

**Research paper****Optimizing Brake Pad Friction Coefficients through Molding Process Parameters Control Using Response Surface Methodology****Ali Partovinia^{1,*} , Elham Khanpour²**¹ *Department of Biorefinery, Faculty of New Technologies Engineering, Zirab Campus, Shahid Beheshti University, Tehran, Iran*² *Research and Development expert, Remapuya Company, Tehran, Iran*^{*} a_partovi@sbu.ac.ir**Article info:****Article history:**

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Abstract

The brake pad friction coefficients depend on materials composition as well as process conditions like initial curing through molding process. In this survey, analysis of variance was used to examine the effect of molding temperature, pressure, and time on normal and hot friction coefficients as the crucial factors of brake pads. The results showed that among main factors, only pressure had the significant effect on normal friction response, however interactions between temperature and two other parameters were also important. But on the other hand, hot friction was strongly influenced by all three factors. Moreover, all mutual effects between temperature and pressure, temperature and time as well as pressure and time played a substantial role in hot friction. This finding emphasizes that the molding process variables have different behavior on the hot and normal friction coefficients. Therefore, understanding these differences helps us see how temperature, pressure, and molding time work together in order to control friction and improve brake pad performance. Furthermore, optimization study showed that a temperature of 170 °C, a molding time of 290 s, and a pressure of 350 kgf/cm² resulted the highest normal and hot friction coefficients of 0.49 and 0.41, respectively.

1. Introduction

Polymer matrix composites are widely used in the automotive industry due to their suitable strength to weight ratio, low density, and versatile processing [1-4]. They are particularly important for brake pad manufacturing, where material performance directly affects safety and reliability [5,6]. Friction composites in brake pads typically consist of resins or binders, reinforcing fibers, lubricants, abrasives, fillers, and friction modifiers [7-9].

Hot molding process plays a critical role in production of automotive brake pads based on

friction materials because it directly influences the physical and mechanical properties. Some characteristics like porosity and compressibility can significantly affect the brake vibration, which in turn contributes to brake noise [10,11]. Process variables, including molding temperature, applied pressure, and pressing time, play a key role in the curing process as well as microstructural and tribological properties. These factors directly influence the coefficient of friction (COF), wear resistance, and long-term stability of the brake pad. Therefore, optimal performance requires careful control of both material composition and processing conditions to



ensure high efficiency, reliability, and noise-free operation [12-16]. For instance, Zhao and co-workers (2025) reported that in One-Factor-At-a-Time (OFAT) approach with molding pressure of 30 MPa, curing time of 15 minutes, variation of temperature between 155 °C and 165 °C had a significant impact on the tribological properties and mechanical performance of modified phenolic resin based friction materials. According to their findings, melamine-modified samples showed higher and more stable friction coefficient at 160 °C, while the COF of boron-modified samples decreases with the increase of the molding temperature [16]. Similarly, Wilairat and co-workers (2019) reported that molding pressure and holding time have the strongest influence on porosity and compressibility of produced brake pads [11].

Recent studies indicate that parameters of hot molding process are fundamental in the tribological behavior of brake pads [11, 13, 16]. To the best of our knowledge, the interaction effects of these molding variables have not yet been thoroughly investigated. The objective of this study was to investigate the effect of molding parameters and their interactive effect on the brake pad performance. Therefore, response surface methodology (RSM) was employed as a statistical approach to investigate and optimize these factors, with the goal of enhancing the frictional performance of the brake pads.

2. Materials and Methods

2.1. Materials Preparation

The copper-free brake pad formulation in this research was based on a non-asbestos organic (NAO) composition. The materials included phenolic resin and rubber (14%) as binders, Fe₂O₃ (22%) as the abrasive, graphite (15%) as a lubricant, fillers such as BaSO₄, vermiculite, and mica (34%), and reinforcements including aramid and steel fibres (15%). All components were carefully weighed according to their respective proportions and mixed thoroughly for 20 minutes to ensure a uniform distribution in two stages. The obtained mix was then pressed into brake pad samples under controlled conditions, with temperature, pressure, and time based on Table 1. This process produced samples with constant composition and density, suitable for following tribological testing.

