A Study of Extrudate Swell Behavior in Tread Die

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ABSTRACT

The purpose of this research is to study extrudate swell behavior in tread die of rubber compound. Single-factor ANOVA was designed for the experiment. There were three load levels in the extrusion; 1.720, 1.735 and 1.750 kg/m According to the experiment, rubber compound melt extrusion by single screw extruder used profile die for tire of sport utility vehicle (SUV) 225/65R17 102 H. The result was load in high level tended to increase nonlinearly die swell ratio of tread and caused width and thickness of tread to be bigger. Also, width of tread increased higher, 9 as much average thickness per higher die swell ratio. This relationship indicated that if tread width could be controlled, the tread thickness or shape could also be controlled. The manufacturer can use the suitable load 1.720 kg/m for tread quality control within specification (weight is 964±24 g/500 mm and width is 214±2 mm), not need to adapt extruder conditions or die modifying. Results from this study led to a higher process capability ratio in tread extrusion process for tread weight from 0.76 to 1.61 and tread width from 0.80 to 1.40.

Keyword:

tread die, Extrudate Swell, rubber compound, single screw extruder, design of experiments

1. INTRODUCTION

Tires are the important components of vehicles. They are the only components which contact with the road. Tires are designed to support weights of vehicles, decrease impact, meet driving and breaking, lower nuisance and vibration, save petrol, and last long. Tires are assembled from a lot of subcomponent, such as tread, sidewall, bead and so on. Each of subcomponents has their specific functions [1]. The main material of tires is 47 percent of rubber compound. Most are found in the surface of tread (32.6 percent of whole rubber compound) [2]. Tread is the only component that contacts with the road. It is designed for abrasion, traction, speed, stability, and casing protection [3].

Tread is manufactured from rubber compound by extrusion process. Heat from heaters and pressure from screw spin press rubber compound melt via die, causing extrudate. It is hard to control tread dimension in low variation because of cross-section area of extrudate more than die during extrusion process of polymers [4-5]. The stored energy release of molecular of rubber compound qualifies polymers. While polymers melt is in melting room, molecular entanglement and molecular disentanglement are occurred, including storing energy during extrusion in die. When polymers melt flows through die, stored energy is released and molecular restores. This phenomenon is called Die Swell or Extrudate Swell [5].

Die swell is the important factor in extrusion process because it can designate size and shape of final product. Die swell depends on three main factors; material, die geometry, and extrusion condition [4-9]. There are many examples of extrusion process. For instance, different characteristic or quality of polymers have effects on different die swell ratio [5], [10-12]. Longer die tends to reduce die swell ratio [4-6], [9]. Different designs of die can lead to different die swell ratio [13-15]. Different temperature [5], [16] and different extrusion condition [9], [16-18] also bring about different die swell ratio. For example, rise temperature tends to reduce die swell ratio [6], [12], [18], [19].

In extrusion process, we found that weight and width of tread without specification led to weight distribution around the circumference of a tire to poor balance [1]. Other studies about die swell behavior focused on circle cross-section die [5-13], [16], [20-23] or annular die [14], Understanding die swell behavior can lead to weight and width tread control, so the purpose of this research is to study extrudate swell behavior in tread die of rubber compound. Design of experiments (DOE) is applied to the research work [24] in order to know load factors influence that effects on die swell ratio. Whilst DOE is important to designate the suitable conditions in the extrusion process [16], [18], [25] or the manufacturing process and control product quality in keeping with specification [26,27].

2. MATERIALS AND METHOD

This research experimented the tread extrusion for sport utility vehicle (SUV) 225/65R17 102 H. The conditions of the product were 964±24 g/500 mm for weight and 214±2 mm for width.

2.1 Materials

There were two materials used for this research; (1) A rubber compound was controlled Mooney viscosity and fluidity which supplied by Michelin Siam Co., Ltd. (2) die made of iron grade S50C and cross-section area (A): 16.87 mm^2.

2.2 Experimental Conditions

This research experimented extrude by two-head single screw extruder, which the size of each screw head was 250 mm. The screw speed was fixed with (1) the screw temperature was 70 °C, (2) the temperature at rubber compound entrance was 60 °C, (3) the barrel temperature at rubber compound entrance was 55 °C, (4) the middle barrel temperature was 50 °C, (5) the barrel temperature was 45 °C and (6) the temperature at head was 90 °C as shown the positions in Figure 1. The loads were 1.720, 1.735 and 1.750 kg/m (the volume flow rate of rubber after leaving the die represented the load in this paper).

