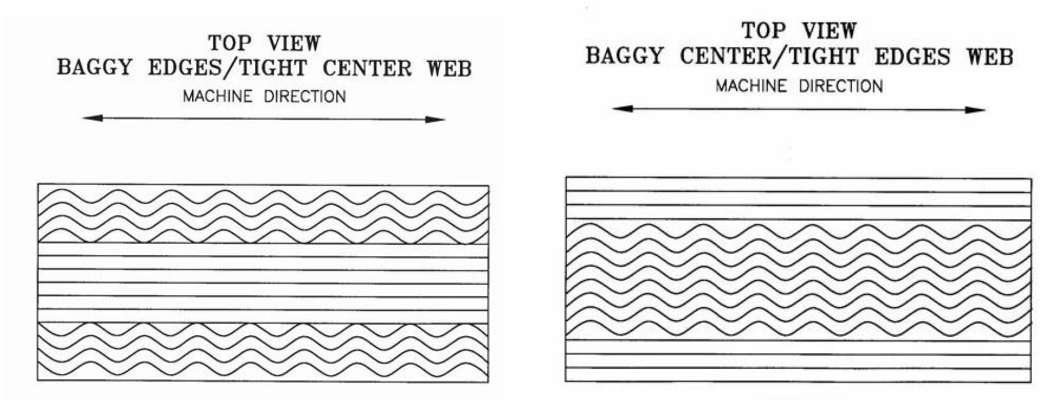


Figure.7 Baggy center or baggy edges [16]

- Poor winding of parent roll, too high-tension specially in outer layers of the roll results in starring effect (i.e., inner layers start to buckle) whereas too low-tension results in slippage of layers making tension control less effective when unwind during converting operation and create intermittent compression and decompression effects.

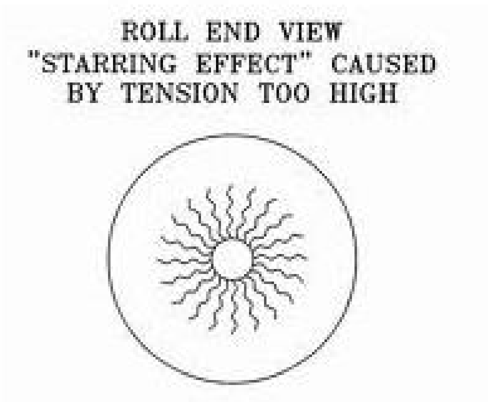


Figure.8 Too tight winding (starring effect) [17]

- Deflection or buckling of an idler roll. The bending and arching of an idler roller can create wrinkles because it will cause web to deviate out of its normal running plane at different time spans.

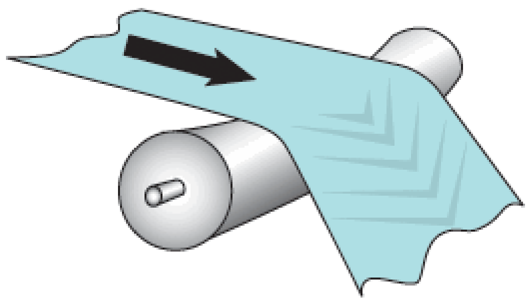


Figure.9 Deflection/buckling of idler roller [18]

- Air entrainment between web and idle roll which causes slippage of web over roll. The web must be in traction with the surface of the roller to follow the web handling principle that the web seeks to be perpendicular to the roll at its entry span, so slippage can cause wrinkles in the web.

- Variation in tension through different stages of operation results in compressive and decompressive forces on the web eventually cause wrinkles.

- A defective roll or defective bearing in an idler roll can also generate wrinkles in the web.

- Web expansion and contraction effects due to heat in plastic and moisture in paper web can cause wrinkles in the web.

- Misalignment between driven and idle rolls can again hinder the web to follow web handling principle resulting in generation of wrinkles in the web.

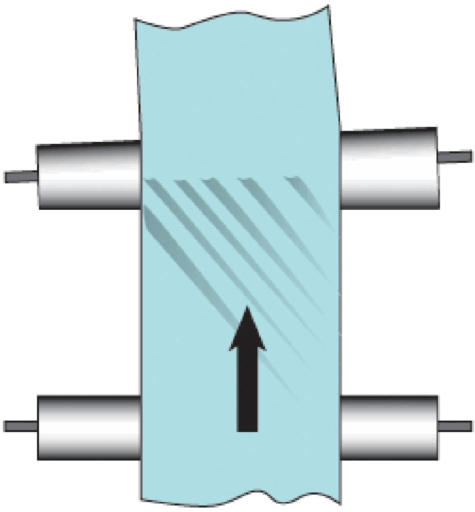


Figure.10 Misalignment between rollers [18]

- Touch-free handling of the web or unsupported travel of the web for too long distance during any converting process can also generate wrinkles due to gravity which results in sagging of the web and tension variation. Although, there is no limit for the maximum span of unsupported web allowed but keeping unsupported spans of the web to less than three times the width of the web is recommended. This unsupported portion of the web can be either horizontal or vertical, but vertical spans are less susceptible to problems as compared to horizontal spans. [13]

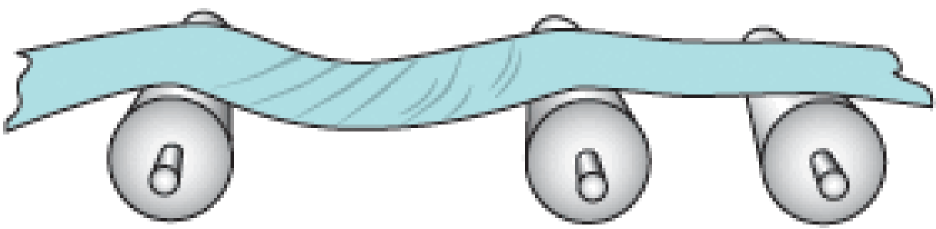


Figure.11 Unsupported web for too long distance [18]