2.2. Brake Pads Sample Preparation

The prepared blend was subjected to a hot molding process, followed by post-curing at 140–180 °C for 8 hours to ensure proper thermosetting and

mechanical properties. The process variables were determined according to the experimental design presented in Table 2. Twenty samples were tested under different factors, including temperature, pressure, and time. The resulting friction data were analysed to evaluate the effects of these factors on the tribological performance of brake pads.

Table 1. Experimental design factors with coded levels and actual ranges.

Factor name	Level -2	Level -1	Level 0	Level +1	Level +2
Temperature (C)	155	160	165	170	175
Pressure (Kgf/cm ²)	275	300	325	350	375
Molding time (s)	270	290	310	330	350

2.3. Friction Coefficient Test Method

Brake pad samples were prepared according to the specified condition and then cut into the 1-inch×1-inch specimen with a thickness of 5 mm for testing on the Chase friction machine according to the SAE-J661 standard [17-19].

2.4. Design of Experiments

This study used RSM with Design-Expert software version 7. The experiments investigated the effects of temperature, pressure, and time on brake pad friction coefficients as the responses. RSM was chosen because it reduces the number of experiments, reveals main and interaction effects, and helps optimize process conditions [20].

Table 2. Experimental design and measured responses for normal and hot friction coefficients.

Run	A: TEMP.	B: PRESS.	C: TIME	NF	HF
1	160	300	290	0.3096	0.2796
2	170	300	290	0.4800	0.384
3	160	350	290	0.4536	0.384
4	170	350	290	0.4860	0.4068
5	160	300	330	0.4524	0.3900
6	170	300	330	0.4188	0.3876
7	160	350	330	0.4920	0.3900
8	170	350	330	0.3888	0.3360
9	155	325	310	0.4452	0.3624
10	175	325	310	0.4620	0.3948
11	165	275	310	0.3984	0.3480
12	165	375	310	0.4932	0.3852
13	165	325	270	0.4140	0.3468
14	165	325	350	0.4752	0.3852
15	165	325	310	0.3936	0.3456
16	165	325	310	0.4104	0.3408
17	165	325	310	0.4116	0.3576
18	165	325	310	0.4008	0.3420
19	165	325	310	0.4560	0.3696
20	165	325	310	0.4128	0.3432

3. Results and Discussion

As shown in Table 2, the experimental results show that normal and hot frictions are influenced by temperature, pressure, and time. For normal friction, the highest value (0.493) was observed at 165 °C, 375 kgf/cm², and a time of 310 s. In contrast, for hot friction, the maximum value (0.406) occurred at 170 °C, 350 kgf/cm², and a shorter time of 290 s. Overall, normal friction tends to increase with higher temperatures and pressures, particularly at moderate times, while hot friction reaches its peak at higher temperatures combined with moderate pressures and shorter times. These observations suggest that both responses are sensitive to the combined effects of the three factors. Moreover, temperature and pressure showed the most noticeable influence, while time have a moderate effect.

3.1. Normal Friction Response: ANOVA Findings and Factor Effects

In this survey, the role of key molding parameters and their interactions in the normal friction of brake pad was studied. The analysis of variance (ANOVA) was employed to evaluate the effects of temperature, pressure, and time to provide a basis for understanding how process conditions affect the friction performance. As shown in Table 3, the ANOVA confirmed that the model is highly significant ($p=0.0004$), which means it can reliably explain the variation in the normal friction coefficients. Among the individual factors, only pressure (B) had a strong influence on the response (Fig. 1), while temperature (A) and time (C) were not significant individually. Interestingly, the interaction effects were more important: both AB (temperature $\times$ pressure) and AC (temperature $\times$ time) showed highly significant contributions, and BC (pressure $\times$ time) had a moderate effect. Since the lack of fit was not significant ($p=0.4037$), the model can be considered a good fit for the experimental data. The ANOVA model for normal friction yielded an R^2 of 0.81 and an adjusted R^2 of 0.73. This result indicated that the model explained a significant portion of the variability in normal friction.

