

Study of Difference in Friction Behavior of Brake Disc Rotor with Various Surface Textures during Running-In by Using Simple Model

Toshikazu Okamura
KIRIU Corp.

ABSTRACT

The most fundamental function of an automobile brake system is assuring stable braking effectiveness under various conditions. In a previous paper (2004-01-2765), the author et al. confirmed that the friction behavior of disc brakes during running-in depends on both the friction materials and discs' friction-surface textures. Various friction pairs were tested by combining discs finished with roller-burnishing and grinding and five friction materials including NAO and low-steel. Some NAO material exhibited large effects on the difference in friction behaviors between the discs' surface textures. A disc finished with roller-burnishing needed a longer running-in period than that with grinding. In another paper (2011-01-2382), a further experiment was conducted by combining eight surface textures (finished under four turning conditions with and without additional roller-burnishing), two NAO materials, and two rotational directions. Notable phenomena were observed, e.g., the coefficients of friction had a peak at the early stage of testing and there was a difference in those at the final stage between surface textures. These behaviors were determined to be due to the contribution of aggressiveness and adhesiveness to friction by comparing the coefficients of friction and discs' surface textures and wear. Friction behaviors at the early stage of use have become more significant since the running-in period has been extended due to the application of large discs for better braking performance and the increase in the number of hybrid and electric vehicles equipped with regenerative braking. In this study, therefore, simplified linear (2D) and areal (3D) roughness models with various surface textures were introduced, and their behaviors of wear and roughness were numerically simulated. The change in discs' surface textures along with increasing wear depended on their initial textures. These models and simulation confirmed the effects of surface textures on friction during running-in, which were experimentally observed in the previous studies.

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INTRODUCTION

Modern automobiles use friction brakes as their service brake. A disc brake system, which is a typical friction brake, converts the kinetic energy of a running vehicle into heat and decelerates the vehicle by using the friction created between a disc and the pads. Brake pads and linings are generally designated as friction materials, but both a disc and pads are necessary to produce friction. Accordingly, a brake disc is a significant part of a friction pair.

Friction in a vehicle brake system is affected by a friction pair in various ways during its life, as illustrated in Fig. 1. The material properties of discs and pads affect friction throughout the life of a vehicle. The third body (or transfer film) generated from disc and pad debris will be mainly effective after running-in. This is the most influential factor on braking effectiveness, particularly for non-asbestos organic (NAO) friction materials. The surface texture of a brake disc significantly affects the braking effectiveness of a vehicle in the early stage of use, which is called "running-in," and was focused on in this paper. The surface texture of a disc is assumed to affect the adhesion behavior of the transfer film as well, which was partly studied by the author in [1], but is beyond the scope of this study.

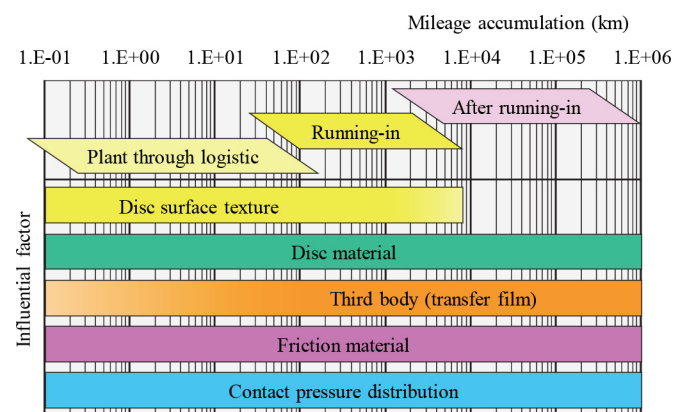


Fig. 1. Factors affecting friction of disc brake during vehicle life

There are various processes for finishing the friction surfaces of a brake disc rotor, such as grinding (GND), turning (TNG), milling, and roller-burnishing (R.B.) [2]. The author et al. [3] presented a paper at the SAE 2004 Brake Colloquium discussing the interactive effects of a disc's surface texture and friction material on friction behavior during running-in. Various friction pairs were tested by combining brake discs finished by roller-burnishing and grinding and

five friction materials including NAO and low-steel materials. The surface textures of the disc had a large effect on the friction pair when tested with some NAO material, while having less of an effect when tested with low-steel material. A disc finished with roller-burnishing needed a longer running-in period than that with grinding.

In another paper [4], a further experiment was conducted by combining eight surface textures (finished under four turning conditions with and without additional roller-burnishing) and two NAO materials (with different degrees of aggressiveness). Notable phenomena were observed, e.g., the coefficients of friction had a peak at the early stage of testing and there was difference in those at the final stage between surface textures. These behaviors were determined to be due to the contribution of aggressiveness and adhesiveness to friction by comparing the coefficients of friction and the discs' surface texture and wear.