- Forcing the web to make a 90^{o} turn with improper geometry can also result in wrinkling problem. 90^{o} wrap angle is not recommended. Additionally, it is recommended to minimize the entry span length of the rollers to avoid wrinkles. [13]

4.2. Web Spreading and types of Web Spreading Rolls

Web spreading refers to spreading of web in cross direction during any web handling operation. Web spreading roll is basically a web conveying roll which causes web movement and spreading in cross direction as web progresses in machine direction. This roll can be a driven roll or idle roll. There are a variety of reasons for web spreading, some of them are removal of wrinkles, widening of web and separation of slits from each other. It can be found in manufacturing as well as conversion operations. There are several types of web spreading rolls, five of them are the most common types:

1) Crowned and concave rolls

2) Grooved (Rigid or Flexible) rolls

3) Nip type rolls

4) Bowed (Curved axis) rolls

5) Surface expanding rolls

Spreader rolls should be stationed in such a way that it can remove wrinkles prior to it becoming a crease, wrinkles become crease when they pass through a nip roll. If multiple spreader rolls are required for an operation, usually rolls of same type are incorporated in a process. Assembling of different type of spreader rolls close to each other in a single operation is something not recommended.[7]

4.2.1. Crowned and Concave Rolls

Crowned and concave spreader rolls are usually made up of steel or aluminum and mostly covered by rubber sleeve. Crowned roll is convex in shape having and arced surface across its face with larger diameter from center and smaller diameter at the corners. This diameter variance greatly depends on application material, usually rolls for flexible films have smaller variance whereas rolls for paper have larger variance. This diameter variation increases tensile stress in center of the web which forces wrinkles to be pushed out towards corners. Typical wrap angle ranges from 30^{o} to 180^{o}. Wrap angle is defined as the angle by which the web is deflected through spreader roll (see fig.3)

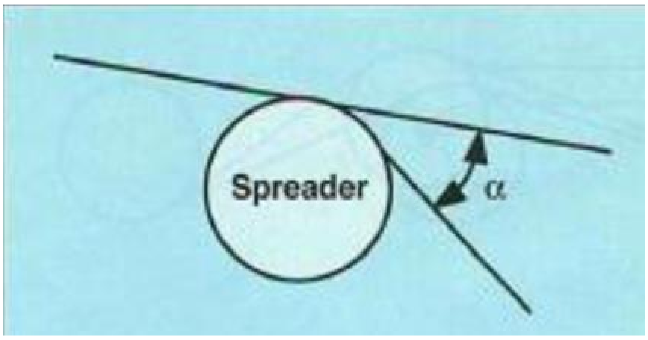


Figure. 12 Wrap Angle

Concave rolls have arced surface across its face with smaller diameter at center and larger diameter at edges which increases surface speed towards edges resulting in wrinkles to move towards edges. [6]

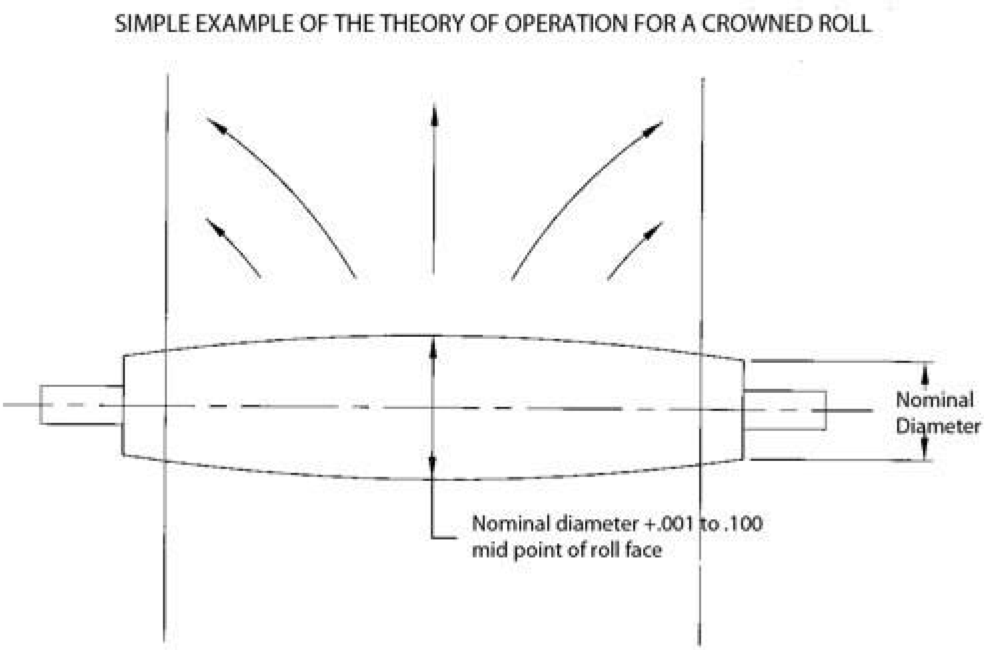


Figure.13 Crowned Roll [16]