The interaction plot (Fig. 2a) shows that the effect of temperature on normal friction depends on the applied pressure. At lower pressure (300 Kgf/cm²), increasing temperature from 160 °C to 170 °C leads to a noticeable increase in normal friction.

In contrast, at higher pressure (350 Kgf/cm²), normal friction decreases slightly as temperature increases. The obtained lines intersect around 169 °C, indicated a crossover point where the influence of pressure changes direction. This confirms the significant AB

interaction observed in the ANOVA results, meaning that pressure and temperature together strongly affect the response, even though temperature alone was not statistically significant.

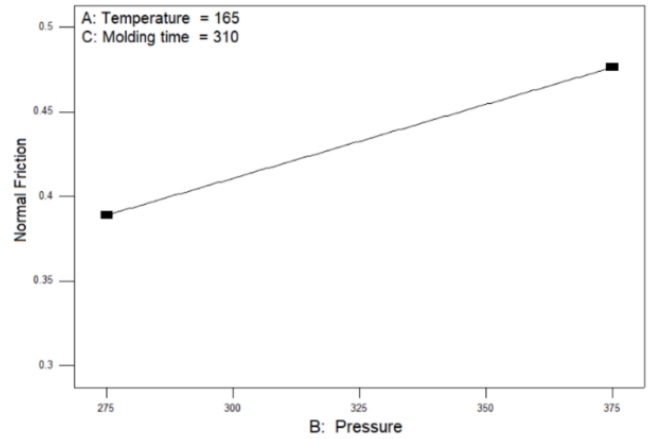


Fig. 1. The effect of pressure on normal friction.

Table 3. ANOVA for normal friction coefficient.

Source	SS*	df	MS*	F value	p value
Model	0.0318	6	0.0053	9.44	0.0004
A-Temp.	0.0006	1	0.0006	1.1	0.3126
B- Press.	0.0076	1	0.0076	13.6	0.0028
C-time	0.0013	1	0.0013	2.35	0.1496
AB	0.0054	1	0.0054	9.59	0.0085
AC	0.0144	1	0.0144	25.7	0.0002
BC	0.0025	1	0.0025	4.39	0.0564
Residual	0.0073	13	0.0006		
Lack of Fit	0.0049	8	0.0006	1.3	0.4037
Pure Error	0.0024	5	0.0005		
Cor Total	0.0391	19			

* SS: Sum of Square, MS: Mean of Square

The interaction plot (Fig. 2b) indicates that the effect of temperature on normal friction is dependent on time. At a shorter duration (290 s), normal friction rises noticeably as temperature increases from 160 °C to 170 °C. Conversely, at a longer time (330 s), normal friction slightly decreases with temperature increment. The two trends intersect near 166 °C, showing a crossover point where the effect of time reverses. This supports the significant interaction between temperature and time observed in the ANOVA results. It shows that their combined influence on the response is substantial, even though temperature alone was not statistically significant. The results shown in Fig. 2c indicate that the effect of pressure on normal friction depends on the molding time. At a longer time of 330 s, increasing pressure from 300 to 350 kgf/cm² had little to no

effect on normal friction. However, at a shorter time of 290 s, normal friction increased noticeably with increasing pressure. This trend is consistent with the ANOVA results, which suggest a possible interaction between pressure and time, with a p-value of 0.0564.

3.2. Hot Friction Response: ANOVA Findings and Factor Effects

This survey investigated how main factors and their interactions influence the hot friction coefficient of brake pads. ANOVA was used to evaluate how temperature, pressure, and time affect performance, providing insight into the role of processing conditions. The ANOVA results as shown in Table 4 demonstrate that the model effectively explains the variation in hot friction, with the overall model being highly significant ($F=19.4$, $p<0.0001$).