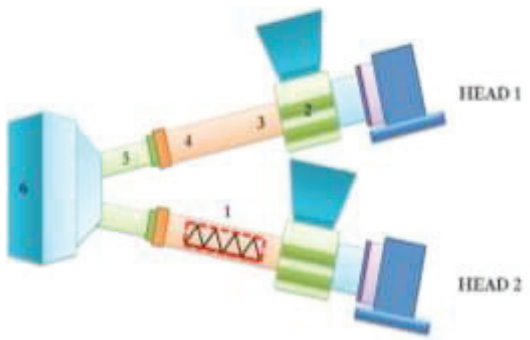


Figure 1: Extrusion Temperature Setting Position

2.3 Die Swell Ratio Measurement

Die swell ratio is a ratio between cross-section area of product and cross-section area of die (Equation 1). This research measured die swell ratio of tread's weight and length of extrudate [4], [7], [8] and calculated die swell ratio of tread as shown in Equation 2.

$$Die\ Swell\ Ratio = \frac{A'}{A} \quad (1)$$

Where, A' = Cross-section area of tread and A = Cross-section area of die.

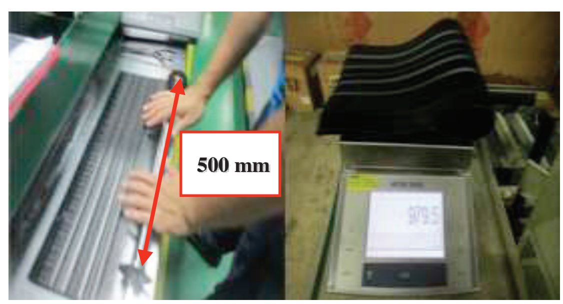
$$Die\ Swell\ Ratio = \frac{W}{D \times A \times L} \quad (2)$$

Where, W = Weight of tread, D = Density, A = Cross-section area of die and L = Length of tread.

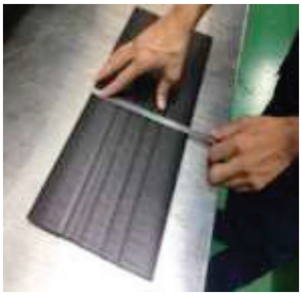
2.4 Design of Experiments

Therefore, we designed the experiments as single-factor design. Load in extrusion divided into three levels; 1.720, 1.735 and 1.750 kg/m to study accurately how die swell behavior impacted on width and thickness tread. Besides, the analysis of variance (ANOVA) is used for analyzing the variance of data and considering whether the different factors can be a cause of the results significantly or not [28].

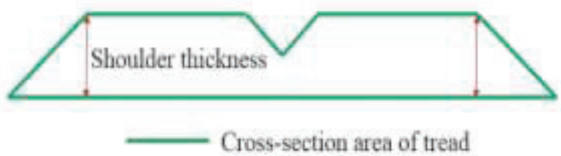
In the extrusion experiments, 10 replications were conducted in each extrusion. Load condition was adapted in run order to decrease mistakes from confounding factors. It also included weighing (W) 500- millimeter (L) sample, measuring the width (averages from three samples continuously) and the shoulder thickness of two average sides of tread (Figure2)



a) Weighing



b) Measuring the width



c) Measuring the thickness

Figure 2: Sample Measurement

3 RESULTS AND ANALYSIS

The experimental responses on single factor design (Table 1) for studying die swell behavior of rubber compound in tread extrusion were taken to the analysis of variance (ANOVA), the adequacy of statistic model and the analysis of optimal level for tread extrusion process by using Minitab program.

Table 1 Experimental Responses

Load (kg/m)	Responses		
	Die Swell Ratio	Width (mm)	Thickness (mm)
1.720	1.621	214.3	9.74
	1.621	214.0	9.74
	1.619	214.0	9.73
	1.623	214.5	9.77
	1.623	214.5	9.79
	1.624	214.5	9.75
	1.624	214.3	9.77
	1.623	214.3	9.77
	1.625	214.7	9.78
	1.620	214.3	9.74
1.735	1.628	214.8	9.82
	1.627	214.8	9.79
	1.625	214.5	9.78
	1.626	214.7	9.81
	1.629	214.8	9.80
	1.628	214.8	9.81
	1.627	214.8	9.78
	1.628	215.0	9.81
	1.629	215.0	9.82
	1.624	214.3	9.76
1.750	1.636	215.5	9.86
	1.639	215.5	9.89
	1.637	215.3	9.88
	1.640	215.7	9.91
	1.637	215.3	9.87
	1.638	215.7	9.90
	1.637	215.5	9.88
	1.636	215.0	9.87
	1.639	215.8	9.90
	1.635	215.3	9.87

3.1 Analysis of Variance

The analysis of variance of tread by single factor design was found that, the load had effects on die swell ratio of tread 5-percent level (α = 0.05) significantly under coefficient of determination (R^2) and also adjusted decision coefficient (R^2adj) to be equal to 93.60% and 93.13% respectively (Table 2).

