Statistical Control and Experimental Design for Edge Bead Reduction in Laminating Process

by

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Submitted to the Department of Mechanical Engineering on August 18, 2010 in partial fulfillment of the requirements for Degree of Master of Engineering in Manufacturing

ABSTRACT

Edge bead formation is a well-known phenomenon typically happening in the lamination due to the physics of this process. It causes the defect of high edge observed in the carton roll after the laminated carton sheets are wrapped around the roller in Company X; the affected carton sheets can no longer be fed into customers' filling machines due to the uneven surface. To address this problem, a model with process parameters and quality characteristics was built to define the lamination. Based on this model, the capability of measurement system was verified and current process capability was calculated. After that, Shewhart control charts were employed to identify the assignable causes and to bring the process to in-control state. Then, a designed experiment was conducted to find the optimal operating conditions. It was found that line speed, screw speed, die-bolt power and die-lip build-up are most likely to be subject to disturbances. In addition, die-bolt power, manifold plug and deckle blade have a statistically significant impact on the edge bead formation. As a result, an out-of-control-action plan was proposed and a recipe is recommended for edge bead reduction in laminating process.

Thesis Supervisor: David E. Hardt

Title: Ralph E. and Eloise F. Cross Professor of Mechanical Engineering

Acknowledgement

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Chapter 1 Introduction

This thesis is based on work done during an 8-month internship in a food-packaging company to help control and improve the product quality. The manufacturer operates a continuous-flow production line to fabricate beverage cartons. The whole line could be divided into three main manufacturing processes: printing, laminating and slitting. The quality issue addressed in this thesis belongs to the laminating process. Since this is a team project, some sections in Chapter 1 and Chapter 3 are shared with the other two team members: Willy Perdana Tanuwijaya and Alan Qi Dai.

1.1 Company Background

Company X is a multinational food processing and packaging company of Swedish origin. So far, it has become one of the largest providers of packaging solutions to milk, juice and other beverages in the industry. The products are shown in Figure 1.1. As part of competitive business strategies, company X also offers the integrated processing, packaging, distributing solutions to customers. [1] It regionalizes its production in four areas: Europe, Central Asia (Middle East) & Africa, Asia Pacific and America. Among its global network, the manufacturing plant in the South East Asia cluster is located in plant J, Singapore, serving customers from more than 17 countries.

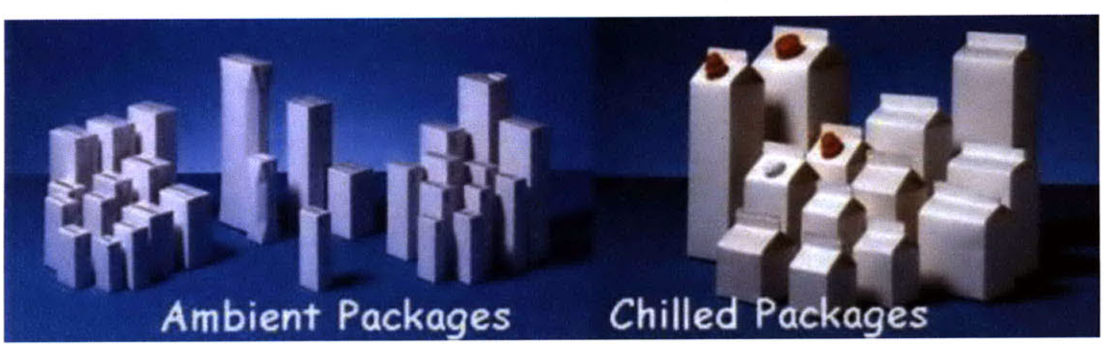


Figure 1.1: Company X's Packaging Solutions [2]

Compared to company X's other plants, plant J operates on small-scale and highly customized orders. Thus, frequent changeovers are necessitated, complicating the production scheduling, quality assurance and on-time delivery of various products. Despite of these challenges, plant J was honored with the Manufacturing Excellence Award (MAXA) for its exceptional performance in innovations, operations and sustainability in 2007. The plant is widely recognized as the leader among all the plants of company X. [3]

The underlying reason for plant J's stellar manufacturing practice is the concept of World Class Manufacturing (WCM) circulating throughout the veins of the organization. It is a process-driven approach where implementations usually involve the following philosophies and techniques, as tabulated in Table 1.1. The concept of WCM is deeply embedded in people's minds, from the top manager all the way down to the operators. In addition, plant J has a dedicated department in charge of leveraging World Class Manufacturing Practice across the organization.

Table 1.1: Philosophies and Techniques of WCM [4]

1	Total productive maintenance
2	Zero defects
3	Cross functional teams
4	Doing it right the first time
5	Cellular manufacturing
6	Make-to-order
7	Quick changeover
8	Small lot sizes
9	Just-in-time
10	Variability reduction
11	High employee involvement
12	Families of parts
13	Multi-skilled employees
14	Visual signaling
15	High employee involvement
16	Streamlined flow

It is noted that, along with other key indicators, Total Productive Maintenance (TPM) is an integral parts of WCM.

1.2 Evolution of Quality Maintenance in TPM

As a new way of defining maintenance, TPM is a proactive approach that essentially aims to prevent any kind of down time from occurrence. Its motto is "zero error, zero work-related accident, and zero loss". The organizational structure of TPM is composed of basic elements called pillar and each pillar is responsible for a particular domain, as tabulated in Table 1.2.

Table 1.2: Organizational Structure of TPM [5]

Pillar Name	Abbreviation
Focused Improvement	FI
Autonomous Maintenance	AM
Planned Maintenance	PM
Training and Education	TE
Early-phase Management	EM
Quality Maintenance	QM
Safety, Health, and Environment.	SHE

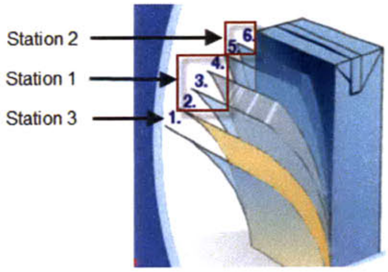
Among all the pillars in TPM, Quality Maintenance aims to improve customer satisfaction through achieving defect-free manufacturing process characterized by on-target specification with minimal variance. Its focus is on eliminating non-conformance continuously. QM manager's daily duty revolves around defects: to monitor them and to remove them from the process.

Over the past ten years, plant J has been undergoing three typical TPM development levels from the perspective of Quality Maintenance. The whole transition is from reactive quality control to proactive quality assurance. Plant J began to be engaged in the pilot level of TPM in 2001. During that period, the main target was to improve the phenomenal quality problems since the overall defect rate was high. By employing automatic control systems, inspection barrier systems and basic quality-control tools like the 5-Whys, the plant progressed rapidly towards the second level when the defect rates were reduced significantly and then Standard Operating Procedures (SOP) started to be implemented. So far, plant J has achieved the third level of TPM. In this phase, defect wastes have been further reduced to 1.37%. [6] And, plant J has gained profound insights into what affects product quality in terms of man, machine, material and method (4M).

However, hundreds of minor defects still remain, comprising a series of fixed defect codes in today's plant J. Each of them is rare, random and then difficult to eliminate. Consequently, more advanced and yet-to-be-implemented tools like Statistical Process Control (SPC) and Design of Experiment (DOE) are of great interest and value to achieve the goal of zero defects. And, the laminating process is the suitable station to apply these thanks to its ready real-time data acquisition.

1.3 Description of Laminating Process

Lamination is a process of placing polyethylene (PE) film between layers of paper and aluminum foil and gluing them together by applying heat and pressure. It is also termed as extrusion coating where polyethylene is coated on the substrate by extruders to serve as either adhesive or protective film. In Plant J, the specific amount and grade of coated PE films depend on what type of product it is. Even within the same product type, the sequence of laminating multiple layers might be different, depending on the specific laminating line. For the purpose of this thesis, we only focus on the lamination process of product type TBA/TWA on the laminating line 22. This product's laminated layers are shown in Figure 1.2. Figure 1.3 illustrates the schematic laminating process station.



No	Name	Material	Functionality
1	Decor	Low Density PE	Protection against moisture
2	Paper	Paper	Stability and strength
3	Laminate	Low Density PE	Adhesion
4	Al foil	Aluminum foil	Oxygen and light barrier
5	Inside 1	Adhesive PE	Adhesion
6	Inside 2	Metallocene PE	Sealing

Figure 1.2: TBA/TWA's Laminated Layers [7]

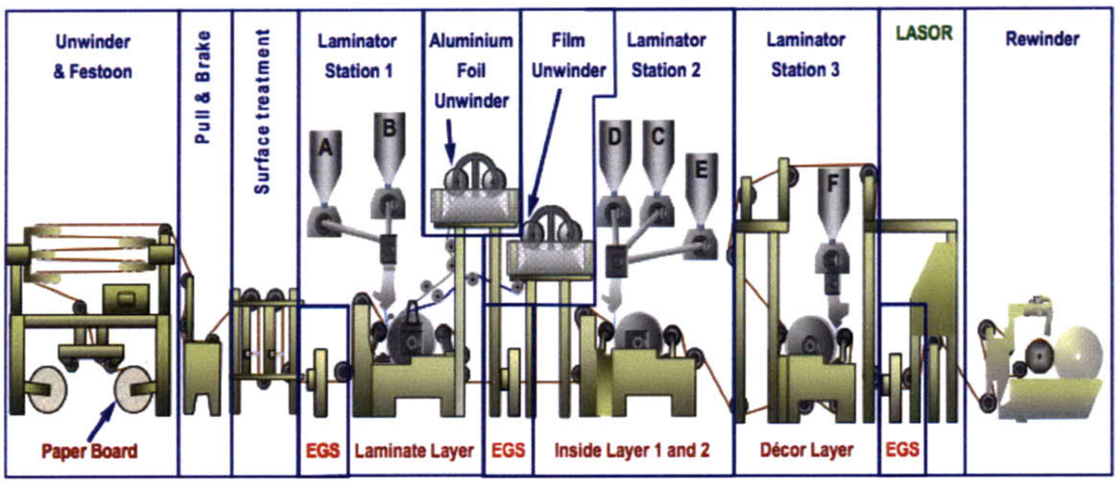


Figure 1.3: Schematic Laminating Process Station [7]

The TBA/TWA has six layers with their distinctive functionality, of which layer 2 is paper, layer 4 is aluminum foil and the rest are all PE films. They are processed sequentially in three consecutive stations: station one for layer 2, 3 and 4, station two for layer 5 and 6, and station three for layer 1. The finished laminated carton sheet is wrapped around a roller to become a carton roll, as shown in Figure 1.4. The challenge of this process is to uniformly coat meet-to-specification amount of PE on the paper and aluminum foil with no other critical-to-quality problems like moisture, strength and adhesion.

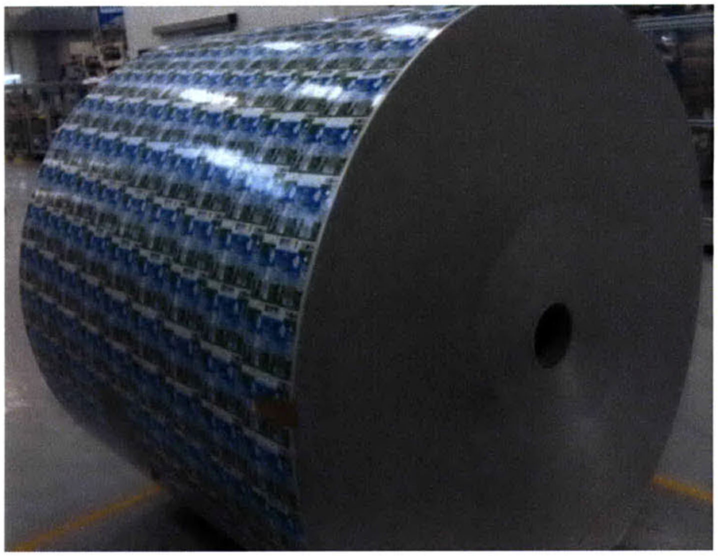


Figure 1.4: Finished Laminated Carton Roll

1.4 Opportunity for Improvement and Benefits

A lot of research on laminating process control has been conducted both in the internal R&D center of Company X and academic institutions all over the world. From the aspect of academic research, some influential inputs have already been highlighted in the literature, serving as good guidelines to improve the laminating process in Plant J. From the aspect of internal research, Company X has its confidential recipes for certain critical process parameters in general, though they are not tailored to specific product types; fine-tuning by DOE is needed to achieve the optimal operating conditions of laminating process on a plant-to-plant and product-to-product basis.

In addition, despite the fact that plant J has already adopted Automatic Profile Control (APC) to monitor and control the coating uniformity, defects associated with the high coating weight on the edge of the substrate still occur sporadically. It indicates the automatic control system alone is inadequate probably because some process parameters subject to disturbance are excluded from the control loop; it will be of great interest and value if we apply additional control methods as a complement. Furthermore, Plant J is keen to apply the statistical control method throughout the production floor as an integral and impressive indicator of World Class Manufacturing. The strong motivation of it comes from the huge potential financial returns on accreditation, increasing market share and selling comprehensive WCM consulting service to customers, provided that SPC is successfully implemented. [8]

1.5 Organization of Thesis

The thesis is organized into seven chapters. Chapter 1 introduces the background of the company, the description of lamination process, its quality improvement opportunity and benefits to the company. Chapter 2 defines the laminating problem in details and discussed the causality in depth. Chapter 3 reviews the process control model, hierarchy of process control methodology and physical fundamentals of the laminating process. Chapter 4 presents the methodology of Define, Measure, Analyze, Improve and Control (DMAIC) to resolve the problem defined in Chapter 2. Detailed tool kits are described under each problem-solving step. Chapter 5 demonstrated the acquired data and conducts statistical analysis on the results. It focuses on the findings of SPC and DOE. Chapter 6 concludes major points and recommends guidelines on implementing statistical control and fulfilling results of DOE in the laminating process. Finally, future work is proposed in Chapter 7.

Chapter 2 Problem Statement

2.1 Problem Definition

The problem is the defect of high edge occurring when the laminated carton sheets are wrapped around a roller to become a carton roll. High edge measures the difference in elevation between the edge surface and the central surface of the carton roll, as illustrated in Figure 2.1. Any magnitude larger than 2 mm is considered to be having the problem of high edge. The current production waste caused by this defect is 0.02%, amounting to S$40,000 per year.

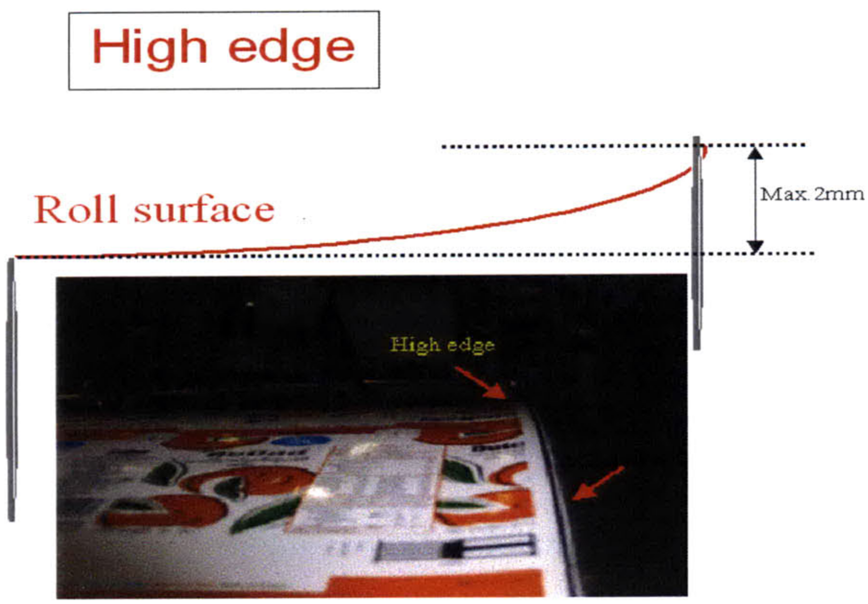


Figure 2.1: Defect of High Edge [9]

The defect of high edge causes the edge of the carton roll to warp up and then makes the affected carton sheets difficult to be fed into the customers' filling machines when those sheets are unwound. The unwound carton sheets are supposed to be flat enough so that they can match filling machines' slots to be transformed into sealed beverage package.

2.2 Problem Causality

Two root-causes combine to create the high edge problem: continuously thicker PE laminate edge and aggregation effect, as shown in Figure 2.2.

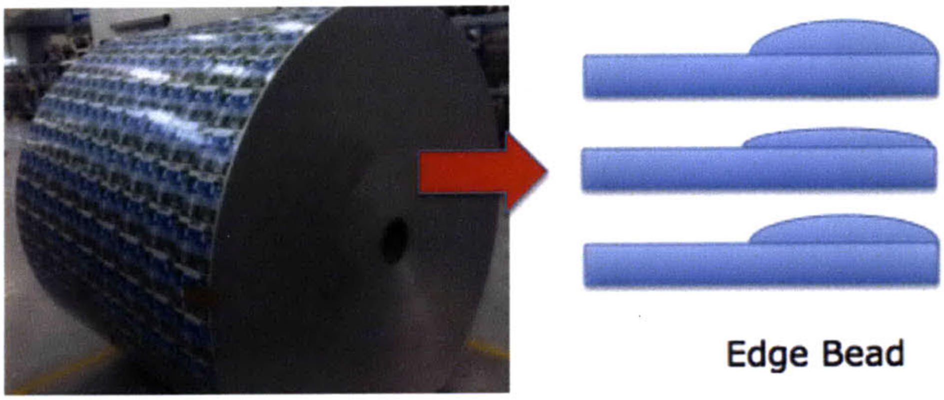


Figure 2.2: Continuously Thicker Laminate Edge and Aggregation Effect

The continuously thicker PE laminate edge means that the amount of coated PE is continuously larger at the edge than in the center along the cross direction of the PE film. When carton sheets are wound and aggregated into a carton roll, the variation in thickness of the single carton sheet is summed up and then the superposition of variation becomes phenomenal along the cross direction, giving rise to the defect of high edge. On one hand, if the amount of coated PE at the edge fluctuated around the average amount of cross-section coated PE, the positive and negative variation would cancel out when carton sheets are aggregated, and thus no high edge would occur. On the other hand, if the carton sheets were not aggregated to become a carton roll, then there would be no superposition of variation and then no high edge.