4.2.2. Grooved (Rigid or Flexible) Rolls

Rigid grooved rolls can be constructed through steel or aluminum whereas flexible grooved rolls are made up of hard rubber. These rolls have grooves like screw threads starting from center and moves towards each edge. These grooves not only push wrinkles out of the web towards edges but also helps removal of entrained air when air entrainment is a problem. Simple construction of these rolls makes them the most common spreader rolls specially for slow web converting processes. Typical wrap angle ranges from 90^{o} to 180^{o}. [6]

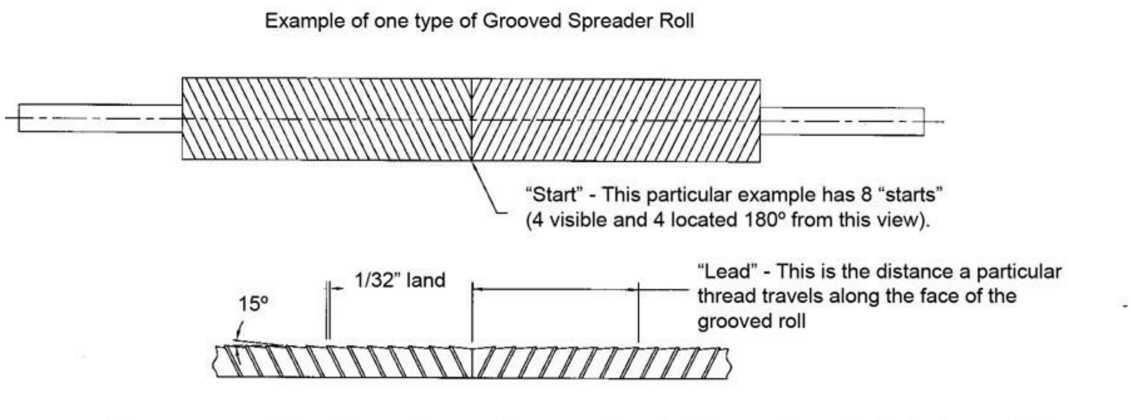


Figure. 14 Example of Grooved Roll [16]

Although, grooved spreading rolls are the most common and widely used spreading rolls, but still studies related to its working model or measurement verifying its benefits are not available. On the contrary, some research suggests its failure to spread the web as intended because of its symmetry and cross direction uniformity. As the web approaches the spreader, it starts to deflect outwards until it reaches to the center of its contact area, but when it passes through the center, the extension pressure is released due to the symmetrical shape of the roller at both upstream and downstream side of the contact area which is usually not the case in any other spreading rolls and this extension pressure release makes the web to come into its original position in cross direction. Another reason mentioned for it not to spread the web as intended its uniformity in cross direction. As web is spread and moves outward by the same amount at each groove, spreading would certainly happen at the innermost groove only at the center of the web. [7]

4.2.3. Nip Type Rolls

These rolls are like other nip rolls and are basically mounted in the form of two sets of small nip rolls at each edge of web parallel to each other. At least one roll of each set is provided with rubber sleeve for traction. Each set on edge is positioned in such a way that they are facing in downstream direction. When the edge passes through these nip rolls, web spreads away from the center as web tends to align itself perpendicular to the roll. This form of spreader rolls is the most aggressive form of spreaders. These rolls do not have any wrap angle. [6]

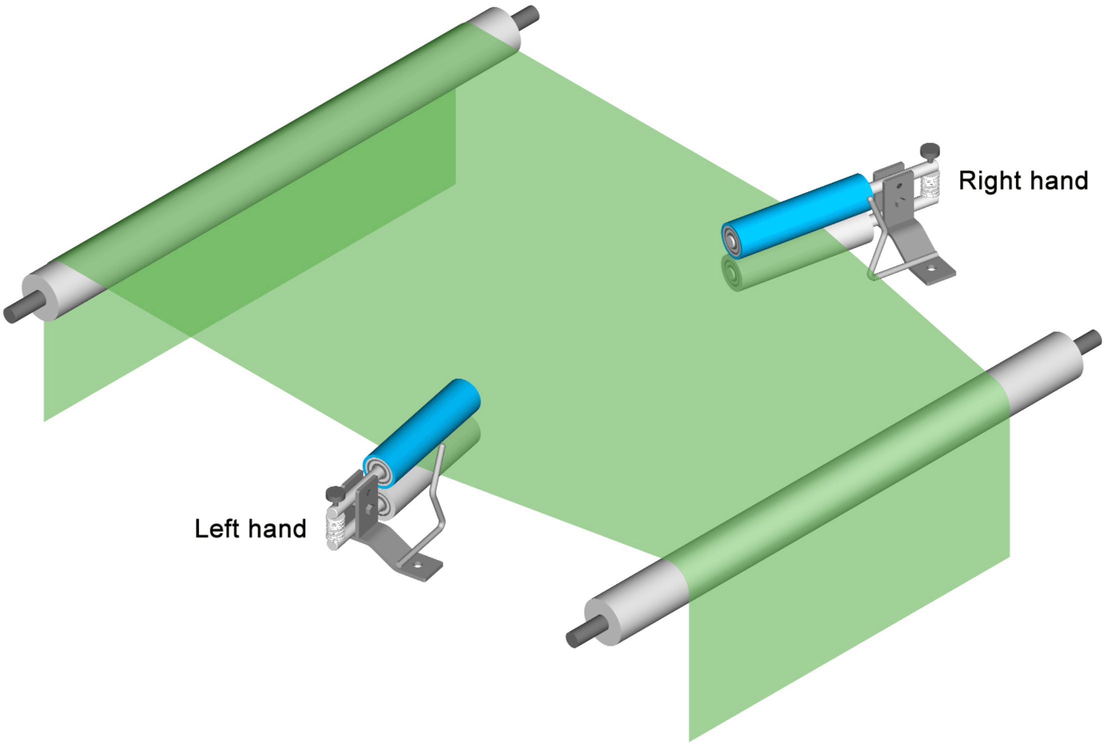


Figure.15 Nip type expanding rolls [16]

