Terbit *online* pada laman web jurnal : http://metal.ft.unand.ac.id

METAL: Jurnal Sistem Mekanik dan Termal

| ISSN (Print) 2598-1137 | ISSN (Online) 2597-4483 |

Research article

Maximizing Retreaded Tire Hardness: An Experimental Investigation

Wahyu Handayani Putri, Feri Afrinaldi, Taufik, Ramadhan Rizki Fernando
Department of Industrial Engineering, Universitas Andalas, Padang 25163, Indonesia

ARTICLE INFORMATION

Article History:
Received : 24 September 2024
Revised : 12 Oktober 2024
Accepted : 27 Oktober 2024

KEYWORDS

Experiment
Retread
Taguchi
Tire

CORRESPONDENCE

E-mail: feriafrinaldi@eng.unand.ac.id

A B S T R A C T

Tires are vehicle parts that have a significant economic impact. When the tires reach their end-of-life, they can be retreaded for further use. A company in Padang, Indonesia, manufactures retreaded tires with hardness specifications of at least 61 Shore A. The technology used by the company is the hot cure retreading. Historical data showed that the process produced 7% of defective tires and cost the company $16 per unit of defective tires. It was identified that curing temperature, mold pressure, inner tube pressure, curing time, and fuel type mixed with adhesive affect tires' hardness. This paper aims to find the best combination of the above parameters so that the hardness of the retreaded tires is maximized. Experiments were performed, and the Taguchi method was employed to design the experiments. Since the experiments have five factors, and each involves two levels, the degree of freedom of the experiments is five. There were three replications for each treatment. Thus, an L_8 orthogonal array was selected. The experimental results showed that the best combination of factors is curing temperature at 140 ˚C, mold pressure at 4 bar, inner tube pressure at 8 bar, curing time for 2 hours, and fuel mixed with adhesive was SBP. The above combination was predicted to produce an average hardness of 63.10 Shore A. A confirmation experiment was then performed by applying the above combination of factors, which resulted in an average hardness of 63.15 Shore A and no retreaded tires having hardness below 61 Shore A.

1. INTRODUCTION

There will be around 1.5 billion vehicles, or one car for every five people in the world, in 2024 [1]. Historical data show that about 25% of them ended up in landfills [2]. It is known that end-of-life vehicles have a negative impact on the environment.

A vehicle is complex and consists of thousands of individual parts. One of the parts that has significant economic and ecological impacts is the tires [3]. When the tires reach their end-of-life, they might be recycled. The raw materials of the tires are extracted and used in other products. Tires can also be incinerated to obtain energy. Another option is to retread the tires for further use [3].

Retreading is the process of replacing the worn tread of a tire with a new one. Among the remanufacturing processes, retreading is one of the most succesfull [4], [5].

The performance of retreaded tires is 60 – 70% compared to brand-new tires [6]. In Indonesia, retreaded tires must conform Indonesian National Standard (SNI 3768:201) to ensure safety. In the European Union (EU), the retreaded tires industry is worth €1.2 billion and supports 32,000 jobs. In EU5 (France, Italy, Germany, Spain, and the UK), retreaded truck tires have a market share of 30%.

Moreover, retreaded tires have environmental advantages. Compared to new tires, retreaded tires

https://doi.org/ 10.25077/metal.8.2.39-48.2024

save 70% natural resource extraction, 29% land use, 24% CO_2 emissions, 21% particulate matter emissions, and 19% water consumption [7].

Tires with worn treads can be retreaded if they do not have broken ply, belt, sidewall, and bead. Two technologies can be applied to retread tires: cold cure and hot cure retreading. The retreading process using a cold cure can be done several times. The process is carried out by pasting new treads on a tire in special chambers. The hot cure retreading process can only be done once. In this process, the new tread is applied to the surface of a used tire and continued with pressing the tire to the pressure of 8 bar and heating to the temperature of 135 - 140 °C. This paper focuses on the hot cure retreading technology.

The hot cure retreading process consists of nine steps. They are initial inspection, buffing, grinding, brushing, adhesive application, gum insertion, cushion gum attachment, hot cure, and final inspection. Schematically, the process is presented in Figure 1.

In the initial inspection process, a trained inspector inspects the used tire to decide whether the tire is within quality limits. If the inspector finds broken ply, belt, sidewall, and bead, the tire does not qualify for retreading. Tires passing the inspection will be buffed. A high-speed rotating buffer mechanically removes the old tread. Suppose there are undetected tears on the inside of the tire which are not detected at the inspection stage; they will be visible at this stage.