The possibility of non-uniform paper layers and Al foil layers is ruled out because no high edge is found when they are aggregated to become raw material rolls, as shown in Figure 2.3 and Figure 2.4. It is after the PE films are coated that the phenomenon of high edge occurs.

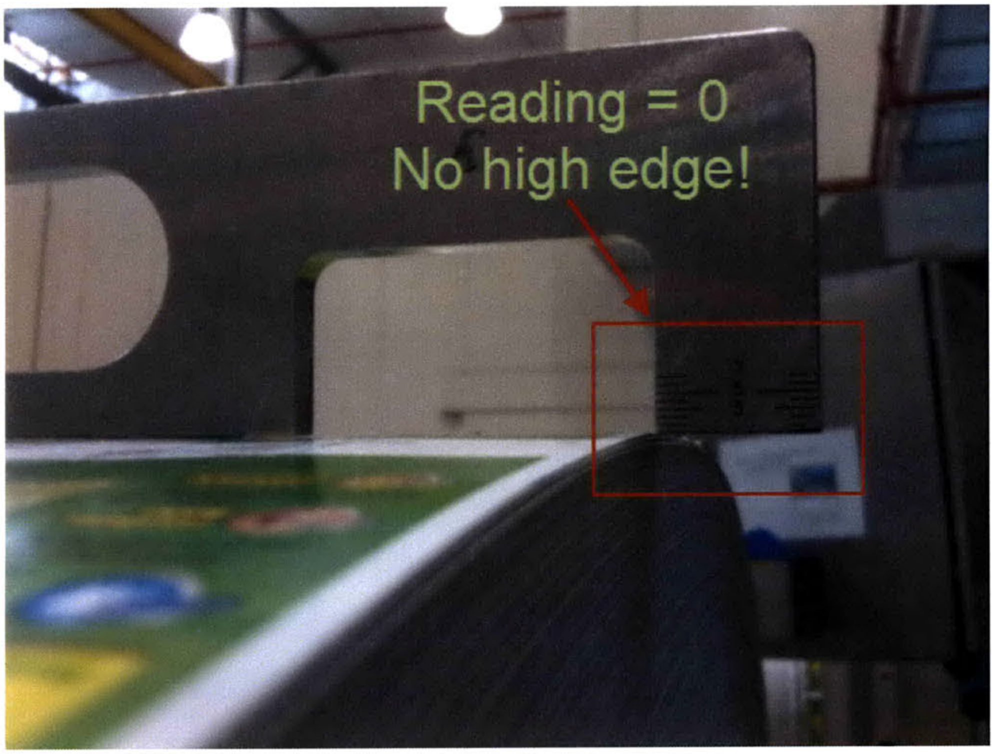


Figure 2.3: Edge Measurement of the Paper Roll

Figure 2.4: Edge Measurement of the Al Foil Roll

Therefore, it is concluded that the solution is to control the process of laminating PE so that we could obtain the uniformity of coated PE films, especially at the edge. The laminator station 2 is of primary focus in this thesis because of its high coating weight. It is well known that the laminating of PE is prone to the problem of edge bead formation: more PE molecules tend to accumulate at the edge than in the center of the PE film. [9], [10] The physics of laminating process and the control methodology are reviewed in the next chapter.

Chapter 3 Literature Review

3.1 Physics of Laminating Process

3.1.1 The Configuration and Function of Laminating Components

Lamination is a process of placing polyethylene (PE) films between layers of paper and aluminum foil and gluing them together by applying heat and pressure in a serial manner. The PE films serve as either adhesive or protective layers of the carton. The configuration of the laminating equipments is shown in Figure 3.1.

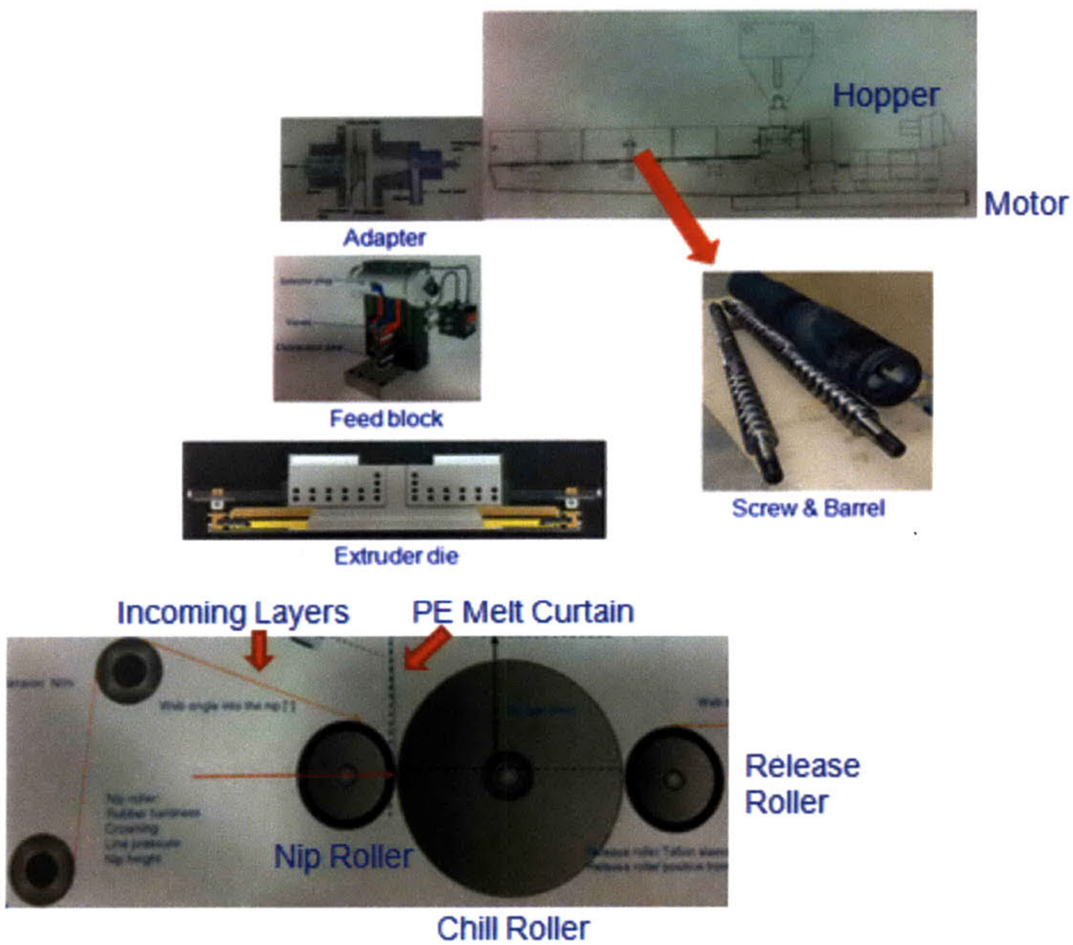


Figure 3.1: Configuration of Laminating Equipments [10]

As can be seen, one laminating station is mainly composed of barrel, adapter, feed block, die and a series of rollers. The PE pallets are fed into the hopper located above the barrel. Then, they fall into the feed zone of the screw driven by a motor and start to melt under the shear stress in the barrel. Along the longitudinal direction, the pressure is gradually built up by the rotating screw due to its decreasing pitch size and increasing diameter. After passing the melting zone, the PE pallets turn into homogenous melt PE flow in the end of the barrel, where the adapter is to ensure the stagnation time and mechanical enclosure for building up the pressure, especially in this metering zone. Also, it plays a role in filtering melt PE. At this point, the converting process of PE from solid to liquid is completed. Once solid PE pallets are converted to liquid melt flow, the feed block under the adapter is used to assemble multiple melt PE streams coming from different extruders and to form a consolidated stream. This single PE stream finally exits the die in the form of molten curtain or film, ready to be laminated on incoming sheets conveyed by series of rollers.

There are three rollers playing a paramount role in the execution of laminating PE film on the substrate: nip roller, chill roller and release roller. Contacting the chill roller, the nip roller is the one pressurizing the PE film into adhering to the incoming substrate. And, the chill roller is employed to dissipate the thermal energy of the PE film so that the strong adhesion between the PE film and the substrate can be achieved. The release roller is to ensure that adequate tension is applied so that the adhesive effect is maintained when the laminate comes out.

3.1.2 Edge Bead and Neck-in Phenomenon

The edge bead is a typical adverse effect of extrusion coating, meaning the amount of coated PE is larger on the edge than in the center of the PE film. This effect is closely related to the neck-in phenomenon, as shown in Figure 3.2.

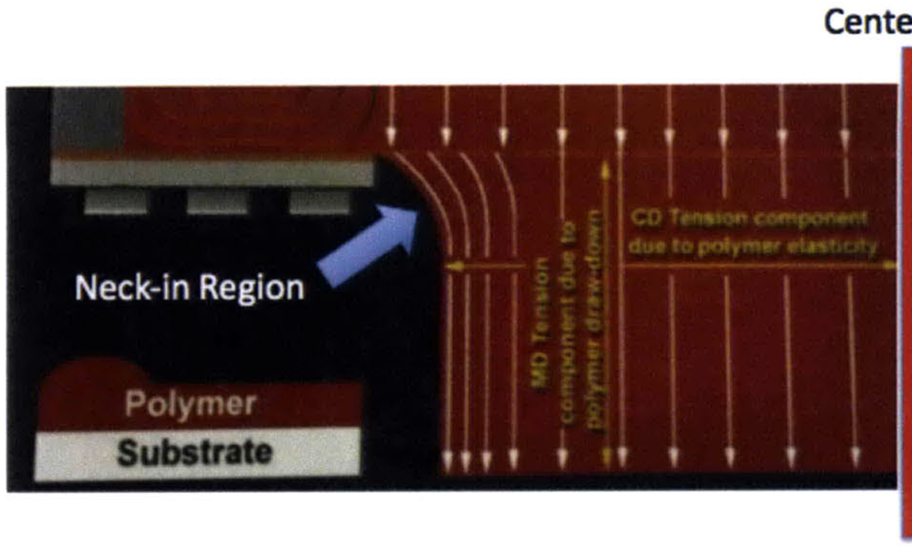


Figure 3.2: Edge Bead and Neck-in Phenomenon [10]

Each arrow indicates the flowing path of the PE stream. The denser the arrows are, the more PE molecules there are. As noted, when exiting the die, melt PE curtain tends to contract toward the centerline due to the fluid dynamic effect; this phenomenon is termed as neck-in. Then, more PE molecules accumulate at the edge than in the center and thus the edge bead forms.

The neck-in phenomenon is caused by combined force of a surface tension of the molten resin around the die portion, the melt elastic effect and the tensile stress of the molten resin towards the take-off direction. Generally, how big the edge bead is depends on how much the neck-in is.

3.1.3 Internal Deckling System for Edge Bead Reduction

Specially designed for edge bead reduction, the internal deckling assembly consists of an internal rod, manifold plug, and full-length deckle blade, as shown in Figure 3.3. It mitigates the effect of neck-in from the aspect of changing the surface tension of the molten resin around the die portion. Nevertheless, if the neck-in is bigger than the moving length of the plug and blade, then the plug and the blade will have little or no effect on the bead.

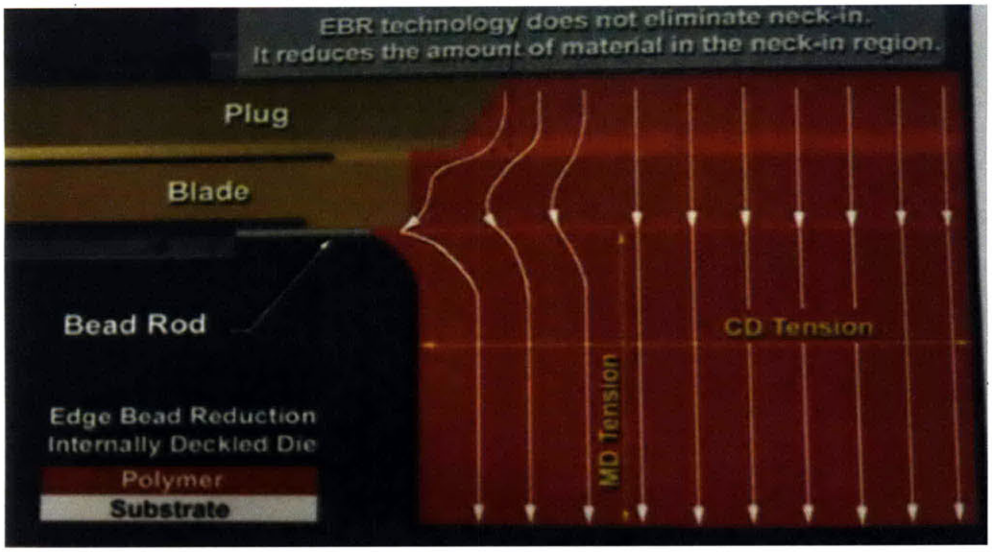


Figure 3.3: Internal Deckling System for Edge Bead Reduction [10]

Located near the die-lip, the internal rod establishes web width. At the same time, influencing the original PE flow pattern, the manifold plug and deckle blade gradually narrow the melt flow path between the plug and the rod. The effect is that more PE molecules are driven towards the centerline of the melt curtain; thus, the edge bead can be minimized.

Internal deckles completely seal off the ends of the internal flow channels of the die, eliminating areas of stagnation and minimizing edge bead formation. However, to fine-tune the edge profile of the polymer flow as it exits the die, a great deal of operator experience and skill are needed to adjust plug and blade's positioning from outside the die. Their different settings and corresponding results are shown in Figure 3.4.

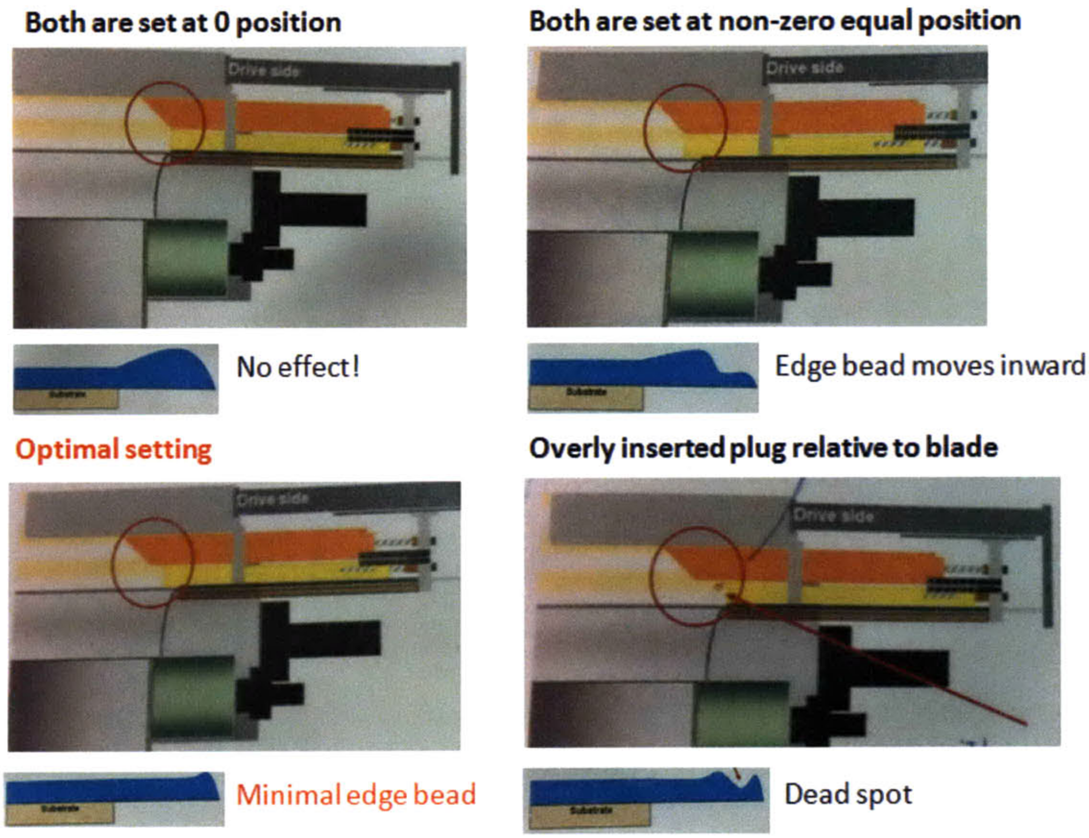


Figure 3.4: Results of Different Plug and Blade Settings [10]

As can be observed, there are four scenarios of plug and blade settings, and only the optimal setting can effectively minimize the edge bead. If plug and blade are set at the zero position, they play no role at all. If plug and blade are set at non-zero but equal position, the edge bead is moved inward the centerline of melt curtain and causes the edge instability. When the plug is inserted excessively further relative to the blade, the problem called dead spot arises; there could be a concave spot occurring at the edge of melt curtain.

3.1.4 Other Process Parameters Critical for Edge Bead and Neck-in

A. Die-bolt Power and Die Gap

The die-bolt power refers to the amount of heat energy provided to the thermal translator to either increase or decrease the die gap by contracting or expanding. Though the die gap can be mechanically adjusted, it is always regulated electrically because die gap and die-bolt power are under the Automatic Profile Control (APC) based on the readings of PE coating weight acquired by EGS, as illustrated in Figure 3.5. Figure 3.6 is a snapshot displaying the PE coating profile and die-bolt power level along the cross direction.