4.2.4. Bowed (Curved Axis) Rolls

A bowed shape spreader roll is fabricated in such a way that a curved axle is provided with ball bearing on its face and a continuous rubber sleeve is mounted on these bearings. The amount of curve can be fixed or adjustable depending on the version of roll either adjustable or non-adjustable. These rolls work in two ways, web tries to align itself at any given point across its width 90^{o} which results in web spreading. Moreover, as the rubber sleeve at entry span is narrower than at exit span as roll rotates, it stretches the web as web moves over it. Wrap angle for these rolls is typically smaller less than 30°, but some research claims that even higher wrap angles up to 180° is better for spreading. [6]

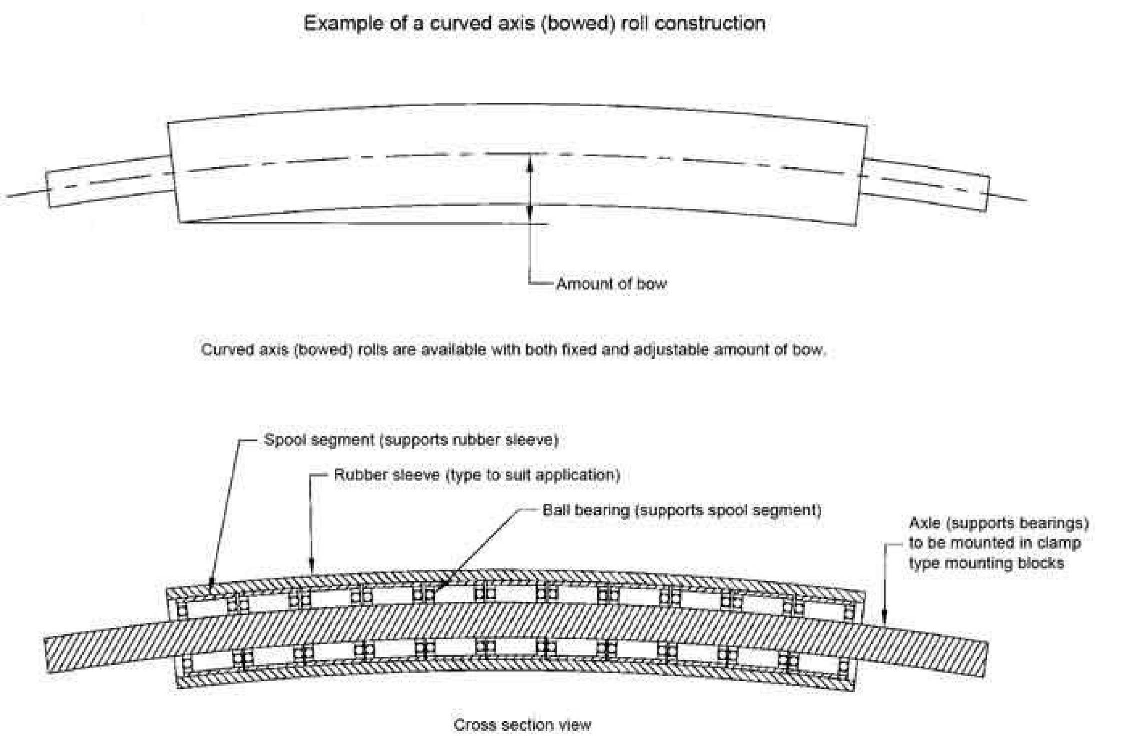


Figure.16 Bowed Rolls [16]

Bowed rolls are specified by its bow percentage which is defined as the percentage distance between the arc of the roll at its center and the chord. Lower percentage bow is usually used for un-slitted web whereas higher percentage bow is used for spreading of slitted webs. Setting of the bow roll is a crucial thing to do in the process. Experiments suggests that spreading used to increase as the bow increases to a point of onset of slippage, after which web loses its traction and spreading would not occur any further. The entry span for these rolls should be large as most of the spreading occurs at entry span whereas the exit span should be small to keep the web spread. [7]

4.2.5. Surface Expanding Rolls

These surface expanding rolls are typically composed of numerous elastomeric bands on its surface attached to the clamps at each end of the roll. The clamping end collar is set at an angle so that these bands move away from the center as the roll rotates. When the web moves over it, the bands attached with the clamp at the corner start to expand away from center towards corner, which spreads the web removing the wrinkles during first half of its rotation. During the second half of its rotation, the bands move back to their original position. Typical wrap angle for this kind of spreaders is 90° to 180°. [6]

