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Loss Reduction in Calendering Process for Tire Production

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Abstract. Tire production usually generated defect work by component depending on material properties, process setting, machine breakdown, and others. This study focuses on rework of product deviation from dimension target during starting up the machine of a tire production process, the majority causes of deformity in extrusion area, that started to study in a calendering process which produces inner liner part and has least complexity in terms of factors variation. The significant factors that impacted on product dimension in this study were Mooney viscosity and screw speed extruder needed to find the relationship. It means they are related to achieving the target of product specification such as thickness and width in mass production that has a high possibility to make loss quantity. Compound type and line speed were controlled excepted temperature and pressure setting at extruder head which were uncontrollable variables that usually are not much changed. The relationship between material properties and screw speed was determined using multiple linear regression for the width and thickness. This study is expected to provide usefulness for product dimension prediction with other compound viscosity values together with screw speed adjustment. The factors were optimized closely to get the desired target of width and thickness to minimize the defect quantity.

Keywords: tire, manufacturing, Mooney viscosity, screw speed, optimization, regression

1. Introduction

At present, the International Monetary Fund predicted that global economic growth has a trend towards declining approximately 4.9 percent in the second quarter of 2020 since the COVID-19 pandemic has spread around the world began by the end of 2019 [1]. The crisis contributed to reducing tire demand in the global market, notably the American and European markets. It leads the tire volume to have more trending export to other needs, for the instant Asia Pacific region, even though it is not a large volume as the previous year. The domestic vehicle export decreased 53.8 percent at the end of the first quarter as reported by the Economic Intelligent Center of the Siam Commercial Bank [2]. This influenced tire demand in Thailand's automotive industry for original equipment (OEM) tires. However, for replacement equipment tire (REM) in this study’s case factory, it has received a higher occasion to export to Asia markets such as China and South Korea since the COVID-19 outbreak still impacts the supply chain. Generally, in the tire industry, concerning high productivity and output, which is related to demand and high efficiency, this mostly means quality in the tire building process, including the losses and defects. Thus, if the company has a higher volume demand, it must be aware of its cost in the production, especially the cost of defect reflecting the quality and amount of finished goods. A product that requires a large quantity of raw material and a complex process should have an immense potential to produce more deficiencies. The tire building process starts with mixing the compound. The primary materials are natural rubber and synthetic rubber combined with the chemical in a defined proportion called recipe percentage, and the appearance becomes sheet then extrudes at high temperature to be a shape of tread, sidewall, and apex components. Another parallel building component step is sheeted at high temperature by a rolling machine and turns into the inner liner, gum rubber sheet, and cord coating. The coating becomes a belt, ply, and cap ply in the cutting process [3-4].

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This research is interested in the production line at an extrusion area. There are three machines to produce components which are sidewall machine, tread machine, and calendering machine producing sidewall-rim strip, tread, inner liner, and gum sheet part, respectively. The problems in the normal production (excluding new product cases) are mainly from loss quantity in starting up the machine, producing over planning, not reaching component weight target, and others. Loss quantity in starting up the machine before storing good pieces into the cassettes happens during the screw torque adjustment step to control the rubber shape from the extruder head to make the specification (i.e., thickness and width) reach their values within the target tolerance. Machine malfunction is the lack of a PLC program for controlling machine working status. Producing over plan means the end of work produces the length more than its planning. Particles block die is the amount of cured compound block die edge during running the process. Auto-scrap poor weight is the automatic function to cut the defect rubber from the weight which does not reach target during run the process. These loss quantities were summarized from three machines accumulation using the Pareto chart as shown in Fig. 1.