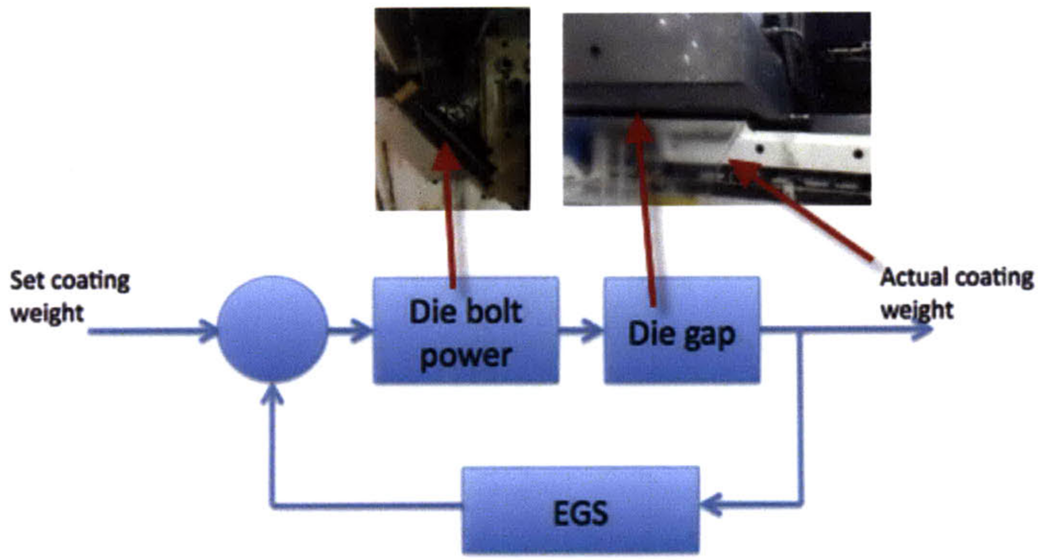


Figure 3.5: Feedback Output Control of PE Coating Weight

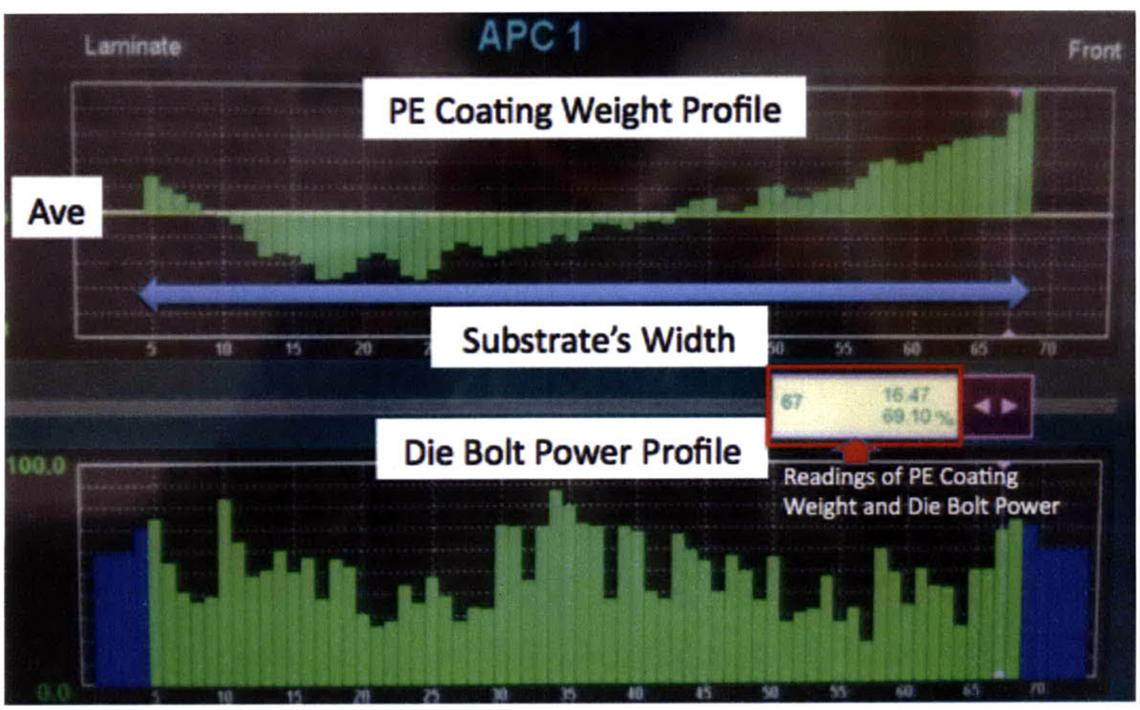


Figure 3.6: PE Coating Profile and Corresponding Die-bolt Power

It's noted that the die-bolt power located outside the edges of the substrate (i.e. blue bars) can either be automatically controlled by APC or be manually specified by operators, whereas die-bolt power within the substrate's width (i.e. green bars) can only be controlled by the output feedback loop.

The die-bolt power has direct impact on the PE coating weight since it determines how big the die gap opening is and then the amount of melt PE exiting the die in the cross direction. Therefore, the edge bead could be caused by inappropriate setting of manually controlled die-bolt power at the edge, or malfunction of automatic control loop.

B. Metering Zone Temperature

Melt temperature is an important parameter in the melt processing of polymers. However, it is not possible to control melt temperature directly, only to influence it using controllable process parameters in the barrel. Among these controllable process parameters are feed zone temperature, melting zone temperature, metering zone temperature, pipe zone temperature and die zone temperature. The metering zone temperature is found to have the most significant impact on the PE melt temperature while others are negligible. [11] The configuration of temperature readings is shown in Figure 3.7 and it is controlled by an array of heaters and coolers around the wall of the extruder.

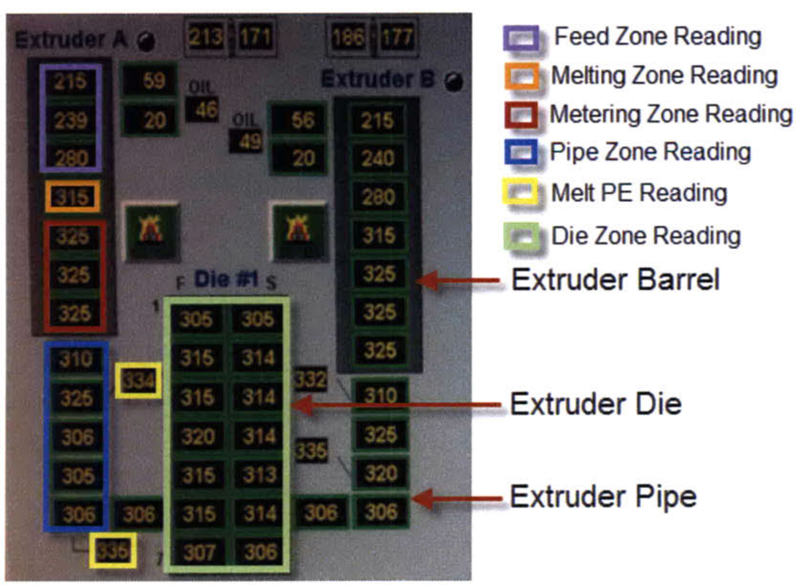


Figure 3.7: Configuration of Temperature Readings in the Extruder

The higher the metering zone temperature is, the higher the melt temperature will be, giving rise to more elastic PE melt curtain. It makes the melt curtain easy to deform under the applied tension (gravity in this case), causing the neck-in and then edge bead. Thus, it is preferable not to have too high metering zone temperature. However, if the metering zone temperature is too low, the ability of the PE melt curtain to be drawn down will decrease due to the less elastic PE melt curtain, resulting in another problem called low draw-down. Therefore, metering zone temperature is a very influential and sensitive process parameter.

C. Screw Speed and Line Speed

Screw speed and line speed are coupled process parameters and they are correlated by the following mathematical equation.

$$APECW = \frac{G \times SS}{LS \times CW} \qquad \text{(Eq. 3.1)}$$

APECW = Average PE Coating Weight [gram/ square meter]

G = Extrusion Capacity [gram/ revolution]

SS = Screw Speed [revolution/ minute]

LS = Line Speed [meter/ minute]

CW = Coating Width [meter]

As line speed is decreased, the system will automatically calculate the corresponding screw speed to maintain the constant average PE coating weight. However, the consequential decreased screw speed also applies less shear rate on the PE in the barrel, causing the elasticity of the molten PE to decline. Less elasticity makes the melt curtain easy to deform and then prone to neck-in phenomenon under tension, building the edge bead on the PE film. As a result, the screw speed and line speed are coupled influential process parameter.

D. Air Gap

Air gap refers to the vertical distance between the die-lip and the contact point of nip roller and chill roller, as shown in Figure 3.8.

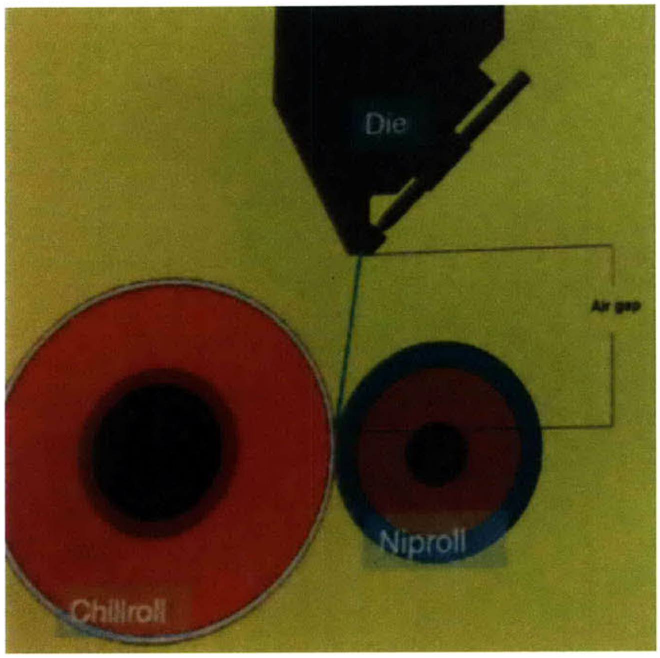


Figure 3.8: Air Gap [10]

The air gap defines the distance over which the melt curtain contracts; the larger the air gap is, the more contraction in the cross direction the melt curtain will be. Due to the difference in surface tension of melt curtain's edge and centerline, excessive contraction renders the accumulation of PE molecules on the edge and eventually contributes to the edge bead. Though it is preferable to have less air gap because of concerns for edge bead, excessively small air gap could result in inadequate oxidation of the PE film. Consequently, air gap is a very sensitive process parameter.

3.2 General Process Control Model

A manufacturing process can be defined as an interaction of equipment with material to transform it into a part conforming to specifications. The interaction takes place in form of mechanical, electrical, thermal or/and mechanical energy exchange. Hardt points out in his paper, since the transformation is always driven by and governed by equipment, the only control inputs over the process, other than changing the material itself, is through the equipment. [12] The output of the produced part can be classified into two categories: geometry and properties. Geometry defines macroscopic shape of the product, like length, height, etc. Properties characterize those constitutive and intrinsic attributes of the part, like stiffness, strength and the like. Figure 3.9 illustrates the schematic diagram of this model.

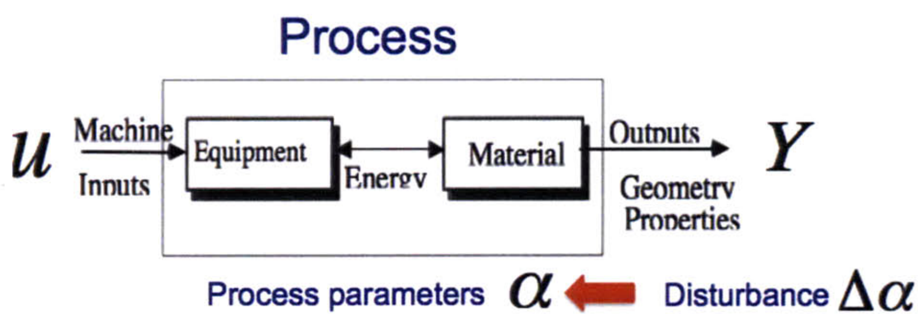


Figure 3.9: Schematic Diagram of the General Process Model [12]

The equipment and material define the process parameters. Those parameters are termed as equipment state and properties as well as material state and properties. [12] State refers to those energy pairs such as pressure-flow, temperature-entropy and voltage-current. Properties are those well-known intrinsic quantities like melting point, viscosity and Young's modulus. State and properties could be either of the equipment or of the material. It's noted that there are always disturbances to process parameters.

To help understand the relationship between process parameters, controllable inputs and outputs, Hardt presents the following equation to characterize the causality. [12] It is noted that the controllable inputs are the subset of the process parameters that are accessible and adjustable in a reasonable time frame relative to the process execution time.

$\underline{Y} = \phi(\underline{\alpha}, \underline{\mu})$ (Eq. 3.2)

$\underline{Y}$ = outputs (geometry and properties)

ϕ = process transformation function

$\underline{\alpha}$ = process parameters

$\underline{u}$ = controllable inputs

3.3 Hierarchy of Process Control Methodology

Based on the process model given in Eq. 3.2, the first-order variation equation is derived: [12]

$$\Delta \underline{Y} = \frac{\partial Y}{\partial \alpha} \Delta \underline{\alpha} + \frac{\partial Y}{\partial u} \Delta \underline{u} \qquad \text{(Eq. 3.3)}$$

$\Delta \underline{Y}$ = variation of the output

$\frac{\partial Y}{\partial \alpha}$ = disturbance sensitivity of the process

$\Delta \underline{\alpha}$ = parameter disturbances

$\frac{\partial Y}{\partial u}$ = input-output sensitivity or "gain"

$\Delta \underline{u}$ = controllable input changes

To minimize $\Delta \underline{Y}$, it is proposed to address the challenge from three aspects with their distinctive methods, [12] and they are summarized in the subsequent sections.

- Reduce sensitivity

  —Design of experiment

- Reduce Disturbance

  —Standard operating procedure

  —Statistical process control

  —Feedback control of process state

- Measure outputs and manipulate inputs

  —Feedback control of outputs

3.3.1 Reduce Sensitivity—Design of Experiment

This method is to minimize the term $\frac{\partial Y}{\partial \alpha}$ such that the variation in outputs is minimized. It would be helpful if we could derive the quantitative form of this partial differentiation characterizing the process. However, in most cases, the physics of the process are too complicated for us to obtain the insight of this level. Therefore, we could use the design of experiment instead to calculate the variation at different operating point and select the one with the minimal variation as our robust operating point. This robust operating point corresponds to a set of optimized process parameters that lead to minimal change in outputs. Also, design of experiment can help us obtain a set of optimized process parameters that contribute to desired process mean.

In the design of experiment, we study the response based on distinctive treatments achieved by varying factors at different levels. These treatments comprise the design matrix. The process response y at each treatment t is assumed to be normally and independently distributed with different mean but identical variance. The underlying mathematical equation is

$y_i = t_i + e \quad i = 1,2,3...$ (Eq. 3.4)

y = process response at the treatment i

t_i = process mean at the treatment i

e = random error subject to N $(0, \sigma)$.

3.3.2 Reduce Disturbance— Standard Operating Procedure

Simply put, standard operating procedure is a series of pre-determined steps used to operate a process for the purpose of minimizing disturbance. It is widely used in either manufacturing or business process and is useful especially when a myriad of complicated human actions, which could be random otherwise, are involved. From the perspective of process control, standard operating procedures can effectively minimize the operator-to-operator and trial-to-trial variation.

3.3.3 Reduce Disturbance— Statistical Process Control

This method is to reduce the disturbance term of ΔY such that the variation in outputs is minimized. Statistical process control is a monitoring tool in nature. Typically, a control chart contains a center line (CL), an upper control limit (UCL) and a lower control limit (LCL). The center line represents the mean of quality characteristic corresponding to the in-control state. The upper control limit and lower control limit are chosen so that almost all the sample points will fall between them if the process is in control. A point plotted outside of the control limits is interpreted as evidence that the process is out of control because of assignable causes. The underlying mathematical model is shown in Equation 3.5. It is noted that the distribution of process response is assumed to be stationary.

$x_t = \mu + \varepsilon \quad t = 1, 2, 3...$ (Eq. 3.5)

x_t = process response at time t

μ = process mean

ε = random error subject to N (0, σ)

Note that once an out-of-control point is detected on the control charts, it provides no prescription for action, but signals that the disturbance exists and then investigation should be conducted to eradicate it immediately before it leads to large changes in outputs. Therefore, except establishing mechanism of data acquisition and plotting the control charts, another important practice is to construct the Out-of-control Action Plan (OCAP). It is the OCAP that offers detailed and practical corrective actions to actually eliminate the disturbance.

3.3.4 Reduce Disturbance－Feedback Control of Process State

As the previous method does, this method is also to reduce the disturbance term of ΔY such that the variation in outputs is minimized. Nevertheless, the difference is that the feedback control loop is employed in this method to ensure the process states conform to what they are supposed to exactly be. Usually, these process states are machine temperature, pressure, velocity and the like, which are directly measured by instruments in a real-time manner. It's noted that the outputs are excluded from the control loop, as shown in Figure 3.10.

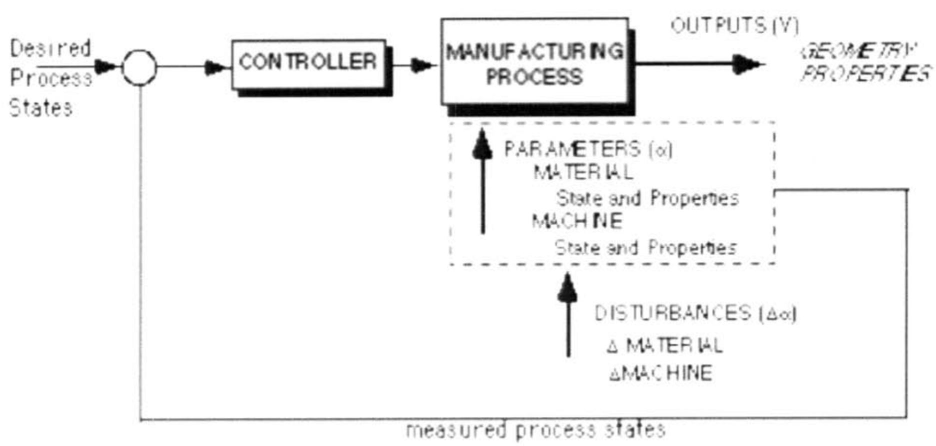


Figure 3.10: Schematic Diagram of Feedback State Control [12]

3.3.5 Measure Outputs and Manipulate Inputs

This method is to measure the outputs and in turn constantly tune the inputs to ensure the minimal change in outputs. It is the most straightforward and powerful way of controlling the process to yield conforming outputs since this strategy encompasses all influences on the processes. However, special attention should be paid to the issues in time delays and accuracy of measurement system. The schematic diagram of this method is illustrated in Figure 3.11.