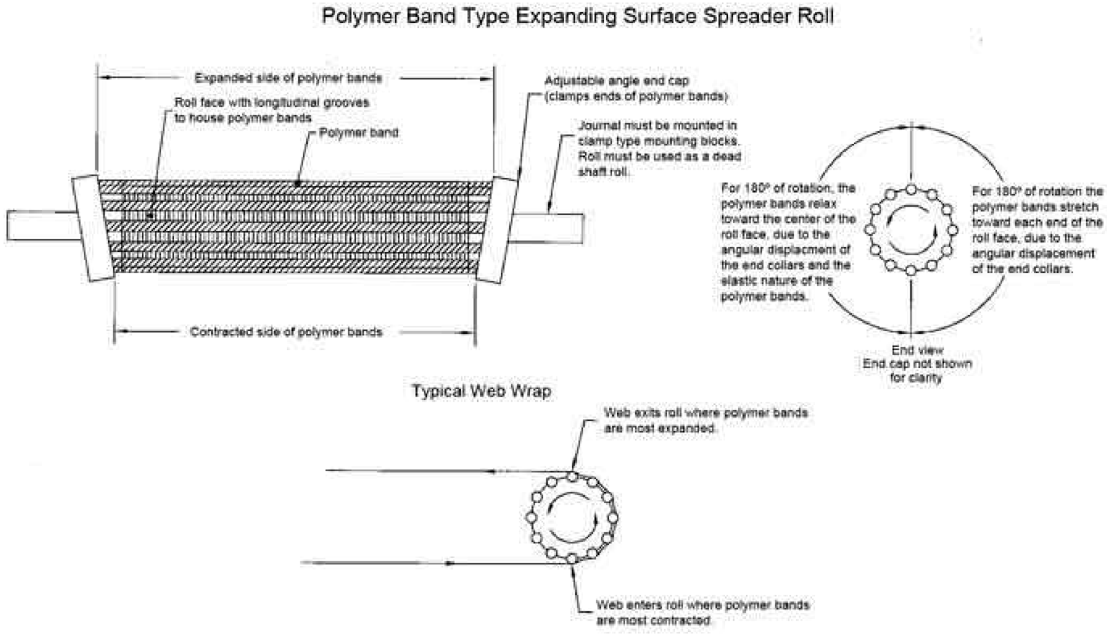


Figure.17 Surface expanding rolls [16]

5. EXPERIMENTAL PART

The experimental work for the thesis was carried out in several steps. Firstly, the problem is observed by running the normal operation. This step included the observation and analysis of the problem i.e., formation of wrinkles, find out the initiation point of those wrinkles, and the nature of the wrinkles. Secondly, a dry run was carried out to test the contact of paper with the banana rolls in IR dryer during operation.

Lastly, a third trial was carried out with the proposed settings and parameters to see the effect of new settings to prevent the formation of wrinkles. All the trials were performed on the pilot extrusion line situated in Material Science and Environmental Engineering unit of Tampere University.

5.1. Material

The sample roll of paper for the trials was supplied by UPM Specialty Papers, United Paper Mills Ltd. The grade of the paper was UPM solide smooth with the basis weight of 65 g/m^2. It is a food grade kraft paper grade which is mainly used for coating and lamination purposes. The width of the paper was 380mm wounded on a 76mm paper core.

The polymer dispersion used for the trials was supplied by BASF Chemicals. The trade name of the dispersion is Eportal 8842 X. It is a glycol ether free acrylic copolymer emulsion used for water-based barrier coatings of paper and paperboard. The technical data of the product can be found in the table 1.

Table 2. Technical Data of polymer dispersion (Source: Technical Data Sheet from product manufacturer)

Non-volatile	~ 39.5 %
Molecular Weight (wt. av.)	>200,000
Brookfield viscosity at 25 °C	10 - 500 mPa.s
pH(25 °C)	7.0 - 8.5
Density at 25 °C	~ 1.02 g/cm^3
Minimum film-forming temperature	~ <5 °C
Glass transition temperature Tg (DSC)	~ 5 °C

5.2. Pilot Line

The pilot line situated in the Materials Science and Environmental Engineering unit of Tampere University was used for the experimental trials of this thesis.