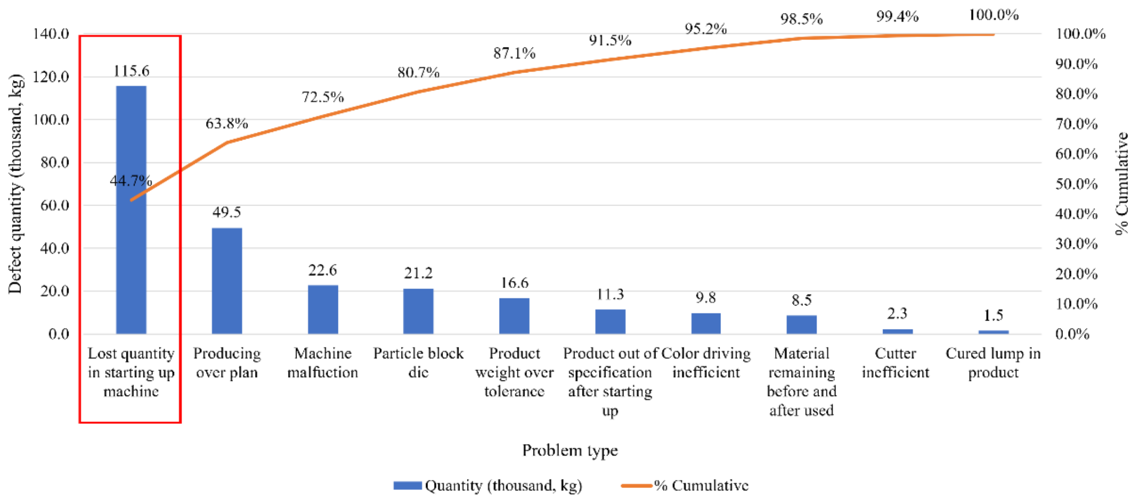

Fig. 1: Pareto's analysis for loss quantity at three machines.

Referring to Pareto rules, this research focuses on loss quantity in starting up machines, which is one of the significant problems for three machines. The pilot study starts first at calendering machine and will continue to the other two in the future. The highly concerned factors of loss quantity in starting up are screw speed, compound properties, extruder head temperature, and line speed. For extruder temperature and line speed, they are generally controlled at the same level with four product types. Extruder temperature or mixture temperature for tread and sidewall-rimstrip compound is in the range of 378K-393K while 368K-373K is the range for innerliner and gumsheet compound due to two machine types (extruder and extruder attached with roller head) that need to control not over the limit. General line speed in running production is about 20-30 m/min with all types. However, screw speed (revolutions per minute, rpm) sets explicitly depending on the product recipe this means screw speed is different and familiar if there is the same value in width or thickness. Starting up machine issue in this study usually happens when the setting that use to run in mass production for each specification would refer to the latest setting or latest adjustment in the previously processed lot, but the outcome dimension does not get satisfied result same as the past lot it is over target such as too thick or thin, narrow or wide than the target. This still happens and always manually adjusts setting for 5-10 min per one lot maximum size 250 m by human skill even if it has changed another batch with the same specification. Screw speed adjustment has directly affected rubber shape, increasing speed pushes more rubber to extrude continuously to avoid quality problems like thin shape or dented edge. In part of the new product, the screw speed should be doing a trial with new die-cutting and compound to receive a recipe value prepared for starting mass production of this type in the nearly planning. This case for the new product is considered to be scrap from die trial not from starting up and it does not include in the scope of this research study.