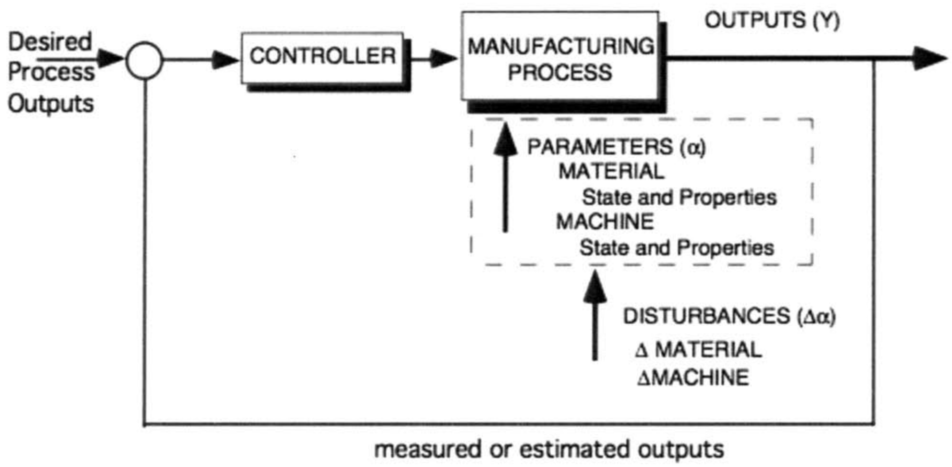


Figure 3.11: Schematic Diagram of Feedback Output Control [12]

Chapter 4 Methodology of DMAIC

4.1 Overview

Define, Measure, Analyze, Improve, and Control (DMAIC) is a structured problem-solving procedure widely used in quality and process improvement. It is often associated with six-sigma activities for project management and implementation. However, DMAIC is not necessarily formally tied to six-sigma, and can be used regardless of an organization's use of six-sigma. [13] It is a general procedure and utilizes process capability analysis, measurement systems capability studies, control charts, designed experiments, and many other basic statistical tools. The DMAIC approach has proven to be an effective framework for improving processes, and was chosen as the methodology to address the problem of high edge in this thesis.

DMAIC focuses on the effective use of small set of tools. Table 4.1 shows the tools, along with the DMAIC steps where they were used to tackle the defect of high edge in laminating process.

Table 4.1: Deployment of Tool Kits in DMAIC Steps

Tool	Define	Measure	Analyze	Improve	Control
Project Charter	■				
Process Model	■	■			
Cause & Effect Analysis		■			
Measurement System Analysis		■			
Process Capability Analysis		■			
Shewhart Control Charts (Screening)		■	■		
Hypothesis Tests, Confidence Intervals			■		
Designed Experiments: 2^{k-p} and RSM				■	
Regression & Variance Analysis				■	
Shewhart Control Charts (Monitoring)					■
Out-of-Control Action Plan					■

4.2 The Define Step

The objective of the define step was to identify the project opportunity as well as boundary, and to verify that it represented legitimate breakthrough potential. [13] The project must be important to both customers and business owner. The most useful tool in this stage was project charter.

4.2.1 Project Charter

The project charter was the first item completed in the define phase. It was a short document containing a description of the project and its scope, the starting and anticipated completion date, success metrics, business benefits, milestones, cross-functional team members and any additional support needed, as tabulated in Table 4.2. Detailed benefits were discussed in the Section 1.4 of Opportunity for Improvement and Benefits.

Table 4.2: Project Charter [14]

Six Sigma Team Charter

Project Name		Process Control for High Edge at L22	
Sponsor		xxx	
Team Leader		xxx	
Core Team members		AAA,BBB,CCC,DDD	
Start Date		21-Dec-09	
Completion Date		30-Aug-10	
	Element	**Team Charter**	
1	Process/System Definition	Lamination Process	
2	Critical Impact on Business	High edge and wavy edge cause customers to have problems in sealing cartons.	
3	Problem Statement		
4	Project Objective	**Baseline**	**Goal**
		Lam layer	ave coating weight=nominal
		Inside layer	ave coating weight=nominal
		High edge	<1mm
		Defect waste	less 0.01%
5	Financial Benefit Estimated (Annual)	$20k worth of defects; accreditation; market share; consulting service	
6	Scope / Boundaries	TWA/TBA at L22,	
7	Schedule / Milestones	Internal schedule	
8	Benefit to Customers or Delivery Partners	They will not faced with uneven edge during filling.	
9	Support Required	To work with EGS specialist to set alarm on total Inside	
10	Hypothesis and Key Success Factors	Lam and inside PE layers are most significant for high edge. Process is within normal condition.	

4.3 The Measure Step

The purpose of measure step was to evaluate and understand the current state of the process, along with the level of its being measured and documented. [13] This involved the development of detailed process model with key process parameters, effective mapping of critical-to-quality characteristics (CTQs) to process parameters, assessment of measurement system for acquiring process data, and appraisal of current process capability.

4.3.1 Process Model

The process model was composed of key process parameters and CTQs. The CTQs were the targeted output we intended to improve. Those process parameters were influential inputs, classified into two categories: state and properties, as reviewed in the Section 3.2 of General Process Model. The process model presented a clear definition of lamination from the perspective of process control. All the future study and results would be based on it. Table 4.3 shows the process model in light of the Section 3.1 of Physics of Laminating Process. Note that this model applies to laminator station 2. Given that the average PE coating weight is highest at laminator station 2, it is of primary focus in addressing the problem of high edge in the following steps.

Table 4.3: Process Model of Laminating Station 2

	Type	Name	Component	Current Control Methodology	Data Acquisition
Process Parameters	States	Metering Zone Temperature	Barrel	State Feedback Control	FIX PLC System
		Screw Speed	Barrel		
		Lind Speed	Line		
		Manual Die Bolt Power	Die		EGS System
		Automatic Die Bolt Power	Die	Output Feedback Control	
	Properties	Die Gap: Mechanical	Die	Standard Operating Procedure	EGS System
		Air Gap	Die/Line		Scale Reading
		Plug and Blade Setting	Die		
		PE Grade	Raw material		Supply Certificate
		Paper Grade	Raw material		
		Al Foil Grade	Raw material		
Output (CTQ)	Geometry	PE Coating Weight	N/A	Output Feedback Control	EGS System

4.3.2 Cause and Effect Analysis

The cause and effect analysis presented theoretical insights into the effect of process parameters on the process output. It strengthened understanding of the process. In addition, by building the physical reasoning and foundation, it provided guidelines on effective usage of statistical process control and designed experiments in the prospective steps. The result is organized in the section 3.1 of Physics of Laminating Process,

4.3.3 Measurement System Analysis

Since the collected data was used as the basis for SPC and DOE, it was very important to evaluate the capability of the measurement system.

At first, we proved the capability of the manual measurement system by conducting gauge repeatability and reproducibility analysis (GR&R). The GR&R was based on analyzing different components of variation to verify the capability of gauging system. The breakdown of source of variation in CTQs is illustrated in Figure 4.1. The repeatability is the variation in measurements taken by a single person or instrument on the same item and under the same conditions. The reproducibility is the variation induced by the different operators measuring the same part. It is noted that one GR&R applies to one complete measurement system, including the part, specification, operator, and method.

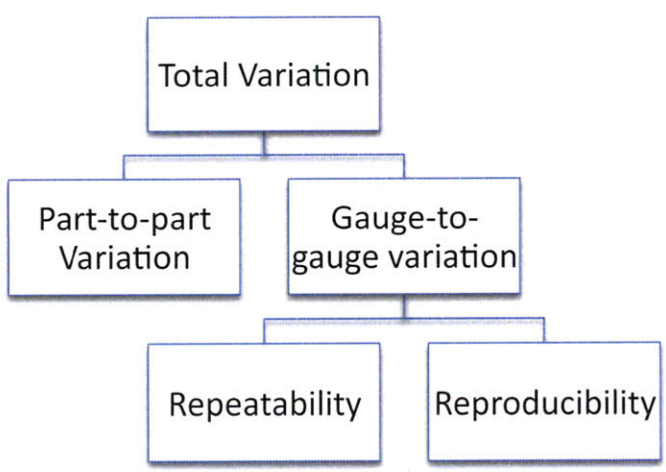


Figure 4.1: Breakdown of Total Variation

Then, we collected samples, manually measured them in the lab, compared the results of lab testing with those of real-time automatic gauging and did hypothesis tests to verity the automatic gauging capability. Paired t-test was employed to prevent the difference between specimens (which could be substantial) from affecting the test on the difference between automatic gauging and manual gauging.

4.3.4 Process Capability

After the verification of measurement system, the process capability of laminator station 2 was calculated to have an understanding of the current status of the process. Tackling the defect of high edge, we defined the Edge Bead Indicator (EBI) to characterize the laminating process capability. It was the difference between PE coating weight at the left or right edge and average PE coating weight along the cross direction, as highlighted in the frame in Figure 4.2.

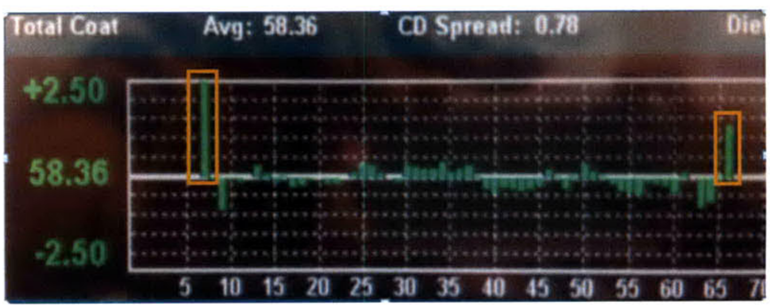


Figure 4.2: Definition of Edge Bead Indicator

Two kinds of metrics were used to calculate the process capability and they were

$$C_p = \frac{USL - LSL}{6\sigma} \qquad \text{(Eq. 4.1)}$$

C_p = process capability ratio
USL = upper specification limit
LSL = lower specification limit
σ = process standard deviation

$$C_{pk} = \frac{Min\ (\ |USL - \mu|\ ,|LSL - \mu|\ )}{3\sigma} \qquad \text{(Eq. 4.2)}$$

C_{pk} = process capability ratio for an off-center process

USL = upper specification limit

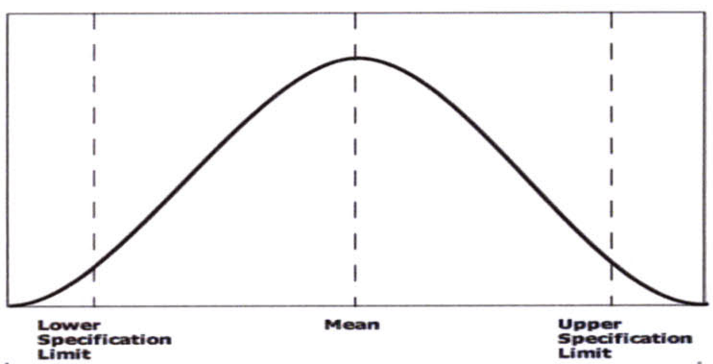
LSL = lower specification limit

μ = process mean

σ = process standard deviation

The difference between them is that C_p is not able to reflect the shift of mean in the calculation while C_{pk} is. The highest process capability occurs when the mean falls on nominal and standard deviation is far narrower than the range of specifications. The relationship between part-per-million (ppm) defective and level of standard deviation are summarized in Table 4.4.

Table 4.4: Interpretation of Process Capability



Spec. Limit	C_p	Percent Inside Sepcs	Ppm Defective
±1 sigma	0.3	68.27%	317300
±2 sigma	0.7	95.45%	45500
±3 sigma	1	99.73%	2700
±4 sigma	1.3	99.9937%	63
±5 sigma	1.7	99.999943%	0.57
±6 sigma	2	99.9999998%	0.002

4.4 The Analyze Step

In the analyze step, the objective was to use the date to explore the tentative causal relationship in the process and to understand the different sources of variability. [13] Generally, the sources of variability are classified into common causes and assignable causes. [15] Common causes are sources of variability that are embedded in the system of process itself, while assignable causes usually arise from improperly adjusted or controlled machines, operator errors and defective raw materials, and thus are the targets of elimination. Removing a common cause usually means changing the process; by contrast, removing an assignable cause commonly involves eradicating specific problems. There are many tools available in this step. Shewhart control charts and hypothesis testing were utilized in this thesis.

4.4.1 Shewhart Control Charts for Process Screening

Walter A. Shewhart invented the Shewhart control charts while working for Bell Labs in the 1920s. [16] Most effective in process screening, they were used to check whether a process was in statistical control and to determine whether a process should undergo a formal examination in order to find out assignable causes. The eventual goal was to eliminate variability in the process before many nonconforming parts were manufactured. And, an in-control process was considered indispensable for design of experiment in the Improve step.

An important factor that needed to be addressed was the design of control charts in terms of selection of sampling frequency, control limit width and sample size. These were respectively related to data autocorrelation, probability of type I error and probability of type II error.

Shewhart control charts work most effectively on uncorrelated data points which are referred to by time series analysts as white noise. It is known that reducing sampling frequency is an effective way to remove the autocorrelation at the cost of losing resolution of acquired data points and increasing type II error. In plant J, it takes 10 minutes to produce a carton roll on average and the sensor refreshes the profile of PE coating weight every 20 seconds. That is to say, we could have 6 data points every two minutes and 5 samples every carton roll. Therefore, the sampling frequency was determined to be a time interval of 2 minutes. But, to avoid data autocorrelation, not all the 6 data points could be taken and the sample size was less than 6.

The probability of type I error α means false alarm concluding the process is out of control when it is really in control. It is dependent on the control limits; widening the control limits can decrease the risk of type I error while increasing the risk of type II error. Consequently, $\pm 3\sigma$ control limits were selected and the probability of type I error was 0.0027. The average run length of the $\bar{x}$ chart when the process was in control (called ARL_0) was

$$ARL_0 = \frac{1}{\alpha} = \frac{1}{0.0027} = 370 \qquad \text{(Eq. 4.1)}$$

Probability of type II error β means missing alarm concluding the process is in control when it is really out of control. It is dependent on the control limits, sampling frequency and sample size. After the specific control limits had been determined to obtain adequately long ARL_0 and sampling frequency had been specified to remove autocorrelation of data, we could obtain satisfactory ARL_1 (i.e. the average run length to detect the process shift) by changing sample size. As a result, sample size of 3 was determined based on the operating-characteristic curve indicating the ability of control chart to detect process shifts of different magnitudes. [17]

The beta-risk is

$$\begin{aligned}\beta &= P\{LCL \le \bar{x} \le UCL \mid \mu = \mu_1 = \mu_0 + k\sigma\} \\ &= \phi(L - k\sqrt{n}) - \phi(-L - k\sqrt{n}) \\ &= \phi(3 - 3\sqrt{3}) - \phi(-3 - 3\sqrt{3}) \\ &= 0.014\end{aligned} \qquad \text{(Eq. 4.2)}$$

LCL = lower control limit

UCL = upper control limit

μ_0 = original process mean

μ_1 = shifted process mean

σ = process standard deviation

k = multiple of process standard deviation

L = three-sigma control limits

The ARL_1 is

$$ARL_1 = \frac{1}{1-\beta} = \frac{1}{1-0.014} = 1 \qquad \text{(Eq. 4.3)}$$

In summary, $\pm 3\sigma$ control limits were chosen and sampling strategy was to collect three consecutive data points of edge bead indicator (EBI) every 2 minutes as a sample. Note that consecutive units of production over the sampling interval were used as rational subgroups to minimize the chance of variability within a sample and maximize the chance of variability between samples.

4.4.2 Hypothesis Testing

There was a close connection between control charts and hypothesis testing. By plotting every point on the control chart, we were actually comparing it with control limits and testing the null hypothesis $\mu_1=\mu_0$. Consequently, a point plotting within the control limits was equivalent to failing to reject the hypothesis of statistical control, and a point plotting outside the control limits was equivalent to rejecting the hypothesis of statistical control.

4.5 The Improve Step

In the measure and analyze steps, we focused on deciding which key process parameters to study, what data to collect, how to analyze and display the data, identified potential sources of variability, and determined how to interpret the data they had obtained. In the improve step, we turned to creative thinking about the specific changes that could be made in the process to head towards the optimized process performance. [13] Design of Experiment (DOE) was the one applied in this step.

4.5.1 Fractional Factorial Design for Process Characterization

The 2^{5-2} fractional factorial design with center point was conducted at each side of the laminator station 2 in order to screen the process and find which main effect of or interaction between five factors of die-bolt power could impact the edge bead indicator. The 2^{5-2} design was chosen because there were five die-bolt power inputs located outside the substrate width and only the main effects of and two-way interaction among them were of interest. A full factorial design would be too costly given the extent of the conclusion we intended to draw; a 2^5 design would need 32 carton rolls and take 7 to 8 hours. The detailed 2^{5-2} fractional factorial design is shown in Table 4.5.