The effects of the surface texture of brake discs on friction behavior have become more and more significant. One reason is that large diameter discs have become popular for vehicles in pursuit of better braking performance. They are designed to maintain a consistent braking performance under severe conditions, such as braking from extremely high speeds, and accordingly, the braking loads in daily use are relatively small for them. Another reason is that the sales volume of hybrid- and battery-electric vehicles continues to increase. These vehicles are equipped with regenerative braking, and their friction brakes work less than those of vehicles driven by conventional internal-combustion engines. As a result, the running-in periods for these vehicles, such as high-performance, hybrid, and electric vehicles, have been extended, so it takes a long period of time for the contact surfaces of a brake disc and the pads to suitably wear down, match each other, and produce stable friction.

The effects of the surface texture on the friction behavior during running-in were studied again when taking the background described above into consideration. Ostermeyer et al. [5,6] developed sophisticated simulation tools based on discretization with a cellular automaton and its extension in order to get an explicit insight into the dynamic changing of the surface topography in the boundary layer of friction brake systems. Dufrenoy et al. [7] proposed a multiscale strategy to integrate the microscopic behavior of the pad-and-disc contact interface in a macroscopic numerical model considering asperities and plateaus. In this study, the simplified models of linear (2D) and areal (3D) surface textures of discs' friction surfaces with various roughness profiles were introduced, and their behaviors of wear and roughness were numerically simulated. The change in the discs' surface textures along with increasing wear depended on their initial textures. The simulation using the surface texture models confirmed the effects of surface textures on friction during running-in, which were experimentally observed in the previous studies.

This paper consists of the following sections.

- Interaction between discs' surface textures and friction material, which was extracted from a previous paper [3],

- Modeling of surface textures and their change along with wear, which describes 2D and 3D models, and simulation of their behavior along with increasing wear,
- Abrasive and adhesive friction, which was extracted from another paper [4],
- Discussion on difference in friction behavior between discs' surface textures found by comparing previous experimental results and findings from introduced surface-texture modeling and simulation.
- Summary

INTERACTIVE EFFECTS OF DISCS' SURFACE TEXTURE AND FRICTION MATERIAL

In this section, the interactive effects of discs' surface textures and friction materials on friction and the significance of tangential roughness are extracted from a previous study presented at the SAE 2004 Brake Colloquium [3].

Coefficient of Friction during Running-in

Various friction pairs were tested by combining brake discs with different surface textures and five friction materials including NAO and low-steel materials. Roller-burnishing and grinding were selected as the finishing processes for disc friction surfaces because they are typical and produce quite different surface textures. Table 1 lists the major specifications of the brake discs and the braking conditions for the experiment referred to in this section.

Table 1. Brake disc specifications and braking conditions [3]

Brake disc specification	Type	Front ventilated
	Material	G3000
	Outer diameter	296 mm
	Friction plate thickness	24 mm
	Friction surface finish	Grinding and roller-burnishing
Braking condition	Vehicle speed	65 km/h to 0
	Deceleration	3.5 m/s ²
	Brake application	700
	Additional effectiveness testing	Before, midst, and after burnish braking

The friction behavior of a disc brake during running-in depended on both friction materials and the discs' friction-surface textures. The surface textures of the disc had a large effect on the friction pair when tested with some NAO material, while having less of an effect when tested with low-steel material. Figure 2 exhibits the mean coefficients of friction for burnish braking extracted from previous tests combined with the least aggressive NAO material, A1, among five, which caused the largest difference in friction behavior between the discs' surface textures. A disc finished with roller-burnishing needed a longer running-in period than that with grinding.

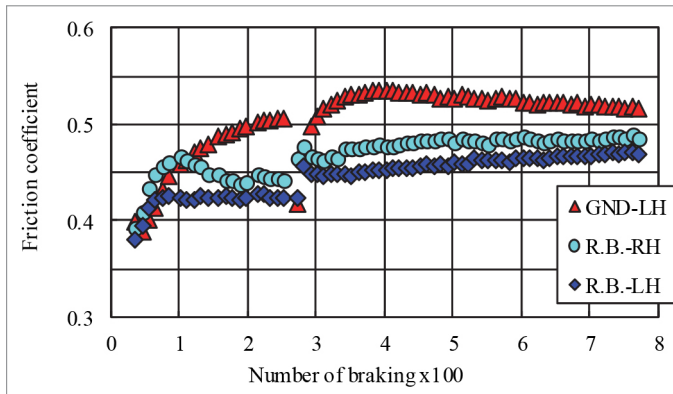


Fig. 2. Coefficient of friction during running-in for grinding-finished and roller-burnished discs tested with NAO friction material A1

In Fig. 2, discs finished with roller-burnishing revealed a little difference in the coefficient of friction between two directions of rotation for left-hand (R.B.-LH) and right-hand (R.B.-RH) wheels. This phenomenon is beyond the scope of this paper, and some studies on it are described in the previous papers by the author [1,3,4].

Surface Textures Finished with Various Processes

The surface textures of disc rotors finished with grinding and roller-burnishing are compared in Fig. 3. The upper photos in Fig. 3 indicate the surface appearance, and the lower images indicate 3D surface-textures, which were measured with a laser displacement sensor. The surface texture finished with grinding on the left has cross-hatch grooves created by wheel-face grinding with rotary workpiece motion.