Accordingly, there is some points difference between the new product and general product. The new product has to create die cutting with trial and error parameters like screw speed from that compound lot or it is called die trial. Die trial is the method to test with the tooling that cut for new product and must test to investigate the output whether it is similar to its specification or not. For the trial, it needs to record process parameter that is fitted to the outcome like screw speed and line speed. The die with good dimension result from the trial stage will use this parameter value in running mass production. So, this step needs time to achieve the target for 5-15 min relating to the difficulty of the dimension and compound properties. For the general product, it is usually fixed the line speed at 30 m/min and uses the setting value of screw speed (rpm) from the trial stage with the same die acted as a standard setting. But the compound lot does not have the same viscosity because of mixed at a different time even this viscosity result is in the tolerance. So, the find-tune screw speed at starting up period is necessary for the term of time and material usage. If it uses more tuning time the material will be more consumed in the process this means it has less potential to receive a good product in a commitment plan. Finally, the general product must use this setting from starting up step which generates dimension within target tolerance continue to use in the long run or steady state of this lot which is no need to adjust screw speed like starting up step to receive planning length at a time. This latest setting at steady state is used in another planning lot as well and if there is a difference in compound viscosity the setting has to adjust again until receiving a good product dimension then this continues to use in a steady state and another lot, or it means all of this will do it iteratively following the explanation for general product step.

In the extrusion process, the input is a rubber compound that is mixed with chemicals and other materials from the previous process the properties need to be concerned with compound viscosity (Mooney). Mooney viscosity is a composite measurement of an elastomer's viscoelastic behavior [5]. From plant investigation found that each compound type is controlled with different tolerance; for example, compound used to produce innerliner is halobutyl (Cl-, Br-) rubber the viscosity should be in range 44.5-52.5 MU (1+3, an hour for heating before testing with three hours for reading value from viscometer) while some compounds are in the range 16-80 MU at test temperature 127°C by Mooney viscometer. High compound viscosity risks over cured problem since when rubber stays in extruder it moves slowly and receives more heat from rubbing with screw and inside barrel wall, so the rubber is easily for degradation and cured to be a solid lump [6]. If it is low compound viscosity, the lack of dimension could happen cause rubber with low viscosity has less potential of heat transfer and degradation, then when it is extruded some product position may not reach the target. These two cases of viscosity problems must not use in the component building process.

The research started with the simplest machine with the least variance; it is a calendering machine. Studying and improving methods in real production with the complex machine-like tread and sidewall machine with no basic foundation can affect the producing components and continue to create larger defect quantity and loss costs. These two machines have various rubber characteristics of compound viscosity, which use more than five compound types to produce one component depending on the product version. Moreover, there is a difficulty in 3-dimension for die-cutting; the tool builds rubber to be a component in shape and human skill of a die maker [7]. As a result, studying with the least complexity is considered as the best option to understand theoretical background about the relationship between parameters to adjust them during machine starting up and compound viscosity, which affects product quality then applies to other machines. Moreover, it usually makes less impact on rework generation due to low variation from compound properties, which has one type. Also, one kind of die is generally used in this machine. Thus, there is a less challenging issue to be concerned about.

2. Materials and Method

2.1. Material Type

There are generally two types of rubber which are natural rubber (NR) and synthetic rubber, such as styrene-butadiene rubber (SBR), butadiene rubber (BR), acrylonitrile-butadiene rubber (NBR), butyl rubber (IIR), ethylene propylene diene rubber (EPDM), etc. [8].

Natural rubber is obtained directly from the latex of rubber trees and processed into the building blocks for industry. Its characteristics with high elasticity, physical-dynamic mechanical properties, and abrasion resistance are mainly used to produce body compounds such as sidewall, rimstrip, and apex with a high rubber ratio [9]. In part of synthetic rubber, chemical synthesis can be produced that used emulsion or solution polymerization technique to make homo- or copolymer of diene monomers [10].

The various types of synthetic rubber have different purposes due to their characteristics. For example, SBR is good in abrasion and aging resistance, elasticity but not resistant to oil, ozone. It has to add reinforcement like silica to the compounding process. Then SBR is commonly used to produce tread tire component. While IIR is good in ozone and water resistance, heat stability, low gas passability so it is crucial to make the part that prevents gas permeability is needed like the inner liner [11]. Natural and synthetic rubber has low mechanical and thermal properties, so they have to add various ingredients such as carbon black, silica, vulcanizing agent, plasticizers, processing aid, etc., to improve their functional properties or control price [10]. The general rubber tests from ASTM rubber standards include viscosity, cure characteristics, physical and dynamic properties [12].