Table 4.5: 2^{5-2} Fractional Factorial Design

```
Factors:    5   Base Design:          5, 8   Resolution:  III
Runs:      90   Replicates:             10   Fraction:    1/4
Blocks:     1   Center pts (total):     10

* NOTE * Some main effects are confounded with two-way interactions


Design Generators: D = AB, E = AC


Alias Structure

I + ABD + ACE + BCDE

A + BD + CE + ABCDE
B + AD + CDE + ABCE
C + AE + BDE + ABCD
D + AB + BCE + ACDE
E + AC + BCD + ABDE
BC + DE + ABE + ACD
BE + CD + ABC + ADE
```

Each of the die-bolt powers was set at two levels and 10 replicates were designed for cube points. Also, the technique of aliasing was employed by specifying generators D = AB and E = AC; not all the possible combinations of the levels of factors were investigated. This was because the incurred cost mostly lay in the changeover instead of replicates. In addition, ten center points were added in order to examine the curvature of fitted model. And, the residuals were checked for the assumption that they were normally distributed with identical variance.

Note that the five die-bolt powers could be specified to be either automatically controlled or manually controlled (Those within the paper width were automatically controlled and no change could be made). For the purpose of studying their effects, die-bolt power A, B, C, D and E were all set to be manually controlled in the experiment, as shown in Figure 4.3.

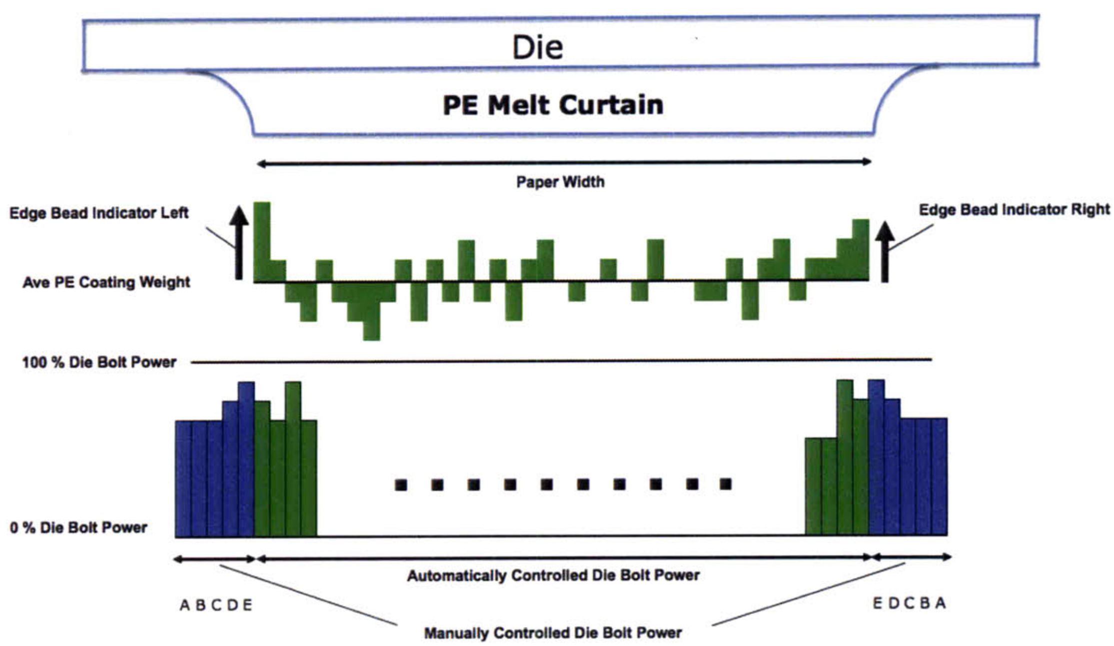


Figure 4.3: PE Coating Profile and Corresponding Die-bolt Power

In order to ensure the collected data is representative of the normal distribution at each treatment, special attention was given to the reduction of disturbance during the experiment. Specifically, before performing the experiment, we conducted planned maintenance on the laminator station 2; routine cleaning was done to remove the oxidized PE remaining on the die surface, as shown in Figure 4.4. Also, we collected the data only after the process had been in steady state, avoiding the ramp-up stage every time we changed the treatment.

Figure 4.4: Die Cleaning for Disturbance Removal

4.5.2 Response Surface Model for Process Optimization

After the influential die-bolt powers had been identified, the central composite design was used to establish the response surface model with the purpose of determining the optimum operating conditions for the process (i.e. on-target mean and minimal variation). In details, based on the result of previous 2^{5-2} design, die-bolt power together with plug setting and blade settings, were selected to form cube points with 10 replicates. In addition, center points and axial points with 10 replicates were added to capture the quadratic effect. The general configuration of central composite design is shown in Figure 4.5.

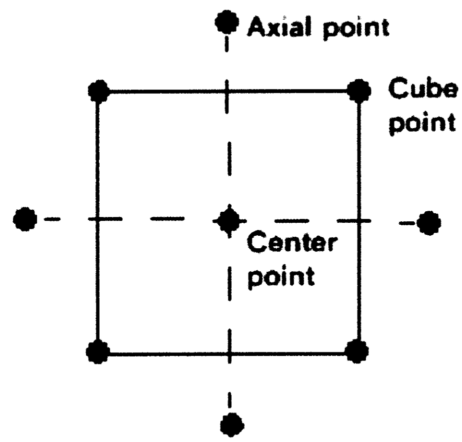


Figure 4.5: Central Composite Design

Cube points allowed for the estimation of linear and interaction effects, but not curvature. These points were comparable to the corner points of a 2^k factorial design. The point in the middle of the cube represented the center points for both the cube and the axial blocks. Center points enabled us to check for curvature, but not individual quadratic terms. We added axial points, in addition to center points, to estimate quadratic terms. The points joined by dotted lines indicate points outside or on the surface of the cube.

Recall the process model developed in section 4.3.1. The rest of the process parameters were excluded because of concerns raised by experienced engineers on their negative impact on other CTQs like adhesion properties. Any change to them would pose a risk to the laminating process performance in general.

As we had done in conducting experiment of 2^{5-2} fractional factorial design, efforts were made to eliminate the disturbance as much as possible.

4.6 The Control Step

The objective of the control step was to complete all remaining work on the project and to hand off the improved process to the process owner along with a process control plan and other necessary procedures to ensure that the gains from the project would be implemented. [13]

4.6.1 Shewhart Control Charts for Process Monitoring

When applying the Shewhart control charts in the analyze step, we had identified assignable causes and made efforts in eliminating them to achieve statistical control. Based on the newly collected samples, reliable phase-two monitoring control limits and process mean were computed for the purpose of on-line process surveillance in the future production, and, they would be reviewed periodically for effectiveness.

4.6.2 Out-of-control Action Plan (OCAP)

The OCAP was drafted to provide detailed instructions on what actions should be taken sequentially if an out-of-control point was detected on the control charts. Serving as a recipe of corrective action for statistical process control, it could effectively help operating personnel to remove those assignable causes swiftly before they led to large variation in the edge bead indicator. Often additional input and support from engineers, management, and quality engineering staff was necessary.

Chapter 5 Results and Discussion

5.1 Measurement System Analysis

5.1.1. Capability of Manual Measurement System

Three operators, a common weight scale and a particular product specification comprise a manual measurement system. Each of the operators is assigned to measure each sample's PE coating weight for three times. The samples are randomly collected from 4 batches and are placed in a random order. Based on the data, the ANOVA is conducted to compare the different sources of variation originating from operators, parts and gauging trials and to judge whether the part-to-part variation component is dominant. The collected data is shown in Table 5.1 and the ANOVA is shown in Table 5.2.

Table 5.1: Collected Data

Category	Number	Variability	Remark
Operator	3	Op-to-op	Reproducibility
Sample	4 (from 4 different batches)	Part-to-part	Inheret randomness
measurement per sample	3	Gauge-to-gauge	Repeatability

	Technician	Sample NO	PE coating weight		Technician	Sample NO	PE coating weight
1	S	1	19.23	19	M	3	20.39
2	S	1	19.5	20	M	3	20.38
3	S	1	19.38	21	M	3	20.5
4	S	2	18.97	22	M	4	22.07
5	S	2	18.76	23	M	4	22.02
6	S	2	18.93	24	M	4	22.47
7	S	3	20.37	25	Y	1	19.58
8	S	3	20.24	26	Y	1	19.71
9	S	3	20.42	27	Y	1	19.69
10	S	4	21.89	28	Y	2	18.81
11	S	4	21.91	29	Y	2	18.78
12	S	4	22.25	30	Y	2	18.87
13	M	1	19.56	31	Y	3	20.61
14	M	1	19.43	32	Y	3	20.39
15	M	1	19.53	33	Y	3	20.44
16	M	2	18.97	34	Y	4	22.21
17	M	2	18.59	35	Y	4	22.06
18	M	2	18	36	Y	4	22.27

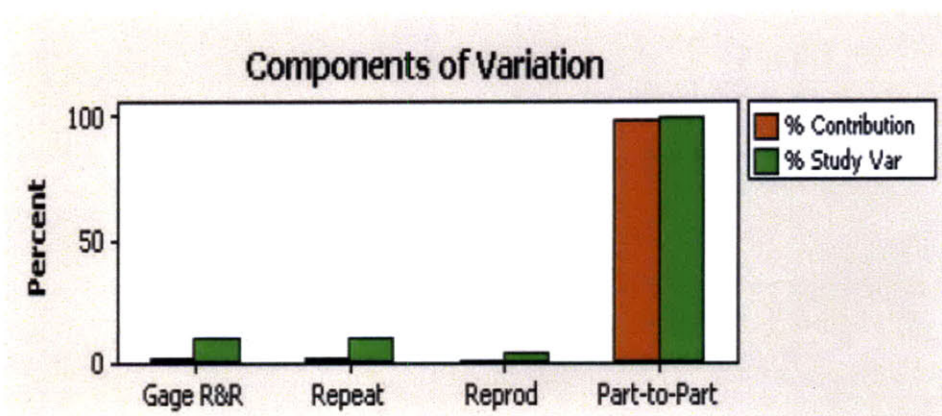
Table 5.2: Two-way ANOVA

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
Sample No:	3	54.7199	18.2400	947.303	0.000
Technician	2	0.1044	0.0522	2.711	0.145
Sample No: * Technician	6	0.1155	0.0193	1.037	0.426
Repeatability	24	0.4457	0.0186		
Total	35	55.3855			

Based on the p value of 0 for the sample number, it is concluded that the factor of sample number has a significant impact on the measurement result while the effects of different technicians and technician-sample interaction are negligible with the confidence level of 95%.

A further analysis of component of variance is conducted and the result is shown in Figure 5.1.



Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.02150	1.05
Repeatability	0.01871	0.91
Reproducibility	0.00279	0.14
Technician	0.00279	0.14
Part-To-Part	2.02458	98.95
Total Variation	2.04608	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.14662	0.87973	10.25
Repeatability	0.13677	0.82063	9.56
Reproducibility	0.05283	0.31700	3.69
Technician	0.05283	0.31700	3.69
Part-To-Part	1.42288	8.53727	99.47
Total Variation	1.43041	8.58248	100.00

Number of Distinct Categories = 13

Figure 5.1: Components of Variance

Based on the part-to-part's variance component contribution of 98.95% and its study variance component of 99.47%, the conclusion is drawn that the manual measurement system is capable enough to be utilized to check the capability of automatic measurement system.

5.1.1. Capability of Automatic Measurement System

After GR&R is conducted to verify the goodness of manual measurement, data collected by manual measurement is compared with the data set acquired by automatic measurement. A paired t-test is performed to check the null hypothesis that two means from two samples are identical. The result is shown in Table 5.3.

Table 5.3: Paired T-test

Paired T for Manual Measurement - Automatic Measurement

	N	Mean	StDev	SE Mean
Manual Measurement	36	20.224	1.258	0.210
Automatic Measurement	36	20.250	1.105	0.184
Difference	36	-0.0256	0.3663	0.0610

95% CI for mean difference: (-0.1495, 0.0984)
T-Test of mean difference = 0 (vs not = 0): T-Value = -0.42 P-Value = 0.678

Since the p value is 0.678, it is concluded that the null hypothesis cannot be rejected at the confidence level of 95% and that the means from automatic measurement system and manual measurement system are identical. Therefore, the capability of automatic measurement system is verified.

5.2 Process Capability

The current process capability at laminator station 2 is calculated based on the edge bead which is defined as the difference between PE coating weight on the left or right edge and average PE coating weight along the cross direction. The result is shown in Figure 5.2.

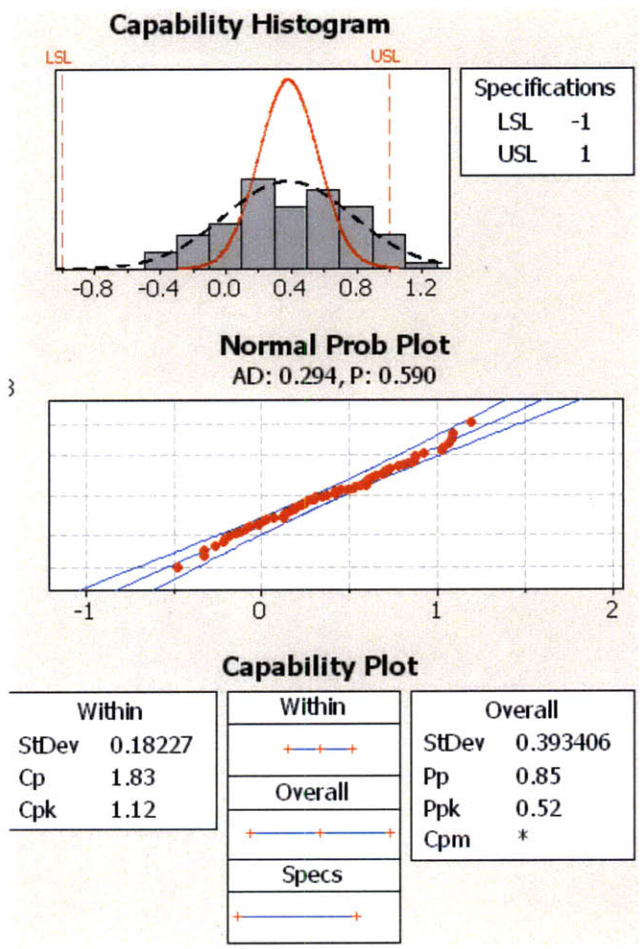


Figure 5.2: Process Capability at Laminating Station 2

As can be observed, the C_p is 1.83 while the C_{pk} is 1.12, and the p-value of the normality plot is 0.59. It indicates that the assumed normal distribution is valid but it is skewed to the right. Note this positive mean of the edge bead indicator could potentially contribute to the problem of high edge.

5.3 Shewhart Control Charts for Process Screening

In Section 4.4.1, it is determined that $\pm 3\sigma$ control limits are selected and sampling strategy is to collect 3 consecutive data points every 2 minutes. And, the edge bead indictor in the laminator station 2 is the metric of being measured. It has been found the process is in control in most of the time. Some typical out-of-control charts are demonstrated in this section for the purpose of discussion on assignable causes.

5.3.1 Abnormality between Two Carton Rolls

Xbar-S Control Charts of edge bead indicator with typical out-of-control points in laminator station 2 are shown in Figure 5.3 and Figure 5.4. Note that the control limits are set based on the run data itself instead of historical data.

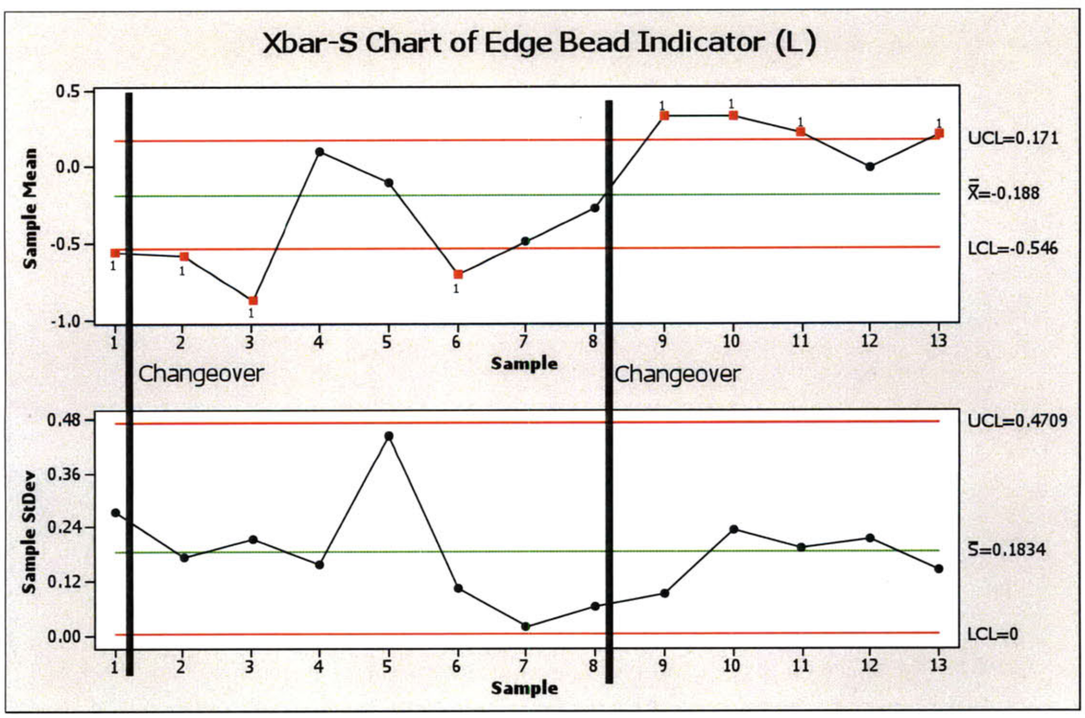


Figure 5.3: Xbar-S Control Charts of EBI (L) at Laminator Station 2

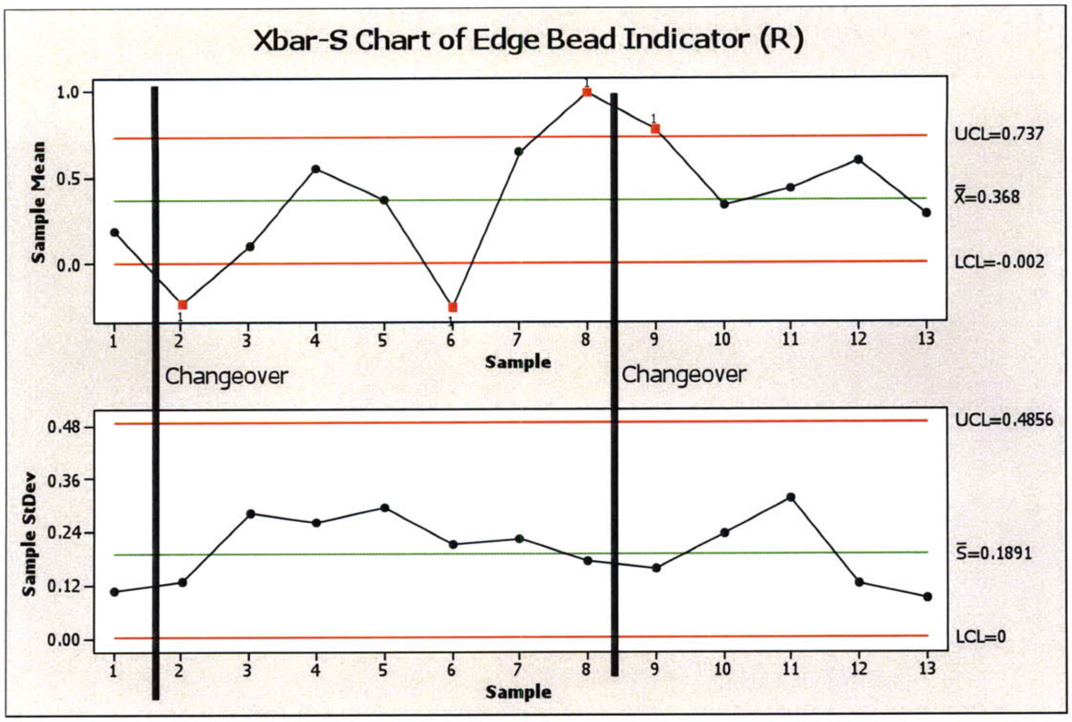


Figure 5.4: Xbar-S Control Charts of EBI (R) at Laminator Station 2

A cursory examination informs that the mean of the process is not in statistical control due to the out-of-control point above or below the control limits. However, a close scrutiny discovers that most of these out-of-control points occur when the changeover happens. It indicates that some factors associated with the action of changing one carton roll to another disturb the process and causes its mean to shift from the nominal value. In details, there are two kinds of moving patterns detected in the Xbar chart of EBI. For the Xbar chart of EBI (L) in Figure 5.3, the process mean steadily drifts to the increased value and seems to stay in the new level; the assignable cause leads to the sustained shift. For the Xbar chart of EBI (R) in Figure 5.4, the process mean increases abruptly, but the assignable cause is short-lived and the mean returns to its nominal or in-control value very soon.