The process continues with grinding. A trained operator grinds the surface of the tire to make minute rips visible. After grinding, the operator brushes the tire's surface, freeing it from dirt and dust. A clean surface makes the gluing process easier. Special adhesive is then applied to the surface of the tire. The adhesive is used to attach the cushion gum.

The next step is gum insertion, this process aims to close the tears on the tire's surface. This process prevents bloating. Cushion gum is then attached to the tire's surface (cushion gum attachment). This step aims to glue the tire's casing to the new tread. The process continues with the hot curing step.

In the hot curing step, the new tread has no tread pattern yet, so it is called compound rubber. After the compound rubber is attached to the tire's surface, the tire is placed on a plate. An inner tube is inflated with a pressure of 8 - 10 bar. The tire is then placed inside a mold. The mold is pressurized (3 - 4 bar) and heated at the temperature of 135 - 140 ˚C. This process lasts for at most 2 hours. The combination of heat, pressure, and time produces tread pattern and depth as intended.

After the curing process is completed, the final inspection is performed**.** In the final inspection, the hardness of the tire tread is inspected to determine whether it meets specifications. The hardness of the tire produced by this process is measured in the Shore A unit. Shore A is a unit used to measure the hardness of materials, typically polymers. Inspection also ensures that the tire has no defects.

In the literature related to tire recycling, the majority of the studies are on the processes and strategies for tire waste management [8], [9], [10]. There are limited studies on tire retreading process improvement. In this area, most of the studies discussed the energy efficiency of the hot cure process [11], [12], [13]. For the initial screening process of tire retreading, fuzzy logic was suggested to decide whether a tire could be retreaded [14]. In order to improve the bonding between the tread and carcass of the retreaded tires, numerical simulation and experimentation were used [15]. Quality tools have also been used to improve the quality of the retreading process in general [16]. This paper aims to improve the retreading process, focusing on the hot cure retreading, by finding the best combination of the process's parameters to maximize tires' hardness.

 https://doi.org/ 10.25077/metal.8.2.39-48.2024

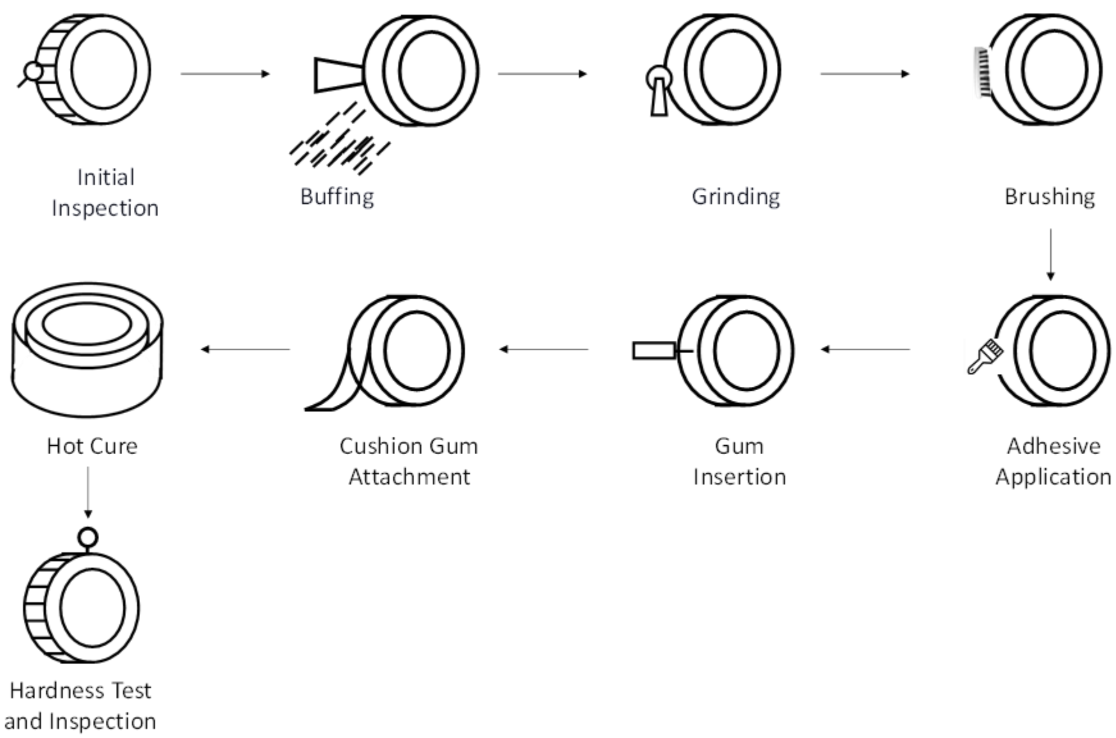

Figure 1. Hot cure tire retreading process

2. PROBLEM DESCRIPTION

PTIV is one of the retreaded tire producers in Indonesia. The company sets the hardness specification of its products to at least 61 Shore A, and the maximum allowable proportion of tires whose hardness does not meet this specification is 4%.