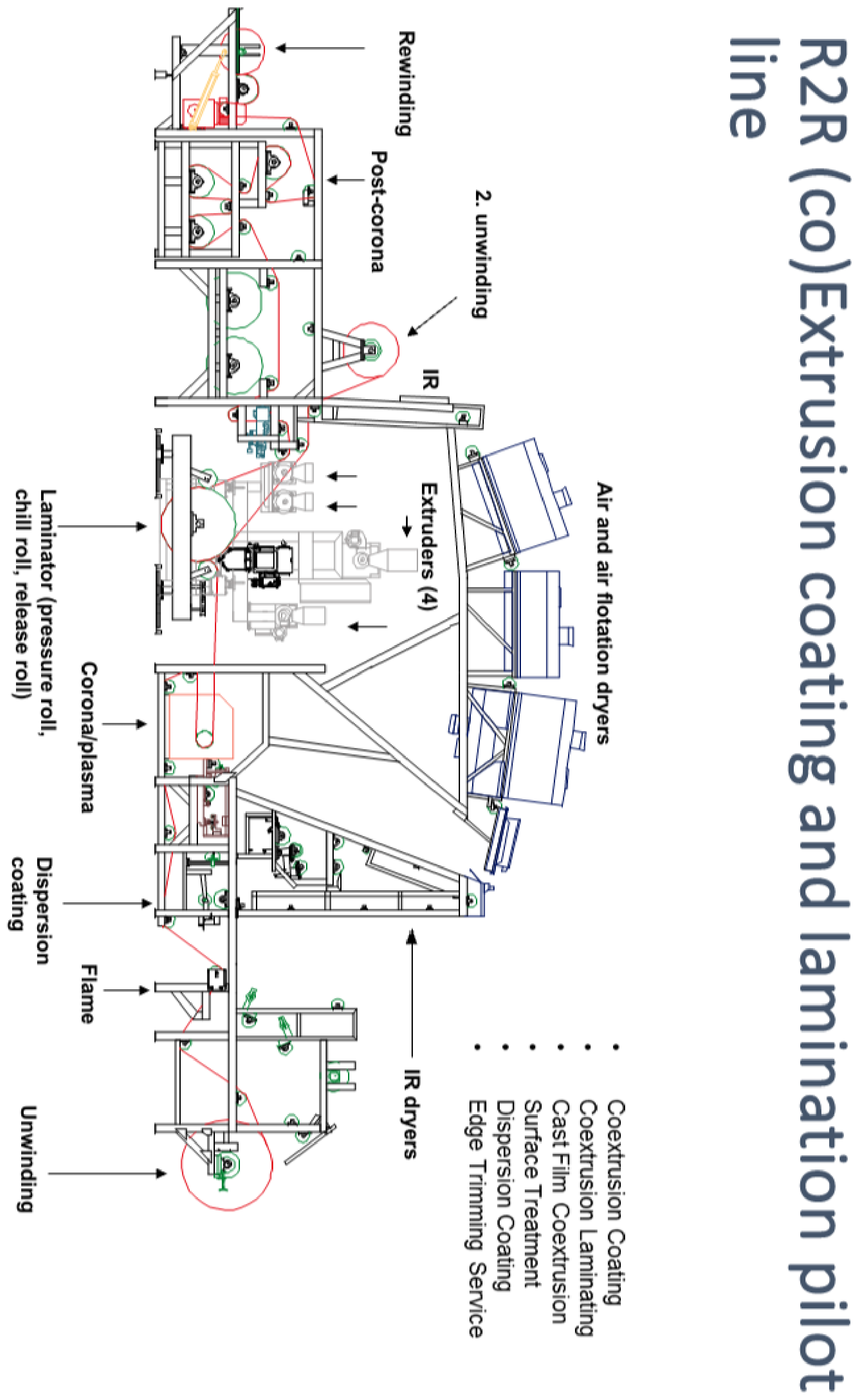


Figure. 18 Schematic Layout of Pilot Line

5.3. First Trial

The purpose of first trial was to analyze and visualize the problem during run. The trial was conducted with rod size #20 and with typical installations such as three banana bars in the IR dryer section.

5.3.1. Parameters

The parameters used for the first trial are listed in table 3.

Table 3 Parameters for First Trial

Dispersion	Eportal 8422 X			
Base material	UPM Solid Smooth 65 g/m2			
Coated surface	Inner			
Mayer Rod	C20			
Line speed	40 m/min			
Unwinder tension	115			
IR Dryer (%)	1	2	3	4
	50	70	70	70
Air Dryer (°C)	1	2	3	
	160	160	160	
Chill roll temperature (°C)	15			
Measured temperatures (°C)	After IR dryer	After air dryer	After chill roll	
	117	66	17	

5.3.2. Analyses and Observations

The purpose of this trial was to analyze and observe the nature of wrinkles, the mechanism of its formation, and the point of its generation in web threading during run. During run, it was observed that the wrinkles were more likely similar to creasing instead of simple wrinkles (fig 6). Creasing can be defined as permanent wrinkles and marks on the web formed by pressing the web during operations. Creasing is usually a non-reversible defect in the web, whereas simple wrinkles can be reversed by using spreading techniques. As the wrinkles defect in this case was identified as creasing, so it was assumed at this stage that the spreading rolls cannot serve as a remedy for this problem, instead we need to find some other solution.

Additionally, it was also observed that the paper web was getting wrinkled right after leaving the IR dryer chamber which implies that the IR drying parameters could have a major impact on the formation of these wrinkles. Besides IR drying parameters and air-drying temperatures, the other parameter which was grabbing the attention was tension of the web during run. Web tension was being controlled through the brakes installed in the unwinder station.

Figure. 19 Picture of the sample depicting wrinkle in the web

Although, different web tension could be tested already during that first trial but there was another fault noticed at that point, and it was related to the core of the paper web on the unwinder shaft, the core was basically slipping on to the shaft. This slippage of paper core on the shaft hinders in maintaining the constant tension in the web, and the web was experiencing varying tension during run. This problem was solved by changing the core and the shaft during next run.

In addition to the above observations, two more observations got attention. One of them was related to the concentration of the dispersion, the same dispersion was working fine with the dispersion coating of paperboard material but forming wrinkles with the dispersion coating of paper which inferred that the solid concentration of the dispersion is not suitable for the paper as paper has greater wettability than paperboard. This could be analyzed by using different dispersion with higher solid contents but working on the material was out of the scope of this thesis. The scope only included the manipulation and troubleshooting of the parameters and installation of some extra supporting rolls and bars.

The other observation was related to the banana bars inside the IR drying chamber. There were three pre-installed banana bars inside that chamber, and a suggestion was arrived that the distance between these supporting banana bars is a bit extra for the paper web. As paper web is less stiff than paperboard, so it might need some extra support in that chamber, which could be done by using two extra supporting banana bars. Additionally, alignment of those bars also needed to be adjusted as paper web was not touching the bars properly at some points, which could lead to the formation of wrinkles.

5.4. Second Trial

The purpose of the second trial was to test the suggested parameters and the installations and their settings to get rid of those wrinkles.

5.4.1. Troubleshooting Parameters and Settings

Before conducting the second trial with the suggested parameters and recommended settings, a dry run was performed. The purpose of the dry run was to evaluate the optimal setting of the banana bars installed in the IR dryer chamber to ensure the proper contact of paper web with the banana bars so to get maximum support to the web during drying. For this purpose, the paper web was threaded and run the machine without dispersion station in contact. During the run, the banana bars were adjusted by tilting them to the appropriate angles so to get them proper contact with the paper web during operation.

