

Friction Coefficient Variation Mechanism under Wet Condition in Disk Brake (Variation Mechanism Contributing Wet Wear Debris)

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ABSTRACT

This paper deals with friction under wet condition in the disk brake system of automobiles. In our previous study, the variation of friction coefficient μ was observed under wet condition. And it was experimentally found that μ becomes high when wear debris contains little moisture. Based on the result, in this paper, we propose a hypothesis that agglomerates composed of the wet wear debris induce the μ variation as the agglomerates are jammed in the gaps between the friction surfaces of a brake pad and a disk rotor. For supporting the hypothesis, firstly, we measure the friction property of the wet wear debris, and confirm that the capillary force under the pendular state is a factor contributing to the μ variation. After that, we simulate the wear debris behavior with or without the capillary force using the particle-based simulation. We prepare the simulation model for the friction surfaces which contribute to the friction force through the wear debris. The simulation results support our hypothesis, that is, under the wet condition assuming the pendular state, the agglomerates of particles are created and contribute to the increase of μ .

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INTRODUCTION

In automotive brake systems, stability of friction force under any circumstances is required because the friction stability leads to ensure the safety of passengers in automobiles. The stability also relates to the reduction of noise and vibration and good brake feeling. In conventional automotive disk brake systems, the friction force is generated by squeezing a brake pad against a disk rotor. The friction force is usually estimated using the compressive force of the brake pad and the friction coefficient μ between the brake pad and the disk rotor.

μ depends on the friction condition, e.g., sliding velocity and compressive force during the friction, as well as environment, e.g. temperature and humidity. For the design of the disk brake system and its components, it is important to clarify μ generation mechanism under usage environment.

Direct observation of the friction surface during the friction is a method to identify the μ generation mechanism [1, 2]. Eriksson [2] utilized the glass as the friction surface and succeed the observation on the friction surface in dry condition. Akita et al. [3] and Goto et al. [4] extend the method to the observation of μ variation under the wet condition, and it was experimentally found that the agglomerates of

wear debris with moisture contribute to the μ variation. Then, μ between the brake disk and the glass rotor becomes high when the wear debris contains only 1.0wt% water.

The wear debris is a kind of powders and the state of the powder which has the water content under at most 20% is called the pendular state [5,6]. The volume ratio of the wet wear debris in the above experimental result is 2.6% which is converted from 1.0wt% using the representative value of the wear debris. Therefore, it is expected that μ variation under the wet condition in a disk brake system appears when the wear debris is in the pendular state. In the pendular state, a capillary bridge connects to each of the wear debris. Then the capillary force is generated between the wear debris. The capillary force is the largest adhesion force in the micro scale objects, and is proportion to the water content of the powder in the pendular state.

Through the experimental studies, we can understand a macroscopic behavior of the wear debris between friction surfaces during the friction and expect that the capillary force is a factor to contribute to the μ variation between the brake pad and the disk rotor. In this paper, based on the results, we propose a hypothesis about the μ variation mechanism under the pendular state. In the hypothesis, it is assumed that the μ variation occurs by next two steps:

1. The wear debris with moisture makes agglomerates which are bonded by the capillary force.
2. When the agglomerates are jammed in the gaps between the brake pad and the disk rotor, large friction force is generated and induces μ variation.

For supporting the proposed hypothesis, firstly, we measure the friction properties of the wet wear debris. Under the pendular state, the capillary force is the largest adhesion force bridging the wear debris. Through the friction test using two kinds of liquid which have different surface tension, we clarify the contribution of the capillary force to the μ variation.

In addition, to clarify the contribution of the microscopic wear debris behavior to the μ variation, we utilize the computer simulation because, in observation approaches, it is difficult to identify how the wet wear debris contributes to the friction forces. For the simulation of the brake disk system the finite element analysis (FEA) is widely applied to analyze squeal and evaluate the noise and vibration of the continuum body [7, 8]. To concern the simulation of the wear debris which is classified into a granular material, one of the approaches modeling a granular material is the discrete element method (DEM) [9] which is a particle based simulation. DEM is widely used in the soil mechanics and geomechanics to understand soil behavior or to confirm a hypothesis about the mechanics based on the experimental data. Therefore we simulate the wear debris behavior using the DEM.

