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FRICTION CHARACTERISTICS OF A PAPER-BASED FRICTION MATERIAL

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ABSTRACT−A bench test set-up is employed to simulate the friction characteristics of a paper-based friction material operating against a steel plate. Dry friction tests are run as well as tests with transmission fluids. Glazed friction material produces a negative coefficient of friction versus sliding velocity (*f-v*) curve for both dry friction and lubrication with transmission fluids. At low sliding speeds, the coefficient of friction when operating in transmission fluids for glazed friction materials is greater than that under dry friction. An appreciable negative *f-v* slope occurs at low sliding speeds for glazed friction materials when running with the transmission fluid. The friction material after running in produces a constant *f-v* curve under dry friction and a negative slope when lubricated with transmission fluid. At low sliding speeds, the coefficient of friction of the run-in friction material is lower than that of the glazed wet material. On the other hand, the run-in friction material has a larger friction coefficient than does the glazed friction material at higher sliding speeds.

KEY WORDS : Friction, Clutches, Running-in, Degradation, Stick-slip

1. INTRODUCTION

Paper-based friction materials (hereafter called friction materials) are used as friction linings in automatic transmissions. The friction material is normally made of cotton and filler particles cured by phenolic resin. The structure of the friction lining is porous and deformable. A fairly high coefficient of friction with low wear rate is provided by the friction material. When utilized as a torque converter during the operation of wet clutches, the friction material is submerged in an automatic transmission fluid (ATF). The fluid acts as a lubricant and a coolant. Friction-induced shudder is a problem which can occur in automatic transmissions. This process is caused by stick-slip which is a phenomenon of non-continuous motion which can be caused by velocity dependent friction. Vibrations produced by stick-slip are undesirable because of their detrimental effects on the performance of mechanical systems. They can produce fatigue failure, severe wear, surface damage and noise. It has been observed that a decreasing friction-velocity curve can produce stick-slip (Ibrahim, 1994).

The friction characteristics of paper-based friction materials which are commonly used in torque converter clutches have been experimentally and analytically investigated (Fish, 1976; Natsumeda and Miyoshi, 1994; Berger, Sadeghi and Krousgrill, 1996). Ito *et al*. (Ito, Fujimoto, Eguchi and Yamamoto, 1993) investigated the transitional friction characteristics of a wet clutch in stable sliding, breaking-away and locking-up processes. The effect of porosity on the coefficient of friction was studied by Matsumoto (Matsumoto, 1995). For new friction materials, a positive friction-velocity curve slope is produced and shudder does not occur. However, a negatively sloped friction-velocity curve can occur for worn out friction materials, and shudder is produced. The correlation between negative slope behavior and shudder has been confirmed by several researchers (Rodgers and Gallopoulos, 1966). Friesen (Osanai, Ikeda and Kato, 1990) also studied the dynamic behavior of wet brakes from the point of view of modeling with a mass-spring-dashpot system. He found that a dynamic instability was produced when the shape of the friction-velocity curve was negative.

Glazing of friction materials is generally thought to be produced due to thermal degradation. High temperatures during engagement can cause degradation of the friction material due to carbonization (Osanai, Ikeda and Kato, 1990). With respect to operating conditions, the presence or absence of lubricating fluids is most crucial. The friction characteristics of this type of friction materials are important to the study of stick-slip and the engagement of wet clutches.

This paper addresses these issues by simulating the

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performance of wet clutches. Due to the importance of the coefficient of friction-velocity curve to stick-slip friction, the effect of sliding velocity on the friction coefficients of friction materials has been experimentally investigated. An empirical equation has been developed to describe the friction-velocity curve. The normal load effects on the friction characteristics were also studied. Tests were run with and without transmission fluids and the friction behavior for run-in and glazed materials was investigated.