A sample of 100 retreaded tires produced by the company using the hot cure process was randomly selected. It was found that the hardness mean was 61.87 Shore A, the standard deviation was 0.54 Shore A, and there were seven tires whose hardness was below 61 Shore A. It was indicated that the proportion of tires whose hardness was below 61 Shore A was 7%. It was 3% higher than the maximum allowable proportion.
The out-of-specification tires are discarded and cost the company $16 per unit. Since the hardness is the case of the The-Larger-The-Better (L Type) quality characteristic, the loss function associated with the L Type can be applied to calculate the loss. Using the 100 observations taken, it is found that the loss is,

$$L = A\Delta^2 \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} = 16 \times 61^2 \times \frac{1}{100}\left(\frac{1}{62^2} + \frac{1}{60^2} + \cdots + \frac{1}{62^2}\right) = \$15.56 \text{ per unit},$$

where A = cost of a defective tire, Δ = lower specification limit, n = sample size, and y_i = the hardness of the ith tire in the sample.

Therefore, there is a need to improve the process and reduce the percentage of retreaded tires that do not meet the specification limit.

Several factors might contribute to the out-of-specification tires, such as the type of fuel mixed with the adhesive, operators' skills, especially in the initial inspection step, equipment performance, inner tube pressure, mold pressure, mold temperature, and curing duration. Some of those factors are controllable, and some are uncontrollable.

Almost all operations are completed manually by the operators. Thus, it is challenging to control the operations they conduct. Therefore, this research focused on controllable factors influencing the tires' hardness. Those factors are curing temperature, mold pressure, inner tube pressure, curing time, and the type of fuel mixed with the adhesive. The objective of this paper is to find the best combination of hot cure retreading process parameters that will maximize the hardness of the retreaded tires and reduce the tire's percentage not meeting the specification limit.

3. METHOD

3.1. Experimental Design

Factors influencing the hardness of the retreaded tires considered in this research are curing temperature, mold pressure, inner tube pressure, curing time, and the type of fuel mixed with the adhesive. The setup of the experiment is presented in Figure 2.

The input was shaved tires. They were tires whose worn-out treads had been inspected, buffed, grinned, and brushed. Their conditions were maintained the same. The adhesive, previously mixed with an additive, was then applied to the shaved tires. Two types of additives were considered in the experiment, Pertamax and SBP.

Gum insertion was not part of the experiment factors, but the process must have been completed before the cushion gum was attached. Thus, the type of gum used was kept the same. Similarly, the cushion game attachment process was maintained uniformly, and the type of cushion gum attached was the same.

The majority of the variables analyzed in the experiment were in the hot cure process. They were mold temperature, mold pressure, inner tube pressure, and curing time. The variables' levels were set up using an indicators panel, which was part of the mold system. Pressure and temperature were built and increased by flowing steam into the mold. The last step was the hardness checking of the retreaded tire using a durometer.

Several levels were chosen for the factors considered in this experiment. The levels' values depend on the prior knowledge about the process, equipment capability, and resources available. Based on the direct observation and operators' experience, it was decided to use two levels for each controllable factor. Their values are presented in Table 1. The dependent variable is the hardness of the retreaded tire expressed in Shore A.

Table 1. Factors and levels

Factors	**Level 1**	**Level 2**	**Unit**
Curing temperature	135	140	˚C
Mold pressure	3	4	bar
Inner tube pressure	8	10	bar
Curing time	1.5	2	hour

Since the experiment would be conducted on the production floor, it was only possible to have a few experimental units. The experiment must not disrupt the production process. Therefore, a lesser experimental unit than the factorial design was required. For this reason, the Taguchi method was applied.

The experiment's degree of freedom (DoF) is 5 × (2-1) = 5, where 5 is the number of factors and 2 is the number of levels for each factor. Based on the degree of freedom and Table 2, L_8 orthogonal array was selected.