Through the DEM simulation results of the wear debris behavior under the dry and wet conditions, we confirm the contribution of the wear debris to the μ variation under the pendular state and discuss its μ variation mechanism. In the DEM simulation, we assume that the friction surface of the brake disk system is classified into the two domains; one is the contact domain where the friction surfaces directly contact, and the other the gap domain where the wear debris are jammed in the gaps between the friction surfaces. For the purpose of the understanding the contribution of the wear debris to the μ variation, we prepare the simulation model of the gap domain assuming the periodicity and the regularity based on the experimental results. The wet condition in the simulation is modeled using the capillary force assigned at all of the contacting points.

This paper is organized as follows. In [Section 2](#), we first measure μ of the wear debris under the wet condition, and then explain contribution of the capillary force to μ variation in the pendular state. [Section 3](#) introduces the simulation for the wear debris behavior under the pendular state based on the particle based simulation, and estimates the μ variation mechanism. Finally, [Section 4](#) gives the concluding remarks supporting the proposed hypothesis.

FRICITION TEST OF WEAR DEBRIS UNDER WET CONDITIONS

In this section, we begin with the experimental settings for the friction test using the wet wear debris, and then describe the experimental results and discussions focusing on the effect of the capillary force.

Experimental Settings for Friction Test

[Fig. 1](#) shows the schematic image of the friction tester (NS-S, Nano seeds Inc.) for measuring μ of the wear debris. This machine can measure small friction forces ($>100\text{mN}$) of powders during the friction with slow sliding velocity ($>5\mu\text{m/s}$). Using this tester, we measure μ between the brake pad and the wear debris under the wet condition. The sliding velocity of the friction test is set to $10\mu\text{m/s}$.

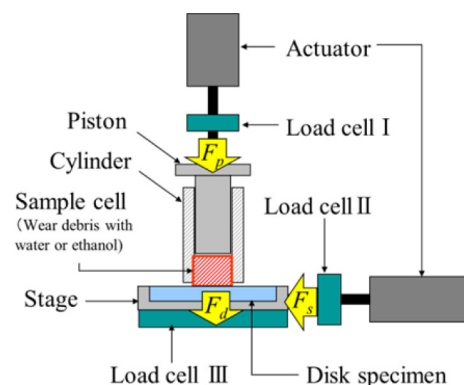
[Table 1](#) shows the friction test conditions. In this friction test we focus on the friction property of the wear debris under the pendular state. The wear debris is collected from the same brake pad under the same friction condition, and is mixed with the liquid which is controlled to realize the pendular state. In the experimental setting, we prepare up to 5.0 wt% liquid content. Converting wt% to the volume ratio (%) using the wear debris density, the liquid content is 16%. It is expected that the condition of the wet wear debris is the pendular state [5].

To clarify the contribution of the capillary force to the μ variation, we prepare two kinds of liquid, water and ethanol, these surface tensions are $72.0\mu\text{N/m}$, $22.0\mu\text{N/m}$, respectively. The liquid content is controlled under 5.0 wt%. Note that 0.0 wt% means the dry condition.

Experimental procedure is as follow:

1. Fill the sample cell with the wear debris w/o water or ethanol.
2. Press the wear debris to the disk specimen on the stage and measure the compressed forces F_p and F_d on the piston and disk sides by the load cells I and III.
3. Keep the above condition for 120 seconds to stabilize the load condition.
4. The stage is moved to the shear direction. The shear force F_s is measured by the load cell II.

The friction test is done several times using the wear debris with the same liquid content. The average value of the measurement forces is utilized to calculate μ between disk specimen and the wear debris. Then we utilize F_d which is smaller than F_p because F_p implicit include the friction force generated between the wear debris in the sample cell and the cylinder wall.



[Fig. 1](#). Schematic image of a friction tester.

Table 1. Friction test conditions

Disk material	Cast iron
Disk diameter	50.0 mm
Cylinder diameter	15.0 mm
Applied load	50, 100, 150, 200 N
Amount of liquid	0, 1.0, 3.0, 5.0 wt%
Sliding velocity	10.0 $\mu\text{m/s}$

Results and Discussion of the Friction Tests Using Different Liquids

Fig.2 shows $\Delta\mu$ which is the difference of μ between dry or wet conditions. μ of the wear debris with water increases over 0.3 under 5.0 wt%, while that with ethanol 0.05 at most. In both two cases, $\Delta\mu$ becomes large when 1.0wt% liquid content is added. As the similar result was observed in the friction test using the brake pad and the disk rotor [4], we consider that the wet wear debris under the pendular state contributes to the μ variation in the disk brake system.