2. EXPERIMENTAL MATERIALS AND METHODS

The friction materials used in this experiment are paper based. They are composed of cellulose fibers and hard particulate filler bonded by a thermo-set resin and finally processed to give a porous structure. Run-in and glazed friction materials are employed in this paper to study their friction characteristics. The run-in friction material is obtained after the new friction material is run with the mating steel plate for 5000 cycles at room temperature. Figure 1 shows an optical photograph of the run-in friction material. The glazed friction material is produced by rubbing against the mating steel plate for 5.0×10^4 cycles at 150ºC. An optical photograph of the glazed friction material is shown in Figure 2. The plate on which the friction material is rubbed is steel with a hardness of 75.8 HRS_{100kg}. The roughness of the steel plate is 0.39 μm (*Ra*). The experiments are carried out on a modified pin-on-disk simulator, as shown in Figure 3. The lower mating steel plate is driven by a 373.2 Watt DC motor. The rotation speed is variable with a maximum speed of 300 rpm. The transmission fluid has a viscosity of 5.846×10^{-3} Pa·s at 100ºC. The friction force is measured by using a strain gage arm. Three pieces of friction materials are assembled on the upper plate and are spaced 120 degrees apart. The measured friction force is divided

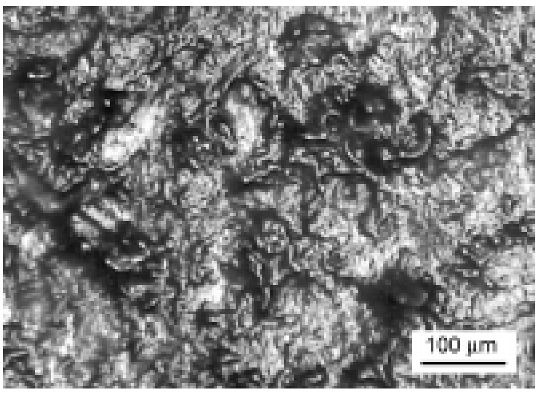

Figure 1. Optical photograph of run-in surface.

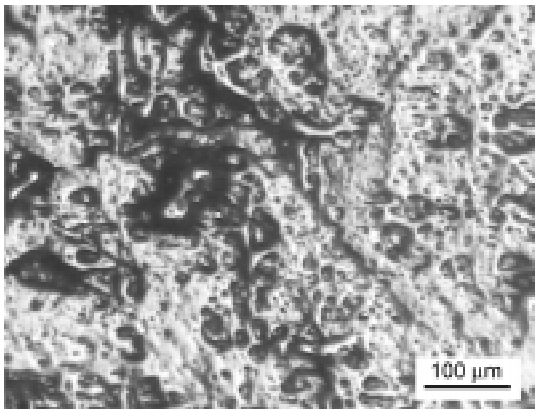

Figure 2. Optical photograph of glazed surface.

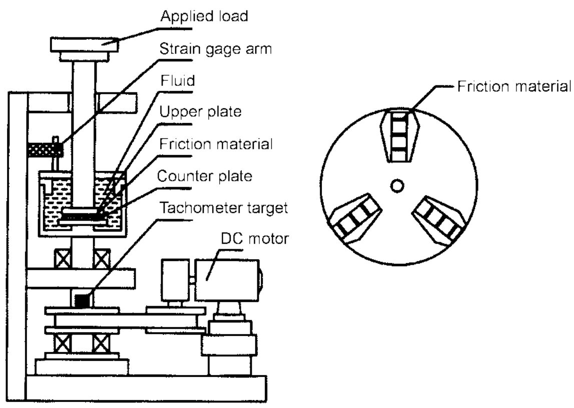

Figure 3. Schematic diagram of experimental set-up.

by the normal load to determine the coefficient of friction. The simulation is done both for dry friction and for lubrication with transmission fluid.