The study used one type of rubber compound, Halobutyl rubber, to produce the inner liner component which natural rubber and synthetic rubber mixed with chemical substances (e.g., oil, carbon black, silica, sulfur) in the specific recipe as shown in Table 1. The material is processed in the mixing process. The proportion of raw material and chemical variation is not in this scope of the study.

Table 1: Chemical composition of the inner liner compound (halobutyl rubber)

Material type	Composition (%)	Remark
Fillers	37.25	Carbon black, Silica, and Calcium carbonate
Rubber polymers	33.20	Natural rubber and Synthetic rubber
Plasticizers	15.87	Oil, resin, reclaim polymer, and plasticizer
Downgraded compound	11.06	Rework from a calendering process
Vulcanization materials	2.62	Sulfur, Stearic acid, Zinc oxide, and MBTS

2.2. Calendering Process

The inner liner is a product of mixing rubber that passed through a roller head machine or two-roll mill calendering machine after homogenizing by the extruder to be a shape with thickness and width as the customer required. The main processes from the case study are shown in Table 2.

Table 2: The main process of the inner liner production

Step	Process	Equipment
1	Feeding rubber compound	Feeding conveyor and hopper
2	Homogenizing rubber	Single-screw extruder
3	Sheeting homogenized rubber	Two-rolls calendering
4	Cooling product	Cooling conveyor
5	Cutting product edge to get the desired width	Trimming roll
6	Cutting product length	Cutter
7	Winding product	Winder

The first step before sheeting the compound is feeding rubber into barrel parts attached to the extruder head. The extruder head has a die to control the rubber flow direction after homogenization in the barrel. The extrusion temperature usually is set with different values depending on the barrel part. The temperature control unit (TCU) that set for feeding screw is 323K, screw temperature at barrel 1 is 333K, 338K for barrel 2, screw temperature itself is 348K, and the head temperature is 353K while the rolls are controlled their temperature at the same level. They are summarized in Table 3.

Table 3: The summary of temperature control unit setting

Section	Temperature (K)
Feeding screw	323
Screw-barrel 1	333
Screw-barrel 2	338
Screw	348
Head	353
Calender top roll	353
Calender bottom roll	353

Homogenized rubber is continuously shaped by two-rolls horizontal calendering with a roll diameter of 33 cm; it is shown in Fig. 2 to be long-thin with a specific thickness around 1.5-2.5 mm. The top roll has a base relief of a straight pattern at the middle in a perpendicular angle to roll. This marks a line on the inner liner continuously, controversy to the bottom roll as shown in Fig. 3. Then, the product getting from this process is called the "Inner liner" component which can be represented in the top and front view of the product as shown in Fig. 4. Homogenized rubber passes through the die and is sheeted immediately via the rollers. The line speed is constant at 30 m/min in case the line speed is changing, screw speed is also automatically evolving in the same direction to prevent the lack of processing rubber between head and rollers. If the line speed decreases, the screw speed decreases to reduce rubber extruded from the extruder head. It affects inner liner thickness that may not align with customer specifications.

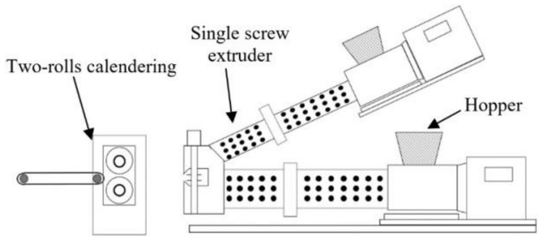

Fig. 2: Side view of two-rolls calendering.

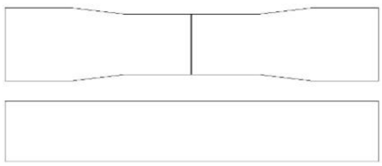

Fig. 3: Front view of calendering rolls.