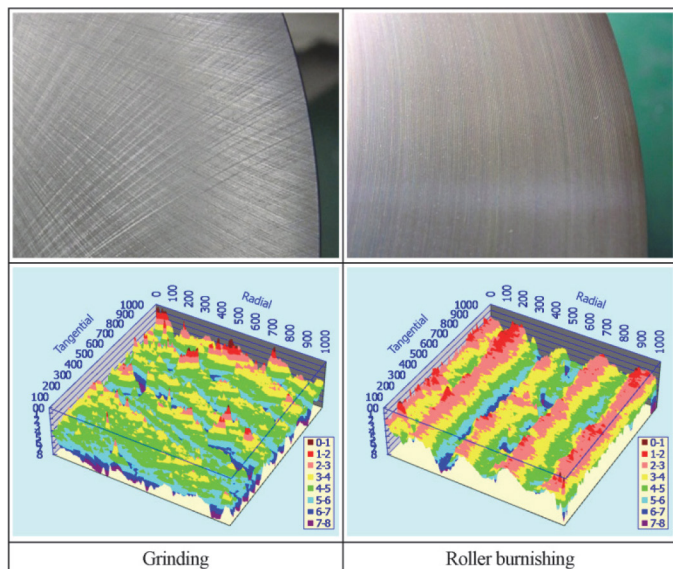


Fig. 3. Friction surface texture of grinding-finished and roller-burnished discs

The surface appearance finished with roller-burnishing on the upper right in Fig. 3 cannot be distinguished from that finished with turning without roller-burnishing. Discs finished with turning alone have deep directional markings, which may cause pad walk and noise. This problem is solved by roller-burnishing, where a roller or a pair of rollers produces plastic deformation in the sharp peaks of turning-

finished surfaces and smoothen their roughness, as illustrated on the lower right in Fig. 3. The radial wave length of the roller-burnished surface is identical to the feed rate of turning before roller-burnishing.

The roughness of brake disc rotors is measured radially in general. Some finishing processes, however, cause differences in the roughness between tracing directions. Figure 4 plots the relationship between tangential and radial roughness before testing for discs finished with grinding with three levels of roughness, i.e., rough (G-R), medium (G-M), and smooth (G-S), and those with roller-burnishing (R.B.). The roughness parameter (R_k^*) plotted in Fig. 4 was introduced as an index for the roughness of the friction surface of a brake disc, whose surface texture considerably changes along with its wear due to braking. Core roughness depth R_k (designated in ISO [8] for height characterization using the linear material ratio curve or Abbott-Firestone curve) is calculated from an equivalent straight line with the smallest gradient in a material ratio of 40%. To simplify calculation, R_k^* in this study was calculated by linear regression from material ratios of 8% to 92%. Therefore, R_k^* is larger than R_k and smaller than the maximum height of profile (R_z). The Abbott-Firestone curve was also applied to pad surface evaluation between brake applications [9].

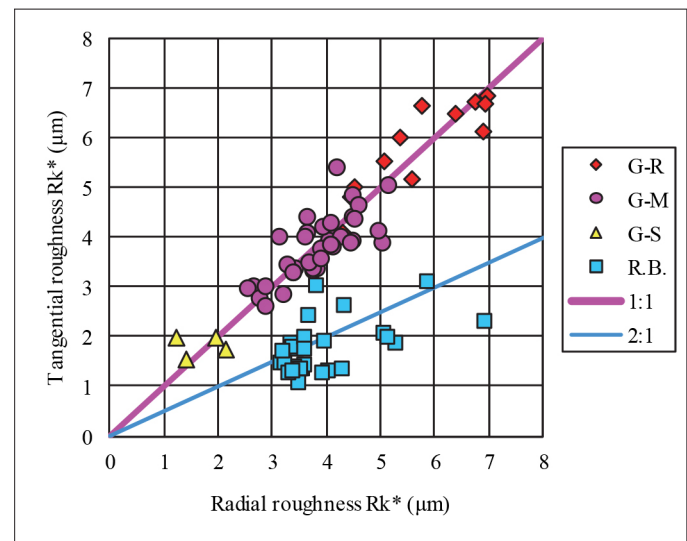


Fig. 4. Radial and tangential roughness (R_k^*) of grinding-finished discs with three levels of roughness, i.e., rough (G-R), medium (G-M), and smooth (G-S), and roller-burnished (R.B.) ones before testing

The tangential roughness of discs finished with grinding is almost the same as the radial one since the surface of those discs has cross-hatch grooves, as exhibited in Fig. 3. The surface texture of a disc finished with roller-burnishing has regular radial waviness corresponding to the feed rate of the final turning process, and its tangential roughness is far smoother than the radial one. The roughness of disc rotors is measured radially in general since it represents the characteristics of surface textures created by turning-based surface-finish processes. A brake disc and pads, however, rub against each other in the tangential (or circumferential) direction of the friction ring of a disc.

Accordingly, it is necessary to examine the roughness of a disc tangentially in addition to radially to discuss the effects of a disc's surface texture on friction behavior.