3. RESULTS AND DISCUSSION

Degradation of the paper-based friction material can occur due to heat-induced carbonization (Fish, 1976; Osanai, Ikeda and Kato, 1990). The friction characteristics vary with change in surface conditions such as surface topography and thermal glazing. Figure 4 shows the friction curves of the run-in material and the glazed material produced with a normal load of 70.0 N. Negative *f-v* curve slopes are produced for both paper-based friction materials. The friction coefficients at lower speeds are higher than those at higher speeds. This type of negative *f-v* curve slopes makes the friction system act as an energy source rather than an energy sink resulting in stick-slip during wet clutch engagement (Chen, 1998). In addition, the *f-v* curve of the glazed surface becomes more negative than that of the run-in surface due to the

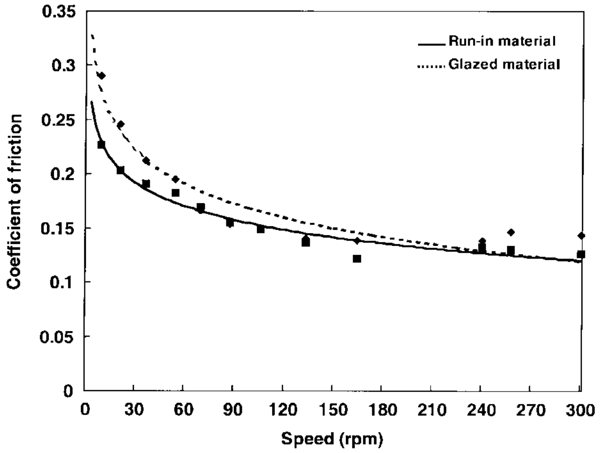

Figure 4. Comparison of friction curves between run-in and glazed friction materials operating in ATF at W = 70.0 N.

higher friction coefficients at the lower speeds. The experimental data is approximated using logarithm equations as seen in Equation (1) and Equation (2). The empirical results agree well with the experimental results. The best-fit equations for the run-in and glazed surfaces are as follows.

For the run-in surface:

$$f = 0.2926 - 0.0308\ln(\omega_{rel}) \quad (1)$$

For the glazed surface:

$$f = 0.3695 - 0.0437\ln(\omega_{rel}) \quad (2)$$

where f is the coefficient of friction, and ω_{rel} is the relative angular sliding speed between the friction disk and the counter steel disk, rev/sec. Similar empirical equations were used to calculate the torque response and system dynamics during the wet clutch engagement (Anderson, 1972; Holgerson, 1997; Yang, Lam and Fujii, 1998). The friction characteristics of the paper-based friction material are not only affected by the relative sliding speed but also by the fluid formulation, temperature and surface topographies. These empirical expressions assume that all of the influencing parameters except sliding speed are held constant.

The surface topography of the friction materials was examined using a stylus surface tracer. Figure 5 shows the surface profiles of the run-in and glazed friction materials. The surface parameters for the run-in material are $R_q = 4.13$ μm and $R_{sk} = -0.56$. The glazed surface becomes smoother with wear and removal of surface peaks. The surface parameters of the glazed material are $R_q = 3.15$ μm and $R_{sk} = -0.98$. For the glazed surface, the fibers inside the friction material are exposed and make a major contribution to the surface texture. The real contact

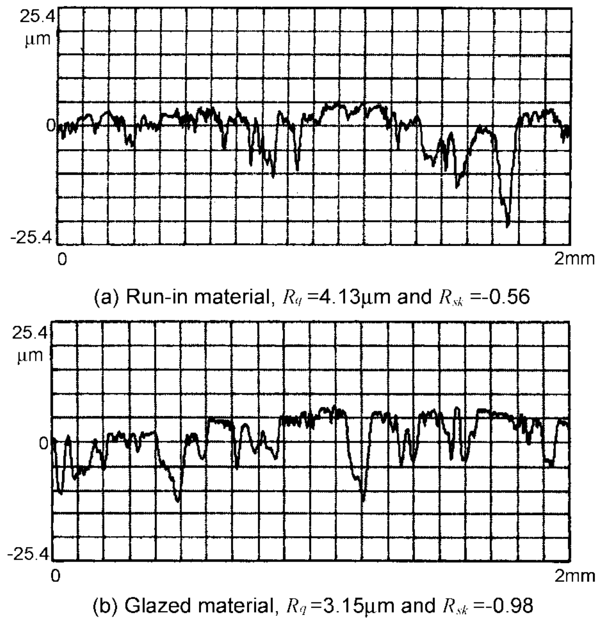

Figure 5. Surface profiles of run-in and glazed friction materials.