Significantly and statistically, the extrusion load impacted on width and thickness tread 5-percent level percent (α = 0.05) under coefficient of determination (R^2) which was equal to 82.39% for width (Table 3) and 89.33% for thickness (Table 4).

3.2 Adequacy Checking of Statistic Model

We checked adequacy of statistic model in experiment, under the assumption $e_{ij} \sim N(0.\sigma^2)$ by residual analysis: e_{ij}; namely, normal distribution and independence of the random error or residual with equal variance of each factor levels [28].

After checking result, we found that the residuals of all responses (die swell ratio, width and thickness) had normally distribution and independence with equal variance of each factor levels. So it could be concluded that the statistic model in experimental was resistance. Moreover, the observations value or responses of experimental were good quality (not error from statistic model) which was reliable following assumption $e_{ij} \sim N(0,\sigma^2)$.

3.3 Analysis of Factor Levels

Considering die swell ratio from average factors levels, we found that the high load will made the flow velocity of melt rubber compound after leaving the die decrease more than the low load. It effected on increase of volume flow rate and molecular chain's capability in releasing more the accumulated energy that led to more of die swell ratio. During the increase of die swell ratio, it caused width and thickness of tread increase.

Table 2 ANOVA of Die Swell Ratio

Source	DF	SS	MS	F	P
Load	2	0.0011905	0.0005952	197.44	0.000
Error	27	0.0000814	0.0000030		
Total	29	0.0012719			
R-Sq = 93.60%			R-Sq (adj) = 93.13%		

Table 3 ANOVA of Tread Width

Source	DF	SS	MS	F	P
Load	2	6.4220	3.2110	63.14	0.000
Error	27	1.3730	0.0509		
Total	29	7.7950			
R-Sq = 82.39%			R-Sq (adj) = 81.08%		

Table 4 ANOVA of Tread Thickness

Source	DF	SS	MS	F	P
Load	2	0.081500	0.040750	113.08	0.000
Error	27	0.009730	0.000360		
Total	29	0.091230			
R-Sq = 89.33%			R-Sq (adj) = 88.54%		

Furthermore, it could be established polynomial regression model (the nonlinear was rather than linear) for prediction the die swell ratio (B) from the extrusion load as shown in Equation 3 at the coefficient of determination (R^2) at 93.6%, as well as, regression model for prediction the width (Figure 3) and thickness (Figure 4) of tread from the die swell ratio (B) as shown in Equation 4 and 5 at the coefficient of determination (R^2) at 92.4% and 96.4% respectively. The coefficient of die swell ratio parameter in Equation 4 and 5 reflects the die swell ratio sensitive to width more than tread thickness.

