

Experimental Study of Interaction between Brake-Disc Surface Texture and Friction Material on Friction and Wear through Small-Scale Tests on Tribotester

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ABSTRACT

There are various processes for finishing the friction surfaces of a brake disc, which affect the braking effectiveness of a vehicle in the early stages of use in some cases. To examine the interaction between the disc surface texture, rotational direction, and friction material, a series of experiments on a tribotester using small-scale specimens was conducted.

In a previous paper (2013-01-2056), the results from the first series of experiments, which involved of thirty disc surface textures and a less aggressive non-asbestos organic (NAO) friction material in on-brake-drag conditions combining constant speed and normal-load, was reported. Disc surfaces were finished by the following finishing processes in two rotational directions: turning under four cutting conditions, roller burnishing after turning, turning with a wiper insert, and grinding with two stones. Contact-pressure dependency of friction and wear was confirmed. Roller-burnished and wiper-turned discs exhibited different friction and wear at a certain contact pressure between rotational directions in the turning process.

In the present study, four discs finished by grinding in a different cross-hatch pattern from that in the previous study and two friction materials (aggressive NAO and low-steel friction materials) were additionally tested. The findings from the test results on friction, wear, and transfer-layer build-up are presented. The directional difference in friction and wear was confirmed to depend on the combinations of disc surface texture, friction material, contact pressure, and test period. Even a grinding-finished disc and low-steel friction material exhibited a directional effect in some cases.

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INTRODUCTION

The automobile brake system, among those of driving, steering, and stopping, is the most significant. 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 pads. Brake pads and linings are generally designated as friction materials, but a disc-and-pad pair is necessary to produce friction. Accordingly, a brake disc is also a friction material.

There are various processes for finishing the friction surfaces of a brake disc such as grinding, turning, milling, and roller burnishing [1]. Roller burnishing as well as turning are directional finishes. Brake discs usually turn in one rotational direction during their finishing process and have a directional tool mark in a fine-pitched spiral. However, they are used in two rotational directions even if a vehicle moves forward since

they are mounted on both the left-hand (LH) and right-hand (RH) wheels on a vehicle. In one case, the rotational direction of a disc against the brake pads on a vehicle is the same as that against the cutting tool in the turning process. In the other, the rotational direction against the brake pads is opposite that against the cutting tool. Therefore, the directional surface texture of a brake disc in some cases affects the braking effectiveness of a vehicle or wear of a disc and pads in the early stages of use, which is called running-in. The directional surface textures of brake discs finished by turning or additional roller burnishing may cause this directional interaction to become more severe than those by grinding, and in some cases may cause brake pull or poor braking effectiveness [2,3].

Okamura et al. presented a paper [4] at the SAE 2004 Brake Colloquium discussing the effect of the surface texture of brake discs 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 non-asbestos organic (NAO) and low-steel materials. Some NAO materials exhibited a large difference in friction behavior between the disc surface textures and the rotational directions, while low-steel materials caused less difference.

The effects of the surface texture of brake discs on friction behavior have recently become more significant. One reason is that large-diameter discs have become popular for improved braking performance. They are designed to maintain consistent braking performance under severe conditions, such as braking from extremely high speeds; accordingly, the braking loads in daily use are relatively small. Another reason is that the sales volume of hybrid and battery electric vehicles continues to increase. They are equipped with regenerative braking and their friction brakes are worked to a lesser degree than those on vehicles driven by conventional internal-combustion engines. As a result, the running-in periods for such vehicles (e.g., high-performance, hybrid, and battery-electric vehicles) have been extended, and it takes longer for the contact surfaces of a brake disc and pads to suitably wear down, match each other, and produce stable friction. It is important for foundation brakes to exhibit consistent braking performance, even though sophisticated electronically controlled brake systems can compensate for the effects, if any, of surface texture of brake discs on braking effectiveness.

Taking the background described above into consideration, the effects of surface texture on friction behavior during running-in were studied again [5]. A factorial experiment was conducted by combining eight surface textures (finished under four turning conditions with and without additional roller burnishing), two NAO friction materials (with different degrees of aggressiveness), and two rotational directions (LH and RH for a vehicle) on a brake dynamometer. Turning-finished discs without roller burnishing tested with a less aggressive NAO friction material exhibited less directional difference in friction coefficient but had a larger variance in friction behavior during running-in than roller-burnished discs. Roller-burnished discs tested with a less aggressive NAO friction material exhibited less variance in friction behavior but consistently exhibited different friction coefficients to some extent between rotational directions during running-in. Full-scale tests using actual friction pairs are effective for estimating the total braking performance of a full vehicle or its corners. However, they are exposed to various factors, i.e., the operating stability of a caliper, contact-pressure distribution between the disc and pads, running-in effect of the friction material, and radial difference in sliding speeds and distances on disc friction surfaces. Consequently, different brake-disc locations created different friction and wear histories. The author, therefore, concluded that fundamental experiments using small-scale specimens for discs and pads on a tribotester is necessary to examine the details of interactions between the disc surface texture, rotational direction, and friction material.