Table 4. ANOVA for hot friction coefficient.

Source	SS	df	MS	F value	P value
Model	0.0158	9	0.0018	19.4	< 0.0001
A-Temp.	0.0011	1	0.0011	12.7	0.0052
B- Press.	0.0014	1	0.0014	15.5	0.0028
C-time	0.001	1	0.001	10.9	0.0079
AB	0.0022	1	0.0022	24.5	0.0006
AC	0.0042	1	0.0042	46.5	< 0.0001
BC	0.004	1	0.004	44.1	< 0.0001
Residual	0.0015	1	0.0015	16.1	0.0025
Lack of Fit	0.0005	1	0.0005	5.89	0.0356
Pure Error	0.0005	1	0.0005	5.51	0.0408
Cor Total	0.0009	10	9E-05		

Temperature, pressure, and time all exhibit strong individual effects, indicating that each factor independently influences hot friction. Moreover, significant interactions between temperature $\times$ pressure, temperature $\times$ time, and pressure $\times$ time reveal that the effect of one factor depends on the level of the others. The significance of the quadratic terms for temperature, pressure, and time further highlights non-linear relationships with hot friction. The non-significant lack-of-fit ($p=0.8425$) confirms that the model provides a good fit to the experimental data. Overall, these findings indicate that hot friction is substantially affected by both the main factors and their combined, non-linear interactions. In the case of hot friction, the model shows an even stronger performance, with an R^2 of 0.95 and an adjusted R^2 of 0.90, demonstrating an excellent fit and indicating that the majority of hot friction variation is well represented by the model.

As shown in Fig. 3a, temperature produced a nonlinear response, with the friction coefficient dropping at first, reaching its minimum around 162 °C, and then rising again. Fig. 3b shows that pressure had a consistent effect, as higher compression gradually increased the hot friction coefficient. Fig. 3c shows that longer time leads to higher hot friction across the studied range. Taken together, these findings offer useful insights for optimization of the brake pad manufacturing process to achieve stable friction performance.

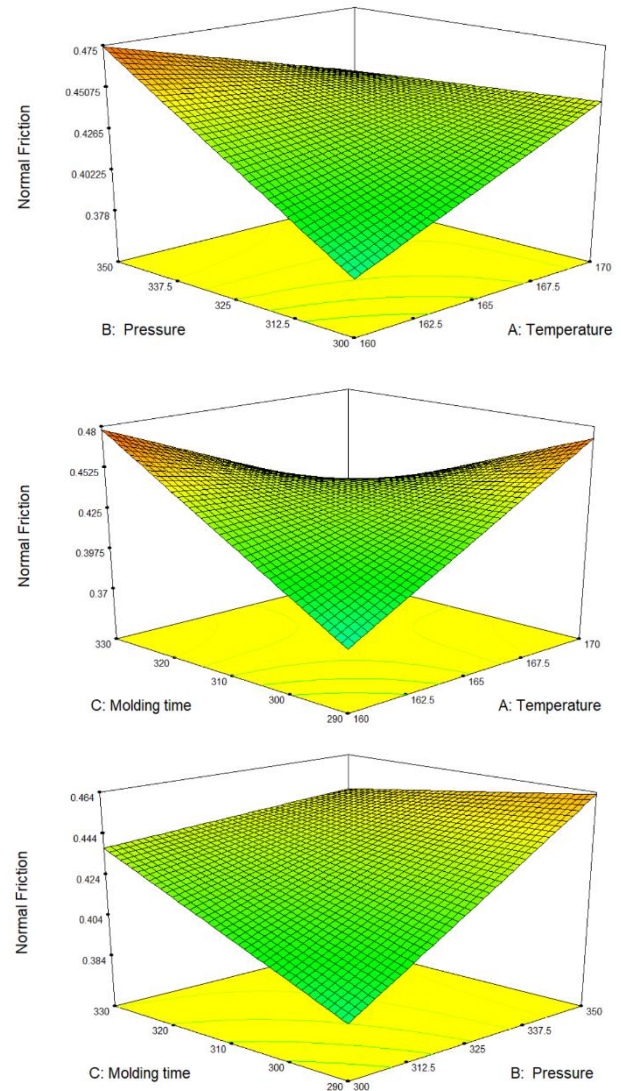


Fig. 2. 3-D plots of simultaneous effects of (a) temperature $\times$ pressure (b) temperature $\times$ time (c) pressure $\times$ time on normal friction.