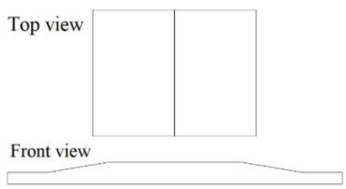

Fig. 4: Top and front view of product.

2.3. Starting Up Process

The starting up process is the beginning process to adjust screw speed getting required product dimension before starting long production run which is needed time around 30 minutes to an hour. Starting up includes the process of feeding rubber into screw then extruded passed die and sheeted by calendering rolls. Normally, the operator is doing trial and error for screw speed adjustment until product dimension (width and thickness) meet the target without focusing on compound properties. And the high amount of defects from product dimension over or less than the desired target could happen. However, there is no manual about the method to adjust screw speed with current Mooney viscosity to get a good product dimension (less deviate) the first time. It is almost from the individual skill of operator and experience.

2.4. Vulcanization

Vulcanization is a process generally applied to rubbery or elastomeric materials. Usually, the unvulcanized rubber network is not strong; it cannot recover to its original shape after a large deformation and is sometimes truly sticky [13]. The vulcanization makes the cross-link between polymer chains during mixing an elastomer with chemicals [14]. The process improves mechanical properties, tensile strength, and elongation at break, elasticity, and stability. Moreover, it would help decrease its plasticity, tackiness, and sensitivity to heat and cold. However, if the rubber compound has an extensive cross-link of an elastic network, the compound will no longer be deformable and cannot be shaped or further processed; this is called cured lump or scorch. Scorch can be explained by the time that heat compound stays in the plastic phase until it converts to elastic phase, so if the compound scorch before constructing a shape, it will no longer be used [15].

2.5. The Relation of Viscosity, Screw Speed, and Product Dimension

Mooney viscosity is the stiffness properties of an uncured compound measured by Mooney viscometer in MU unit [6]. When the rubber compound has a high or low Mooney value, this can explain the increased or decreased resistance to plastic deformation. The screw speed must be adjusted to improve the rheology in the extrusion machine, the difficulty in fluid flow (i.e., high Mooney) needs to increase the shearing force with screw rotation measured by the speed of revolution per minute (rpm) and less vulcanized time which happening during the screw rotating to form the compound into a desirable shape. Controversy, if the compound is low viscosity with a more viscous phase, the process needs less force or low screw rotating speed. In the case of high viscosity due to a complex cross-link network; the compound is stiff, and it needs an immense screw speed and longer vulcanization time to cure the rubber until the hardness decreases and is easier to deform into a shape [6][16].

The effect from other factors on product dimension, for example, TCU settings are constant along production does not depend on product size. For the cooling unit, the cooling conveyor controls the temperature at around 299K using fan winding and keeps it constant with all products by only turning a switch on and off. For the other factors such as pressure, it will be changed directly when screw speed is adjusted in a range of 14-18 rpm. The average pressure is approximately 75 bar at the screw and 100 bar at the feeding hopper. The production line length is about 100 m and mainly monitors temperature when the material is visiting each machine part for the whole line. This shows the factors are almost controlled and keep it stable in a real production run. Any changes, such as the temperature, pressure, or cooling fan, could affect the product. Accordingly, it is considered as a limitation of this study. Regarding the following description, the experiment had been defined into two factors that have hugely affected and can allow studying for the product dimension; Mooney viscosity and parameter setting in the inner liner process focused on screw speed.

2.6. Research Design

Our experiment studied one product type, tire dimension 225/50 R 18. The relationship between screw speed and material viscosity (Mooney) on product specification study was designed to collect twenty-five samples. The data about actual screw speed during machine running and Mooney viscosity for each compound lot were recorded together with the result of product dimension in thickness and width during dayshift that measured as shown in Fig. 5. The machine sensor measured dimension in millimeter unit. The width is a front length from the left edge to right edge while thickness is the base height from bottom to middle top because at the top would be no different due to gap between two rolls and this is automatic adjustment by machine.