Table 2. DoF and orthogonal array

DoF	***Orthogonal Array***
2 – 3	L_4
4 – 7	L_8
8 – 11	L_{12}
12 – 15	L_{16}

 https://doi.org/ 10.25077/metal.8.2.39-48.2024

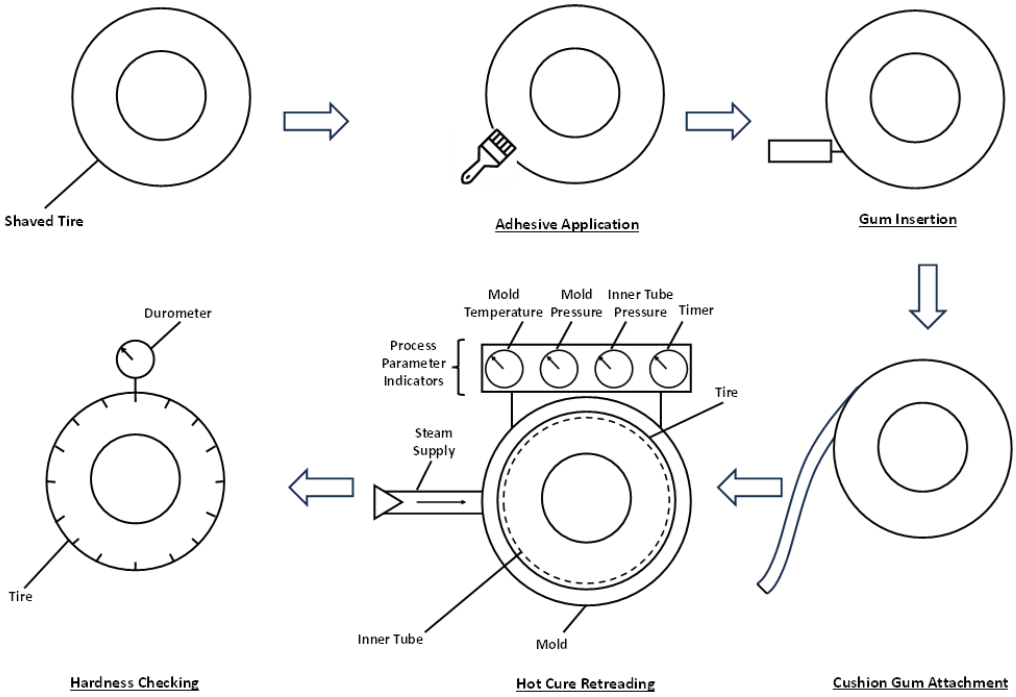

Figure 2. Experimental set-up

3.2. Data Collection

The experiment was conducted on the production floor. Based on the L_8, measurements were carried out, and three replications were made for each treatment. The instrument used to measure tire hardness was a rubber hardness tester, called a durometer, presented in Figure 3. The measurements were carried out by pressing the device against the tire's tread that will make contact with the road.

Figure 3. Measuring tire hardness using durometer

Observations were collected based on the fuel mixed with the adhesive. When the company used Pertamax, treatments number 1, 3, 6, and 8 were conducted, see Table 3. On a day, two treatments were conducted. So, when Pertamax was used, treatments number 1 and 3 were conducted on the first day. On the next day, treatments number 6 and 8 were completed. There were three replications for each treatment. Thus, there were six observations per day. For the SBP, the same procedure was followed. The treatments were conducted when the company used SBP.

3.3. Confirmation Experiment

The combinations of factors and levels maximizing the hardness mean and signal-to-noise (S/N) ratio were implemented in a confirmation experiment. It was decided that ten observations were collected. The confirmation experiment was completed in a day.

3.4. Statistical Analysis

The observations collected were analyzed to determine factors maximizing the mean and S/N ratio. The first analysis was the Analysis of Variance (ANOVA) for mean and S/N ratio. From the ANOVA, factors having a significant influence on the mean and S/N ratio of retreaded tire hardness were decided.

Next, response tables for mean and S/N ratio were presented. From the tables, the ranking of the factors and levels maximizing mean and S/N ratio were determined. Also, factors that increased or decreased the mean and S/N ratio were decided.

After that, the main effect plots for the mean and S/N ratio were presented.

