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Friction-induced stick-slip intensified by corrosion of gray iron brake disc

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ABSTRACT

The effect of brake disc corrosion on friction-induced stick-slip was studied to find the possible causes of friction instability in humid conditions. The friction and wear characteristics of gray iron discs and a commercial friction material were examined using a 1/5 scale dynamometer. Use of the corroded discs resulted in a higher friction coefficient, and a larger oscillation amplitude of the brake torque. Disc corrosion increased the critical velocity showing transition from steady sliding to stick-slip. This suggests a rapid increase of the initial static friction coefficient as a function of dwell time in a humid condition, which is supported by the increased hydrophilicity of the friction films. The contact stiffness of the friction material surface was increased after rubbing with corroded discs, due to densification of the friction films by iron oxide nanoparticles transferred from the disc surface. The wear rate of the friction material also increased with corrosion of the gray iron discs.

1. Introduction

Friction-induced vibrations that occur during braking have been ascribed to various causes, ranging from microscopic stick-slip at the sliding interface to faulty structural design of the brake system. Exhaustive research effort has been expended to reduce brake noise and vibration, since they significantly degrade the overall performance of a vehicle. Since the early years of vehicle development, various investigations based on model studies, lab-scale tribotests, dynamometer tests with full-size brake components, and in-vehicle tests have been performed to find the root causes of friction-induced noise and vibration. However, brake-induced noise has never been eliminated, and remains a critical issue in the vehicle development [1,2]. The difficulty in eliminating brake noise is mainly due to a lack of fundamental understanding regarding the mechanism for triggering of noise at the sliding interface. Recent studies in noise reduction, therefore, have focused more on the triggering of friction oscillation, such as stick-slip or harmonic oscillations since the friction fluctuation at the sliding interface triggers the brake noise [3–6]. It is reported that perturbations at the sliding interface can change the oscillatory pattern of friction force from steady sliding to saw tooth type stick-slip, sinusoidal oscillation, and irregular oscillation upon changes in the braking conditions or dynamics of a brake system [3].

In general, when friction-induced noise and vibration decrease the quality level of brake performance, brake noise has often been imputed to brake friction materials [7], whereas low-frequency vibration such as judder has been ascribed to uneven wear of a disc [8,9]. However, gray iron discs also have been blamed for noise-related problems when the friction instability occurs in humid weather or after disc corrosion. Efforts to improve the corrosion resistance of gray iron brake discs have been given and they involved alloy design [10], surface modification [11,12], and the development of new disc materials using copper alloys [13], non-ferrous metal composites [14], and ceramic discs [15]. However, commercialization of brake disc materials other than gray iron is very limited and the reports concerning the correlation between noise generation and corrosion of gray iron discs are very limited. Blau et al. [16] reported changes in the friction and wear characteristics of gray iron discs upon corrosion. They studied the corrosion of gray iron by salt solutions and found that the corrosion scales initially acted as an abrasive, causing the system to attain a peak friction level, and gradually changed to a lubricant. Shin et al. [17] reported the friction instability induced by corrosion of the gray iron disc in ambient conditions. They found that disc corrosion was accelerated due to water condensation when the disc was colder than ambient temperature. They showed that the friction level, friction oscillation, and wear of the corroded discs were strongly affected by the aggressiveness of the friction material.

In order to reduce corrosion-induced friction instability, it is necessary to suppress friction oscillation at the sliding interface by

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managing the corrosion products at the sliding interface. This is because the corrosion products strongly affect the amplitude and frequency of the friction-induced oscillation such as stick-slip and sinusoidal oscillation and propensity, which determine the propensity of noise and vibration such as creep groan, grind noise, and higher frequency squeal noise. However, it is not yet clear how the friction oscillation is triggered by the corroded gray iron discs, and how it may be amplified by their corrosion.

In this study, corrosion-induced friction instability was investigated by focusing on friction oscillations at the sliding interface. Mechanical and physical properties of sliding surfaces, such as contact stiffness and hydrophilicity, and how these properties changed upon the transfer of corrosion products from the disc surface were examined to find the cause of friction force oscillations produced during brake applications after disc corrosion.

2. Materials and methods

2.1. Disc materials and corrosion

The microstructure of the gray iron discs used in this study resembled that of commercial brake discs, showing type A graphite flakes in a pearlitic matrix (Brinel hardness: $H_B = 188 \pm 11$). The composition of the gray iron discs is given in Table 1. Commercially available brake friction material, corresponding to the front brake of the Kia Sportage vehicle, was used for friction tests. The friction material was non-steel type, and its constituents were classified as proprietary information; its composition, obtained from X-ray fluorescence analysis, is given in Table 2.