area for the run-in and glazed surfaces during wet clutch engagement was studied by taking both surface roughness and skewness into account (Gao and Barber, 2002). The material-to-material contact area of the run-in friction material is smaller than that of the glazed material although its surface is rougher than that of the glazed surface. This is due to the skewness effect on the real contact area. At lower speeds, boundary lubrication dominates between contact surfaces. Since the asperity contact area of the glazed surface is greater than that of the run-in surface, the coefficient of friction for the

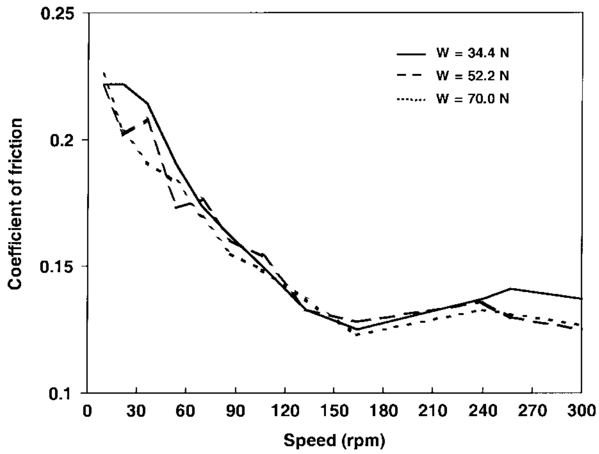

Figure 6. Normal load effects on friction curves of run-in firction materials under lubricated condition with ATF.

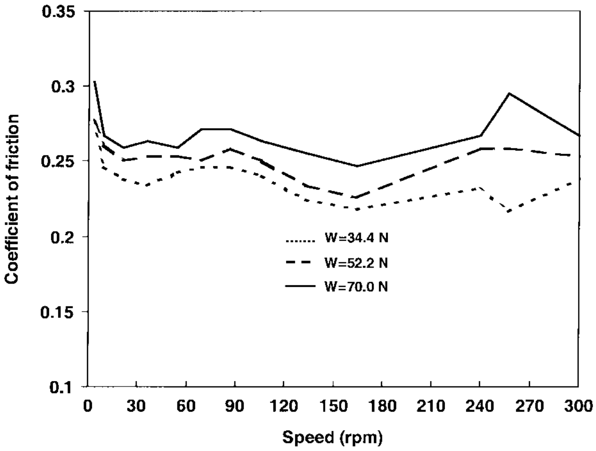

Figure 7. Normal load effects on friction curves of run-in friction materials under dry friction condition.

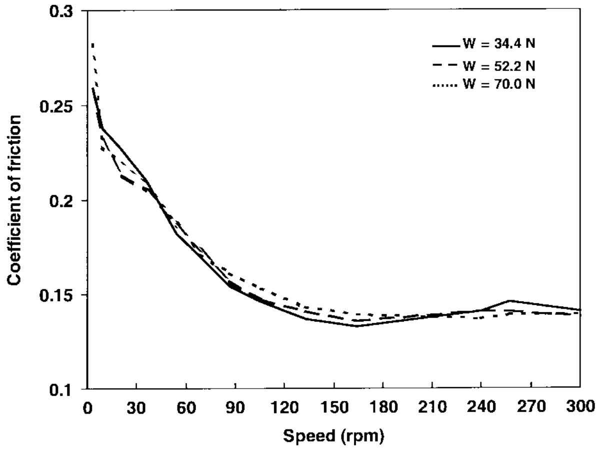

Figure 9. Normal load effects on friction curves of glazed friction materials under dry friction condition.

glazed surface is higher than that for the run-in one. As a result, a more negative friction curve is produced for the glazed surface than that for the run-in surface.