Table 3. Experimental results

No.	Curing temperature (˚C)	Mold pressure (bar)	Inner tube pressure (bar)	Curing time (hour)	Fuel mixed with adhesive	Retreaded tires' hardness (Shore A)		
						Replication		
						1	2	3
1	135	3	8	1.5	Pertamax	61.0	61.8	62.1
2	135	3	8	2	SBP	61.2	62.4	62.0
3	135	4	10	1.5	Pertamax	61.3	61.8	61.0
4	135	4	10	2	SBP	62.0	62.0	63.0
5	140	3	10	1.5	SBP	62.4	62.0	61.8
6	140	3	10	2	Pertamax	61.7	62.4	62.0
7	140	4	8	1.5	SBP	62.3	62.6	63.2
8	140	4	8	2	Pertamax	63.0	62.7	63.0

The analyses of variance for means and S/N ratio are shown in Table 4 and 5. Table 4 shows that only curing temperature significantly affects the hardness of the tire's treads at an α-level of 0.1 (P = 0.083). Similarly, for S/N ratios (Table 5), only curing temperature is significant at an α-level of 0.1 (P = 0.083).

Table 4. Analysis of variance for means

Source	*DF*	Seq *SS*	Adj *SS*	Adj *MS*	*F*	*P*
Curing temperature	1	0.781	0.781	0.781	10.550	0.083
Mold pressure	1	0.361	0.361	0.361	4.880	0.158
Inner tube pressure	1	0.211	0.211	0.211	2.850	0.233
Curing time	1	0.234	0.234	0.233	3.150	0.218
Fuel mixed with adhesive	1	0.134	0.134	0.133	1.800	0.311
Residual error	2	0.148	0.148	0.074		
Total	7	1.869				

Table 5. Analysis of variance for S/N ratios

Source	*DF*	Seq *SS*	Adj *SS*	Adj *MS*	*F*	*P*
Curing temperature	1	0.015	0.015	0.015	10.620	0.083
Mold pressure	1	0.007	0.007	0.007	4.820	0.159
Inner tube pressure	1	0.004	0.004	0.004	2.810	0.236
Curing time	1	0.005	0.005	0.005	3.150	0.218
Fuel mixed with adhesive	1	0.003	0.003	0.003	1.800	0.311
Residual error	2	0.003	0.003	0.001		
Total	7	0.037				

Table 6 presents that curing temperature is ranked 1, meaning that curing temperature has the highest contribution to tread hardness. Table 6 also shows that the best combination, labeled by *, is curing temperature at level 2 (140 ˚C), mold pressure at level 2 (4 bar), inner tube pressure at level 1 (8 bar), curing time at level 2 (2 hours), and fuel mixed with adhesive at level 2 (SBP).

For S/N ratio, Table 7, curing temperature also has the most significant influence, followed by mold pressure, curing time, inner tube pressure, and fuel mixed with the adhesive. Similarly, to maximize S/N ratio, the best combination, labeled by *, is curing temperature at level 2 (140 ˚C), mold pressure at level 2 (4 bar), inner tube pressure at level 1 (8 bar), curing time at level 2 (2 hours), and fuel mixed with adhesive at level 2 (SBP).

Table 6. Response table for means

Level	Curing temperature	Mold pressure	Inner tube pressure	Curing time	Fuel mixed with adhesive
1	61.80	61.90	62.28*	61.94	61.98
2	62.43*	62.33*	61.95	62.28*	62.24*
Difference	0.63	0.43	0.33	0.34	0.26
Ranking	1	2	4	3	5

Table 7. Response table for S/N ratios (larger is better)

Level	Curing temperature	Mold pressure	Inner tube pressure	Curing time	Fuel mixed with adhesive
1	35.82	35.83	35.89*	35.84	35.84
2	35.91*	35.89*	35.84	35.89*	35.88*
Difference	0.09	0.06	0.05	0.05	0.04
Ranking	1	2	4	3	5

Figures 4 and 5 are the graphical representations of the main effects for means and S/N ratios.

Examining the main effects plots confirms the above results. The goal is to increase tread hardness; factor levels producing the highest mean are wanted. In Taguchi's experiments, the objective is always to maximize the S/N ratio. Based on the results, the curing temperature was set at 140 ˚C, mold pressure at 4 bar, inner tube pressure at 8 bar, curing time for 2 hours, and fuel mixed with adhesive was SBP.

Based on the above results, the mean, standard deviation, and S/N ratio of the retreaded tires' hardness were predicted. Factor levels used for prediction were curing temperature at 140 ˚C, mold pressure at 4 bar, inner tube pressure at 8 bar, curing time for 2 hours, and SBP as the fuel mixed with the adhesive. The predicted values of the mean, standard deviation, and S/N ratio are presented in Table 8.