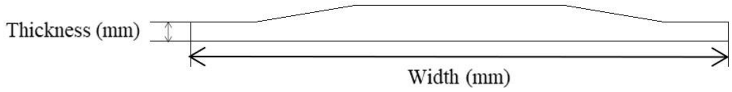

Fig. 5: Inner liner dimension.

In the experiment, the machine automatically recorded the results in terms of dimension and screw speed then exported and analyzed by the authors. After getting the experiment results, the relationship equation was constructed to study for general product model. There are two functions for specified dimensions; width and thickness defined as $\hat{y}_1$ and $\hat{y}_2$, respectively. $\hat{x}_1$ is material viscosity (Mooney) and $\hat{x}_2$ is screw speed (rpm). The relationship equations can be written as in (1)-(2) for width and thickness prediction, respectively. Then, the optimized value for variables is required and created using Minitab 18 getting closely to width target 420.00 mm and thickness 1.50 mm.

$$\hat{y}_1 = b_0 + b_1 x_1 + b_2 x_2 \tag{1}$$

$$\hat{y}_2 = b_0 + b_1 x_1 + b_2 x_2 \tag{2}$$

3. Results and Discussion

Multiple linear regressions with coefficients were constructed as the following (3)-(4). The width and thickness seem compound viscosity and screw speed were more sensitive to width than thickness. ANOVA resulted at 95% confidence level exposed these models were useful for prediction and passed the statistical hypothesis as presented in Table 4. The result *F*-value of regressions is larger than *F-critical* = 3.44. They were under coefficient of determination (R^2) for width at 88.56% and 90.25% for thickness while adjusted (R^2) were at 87.52% and 89.36%, respectively.

$$\text{Width} = 464.66–0.49\text{Compound viscosity}–1.21\text{Screw speed} \tag{3}$$

$$\text{Thickness}= 2.04–0.02\text{Compound viscosity}+0.03\text{Screw speed} \tag{4}$$

Table 4: ANOVA results of regression for width and thickness

Width					
Source	*Df*	*Sum of squares*	*Mean squares*	*F-value*	*P-value*
Regression	2	16.693	8.346	85.140	0.000
Error	22	2.157	0.098		
Total	24	18.850			

Thickness					
Source	*Df*	*Sum of squares*	*Mean squares*	*F-value*	*P-value*
Regression	2	0.010	0.005	101.790	0.000
Error	22	0.001	0.000		
Total	24	0.011			

In terms of the relationship between product dimension and parameters, the result found that when Mooney is high, the shearing force needs to be decreased by putting less screw speed. It helps to destroy the cross-linked network and makes plastic easier deformation. But it can get a larger dimension than specification. If it gets low viscosity, the rotating speed is increased to prevent a high viscous phase this impacted on lower dimension result. After optimizing the value of two parameters by response optimizer in Minitab 18, it found the width and thickness were closer to target when compound viscosity was 49.13 MU and screw speed was 16.80 rpm with composite desirability 1.00. The equations and optimized values were applied in a real production of 10 runs. As a result, it enhanced to reduce loss amount from machine starting up around 81.67% of calendering machine or 4.24% based on the calculation of three machines.

4. Conclusion

Tire production has normally lost quantity during starting up a machine. This research studied the calendering process which is one of the three machines that have a screw extruder to find the relationship between the product dimension and parameters (compound viscosity and screw speed). The regression equation of width and thickness was generated and useful for prediction to get the product dimension nearest the target together. The optimized parameters had been applied to the real production. It has been found that the optimized parameters from the analysis reduce the loss of calendering process and also have the potential to reduce the defects during starting up in complex machines. The case study provides practical and useful results. Possibly, the future work can be extended with tread and sidewall machine to reduce the main large defect quantity in production.

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