The interaction plot (Fig. 4a) for temperature (160–170 °C) and pressure (300–350 kgf/cm²) shows that the effect of temperature on hot friction depends on the applied pressure. At a low pressure of 300 kgf/cm², hot friction increases as temperature rises from 160 °C to 170 °C. At a high pressure of 350 kgf/cm², hot friction shows only a slight,

negligible decrease over the same temperature range. The interaction plot (Fig. 4b) between time and temperature shows that the effect of time on hot friction depends on the temperature. At 160 °C, increasing the time from 290 s to 330 s leads to an increase in hot friction. In contrast, at 170 °C, the trend is reversed, with hot friction decreasing as time increases. The two trends intersect at approximately 317 s, indicating a crossover point where the influence of temperature changes direction.

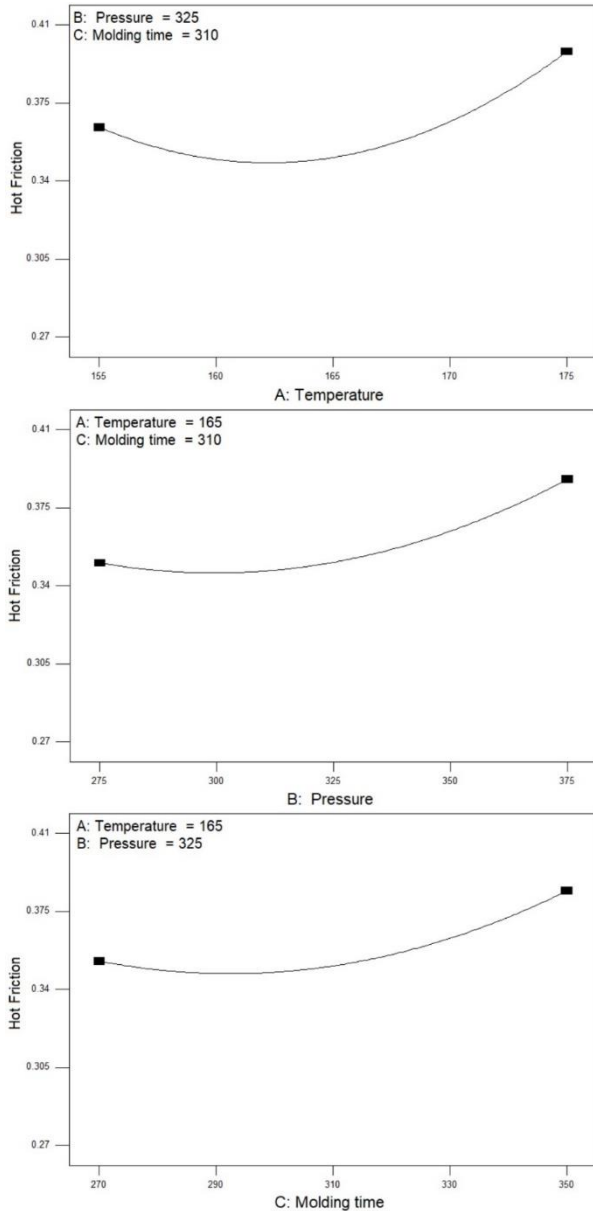


Fig. 3. Variables effect of temperature (a) pressure (b) time (c) on hot friction coefficient.

Fig. 4c shows at a shorter time of 290 s, increasing pressure leads to a rise in hot friction, whereas at a longer time of 330 s, the trend is reversed, with hot friction decreasing as pressure increases. The two trends intersect at approximately 335 kgf/cm²,

showing a crossover point where the influence of time changes direction.