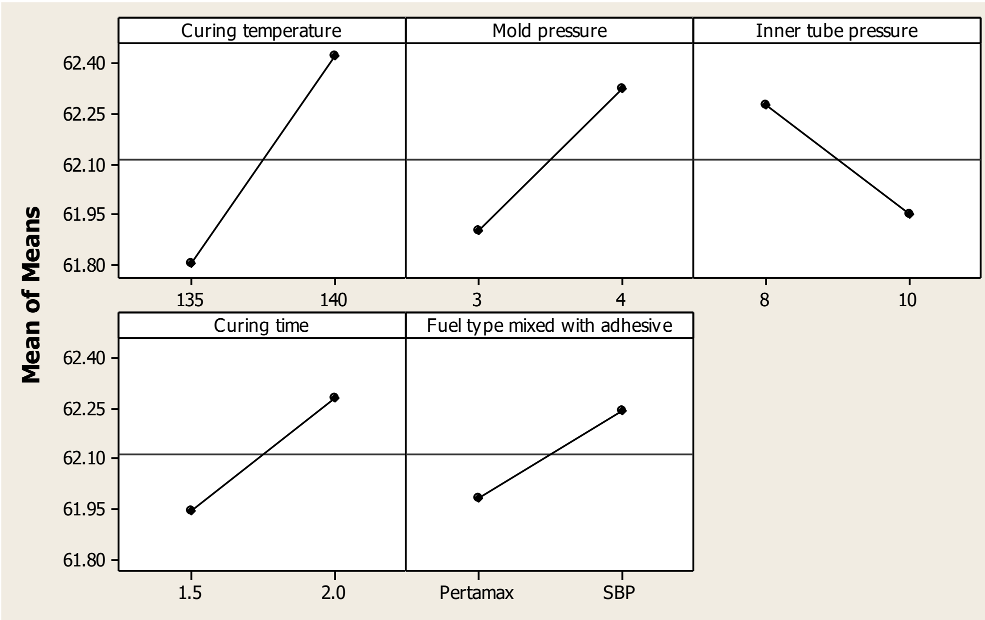

Figure 4. Main effects (data means) plot for means

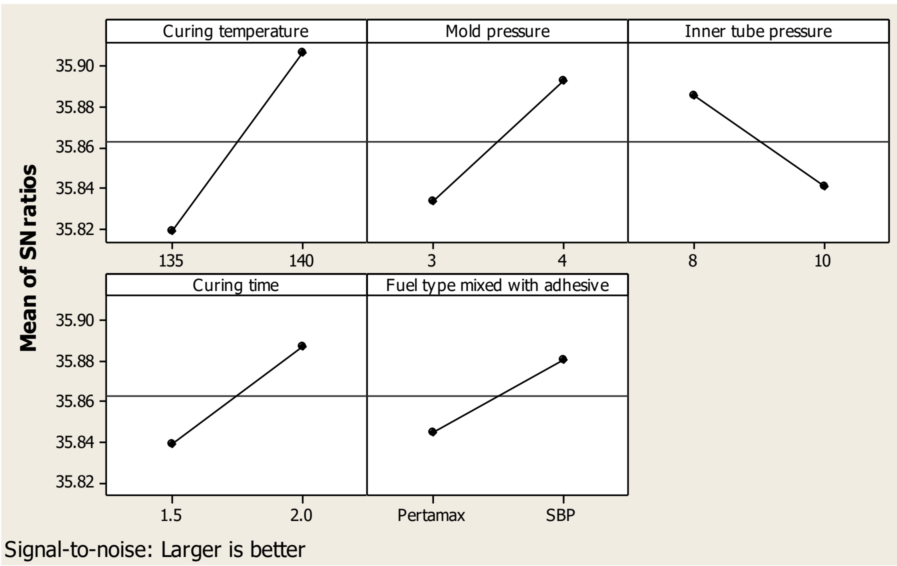

Figure 5. Main effects plot (data means) for S/N ratios

A confirmation experiment was then conducted. Ten retreaded tires were produced using the same factor levels, and the results are (in Shore A) 62.5, 62.7, 62.3, 62.7, 63.5, 63.0, 63.8, 63.0, 64.0, and 64.0. Based on this result, the proportion of retreaded tires that fell below the specification limit of 61 Shore A was 0%. The mean, standard deviation, and S/N ratio are summarized in Table 8.

The table shows that the results of the confirmation experiment are very close to the predicted values.