$$B = 37.55 - 41.91(Load) + 12.22(Load)^2 \quad (3)$$

$$Tread\ Width = 92.28 + 75.24(B) \quad (4)$$

$$Tread\ Thickness = -3.732 + 8.315(B) \quad (5)$$

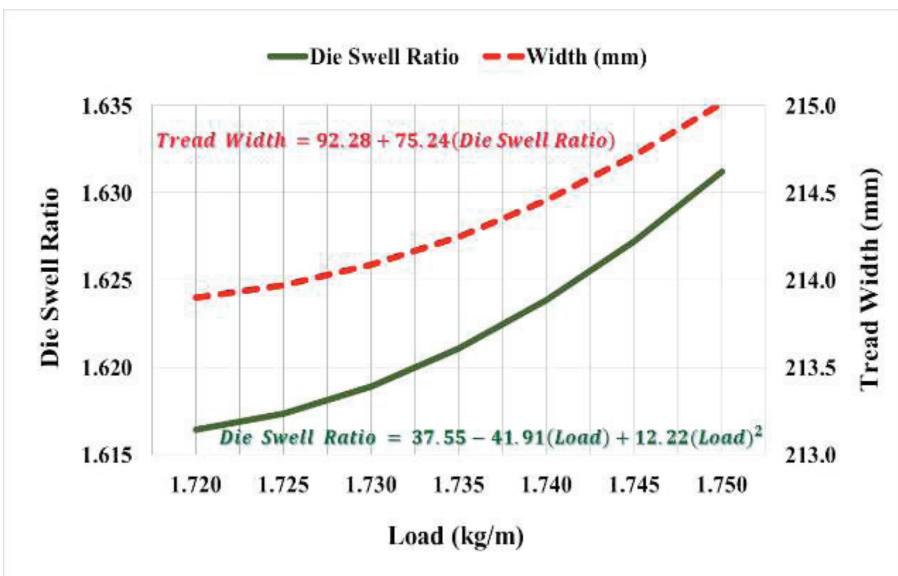


Figure 3: Die Swell Ratio and Tread Width versus Load

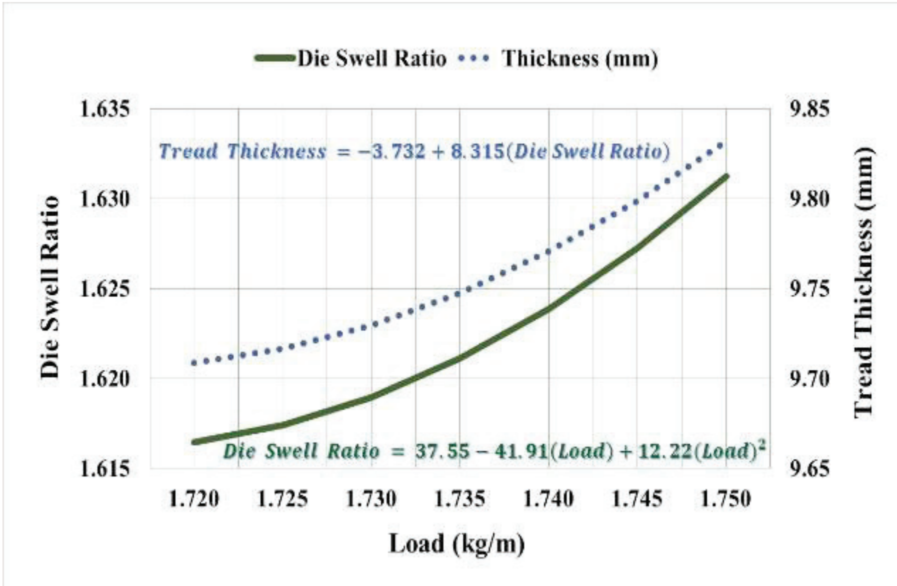


Figure 4: Die Swell Ratio and Tread Thickness versus Load

The relationship analysis between the load and dimension of tread (die swell ratio, width and thickness) found that the increasing of 0.030 kg/m load caused the tread to increase die swell ratio at 1.5 percent approximately, width at 1.11 mm approximately and thickness at 0.12 mm. In addition, we found that the tread width increased more than thickness at approximately 9 as much. This relationship indicated that if tread width could be controlled, the tread thickness or shape can also be controlled.
From the analysis of relationship between extrusion load and tread dimension, they could be determined the optimal load on 1.720 kg/m of tread extrusion process which led to quality control of tread within specification (964±24 g/500 mm for weight, or 1.604±0.04 in die swell ratio term, and 214±2 mm for width). We can see that this load could save the lowest cost.

4 TEST RESULT CONFIRMATION

After the analysis, the suitable loading level 1.720 kg/m, can designate the weight and the width of the treads. The experiment can be confirmed by replications and 30-sample treads.

We found that 1.720 kg/m is the suitable loading level to designate weight and width of the treads. When analyzing process capability ratio found that a higher process capability ratio in tread extrusion process for tread weight from 0.76 ($C_{pk\ before} = C_{pu\ before}$ = 0.42) to 1.61 ($C_{pk\ after} = C_{pu\ after}$ = 1.23) and tread width from 0.80 ($C_{pk\ before} = C_{pu\ before}$ = 0.33) to 1.40 ($C_{pk\ after} = C_{pl\ after}$ = 1.31). Which can be indicated that the process capability ratio has been increased better than the specifications (almost equal to 1.33) [29].

5 CONCLUSION

According to study of die swell behavior in tread die of rubber compound for sport utility vehicle tire (size 255/65R17 102H) on single screw extruder by applied experiments with a single factor, we found that the load increasing made die swell ratio of tread increase and also weight and width increase. The tread width increased more than thickness statistically and significantly. Therefore, we will be able to control the thickness or shape of the tread when we can control the width of the tread.

The study results contribute deeper understanding in die swell behavior of rubber compound and know the optimal extrusion process. It leads to quality control in the specifications of tread without adapting extruder conditions and modifying die.

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