First suggestion was to install two more banana bars in the IR drying chamber to get extra support for the wet web during drying. Originally, the IR dryer section had three banana bars in the chamber as shown in figure 19. The suggestion was to install two extra bars in between these three existing bars to provide some extra support to wet paper during drying as shown in figure 20. The first part of the trial was to test the effect of installation of these extra bars, so the trial started with the same set of parameters as that of the previous trial. The only difference was the two extra banana bars in the IR dryer chamber.

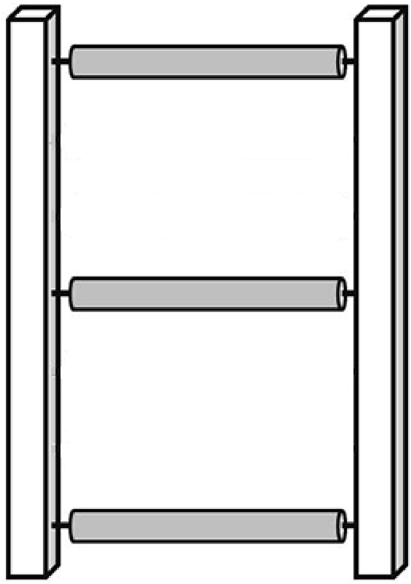


Figure. 20 IR chamber before suggested setting

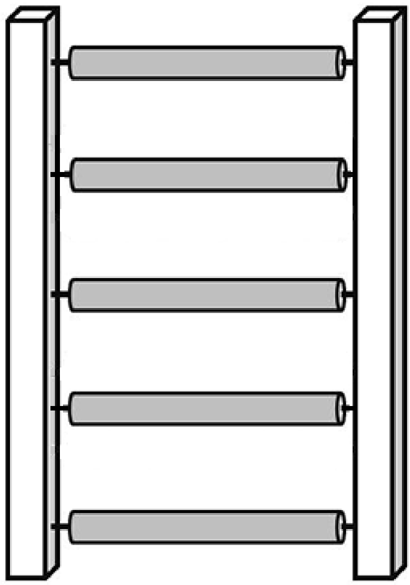


Figure. 21 IR chamber after suggested setting

Second suggestion was to minimize the heating effect of the dryers on the paper web as it might be the reason for the wrinkles to form that the paper web is drying too quickly, so it was suggested to lower down the heating percentages of the IR heaters and to try some lower temperatures for air dryers. The new set of parameters trialed is shown in the table 4.

Table 4 Suggested set of parameters

Dispersion	Eportal 8422 X			
Base material	UPM Solid Smooth 65 g/m2			
Coated surface	Inner			
Mayer Rod	C20			
Line speed	40 m/min			
Unwinder tension	115			
IR Dryer (%)	1	2	3	4
	50	60	60	60
Air Dryer (°C)	1	2	3	
	155	150	150	
Chill roll temperature (°C)	15			
Measured temperatures (°C)	After IR dryer	After air dryer	After chill roll	
	119	68	17.2	

The third suggestion was to test new values for the tension of the paper web. The tension control in the web is basically a process of maintaining an equal amount of stress or strain on the web between two points so to prevent its form and appearance and to prevent it from any defects such as lagging or wrinkles. There are usually two types of tension control systems in used, one is unwinder torque controlling and the other one is rewinder torque controlling. In case of fixed torque, with an unwinder application, the tension in the web increases with decrease in the diameter of the unwinding roll whereas with the rewinder application, the tension in the web decreases with the increase in the rewinder roll. To maintain the tension in the web at an optimal value throughout the process, the torque in the unwinder or rewinder must be adjusted with the increase or decrease of the diameter of the unwinder or rewinder roll.

The tension control system used in this process is unwinder torque controlling application system. The torque is controlled by applying brakes through braking system in the unwinder section according to the diameter of the unwinder roll. The original value for the tension in the first trial used was 110 N. For this part of the trial, different values of tension were tried and analyzed. First, the values of the tension higher than the first trial was analyzed and then the values of the tension lower than the first trial was examined.

5.4.2. Results and Discussions

The first part of the trial was included the installation of two extra banana bars in the IR drying section. The results obtained with this part of the trial was not satisfactory as there was no difference between the samples of the first trial and the samples taken with two extra banana bars. The wrinkles were still there with the same intensity and nature.

The second part of the trial was to test new set of parameters with the decreased value of heating in IR and air-drying chambers. The results of this part of the trial also found unsatisfactory as this new set of parameters also failed to cure wrinkles. The problem persisted with the same intensity and nature.

The third part of the trial included the testing of the new parameter set with different values for the tension of the web. Initially, the value of the tension was increased to 115 N from its previous set point which was 110 N. The result of this increase in the tension value even worsened the case and the intensity of the wrinkles got increased which implies that this tension value is a bit higher for paper web.

The next set of tension parameter to be tested was the decreased values for tension than the previous trial. The tension value was decreased gradually from 110 N to 100 N. The result of this decrement was a bit better than the previous trial and the condition of wrinkles, and their intensity got decreased which implies that the previous higher values for tension was not suitable for paper web.

The value of the tension was then gradually decreased to even lower side and further lower values for tension was examined. The different values which were tested included 100 N, 90 N, 80 N, 70 N, 60 N and 50 N. The other parameters were set at the same values as that of the second part of this trial. The samples were continuously being monitored and examined and it was observed that the intensity of wrinkles was decreasing with the decrease in tension values.