Compared to the 100 tires' hardness previously collected, it was found that the result of the confirmation experiment has a higher average and less standard deviation. Data previously collected had an average of 61.87 Shore A, and a standard deviation of 0.54 Shore A.

By using the results of the confirmation experiment and the loss function associated with the L Type, it was found that the loss,

$$L = A\Delta^2 \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} = 16 \times 61^2 \times \frac{1}{10}\left(\frac{1}{62.5^2} + \frac{1}{62.7^2} + \cdots + \frac{1}{64.0^2}\right) = \$14.93 \text{ per unit.}$$

This result indicates that by applying the result obtained using the Taguchi experiment, a 63 cents or 4% saving per unit of retreaded tire produced was gained. On average, the monthly production rate was 240 tires. Thus, the yearly saving was predicted to be $1,814.4 on average.

Table 8. Prediction and confirmation experiment results for mean, standard deviation, and S/N ratio

	Mean (Shore A)	Standard Deviation (Shore A)	S/N Ratio
Prediction	63.10	0.370	36.00
Confirmation experiment	63.15	0.631	36.01

4. DISCUSSIONS

This research found that the combination of factors maximizing the retreading tire hardness is the curing temperature at 140 °C, mold pressure at 4 bar, inner tube pressure at 8 bar, 2 hours of curing time, and fuel mixed with adhesive is SBP. Previous research found similar results, including curing temperature at 110 °C, pressure at 4 bar, capsule pressure at 7 bar, and 2.5 hours of curing time [17]. The difference in mold temperature and inner tube pressure is due to the difference in the type of tire investigated. This research investigated truck tires, and the previous investigated passenger car tires. The difference in the efficiency of the heat transfer process in the mold could cause a difference in curing time.

The statistical analysis showed that only curing temperature significantly affected the retreading tire hardness; the higher the temperature, the harder the tire. A higher temperature is needed because of the mold's heat transfer process's inefficiency. The sources of the inefficiency are the use of steam and the inflation method of the bladder [13]. Thus, a more efficient method for heating and inflating is required to improve the process. Another study suggested minimizing the temperature difference between the upper and lower parts of the bladder (one of the components of the mold) [18]. This is important because inefficiency in heat transfer affects the curing time. Longer curing time means lower productivity. The effect of heat flow during the curing process was also emphasized in the literature [19].

Furthermore, mold temperature affects the performance of the adhesive. A previous study found a stable adhesion formed at 130 – 175 °C [20]. The curing temperature suggested by this research is in that interval.

As an additive, SBP performs better than Pertamax at the above temperature. SBP helps transfer vulcanizing agents into the rubber compound better than Pertamax. Thus, it improves the binding force between the tire and its cushion gum.

It is important to note that the initial diagnostic process of the worn-out tires plays a crucial role in determining the quality of the retreaded tires. In this study, the tires were eligible to be retreaded, and their conditions were homogenous. Previous research showed that it is not only the curing process that affects the quality of the tire but also their initial conditions, such as the distance that the tires had traveled [3]. Final inspection is also crucial. Besides the hardness specification, it must be ensured that the retreaded tire has no carcass defect [17].

Improving the energy efficiency of the process will be one of the directions for future research. Improvement in energy consumption of the proceeds will directly affect the emissions of the process. Thus, assessing the environmental impact and eco-efficiency of the process will be another direction for future research.

5. CONCLUSION

This paper identified factors affecting the hardness of retreaded tires produced by the hot cure retreading process. The factors are curing temperature, mold pressure, inner tube pressure, curing time, and fuel mixed with the adhesive. The specification of the retreaded tires is that they must have hardness at least 61 Shore A. An experiment was designed using the Taguchi method to determine the combination of factors that maximize retreaded tire hardness. The result of the experiment showed that the best combination is curing temperature at 140 ˚C, mold pressure at 4 bar, inner tube pressure at 8 bar, curing time for 2 hours, and fuel mixed with adhesive was SBP. A confirmation experiment was then conducted by using the above combination. The confirmation experiment showed that the average hardness of 63.15 Shore A was produced, and no retreaded tires had hardness below 61 Shore A. By using the above combination, the company is expected to save $1,814.4 annually. For future research, it is suggested to investigate the eco-efficiency of the hot cure retreading process.

REFERENCES

[1] Hegges and Company. “How many cars are there in the-world.” Accessed: Oct. 1, 2024, [Online.] Available: hedgescompany.com/blog/2021/06/how-many-cars-are-there-in-the-world/

[2] J. Suterland, “Automotive industry.” Michigan Techn. University, SAD., 2000.