Recall the process model developed in Table 4.3 in Section 4.3.1. Die gap, line speed and its coupled screw speed are the three most likely parameters subject to disturbance and then cause the EBI to deviate from its original mean.

Specifically, when changeover happens, line speed and its coupled screw speed will be suddenly reduced to a low level for a while and then return to its original level. The abrupt drop in the screw speed causes the shear rate applied on molten PE to decline and then leads to its lower elasticity making PE film easy to contract towards the centerline and to form edge bead; this could be the cause for abrupt increase in the mean of EBI in Figure 5.4.

The reason for sustained increase in EBI mean in Figure 5.3 is most likely due to the die-lip build-up, as shown in Figure 5.5.

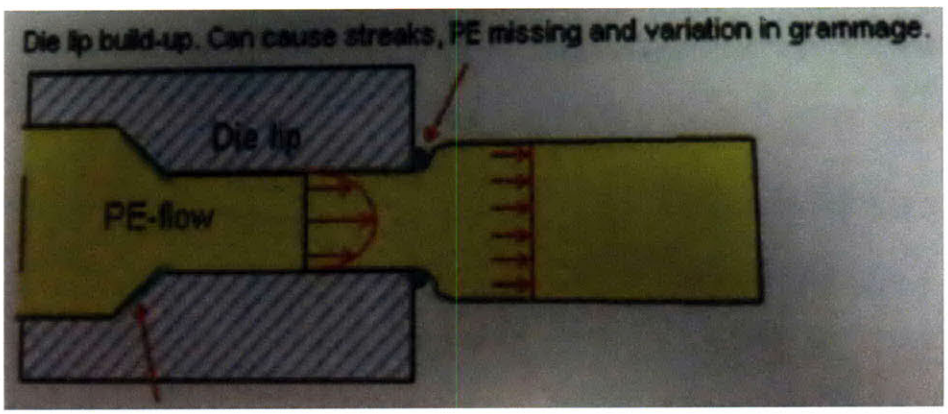


Figure 5.5: Die-lip Build-up [10]

Die-lip build-up is the result of progressive deposition of components of the PE exiting a die during the extrusion process. It gives rise to surface irregularity of the coated PE layer. If the accumulated PE at the die-lip is not cleaned in a routine manner, this phenomenon will disturb the flow pattern of molten PE exiting the die and impact PE coating uniformity.

5.3.2 Abnormality within One Carton Roll

Xbar-S Control Charts of edge bead indicator (L) and edge bead indicator (R) in laminator station 2 are shown in Figure 5.6 and Figure 5.7.

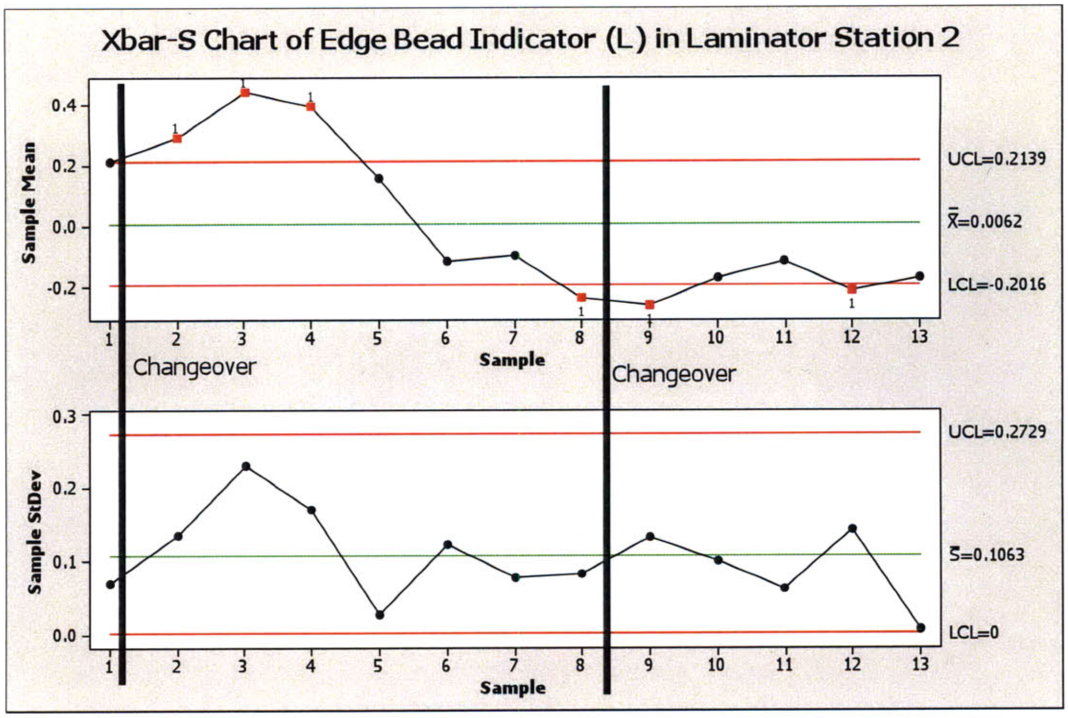


Figure 5.6: Xbar-S Control Charts of EBI (L) at Laminator Station 2

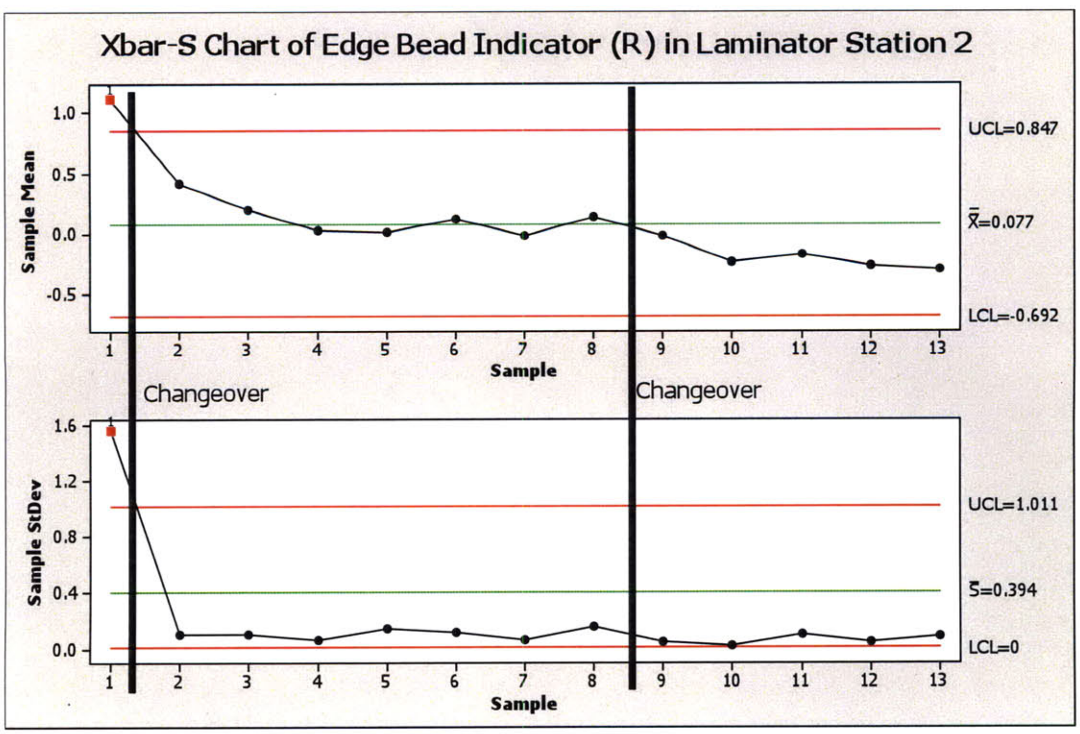


Figure 5.7: Xbar-S Control Charts of EBI (R) at Laminator Station 2

As observed in Figure 5.6, the process is not in statistical control due to the out-of-control points. Also, thought the points are all within the control limits in Figure 5.7, the application of sensitizing rules informs that the process is out of control because of the non-random pattern. Note that the wide control limits in Figure 5.7 is because the out-of-control point enlarges the estimated standard deviation based on the run data. One common point between these two figures is that the mean tends to decrease in a steady manner and maintain at the decreased level.

One possible cause for this is the faulty die-bolt power. Figure 5.8 shows the profile of PE coating and corresponding faulty die-bolt power. The below half of the chart shows the profile of die-bolt power level, where green bars mean they are automatically controlled, blue bars mean they are manually controlled, and red bars mean they have either reached the maximum 95% or minimum 5%.

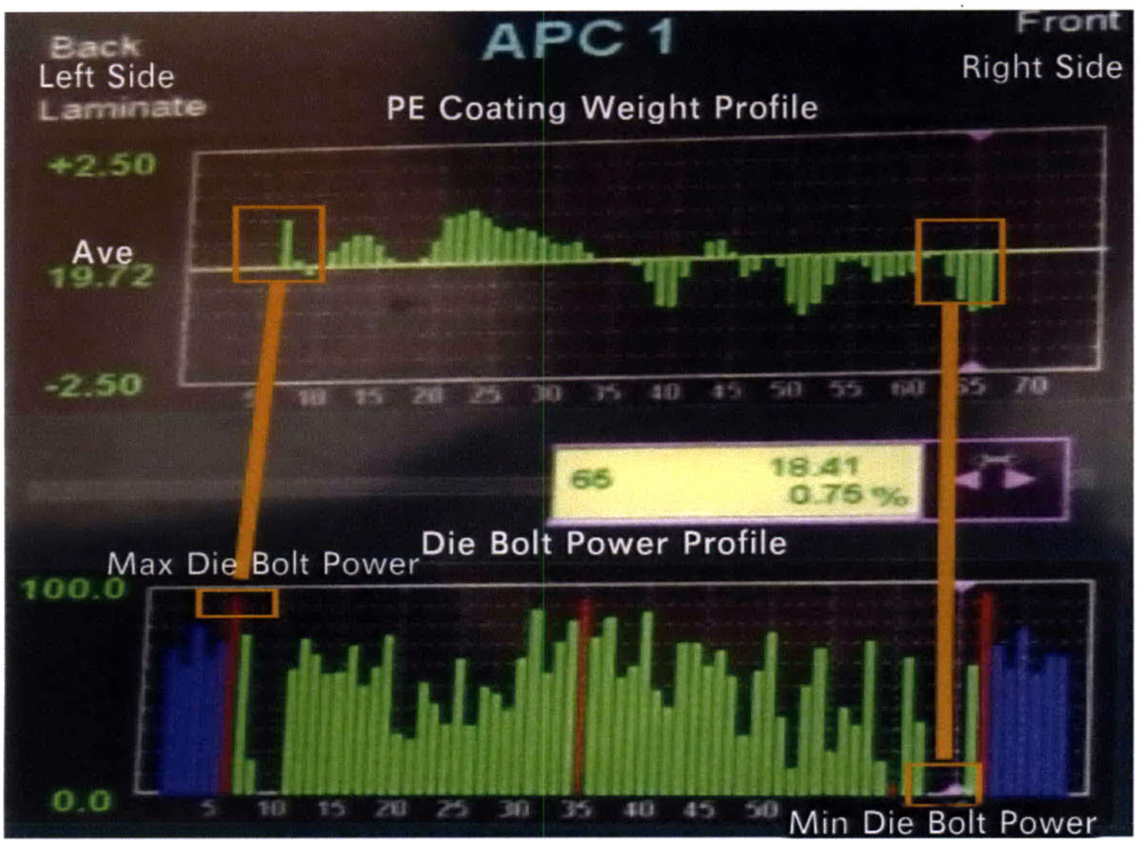


Figure 5.8: PE Coating and Corresponding Faulty Die-bolt Power

Based on the actual coating weight along the cross direction, the automatically controlled die-bolt power is continuously adjusted by the output feedback loop. Whenever more-than-average PE coating is detected at the edge, Automatic Profile Control System signals the corresponding die-bolt power to increase its power level so that the die gap is closed. However, when the level of die-bolt power has already reached the maximum of 95%, the die gap can no longer be electrically closed, as highlighted in the left orange fame in Figure 5.8; it has to be mechanically adjusted by operators during off-line maintenance. Conversely, when the level of die-bolt power has already reached the minimum of 5%, the die gap can no longer be electrically opened and less PE coating weight will occur, as highlighted in the right orange frame in Figure 5.8. That explains why there could be a steady increased or decreased drift, no matter during the changeover or not.

5.4 Fractional Factorial Design for Process Characterization

At each of the substrate's two edges, a 2^{5-2} fractional factorial design with center points is used to study the effect of 5 manually controlled die-bolt power and to determine the influential ones for the purpose of building the RSM in next step. The ANOVA, residual plots and variance analysis of both EBI (L) and EBI (R) are discussed in this section.

5.4.1 Edge Bead Indicator (Left)

The residue plots for EBI (L) are shown in Figure 5.9 to check the NID (normally and independently distributed) assumption.

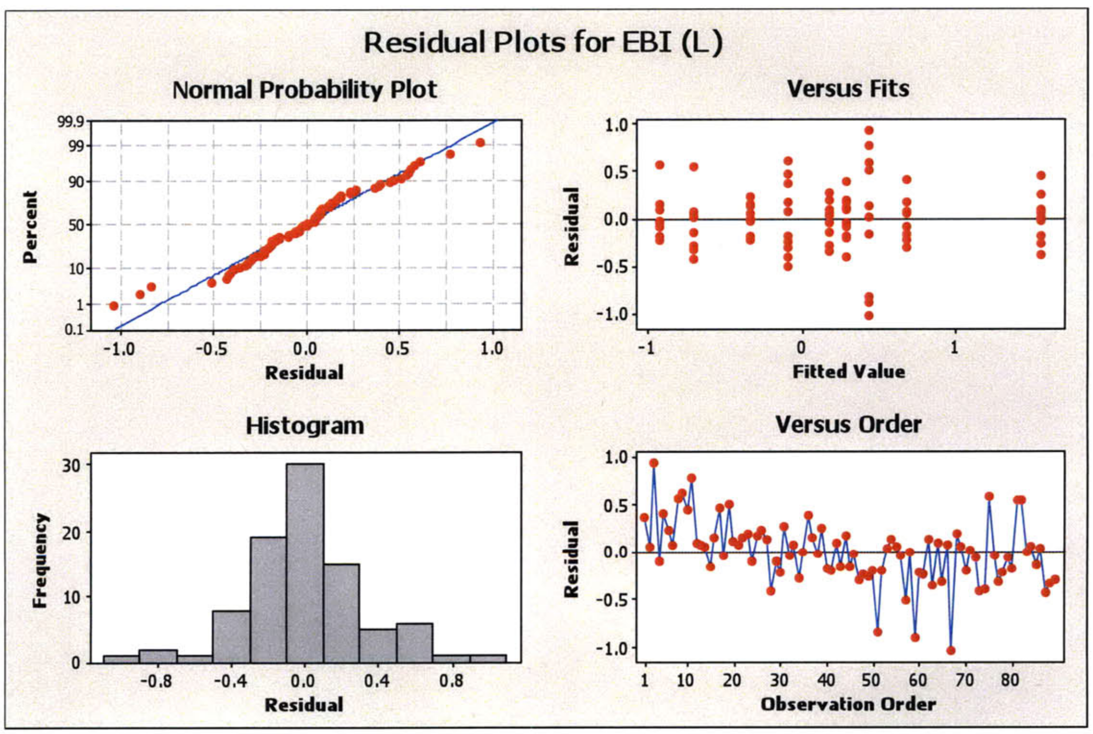


Figure 5.9: Residual Plots for EBI (L) in Factorial Design

The normality plot demonstrates a well-fitted pattern, so does the histogram. The variance at fitted value is almost identical, except the relatively large dispersion at one particular fitted value of 0.5. Consequently, the residuals' NID assumption holds.