Figure. 22 Sample from the trial with tension value of 100 N

Figure. 23 Sample from the trial with the tension value of 80 N

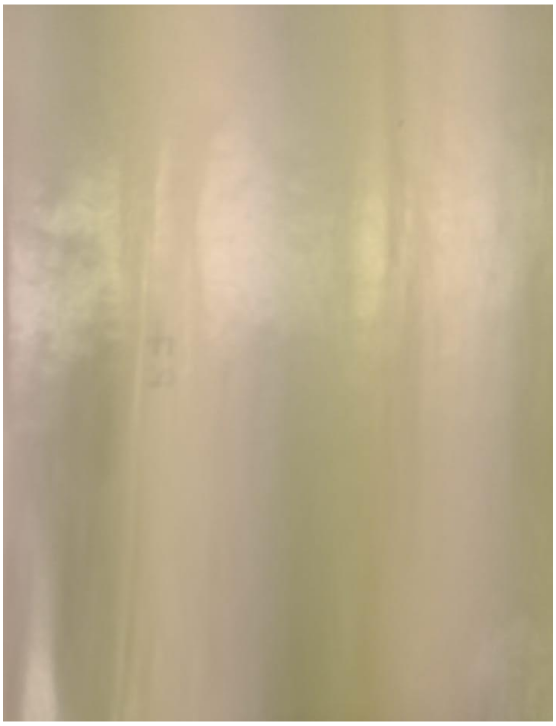


Figure. 24 Sample from the trial with tension value of 70 N

Figure. 25 Sample from the trial with the tension value of 50 N

Although the samples taken at tension values of 60 N and 50 N were apparently same and satisfactory but with close examination, it was observed that the sample with tension value of 50 N was the best among them.

In addition to these samples, one more sample was taken with the new tension value of 50 N but the IR parameters were set at the same values as that of the first trial. The samples taken at tension value of 50 N with both IR parameters found similar which implies that the tension values had the maximum effect on the generation of wrinkles and all other parameters did not have immense effect on the generation of wrinkles.

The samples were then examined and tested for the coating weight of dispersion coating on paper web. For this purpose, four parallel samples of 10 dm² from each trial was taken. These samples were then kept in constant condition chamber with 25°C and 50 % relative humidity for 24 hours. These samples were then weighted with the help of weighing balance to find the coating weight for each trial. Although it was not evident and not very much significant, but there was a declining trend in coating weight of the web with the decrease in tension values of the paper web.

Table 5 Coating weights of samples

Trial	Sample weight (g/m²)					
	1	2	3	4	Average	Coating weight (g/m²)
Uncoated paper sample	65.06	65.44	65.55	65.48	65.38	
Trial with tension value of 90 N	74.27	73.76	74.52	71.9	73.61	8.23
Trial with tension value of 80 N	73.1	74.21	74.52	73.05	73.72	8.33
Trial with tension value of 70 N	74.1	74.04	73.7	73	73.71	8.32
Trial with tension value of 60 N	73.71	74.04	73.8	72.96	73.62	8.24
Trial with tension value of 50 N	72.65	73.78	74.34	73.35	73.53	8.14

6. CONCLUSIONS

The goal of this study was to find out the possible solution for the wrinkling problem of paper web during its dispersion coating. Wrinkling is quite common in case of paper web as paper is less stiff than paperboard and having lesser dimensional stability while getting wet with dispersion. To achieve this goal, there were two pathways of investigation for the study, either to work on the modification of the properties of the raw material (i.e., dispersion or paper) or to investigate for finding the optimal settings and set of parameters to either counter or to cure this wrinkling problem of paper web during processing. The scope of this study only covers the investigation related to parameters and settings and does not include the raw material study.

Initially, the nature of the wrinkles and its generation point was investigated. The first trial implied that the wrinkles were somewhat similar to creasing and the problem was arising right after the web leaving the dispersion station. The wrinkles were already occurring inside the IR dryer chamber. The location of the wrinkle’s generation point and its nature inferred that the solution to the problem should prevent the wrinkles from occurring instead of curing or treating it after happening by some means such as spreading. Additionally, the support for the web between the rollers was also investigated as due to the less stiffness of the paper web, the paper web might need extra support during touch-free handling of the web between rollers.

The plan of the study then focused on to study and test some suggested settings and set of parameters to prevent the web from wrinkling. These settings and parameters were then studied and tested step-by-step. The installment of two extra banana bars to incur some extra support to the web inside the IR drying chamber was studied and evaluated. In addition to this, the bars were adjusted according to new settings by tilting them to optimal angles. However, these new settings did not show any sign of betterment to the problem.

Drying parameters i.e., IR drying parameters and air-drying temperatures were the next parameter to be studied and evaluated. The trial was conducted with relatively lower values of IR drying parameter and air-drying temperatures. These new parameters also failed to bring any betterment to the wrinkling problem. New tension parameters for the web were then tested which shows satisfactory results. The tension of the web controlled by the braking system in the unwinder section was gradually decreased step-by-step, and it was observed that the wrinkles were disappearing gradually. The trials were conducted with different values of tension ranging from 110 N to 50 N and samples were examined and evaluated continuously during the trials. Although, the samples obtained at 60 N and 50 N, both did not contain wrinkles but results at 50 N had better appearance.

Moreover, the trials were conducted with these new lower tension values while all other parameters remain unchanged which implies that all other factors besides tension did not have immense effect on the formation of wrinkles. Hypothetically, it can be concluded that the higher tension values were not suitable for paper due to its lower stiffness and dimensional instability against moisture. The absorbency of paper is higher than that of paperboard and the water molecules in water-based dispersion might be plasticizing the fibers in the paper which could lead to dimensional insatiability of structure and hence forming wrinkles.

Additional studies related to raw material could be helpful as well such as studies involved using the dispersion with relatively higher solid contents and investigation and trials conducted with the paper having different properties such as paper grade with relatively lower cobb value i.e., paper having relatively lower water absorbency could be helpful for further studies.

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