Accordingly, a series of friction tests using small-scale specimens for discs and pads on a tribotester has been conducted. The results of the first series of experiments, which

involved thirty disc surface textures and a friction material under on-brake-drag conditions combining constant speed and normal-load, were reported at the 2013 SAE Brake Colloquium [6]. Disc surfaces were finished by the following processes in two rotational directions: turning under four cutting conditions combining two single-nose-radius inserts and two feed rates, roller burnishing after turning, turning with a wiper insert, and grinding with two stones. The NAO friction material, which caused a large difference in friction behaviors between disc surface textures, was selected from previous studies [4,5]. Contact-pressure dependency of friction and disc wear was confirmed in the preliminary tests. Roller-burnished discs exhibited different friction and wear in on-brake-drag tests at a certain contact pressure between rotational directions in the turning process before roller burnishing. Transfer layers were confirmed to have a significant effect on these differences in friction and wear between disc surface textures and contact pressures. Factors affecting friction and wear at the early stage of use were summarized in Fig. 1 [6]. The effect of disc surface textures and their interaction with rotational directions and friction materials on friction and disc wear was the main focus of the present serial study.

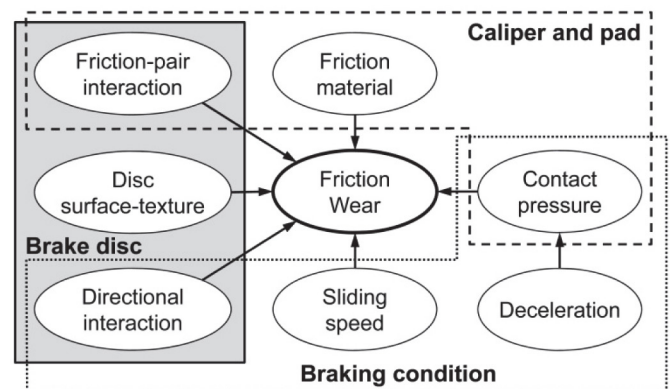


Figure 1. Relation diagram of factors affecting friction and wear [6]

In the present study, the author reports the results of another series of small-scale experiments, in which four discs finished by grinding with a different cross-hatch pattern from that in the previous study were additionally tested. On-brake-drag friction tests for thirty-four discs including those for examining contact-pressure dependency were conducted in the pairs with a different NAO friction material (which is more aggressive than that used in the previous small-scale tests) and a low-steel friction material. The findings from the test results on friction, wear, and transfer-layer build-up are presented. Directional difference in friction and disc wear depended on the combinations of disc surface texture, friction material, contact pressure, and test period. Even a grinding-finished disc and a low-steel friction material exhibited a directional effect in some cases.

The content of this paper is divided into the following sections:

- Experimental setup
- Extracted test results of first series of experiments
- Test results of second series of experiments

- Summary of interaction between disc surface texture, friction material, and contact pressure
- Concluding remarks

EXPERIMENTAL SETUP

Test Equipment and Outline of Small-Scale Specimens

Photographs of a tribotester and small-scale specimens used for this serial experiment are shown in Fig. 2. This block-on-disc type tribotester was originally designed for lubricated metal friction pairs and was used in a previous paper [7] to study the effect of material homogeneity of disc rotors on differential wear causing brake judder.

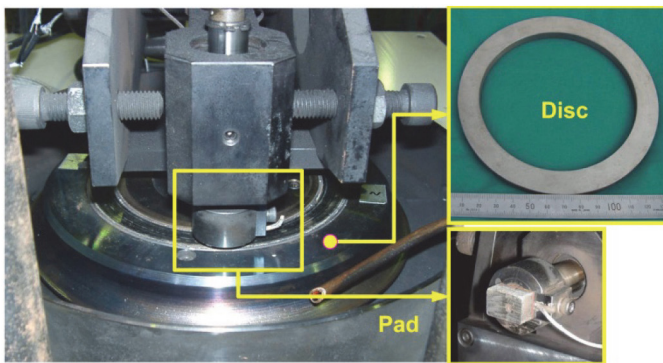


Figure 2. Disc and pad set on tribotester

The small-scale discs were made of gray cast iron equivalent to G3000, the specifications (which were the same as those for the previous study [6]) of which are listed in Table 1. The effective brake-radius was 61 mm, about half that of actual brake discs.