[3] S. Dabić-Ostojić, M. Miljuš, N. Bojović, N. Glišović and M. Milenković, “Applying a mathematical approach to improve the tire retreading process,” *Resources, Conservation and Recycling*, vol. 86, pp. 107-117, May 2014.

[4] W. Han, D. Han and H. Chen, “Pyrolysis of waste tires: a review,” *Polymers*, vol. 15, no. 7, 2023.

[5] G. Ferrer and D. C. Whybark, “Communicating product recovery activities: Processes, objectives, and performance measures,” in *Handbook of Environmentally Conscious Manufacturing*, C. N. Madu, New York, NY, USA: Kluwer Academic Publishers, pp. 81-99, 2001.

[6] Hyundai. “Pengertian ban vulkanisir, risiko, kerugiannya.” Accessed: Oct. 4, 2024, [Online.] Available: https://www.hyundai.com/id/en/hyundai-story/articles/pengertian-ban-vulkanisir,-risiko,-kerugiannya-0000000110

[7] E. Mugnier, F-M. Lambert and P. Canfin, “The socio-economic impact of truck tyre retreading in Europe: The circular economy of tyres in danger.” EY, London, 2016.

[8] M. L. Uriarte-Miranda, S. O. Caballero-Morales, J.L. Martinez-Flores, P. Cano-Olivos and A.A. Akulova, “Reverse logistic strategy for the management of tire waste in Mexico and Russia: Review and conceptual model,” *Sustainability*, vo. 10, no. 10, 2018.

[9] A. Molino, A. Donatelli, T. Marino, A. Aloise, J. Rimauro and P. Iovane, “Waste tire recycling process for production of steam activated carbon in a pilot plant,” *Resources, Conservation and Recycling*, vo. 129, pp. 102-111, Feb. 2018.

[10] J. Park, N. Díaz-Posada and S. Mejía-Dugand, “Challenges in implementing the extended producer responsibility in an emerging economy: The end-of-life tire management in Colombia,” *Journal of Cleaner Production*, vol. 189, pp. 754-762, Jul. 2018.

[11] J. Guo, H. Li, H. Yang and S. Zhang, “A collaborative detection approach for internal steam leakage of tyre vulcanization workshop with artificial immune algorithm,” *Computational and Applied Mathematics*, vol. 37, pp. 4219-4236, Jan. 2018.

[12] J. Guo and H. Yang, “A fault detection method for heat loss in a tyre vulcanization workshop using a dynamic energy consumption model and predictive baselines,” *Applied Thermal Engineering*, vol. 90, pp. 711-721, Nov. 2015.

[13] L. K. Pentakota, P. Albertelli and M. Strano, “Energy efficiency of the vulcanization process of a bicycle tyre,” *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 10, no. 4, pp. 979-998, Mar. 2023.

[14] G. C. Angles Medina, K. Rosas Paredes, M. Zúñiga Carnero and J. Sulla-Torres, “Diagnostics in Tire Retreading Based on Classification with Fuzzy Inference System,” *Applied Sciences*, vol. 12, no. 19, Oct. 2022.

[15] P. Qi and J. Chu, “Research on discrete data analysis of vehicle retread tire performance based on radial stiffness method,“ *Journal of Physics: Conference Series*, vol. 2074, no. 1, 2021.

[16] B. Behnam and H. Alvelos, “Exploring the potential of quality tools in tire retreading industry: A case study,” *International Journal of Engineering Science and Technology* (IJEST), vol 3, no. 6, pp. 5337-5345, 2011.

[17] P. Fu, X. P. Zhao, X. F. Su and H. Yan, “Research on the Passenger Car Tire Retreading Technology and Processing,” *Key Engineering Materials*, vol. 717, pp. 86-90, 2017.

[18] M. Pandya, R. N. Patel and S. K. Amarnath, “Determination of time delay and rate of temperature change during tyre curing (vulcanizing) cycle,” Procedia Engineering, vol. *51*, pp. 828-833, 2013.

[19] M. H. R. Ghoreyshi and G. Naderi, “Three dimensional finite element modelling of truck tyre curing process in mould,” *Iranian Polymer Journal*, vol. 14, no. 8, pp. 735-743, 2005.

[20] G. S. Jeon and G. Seo, “Influence of cure conditions on the adhesion of rubber compound to brass-plated steel cord,” *Part I. Cure temperature*, *The Journal of Adhesion*, vol. 76, no. 3, pp. 201-221, 2001

 https://doi.org/ 10.25077/metal.8.2.39-48.2024