The estimated effects and ANOVA is shown in Table 5.4.

Table 5.4: Estimated Effects and ANOVA for EBI (L) in Factorial Design

Factorial Fit: EBI (L) versus A, B, C, D, E

Estimated Effects and Coefficients for EBI (L) (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		0.2260	0.03896	5.80	0.000
A	-0.1570	-0.0785	0.03896	-2.01	0.047
B	-0.4605	-0.2302	0.03896	-5.91	0.000
C	-0.6485	-0.3242	0.03896	-8.32	0.000
D	-0.4695	-0.2347	0.03896	-6.03	0.000
E	-0.9085	-0.4542	0.03896	-11.66	0.000
B*C	-0.0890	-0.0445	0.03896	-1.14	0.257
B*E	0.4270	0.2135	0.03896	5.48	0.000
Ct Pt		-0.9382	0.12251	-7.66	0.000

S = 0.348464 PRESS = 153.907
R-Sq = 82.24% R-Sq(pred) = 0.00% R-Sq(adj) = 80.47%

Analysis of Variance for EBI (L) (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	34.061	34.061	6.8123	56.10	0.000
2-Way Interactions	2	3.805	3.805	1.9025	15.67	0.000
Curvature	1	7.121	7.121	7.1212	58.65	0.000
Residual Error	80	9.714	9.714	0.1214		
Pure Error	80	9.714	9.714	0.1214		
Total	88	54.702				

Based on the p value of the terms, it is found that each single die-bolt power has a significant effect to the confidence level of 95%. And, the p value of 0 of curvature indicates the evidence of pure quadratic effect. Concerning the effects of die-bolt powers, all of them are negative numbers, indicating an inverse relationship with the response, which is in accordance with the physical reality that increasing die bolt power leads to decreasing die gap and then less PE coating weight. Note that the R^2 of 82.24% demonstrates a fairly good fit.

The variability analysis is conducted and the result is tabulated in Table 5.5.

Table 5.5: Variability Analysis for EBI (L) in Factorial Design

Regression Estimated Effects and Coefficients for Ln of St.dev (coded units)

Term	Effect	Ratio Effect	Coef	SE Coef	T	P
Constant			-1.3055	0.08331	-15.67	0.004
A	-0.4366	0.6462	-0.2183	0.08331	-2.62	0.120
B	0.2356	1.2656	0.1178	0.08331	1.41	0.293
C	-0.5619	0.5701	-0.2809	0.08331	-3.37	0.078
D	-0.0880	0.9158	-0.0440	0.08331	-0.53	0.650
E	0.3622	1.4366	0.1811	0.08331	2.17	0.162
Ct Pt			0.2685	0.26513	1.01	0.418

R-Sq = 92.93%   R-Sq(adj) = 71.70%

Analysis of Variance for Ln of St.dev

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	22.5405	22.5405	4.5081	5.05	0.174
Curvature	1	0.9158	0.9158	0.9158	1.03	0.418
Residual Error	2	1.7857	1.7857	0.8929		
Total	8	25.2420				

Based on the p value, the conclusion is drawn that only the constant is significant in the regression model to the confidence level of 95% and thus the variance of the response is constant over the different treatments. As a result, the variance of EBI (L) is not sensitive to the die-bolt power setting.

5.4.1 Edge Bead Indicator (Right)

The residue plots for EBI (L) are shown in Figure 5.10 to check the NID assumption.

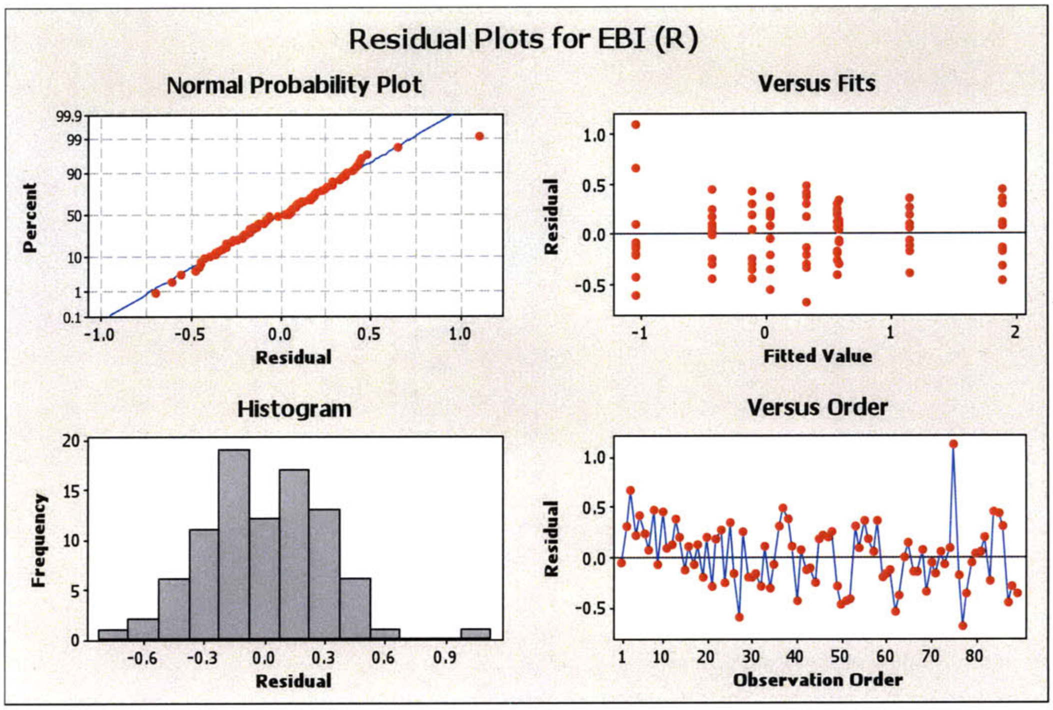


Figure 5.10: Residual Plots for EBI (R) in Factorial Design

The normality plot demonstrates a well-fitted pattern except one outlier, which is most likely caused by a measurement error or suddenly large disturbance to the process. The variance at fitted value is almost identical within the range from -0.5 to 0.5, except the large dispersion at one particular value. This value occurs when the fitted mean of EBI (R) is around -1, indicating the situation where less PE is coated on the edge. Note that this might cause the instability in coated PE's edge, which justifies the large variance around that fitted value of -1. Overall, the residuals' NID assumption holds.

The estimated effects and ANOVA is shown in Table 5.6.

Table 5.6: Estimated Effects and ANOVA for EBI (R) in Factorial Design

Factorial Fit: EBI (R) versus A, B, C, D, E

Estimated Effects and Coefficients for EBI (R) (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		0.3908	0.03611	10.82	0.000
A	0.2605	0.1303	0.03611	3.61	0.001
B	-0.6435	-0.3217	0.03611	-8.91	0.000
C	-0.2285	-0.1142	0.03611	-3.16	0.002
D	-0.2515	-0.1257	0.03611	-3.48	0.001
E	-1.2005	-0.6002	0.03611	-16.62	0.000
B*C	0.8275	0.4138	0.03611	11.46	0.000
B*E	-0.3995	-0.1998	0.03611	-5.53	0.000
Ct Pt		-0.5030	0.11354	-4.43	0.000

S = 0.322944 PRESS = 12.4283
R-Sq = 87.74% R-Sq(pred) = 81.74% R-Sq(adj) = 86.51%

Analysis of Variance for EBI (R) (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	40.772	40.772	8.1545	78.19	0.000
2-Way Interactions	2	16.887	16.887	8.4436	80.96	0.000
Curvature	1	2.047	2.047	2.0466	19.62	0.000
Residual Error	80	8.343	8.343	0.1043		
Pure Error	80	8.343	8.343	0.1043		
Total	88	68.049				

Based on the p value of the terms, it is found that each single die-bolt power has a significant effect to the confidence level of 95%. And, the p value of 0 of center point indicates the evidence of pure quadratic effect. As for the effects of die-bolt powers, all of them except die-bolt power A are negative numbers, indicating an inverse relationship with the response. It could be easily understood that the EBI (R) will decrease if die-bolt power increases; the contracting die-bolt closes the die gap. The explanation for the exceptional die-bolt power A is that it is located far from the edge of the substrate and the molten PE flow is forced to the very edge when increasing die-bolt power closes the die gap. Note that the R^2 of 87.74% demonstrates a fairly good fit.

The variability analysis is conducted and the result is shown in Table 5.7.

Table 5.7: Variability Analysis for EBI (R) in Factorial Design

Regression Estimated Effects and Coefficients for Ln of St.dev (coded units)

Term	Effect	Ratio Effect	Coef	SE Coef	T	P
Constant			-1.2437	0.2079	-5.98	0.027
A	-0.0663	0.9358	-0.0332	0.2079	-0.16	0.888
B	0.0687	1.0711	0.0344	0.2079	0.17	0.884
C	0.0318	1.0323	0.0159	0.2079	0.08	0.946
D	-0.2144	0.8071	-0.1072	0.2079	-0.52	0.657
E	0.0057	1.0057	0.0028	0.2079	0.01	0.990
Ct Pt			0.1990	0.6616	0.30	0.792

R-Sq = 17.19%   R-Sq(adj) = 0.00%

Analysis of Variance for Ln of St.dev

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	1.8049	1.8049	0.3610	0.06	0.993
Curvature	1	0.5032	0.5032	0.5032	0.09	0.792
Residual Error	2	11.1183	11.1183	5.5592		
Total	8	13.4265				

Based on the p value, it is concluded that only the constant is significant in the regression model to the confidence level of 95% and thus the variance of EBI (R) is constant over the different treatments. As a result, the variance of EBI (R) is not sensitive to the different treatments of die-bolt power. However, the R^2 of only 17.19% indicates this linear regression model does not fit the data very well. It is found that this is due to the widely dispersed data at the fitted value of the model.

5.5 Response Surface Model for Process Optimization

In light of the previous experiment of 2^{5-2} fractional factorial design, die-bolt power A, B, C, D and E have been identified as significant factors. Consequently, these die-bolt powers, together with plug setting and blade setting, are intended for building the response surface model. However, it is noted that not all of the die-bolt powers are included, as shown in Figure 5.11.

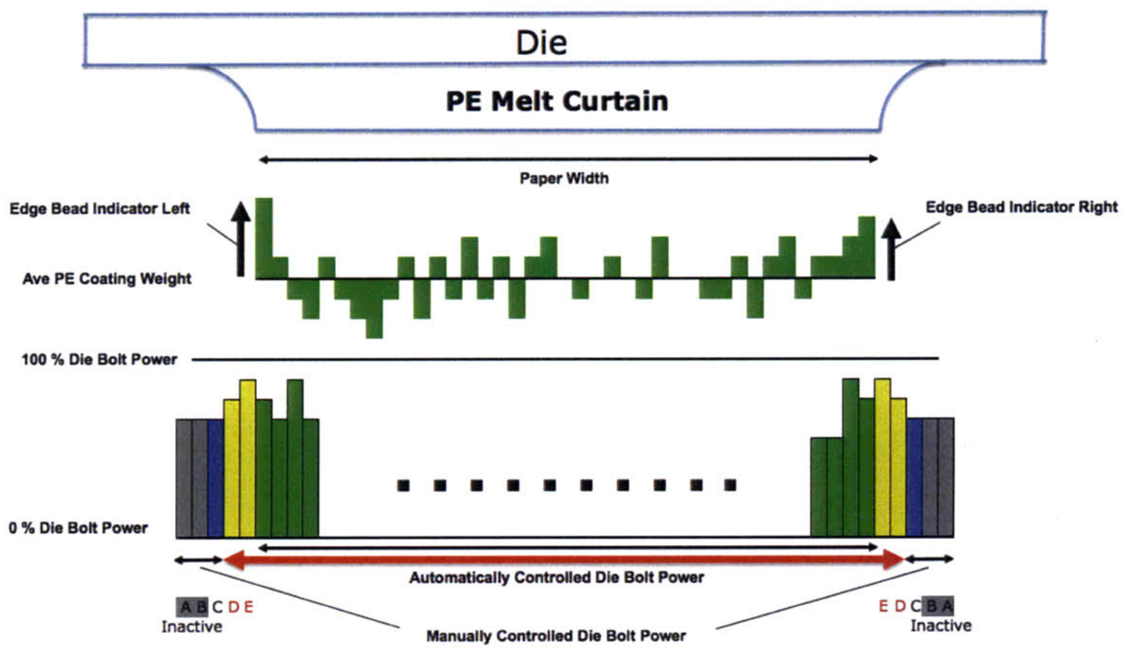


Figure 5.11: Die-bolt Power for Building Response Surface Model

The die-bolt powers highlighted in yellow is specified to be automatically control by Automatic Profile Control in this experiment due to the fact that these two are close to the edge and then should be continuously tuned by feedback loop for uniform coating. Concerning the other three die-bolt powers at each edge, it's better for them to be manually controlled since they are away from the outermost PE coating weight detected by APC; the controlling algorithm embedded in APC might not be sophisticated enough to compensate for the missing information about PE coating weight (i.e. amount of coated PE outside the substrate width). Therefore, they should be manually controlled for better laminating performance. Note that only die bolt power C is included in building the response surface model; inactive in RSM, die bolt power A and B are manually maintained at the constant level of 60%. For one reason, it is believed that we could achieve the optimal operating range by varying only one manually controlled die bolt power; for another, this could tremendously save the experimental cost.

Then, 3 factors are included to build the RSM: die-bolt power C, plug setting and blade setting. The experiment is only conducted at the right side of the laminating station 2 because of the physically ready access to plug and blade settings. The central composite design is shown in Table 5.8.

Table 5.8: Detailed Central Composite Design

Central Composite Design

Factors:	3	Replicates:	15
Base runs:	20	Total runs:	300
Base blocks:	1	Total blocks:	1

Two-level factorial: Full factorial

Cube points:	120
Center points in cube:	90
Axial points:	90
Center points in axial:	0

Alpha: 1.68179

The results of residual plots, estimated effects, quantitative model, variability analysis and optimal operating conditions for EBI (R) are discussed in this section.

5.5.1 Residual Plots for Edge Bead Indicator (Right)

The residual plots for EBI (R) are shown in Figure 5.12 to check the NID assumption.

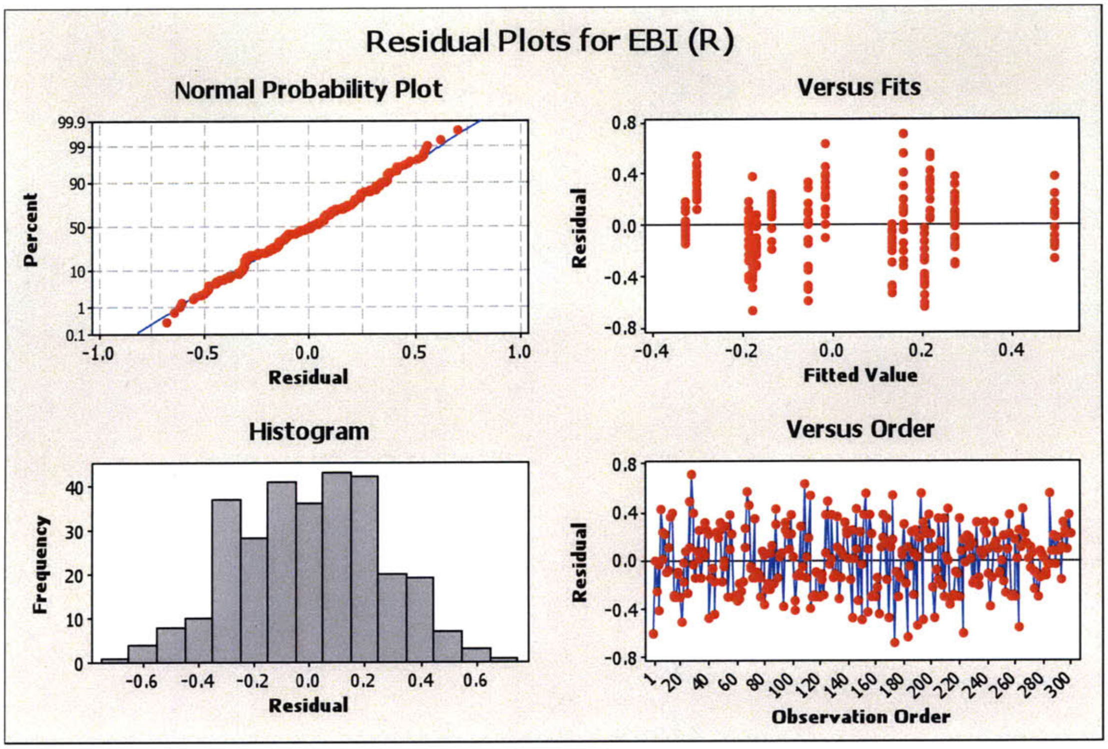


Figure 5.12: Residual Plots for EBI (R) in RSM

As observed, the normality plot and histogram of residuals demonstrate a fairly good fit. And, the variance of residuals (i.e. dispersion in the plot) is generally subject to the equal variance at various fitted value. However, the means of the residuals are not necessarily zero. Overall, the NID assumption holds conditionally.