Overall, our results showed that the tribological performance of brake pads depends on molding parameters and the operating temperature. At low temperatures, pressure is the main factor that affects the friction coefficient, because higher pressure reduces porosity and increases the real contact area between the pad and disc. In these conditions, temperature and curing time have little effect, so the normal friction coefficient is mostly determined by pressure. However, at higher temperatures, all variables like pressure, temperature and curing time play an important role. In high temperatures improve resin flow, and longer curing ensures complete polymerization, together enhancing both the friction coefficient and its stability.

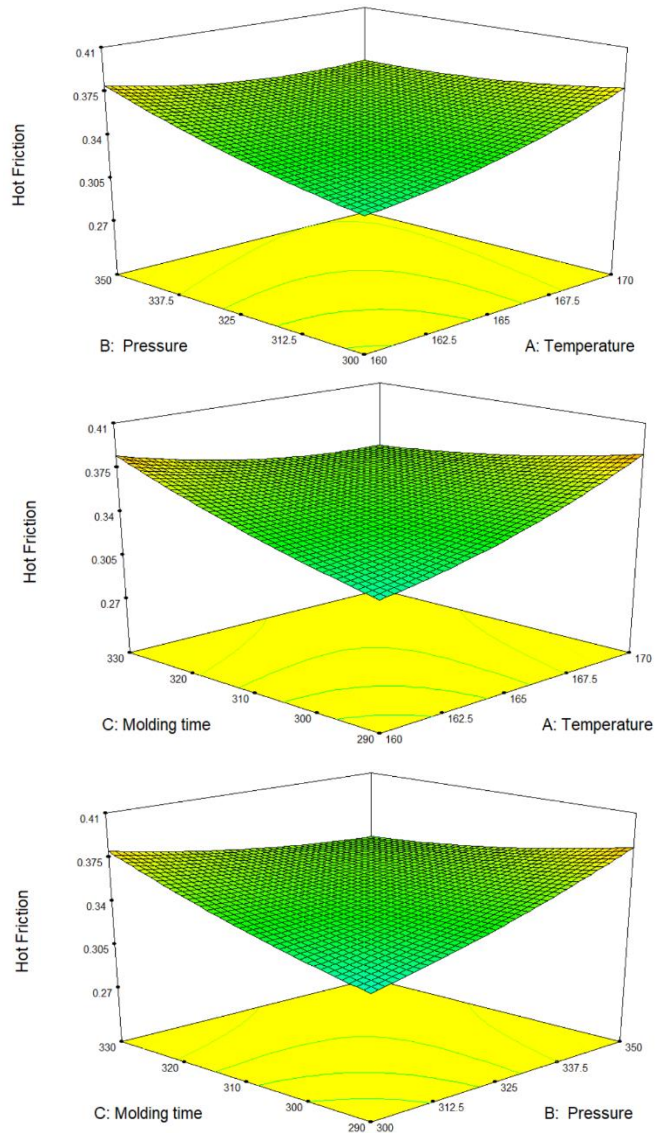


Fig. 4. 3-D plots of simultaneous effects of (a) temperature × pressure (b) temperature × time (c) pressure × time on hot friction.

Previous research has shown that the molding brake pads process has a critical impact on their performance. Shinde and co-workers (2021) revealed that optimization of molding pressure, temperature, and curing time significantly enhances tribological properties such as friction coefficient, wear resistance, and hardness. They also reported that small variations in these parameters may lead to observable variations in friction coefficient stability [21]. Similarly, Doni Widodo et al. (2023) showed that the temperature (80-120°C) during molding process has a major impact on the tribological properties of asbestos-free composite brake pads and the best-performing pads produced at 120°C [13]. Likewise, Ertan and Yavuz (2010) reported that key manufacturing parameters affect the performance of brake lining materials. Their study showed that pressure, temperature, and curing time have a considerable effect on COF, hardness, and wear behaviour. According to their results, higher molding pressures and temperatures led to increase COF and hardness, however longer curing times improved the wear resistance [22]. Our findings support this view and emphasize that thoroughly control of molding parameters is essential to guarantee brake pads have a stable performance in real-world operation.