Corrosion of the gray iron disc was carried out by simulating disc corrosion in the early morning [17] by exposing the cold discs at −20 °C to an ambient condition (26 °C at 32% relative humidity) for 30 min and 60 min. The samples are hereafter abbreviated as C-30 and C-60, respectively. These conditions are similar to parking a vehicle overnight in humid weather. The surfaces of the discs exhibited reddish speckles after corrosion experiments.

2.2. Tribotests

Friction and wear of the discs and friction material samples were examined using a 1/5 scale brake dynamometer with a rigid caliper [18]. The discs were 142 mm in diameter and 8 mm in thickness. Each friction material specimen was machined from a commercial brake pad to produce a block whose dimensions were 45 mm × 18 mm × 7 mm. In order to simulate in-vehicle tests, the discs were first burnished to produce friction films on the disc surface before corrosion. The corroded discs were burnished again for a shorter period, to stabilize the transient surface products produced during corrosion, and to develop friction films on the surface of the friction material. Stick-slip tests were carried out at 4 MPa in the velocity range from 0.1–1.0 mm/s and at relative humidity of 35%. During the stick-slip tests the disk temperature was maintained below 45 °C due to slow sliding speeds. The detailed dynamometer test procedures used in this study are listed in Table 3.

Table 1
Composition of the gray cast iron disc used in this study (wt%).

C	Si	Mn	Cr	Cu	S	P	Sn	Mo	Fe
3.8	1.8	0.5	0.2	0.25	0.09	0.08	0.05	0.05	Bal.

Table 2
Composition of the friction material used in this study.

Element	wt%	Element	wt%
O	31.8	Si	6.32
Fe	14.2	Zr	5.91
Ba	7.72	K	4.22
Ca	6.91	Cu	2.19
Ti	6.80	Mg	1.80
Sn	6.69	S	1.70

2.3. Surface analysis

The surface morphology of the corroded gray iron surface was examined using a scanning electron microscope and a laser confocal microscope. The chemical composition of the oxide layers produced on the gray iron disc surface was obtained by using X-ray photoelectron spectroscopy. The hydrophobicity of the rubbing surfaces before and after the dynamometer tests was evaluated using a contact angle measurement apparatus (MCIK, OCA-15EC) following ASTM D7334 procedures. The static contact angle was measured using a 5 μm droplet of distilled water. The contact stiffness of the friction material was measured using a universal testing machine (Instron, model 3367) using a 10 mm diameter steel ball [18].

3. Results

3.1. Disc corrosion and hydrophilicity

The corrosion of gray iron starts by forming a galvanic cell on the surface, where the pearlitic iron matrix acts as an anode. It is bridged to the cathode (graphite flakes) via an electrolyte (water) and produces a rust deposit near the graphite flakes as per the following chemical reactions; $2Fe^{3+} + 6(OH^-) \rightarrow 2Fe(OH)_3 \rightarrow Fe_2O_3 + 3H_2O$ [19]. Corrosion produced rust relatively quickly when the cold disc was exposed to an ambient atmosphere. After 1 h, approximately 50% of the surface was covered by reddish oxide speckles. Fig. 1 shows the growth of oxides as a function of time, which is presented as a change in the height profiles of two oxide islands on the disc surface. The figure indicates that the oxide islands on the disc surface grow as a function of exposure time until the surface is completely covered by oxide layers. Similar results were found by Cho et al. [20]. They showed that the change of the oxide thickness was approximately linear with time and oxide growth was saturated after 20 h at approximately 40 μm in thickness. The oxide phase on the disc surface was analyzed using an X-ray photoelectron spectroscopy (Fig. 2). Although numerous oxide forms could be produced during corrosion [19], the XPS peaks from the corrosion products showed the typical peaks corresponding to hematite (α-Fe_2O_3).

The hydrophobicity of the disc was examined before and after corrosion. This is because the wettability of water at the sliding interface can change the friction and wear characteristics by influencing the formation of water menisci at the asperity contacts at the sliding interface. Fig. 3 shows the contact angle of a water droplet on the disc surface. The contact angle measurements were

Table 3
Dynamometer test procedure used to evaluate stick-slip using a 1/5-scale brake dynamometer.

	Pressure (MPa)	Velocity (mm/s)	Time (s)	Temperature (°C)
Preburnish	0.5	3000	600	Max. 200
1st burnish	8	16	15,000	–
Disc corrosion	–	–	0,30,60 (min)	25
2nd burnish	2	1.0	800	–
Stick-slip test	4	0.1 ~ 1.0	200	–