Table 1. Specifications of small-scale disc [6]

	Specification
Material	G3000
Outer diameter	139 mm
Inner diameter	105 mm
Effective brake-radius	61 mm
Thickness	7 mm

The small-scale pads were 18 × 12 mm in size and cut from actual brake pads made of the three friction materials listed in Table 2. The first one was a less aggressive NAO friction material (NAO_1), which caused a large difference in friction behaviors between disc surface textures in full-scale tests [4,5] and used in the first series of small-scale experiments [6]. The second one was another NAO (i.e., NAO_2), which is more aggressive than NAO_1 and was also used for those full-scale tests [4,5]. The last one was an original-equipment-manufacturing (OEM) low-steel friction material (LS_3), which is different from that used in a previous full-scale test [4]. A thermocouple was inserted into each pad to monitor the temperature near the friction surface on the effective brake-radius, as shown in Fig. 2.

Table 2. Three friction materials

Material	Aggressiveness
NAO_1	Mild
NAO_2	Medium
LS_3	Severe

Surface Textures of Discs

Friction surfaces of the small-scale discs were finished by the following processes in two rotational directions: turning under four cutting conditions combining two single-nose-radius inserts and two feed rates, roller burnishing after turning, turning with a wiper insert, and grinding with two stones. In the roller burnishing process, a roller or a pair of rollers creates plastic deformation on the asperities of the turning-finished surfaces and decreases their roughness. Material-ratio curves for typical discs finished by the four finishing processes were previously compared [6]. Roller burnishing created plastic deformation at the peak of a turning-finished surface and decreased its roughness; while the valley of the roller-burnished disc had the same curve as that of the turning-finished disc. The wiper insert (which has a wiper cutting edge and decreases roughness) also exhibited a burnishing effect.

Each disc was labeled using a letter and three digits, as indicated in Fig. 3, which was modified from the labeling system of disc specimens used in a previous paper [6]. The first letter represents one of the four finishing processes: T for turning, R for roller burnishing, W for turning with a wiper insert, and G for grinding.

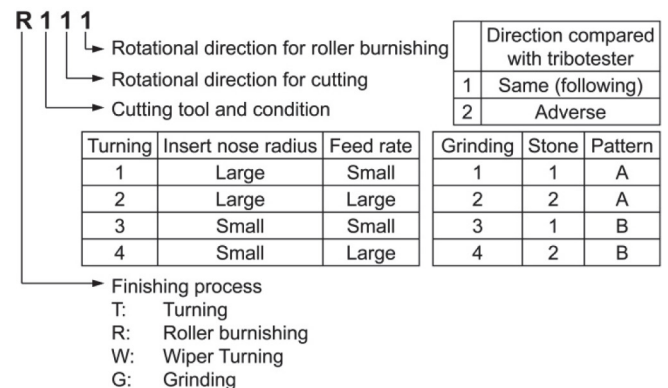


Figure 3. Labeling system of disc specimens

The first of the three digits indicates a combination of a finishing tool and cutting condition. The second digit in Fig. 3 indicates the rotational direction of a disc during the cutting processes (i.e., turning or grinding): 1 for the same (or following) direction as the tribotester (used in this study and exhibited in Fig. 2) and 2 for the adverse direction to the tribotester. In normal turning, the four cutting conditions were applied by combining two inserts and two feed rates, as depicted in Fig. 3. One type of roller-burnishing tool and wiper insert was used. Two abrasive types of grinding stones with the same abrasive-grain size were used in the grinding process.

Two out of the three discs finished by turning under the same condition were additionally finished by roller burnishing in two rotational directions. The first and second digits for roller-

burnished discs designate the preceding turning condition. The third digit indicates the rotational direction of a disc during the roller-burnishing process in the same manner as that during the turning processes, while "0" as the third digit indicates finishing without roller burnishing.

In this study, two grinding conditions (i.e., 3 and 4 indicated in Fig. 3) were added, which have a cross-hatch pattern, B, different from cross-hatch pattern A used in a previous study [6], for the grinding conditions 1 and 2. As shown in Fig. 4, cross-hatch pattern B was designed to have a larger tangential component of groove directions than pattern A in order to make obvious the directional effect on friction caused by plastic metal flow generated by grinding stones. The cross-hatch pattern of disc G410 was not perfectly the same as that of disc G420 to control the relative direction of the discs to the rotating grinding-stone during the grinding process.

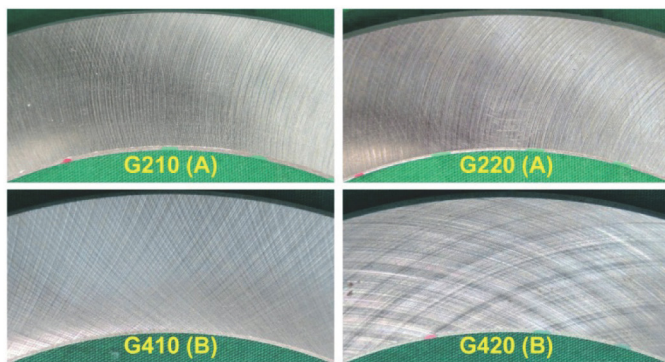


Figure 4. Cross hatch patterns A and B for grinding-finished discs

Thirty-four disc specimens including four additional discs finished by grinding are listed in Tables 3 and 4, which also enumerate the arithmetical mean roughness (Ra) of the texture of each disc surface.