5.5.2 Estimated Effects and Quantitative Model for Edge Bead Indicator (Right)

Table 5.9 presents the estimated effects and T-test for EBI (R) with all the terms included. The proposed quantitative model is

$$\hat{EBI} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_1 x_3 + \beta_9 x_2 x_3 \qquad \text{(Eq. 5.1)}$$

x_1 = blade

x_2 = plug

x_3 = die-blot power

Table 5.9: Estimated Effects and T-test for EBI (R) in RSM (Before)

Estimated Regression Coefficients for EBI (R)

Term	Coef	SE Coef	T	P
Constant	0.27489	0.02821	9.744	0.000
Blade	0.04462	0.01872	2.384	0.018
Plug	0.17952	0.01872	9.591	0.000
Die Bolt Power	-0.11860	0.01872	-6.336	0.000
Blade*Blade	-0.07654	0.01822	-4.200	0.000
Plug*Plug	-0.10671	0.01822	-5.856	0.000
Die Bolt Power*Die Bolt Power	-0.09021	0.01822	-4.951	0.000
Blade*Plug	0.10217	0.02446	4.177	0.000
Blade*Die Bolt Power	0.01583	0.02446	0.647	0.518
Plug*Die Bolt Power	-0.05117	0.02446	-2.092	0.037

As can be seen, all the terms are significant to the confidence level of 95% in the proposed model, except the term of blade*Die Blot Power. Therefore, this term is removed and the reduced quantitative model is

$$\hat{EBI} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_3^2 + \beta_7 x_1 x_2 + \beta_8 x_2 x_3 \qquad \text{(Eq. 5.2)}$$

x_1 = blade

x_2 = plug

x_3 = die-blot power

The recalculated estimated effects for EBI (R) is tabulated in Table 5.10.

Table 5.10: Estimated Effects and T-test for EBI (R) in RSM (After)

Estimated Regression Coefficients for EBI (R)

Term	Coef	SE Coef	T	P
Constant	0.27489	0.02818	9.753	0.000
Blade	0.04462	0.01870	2.386	0.018
Plug	0.17952	0.01870	9.600	0.000
Die Bolt Power	-0.11860	0.01870	-6.342	0.000
Blade*Blade	-0.07654	0.01820	-4.205	0.000
Plug*Plug	-0.10671	0.01820	-5.862	0.000
Die Bolt Power*Die Bolt Power	-0.09021	0.01820	-4.956	0.000
Blade*Plug	0.10217	0.02443	4.182	0.000
Plug*Die Bolt Power	-0.05117	0.02443	-2.094	0.037

As can be observed, all the terms in the modified model are significant to the confidence level of 95%. Consequently, response surface model for EBI (R) is

$$\begin{aligned} E\hat{B}I &= 0.27489 + 0.04462x_1 + 0.17952x_2 - 0.1186x_3 \\ &\quad - 0.07654x_1^2 - 0.10671x_2^2 - 0.09021x_3^2 + 0.10217x_1x_2 - 0.05117x_2x_3 \end{aligned} \quad \text{(Eq. 5.3)}$$

x_1 = blade

x_2 = plug

x_3 = die-blot power

5.5.3 Variability Analysis for Edge Bead Indicator (Right)

Based on the replicates at each treatment, the variance is calculated and the replicates at the center point are employed as residual error. The ANOVA is conducted and the result is tabulated in Table 5.11. The proposed regression model for EBI(R)'s variability is

$$E\hat{B}I_{\sigma^2} = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 AB + \beta_5 AC + \beta_6 BC + \beta_7 ABC \quad \text{(Eq. 5.4)}$$

A = Blade

B = Plug

C = Die Bolt Power

Table 5.11: Variability Analysis for EBI (R) in RSM

Estimated Effects and Coefficients for Var (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		0.042955	0.005535	7.76	0.082
A	-0.006240	-0.003120	0.005870	-0.53	0.689
B	0.006794	0.003397	0.005870	0.58	0.666
C	-0.004015	-0.002008	0.005870	-0.34	0.790
A*B	0.041383	0.020692	0.005870	3.52	0.176
A*C	0.033798	0.016899	0.005870	2.88	0.213
B*C	0.021515	0.010758	0.005870	1.83	0.318
A*B*C	0.006850	0.003425	0.005870	0.58	0.664

S = 0.0166040 PRESS = 0.159109
R-Sq = 96.17% R-Sq(pred) = 0.00% R-Sq(adj) = 69.40%

Analysis of Variance for Var (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00020244	0.00020244	0.00006748	0.24	0.864
2-Way Interactions	3	0.00663559	0.00663559	0.00221186	8.02	0.253
3-Way Interactions	1	0.00009386	0.00009386	0.00009386	0.34	0.664
Residual Error	1	0.00027569	0.00027569	0.00027569		
Curvature	1	0.00027569	0.00027569	0.00027569		
Total	8	0.00720759				

As can be observed, none of the P-values is significant to the confidence level of 95%, meaning the above regression model does not fit the variance data more significantly than the overall average of the variance. The average of the variance in EBI (R) is 0.043. Thus, it is determined that

$$E\hat{B}I_{\sigma^2} = 0.043 \qquad \text{(Eq. 5.5)}$$

5.5.4 Optimal Operating Conditions for Edge Bead Indicator (Right)

Because EBI(R)'s variability has been found to be constant across different treatments, the optimal operating conditions are interpreted as on-target mean of EBI(R). Based on the regression model developed in Eq. 5.3, the contour plot is shown in Figure 5.13. Note that the die bolt power is held at the level of 0, amounting to 60%.

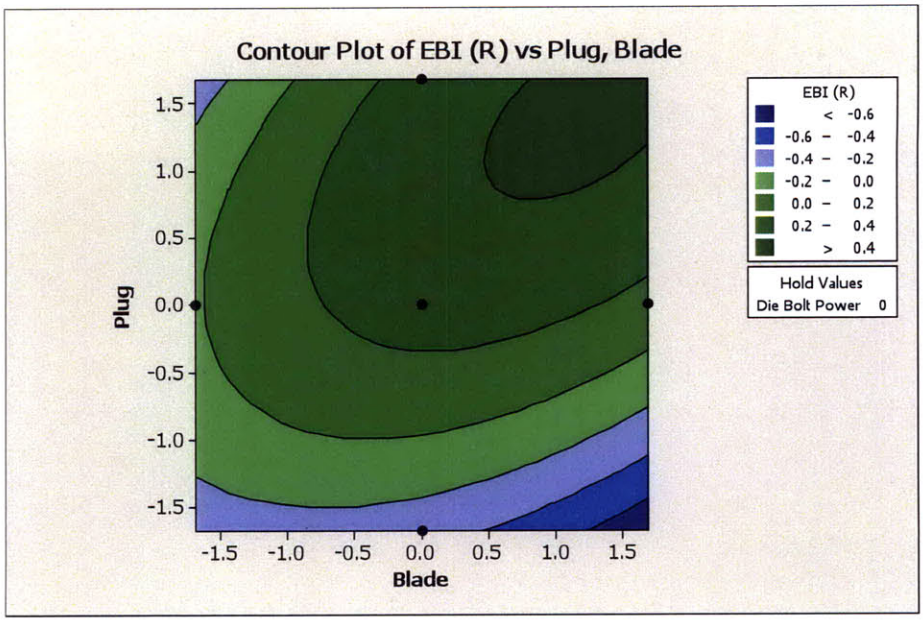


Figure 5.13: Contour Plot of EBI (R) vs Plug and Blade Settings

Different color bands represent the gradient of the predicted mean of EBI (R). The incremental transition can be clearly observed from the upper right corner to the lower right corner in the Figure 5.13. Then, the boundary of [-0.5, 0] is imposed; it is considered a favorable mean of EBI (R) in terms of edge bead reduction. The result is shown in Figure 5.14.

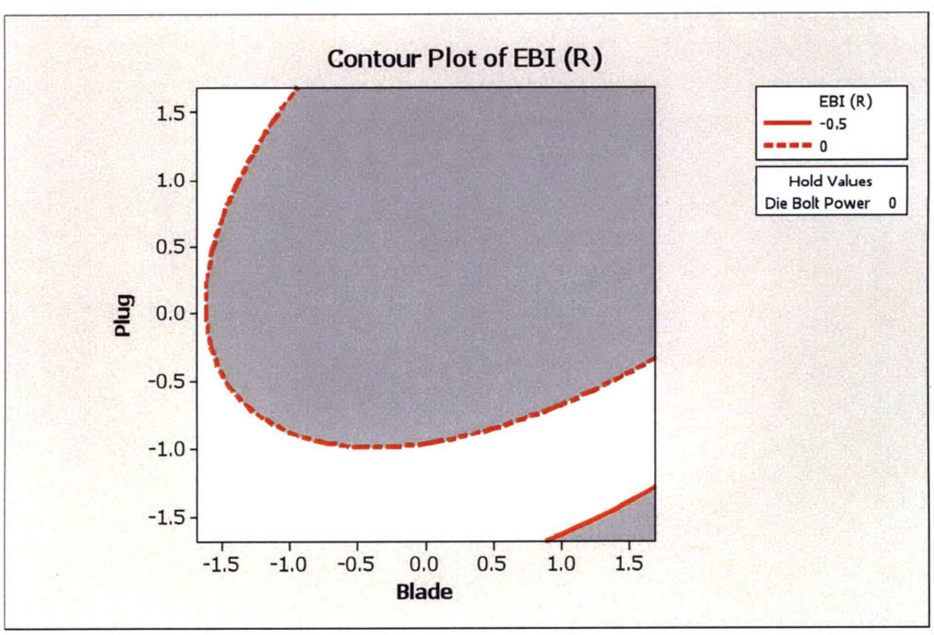


Figure 5.14: Optimal Operating Range of Plug and Blade Settings for EBI (R)

As can be seen, the white color band represents the optimal operating range of plug and blade setting. Theoretically, any combination of plug and blade setting located in the white color band gives rise to the predicted mean of EBI (R) ranging from -0.5 to 0. To be specific, the optimizer embedded in the Minitab® is used to find the optimal operating point, for example, EBI (R) = -0.1. The result is shown in Figure 5.15.

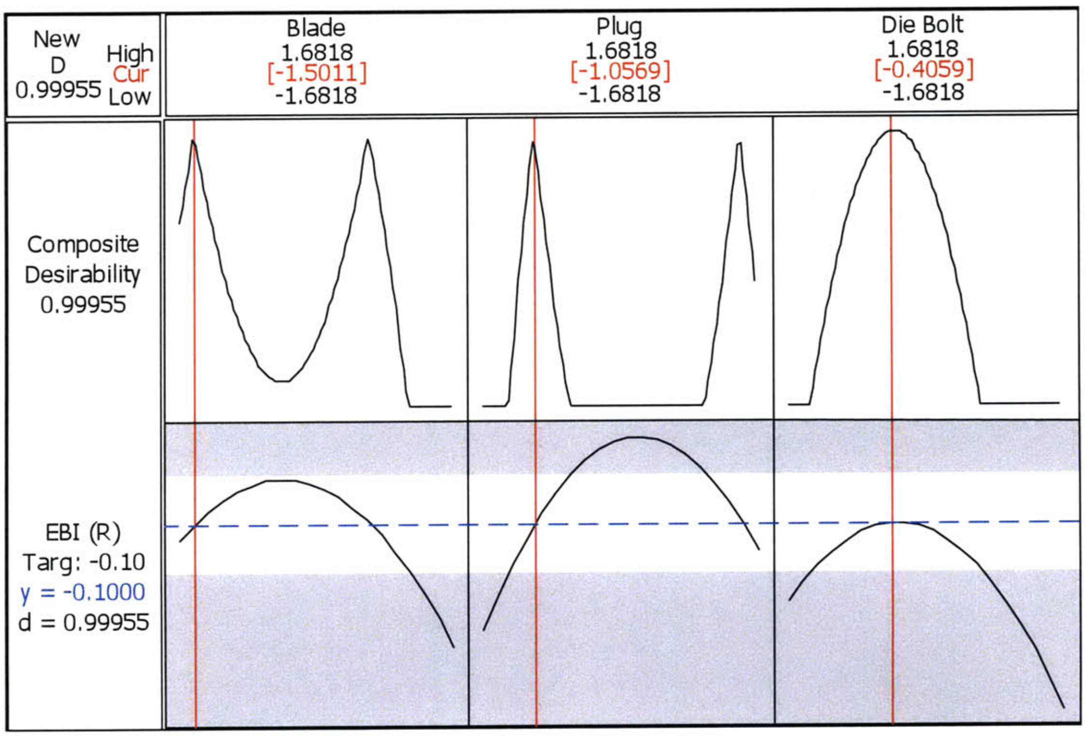


Figure 5.15: One Optimal Operating Point for EBI (R)

The optimization plot shows the effect of each factor on the response with desirability. The vertical red lines and red numbers on the figure represent the current factor settings. The horizontal blue lines and blue numbers represent the response for the current factor level. It is noted that the predicted mean of EBI (R) will be -0.1 when blade is set at -1.5, plug is set at -1 and die bolt is set at -0.4. The desirability of 0.99955 indicates that the settings appear to achieve favorable results for the response.

Chapter 6 Conclusions and Recommendations

The defect of high edge is mainly caused by the larger-than-average PE coating weight at the edge of the substrate. This occurrence is in turn mainly caused by the phenomenon of neck-in and its associated edge bead formation commonly observed in the laminating process. It is the disturbance to process parameters (i.e. assignable causes) and non-optimized setting of process parameters (i.e. common causes) that give rise to this problem.

From the aspect of assignable causes, the most likely sources are identified as line speed, screw speed, die-lip build-up and die-bolt power. The disturbance to line speed and screw speed leads to the temporary fluctuation in the process mean during changeover while die-lip build-up and faulty die-bolt power contribute to the sustained mean shift. In order to better monitor these sources of assignable causes, it is recommended that process mean and control limits should be set as 0 and ± 0.35 for process surveillance in the long term.

From the aspect of common causes, manually controlled die-bolt power, plug setting and blade setting have a statistically significant impact on the edge bead formation, as shown in Table 5.10, and they are recommended to be set based on the contour plot shown in Figure 5.14. The actual value is coded for reasons of confidentiality. It is noted that the process optimization is totally based on the regression model of process mean developed in Eq. 5.3 instead of process variance due to the nature of robustness ($E\hat{B}I_{\sigma^2} = 0.043$) demonstrated in the variability analysis in Table 5.11.

Furthermore, an out-of-control-action plan is suggested for corrective actions, as shown in Figure 6.1. The correct settings are not disclosed in details here due to the confidentiality.

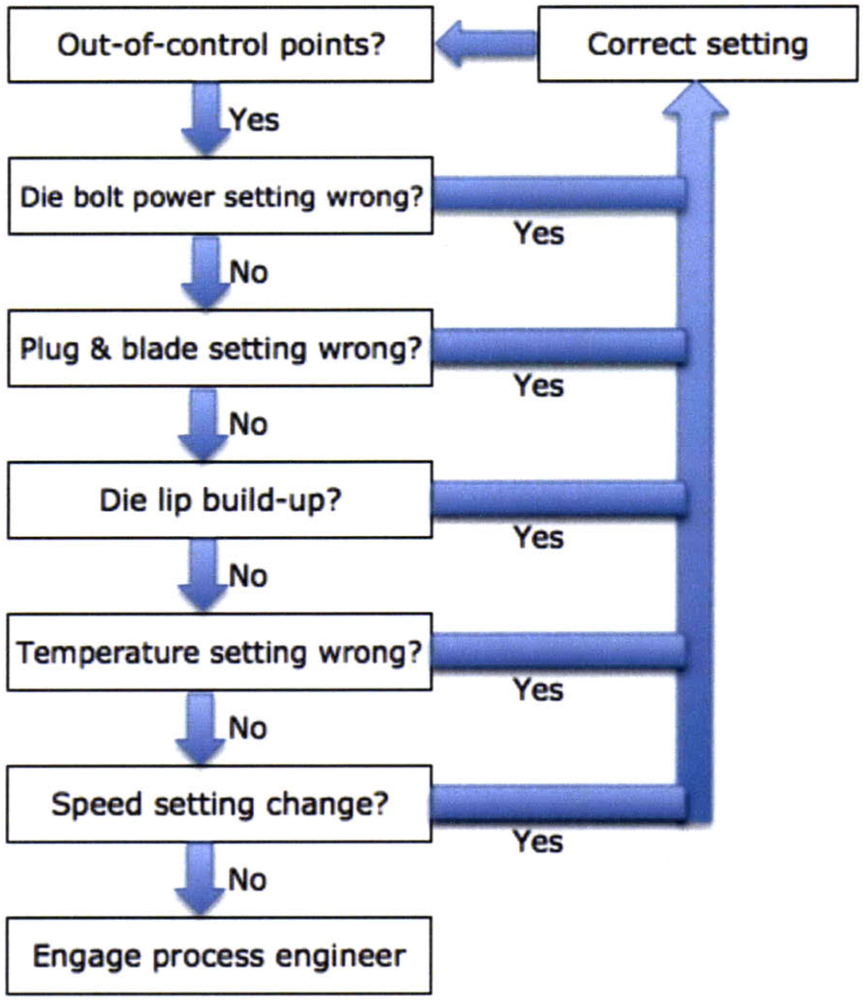


Figure 6.1: Out-of-control Action Plan

In conclusion, with the help of statistical tools, we can solve the problem of high edge by eliminating assignable causes and tuning common causes to achieve the best performance of laminating process. In addition, due to the aggregation effect, the length of each carton roll is advised to be no more than 7,000 meters.

Chapter 7 Future Work

First of all, it is necessary to extend the practice and efforts in controlling edge bead from laminating station 2 to the other two laminating stations. Specifically, the control charts and the optimal operating point should be established for both edges at the other two laminating stations.

In addition, exponentially-weighted-moving-average (EWMA) control charts and multivariate control charts will be of great interest in the future. Different from the Shewhart control chart specializing in detecting large to moderate shift, EWMA is especially designed for detecting minor shift in the process mean and then is suitable for sophisticated process monitoring. Although sensitizing rules could be employed in the Shewhart control charts, they might trigger too many false alarms, undermining the effectiveness in monitoring the process. Also, multivariate control charts are significantly effective in detecting process mean shift in the sense that they can statistically control the amount of the coated PE at both edges in a simultaneous manner. Then, the risk of missing alarm will be dramatically reduced if they are in place.

Last but not least, the defect of high edge is about the additional PE coated at the edge of the substrate. There is another defect mode called missing edge. It means inadequate PE is coated at the edge. The prospective work should be focused on how to balance the two different objectives incurred by opposite mechanism of defects.

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