Figure 6 shows the effects of normal load on the friction characteristics of run-in friction materials operating in ATF. It can be seen that the coefficient of friction does not vary much with change in normal load. However, under dry friction conditions, the coefficient of friction increase slightly with the increase of the normal load, as shown in Figure 7. On the other hand, the coefficient of friction is not sensitive to the normal load for the glazed material under both lubrication with ATF and dry friction conditions, as shown in Figure 8 and Figure 9. The surface topography of the run-in friction material is rougher and has a more irregular asperity height distribution than does the glazed friction material. The glazed friction material has a more negatively skewed surface asperity height distribution than does the run-in friction material. The real contact area for the run-in surface is less than that of the glazed surface under the same load condition. When the applied load increases, the amount of deformation of load supporting asperities of run-in surfaces increases greater than that of glazed surfaces. This means the real contact area increases with the normal load for the run-in material. However, the real contact area varies less for the glazed friction material due to the much greater supporting area than the run-in friction material. Therefore, the friction coefficient of the run-in material is affected by the normal load, but the friction coefficient of the glazed material is not. In addition, the dry friction coefficient changes with the

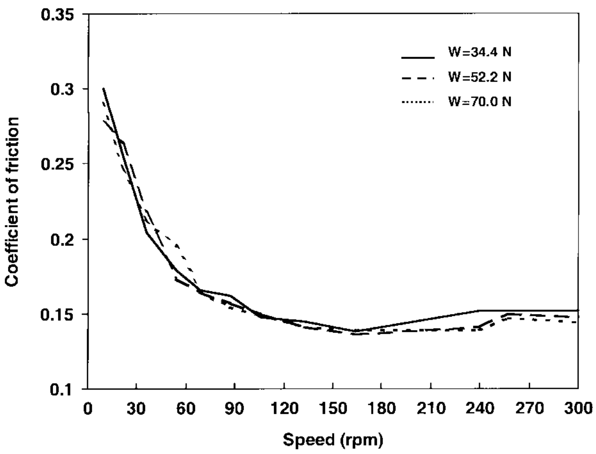

Figure 8. Normal load effects on friction curves of glazed friction materials under lubricated condition with ATF.

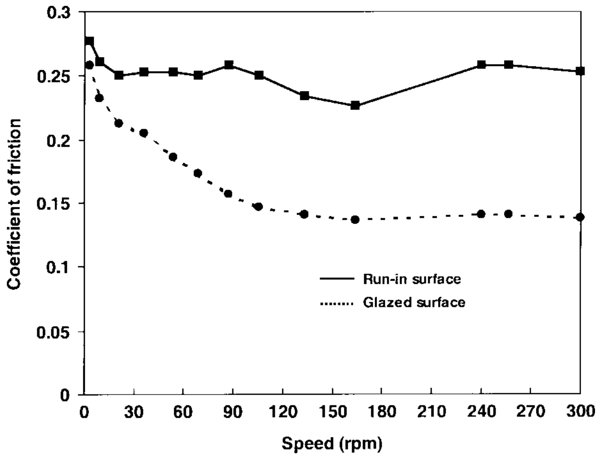

Figure 10. Comparison of friction curves between run-in and glazed friction materials under dry friction condition at W=52.2 N.