The sizes of the wear debris consisting of firstly and secondary particles are 10 μm at most. In the micro scale granular materials the capillary force is the largest adhesion force. Under the pendular state the capillary bridge is generated between each of granular materials and connects them by the capillary force. Regarding the wear debris as the sphere granular material, the capillary force F_c applied to the two materials can be calculated with the surface tension γ :

$$F_c = 2\pi\gamma r_2 \left(1 + \frac{r_2}{r_1}\right), \quad (1)$$

where r_1 and r_2 are the radius of curvature of the capillary bridge. The wear debris used in the friction tests has approximately uniform shape and size because the wear debris is collected under the same brake pad and the same friction condition. Assuming the capillary bridge shapes do not depend on the friction test conditions, the capillary force is proportion to the surface tension. Then the capillary force of the water is larger than that of ethanol. In the experimental results, the $\Delta\mu$ of the water becomes large compared with that of the ethanol. Therefore we consider that the difference of the magnitude of the capillary force affects the μ variation.

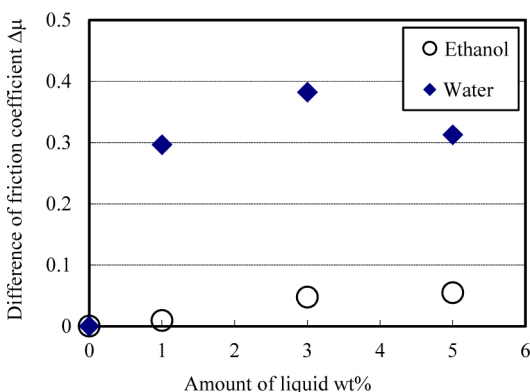


Fig. 2. Variation of friction coefficient with water or ethanol.

WEAR DEBRIS BEHAVIOR SIMULATION UNDER WET CONDITION

This section shows the particle-based simulation of wear debris behavior between a brake pad and a disk rotor in the automotive disk brake system. Firstly, a friction surface model based on the proposed hypothesis is described. Then the simulation model using the discrete element method (DEM) is explained. After that, we show the simulation results and discuss the μ variation mechanism focusing on the differences between the simulation results under dry and wet conditions.

Friction Surface Model

Fig.3 shows the schematic image of a cross section view between a brake pad and a disk rotor based on the proposed hypothesis. We separate the friction surface into two domains.

1. *Contact domain*: The brake pad directly contacts the disk rotor.
2. *Gap domain*: The brake pad does not directly contact the disk rotor. The wear debris contributes to the friction force through the brake pad (Fig.4).

In the proposed hypothesis, it is expected that the friction force generated in *Gap domain* affects the μ variation under the wet condition. Therefore, we prepare the simulation model for calculating the friction force in *Gap domain*.

Using the friction forces F_c and F_g which are generated on *Contact domain* and *Gap domain*, the friction coefficient μ_{total} can be calculated as

$$\mu_{\text{total}} = \frac{F_{cy} + F_{gy}}{F_{cz} + F_{gz}}, \quad (2)$$

where the subscripts y and z corresponding to the sliding (shear) and compressive directions, respectively. The denominator and numerator of Eq.(2) is the sum of the shear and compression forces. μ_{total} corresponds to μ observed in a friction test. Following Eq.(2), when the friction forces on *Gap domain* does not work, μ_{total} is equal to the friction coefficient of *Contact domain* μ_c . Namely, Eq.(2) can directly express the contribution of the wear debris to μ_{total} .

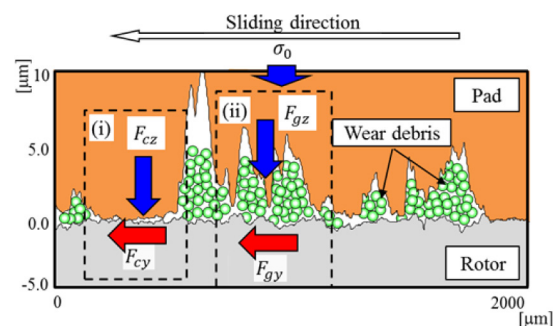


Fig. 3. Schematic image of a cross section view between the brake pad and the disk rotor in the disk brake system. Friction forces F_c and F_g are generated in (i) *Contact domain* and (ii) *Gap domain*.