3.3. Optimization of Friction Coefficients

As illustrated in Table 5, the results indicate that the maximum normal and hot friction, equal to 0.49 and 0.41 respectively, were obtained at a temperature of 170 °C, a pressure of 350 kgf/cm², and a molding time of 290 s.

Table 5. Optimal point for maximum normal and hot friction coefficients.

Temperature	Pressure	Molding time	NF	HF
170	350	290	0.49	0.41

A validation test was carried out at the predicted optimum point to assess the accuracy of the model. At this condition, NF and HF were measured 0.48 and 0.40, respectively which matches the model's predicted values. This result approves the model's robustness in prediction of friction coefficients in the studied range.

As shown in Fig. 5. the optimization analysis demonstrates that both temperature and pressure have a significant influence on the friction coefficients under normal and hot conditions. Within the studied range, the coefficients increase steadily with rising process parameters, reaching maximum values of approximately 0.49 for the normal condition and 0.41 for the hot condition, while the

minimum values in each case are about 0.30 and 0.27, respectively. Although the hot condition consistently yields slightly lower coefficients than the normal one, both exhibit the same increasing trend, with temperature showing a more notable effect than pressure. These results confirm that operating at higher levels of temperature and pressure is required to maximize the friction coefficients and enhance tribological performance.

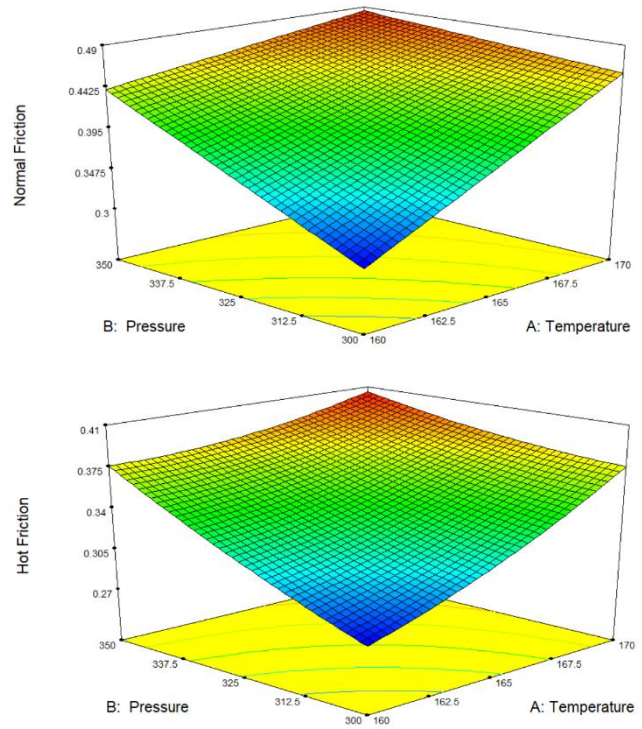


Fig. 5. Response surface plot of optimized (a) NF (b) HF.

4. Conclusion

This research showed that brake pad friction is strongly influenced by molding conditions, but in different ways for normal and hot friction coefficients. Normal friction is mainly determined by pressure and interactions between temperature and pressure as well as temperature and time, while hot friction is influenced by all three factors and their combined effects. Interactions played a crucial role, since the influence of one factor often changed depending on the level of another. Using ANOVA, reliable models with high predictive accuracy were developed, confirming the importance of these parameters. Overall, the findings highlight how careful control of processing conditions can improve brake pad performance, offering a practical path toward safer and more reliable braking systems.

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Declaration of Competing Interest

The authors declare that there is no conflict of interest.

Data Availability

The processed data used and analysed during the current study are available from the corresponding author upon reasonable request.

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