Table 3. Finishing processes, machining conditions, and roughness (Ra) for turning-finished and roller-burnished discs

Sample	Process	Cutter	Feed	Direction	Burnish	Ra (μm)
R111	Burnish	Large R	Small	Follow	Follow	1.23
R112	Burnish	Large R	Small	Follow	Adverse	1.24
T110	Turning	Large R	Small	Follow	NA	2.06
R121	Burnish	Large R	Small	Adverse	Follow	0.79
R122	Burnish	Large R	Small	Adverse	Adverse	0.78
T120	Turning	Large R	Small	Adverse	NA	1.68
R211	Burnish	Large R	Large	Follow	Follow	1.55
R212	Burnish	Large R	Large	Follow	Adverse	1.63
T210	Turning	Large R	Large	Follow	NA	2.58
R221	Burnish	Large R	Large	Adverse	Follow	1.03
R222	Burnish	Large R	Large	Adverse	Adverse	1.06
T220	Turning	Large R	Large	Adverse	NA	1.93
R311	Burnish	Small R	Small	Follow	Follow	1.16
R312	Burnish	Small R	Small	Follow	Adverse	1.22
T310	Turning	Small R	Small	Follow	NA	2.19
R321	Burnish	Small R	Small	Adverse	Follow	1.16
R322	Burnish	Small R	Small	Adverse	Adverse	1.15
T320	Turning	Small R	Small	Adverse	NA	2.11
R411	Burnish	Small R	Large	Follow	Follow	1.58
R412	Burnish	Small R	Large	Follow	Adverse	1.60
T410	Turning	Small R	Large	Follow	NA	2.88
R421	Burnish	Small R	Large	Adverse	Follow	1.47
R422	Burnish	Small R	Large	Adverse	Adverse	1.55
T420	Turning	Small R	Large	Adverse	NA	2.77
W110	Turning	Wiper		Follow	(Wiper)	0.79
W120	Turning	Wiper		Adverse	(Wiper)	0.73

Table 4. Grinding conditions and roughness (Ra) for grinding-finished discs

Sample	Cutter	Cross Hatch	Direction	Ra (μm)
G110	Stone 1	Pattern A	Follow	0.26
G120	Stone 1	Pattern A	Adverse	0.33
G210	Stone 2	Pattern A	Follow	0.31
G220	Stone 2	Pattern A	Adverse	0.34
G310	Stone 1	Pattern B	Follow	0.44
G320	Stone 1	Pattern B	Adverse	0.47
G410	Stone 2	Pattern B	Follow	0.98
G420	Stone 2	Pattern B	Adverse	0.62

On-Brake-Drag Condition for Small-Scale Test on Tribotester

Table 5 lists the on-brake-drag test conditions on the tribotester, which are the same as those for the previous small-scale tests [6] and compared with the full-scale test conducted in a previous study [5]. Normal load, friction force, and pad temperature were monitored during these tests.

Table 5. Braking conditions [6]

	Small-scale test	Full-scale test
Test equipment	Tribotester	Brake dynamometer
Effective brake-radius	61 mm	130.5 mm
Pad length	18 mm	108 mm
Test speed	320 rpm	60 km/h to 0
Sliding speed	2.0 m/s	6.6 m/s to 0
Braking accumulation	120,000 rotations	400 brake applies
Distance swept by pad	2.16 m ²	0.98 m ²
Deceleration	Drag under constant load	2.94 m/s ²
Braking interval		IBT Control
Initial braking temp.	Room Temp.	130°C
Contact pressure	1.0 MPa	1.5 MPa

EXTRACTED TEST RESULTS OF FIRST SERIES OF EXPERIMENTS

In this section, the major test results and findings from the first series of the experiments reported in a previous paper [6] are summarized.

Effect of Contact Pressure in Pair with NAO_1

Before conducting the main tests for studying the effect of disc surface textures, a preliminary test for six discs finished under turning condition 1 in the pair with NAO_1 was conducted to investigate contact-pressure dependency of friction and disc wear. Contact pressures were selected, as specified in Table 6, i.e., half and twice the temporarily selected contact-pressure of 1.0 MPa, which is specified in Table 5.

Table 6. Contact pressures for preliminary test [6]

Contact pressure	1.0 MPa	0.5 MPa	2.0 MPa
Equivalent deceleration	2 m/s ²	1 m/s ²	4 m/s ²