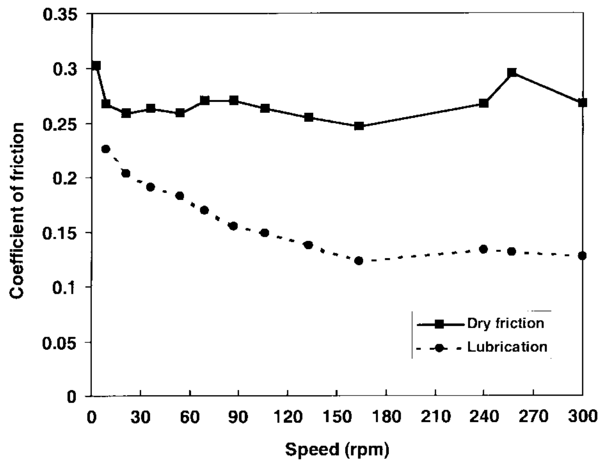

Figure 11. Friction curves of run-in friction materials under dry friction and lubricated conditions at W=70.0 N.

surface conditions for run-in and glazed friction materials. For the run-in surface, the coefficient of friction does not change with the sliding speed under the dry condition, as shown in Figure 10. The real contact area remains constant under a certain load and is independent of the relative sliding speed. The friction generated heat at high speeds does not produce a change of the structure of the run-in surface due to its limited amount of degradation or carbonization. However, the coefficient of friction under the dry condition decreases with sliding speed for the glazed surface. The friction produces more heat with the increase of the relative sliding speed. The carbonized layer on the glazed surface becomes softer due to the friction-generated heat. Therefore, the friction coefficient decreases with the increase of the relative sliding speed at lower sliding speeds. With the further increase of the sliding speed, the friction coefficient becomes stabilized because the increase of the sliding speed is balanced by the decrease of friction. The work done by the friction and sliding speed remains constant at high speeds. A negative *f-v* curve slope occurs for run-in friction materials only when operating in ATF, as seen in Figure 11. At lower speeds, the coefficient of friction for the lubricated condition is lower than that for the dry friction. As the sliding speed increases, more fluid enters the contacting area. The friction is reduced quickly with sliding speed and stays at a constant level after 130 rpm. That means the hydrodynamic lubrication may dominate after 130 rpm. But for the glazed friction materials the negative *f-v* curve slope occurs under both dry and lubricated conditions, as shown in Figure 12.

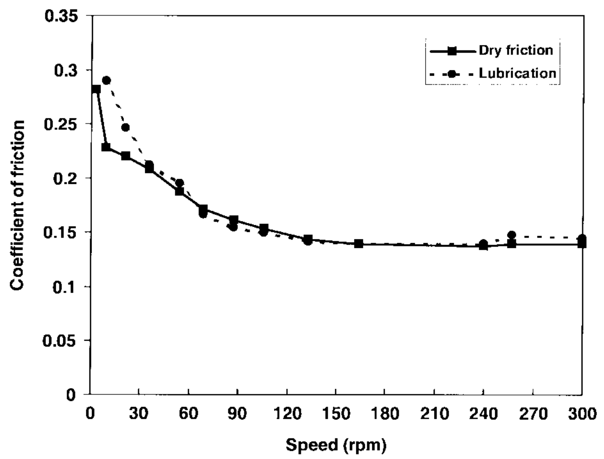

Figure 12. Friction curves of glazed friction materials under dry friction and lubricated conditions at W=70.0 N.

4. CONCLUSIONS

Friction characteristics of a paper-based friction material used in automatic transmissions were experimentally investigated under dry and lubricated conditions. Surface topographies of the friction material were studied for run-in and glazed materials. The results showed that the paper-based friction material produces a negative *f-v* curve slope when lubricated with transmission fluids. The *f-v* curve becomes more negative for the glazed friction materials than that for the run-in material. An empirical equation was developed to describe the friction versus sliding speed curve of this type of friction material. The normal load has little effect on the friction characteristics of friction materials except for the run-in material under dry friction. Automatic transmission fluids have an effect on the friction curves of run-in friction materials and not much influence on those of glazed friction materials.

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