

Study of Durability Prediction Considering Wear Properties for Multiple Plate Clutches

Toshihiro SAITO*
Seiichi TANAKA*

Tamotsu KOTEGAWA*
Kimikazu OHTSUKI*

Yoshiteru MATSUURA*

ABSTRACT

To increase the durability of multiple-plate clutches used in automatic transmissions, attention was focused on the wear history of the facing material. Measurements have confirmed that correlations can be observed between initial wear and disk contact pressure when the clutch is engaged, and between steady wear and plate temperature. Next, simulation technology was developed to quantify the disk contact pressure and plate temperature. When simulated contact pressure distribution and temperature distribution were used to establish correlations with durability wear, good proportional relationships were found in both cases. It was also found that when clutch specifications and driving conditions were varied, the gradient of the correction also varied, but the correlation remained proportional as long as the same facing material was used. The gradient was ranked as a wear property specific to the facing material. By determining the wear property of the facing material, it was possible for the first time to predict wear condition in a test of the clutch as an independent part, for any arbitrary set of clutch specifications and driving conditions.

1. Introduction

Recent increases in engine output have led to demands for lightweight and compact automatic transmissions that have a high torque capacity⁽¹⁾. One feature of Honda transmissions is a compact design that locates the clutch for each speed on three or four parallel shafts⁽²⁾. A smooth shift response with minimal shift shock is achieved by directly controlling the clutch piston pressure that contributes to the response when shifting gears. The parallel shaft mechanism, however, means that the clutch diameter is limited, so torque capacity is achieved simply by increasing the number of disks. In addition, increasing the difference between the inner and outer disk diameters reduces the amount of heat generated per unit disk area, which is considered an effective means for enhancing durability. This makes it important to control disk contact pressure distribution and plate temperature distribution during clutch

engagement. Experience has shown that failure to create an appropriate design can result in abnormal wear and burning of the facing materials⁽³⁾. However, this empiric rule is greatly influenced by the clutch structure, wear properties, operating conditions and other factors⁽⁴⁾, so quantization is difficult. For this reason, clutch durability has been verified up to now solely by long-term durability testing.

Therefore, this paper is focused on the facing material wear history, and clarifies that disk contact pressure distribution and plate temperature distribution both have qualitative correlations to the amount of clutch wear. Simulation technology was developed, allowing the disk contact pressure distribution and plate temperature distribution to be quantified, and making it possible for the first time to predict wear history. This predicted wear history can then be used to set specifications, including clutch durability, in the initial design stages. The details are reported below.

* Automobile R&D Center

2. Study Goals

Figure 1 shows the main section of the 5-speed automatic transmission used for the analysis. As shown in this figure, the clutches and gears for each speed are located on the parallel shafts, and the shifting process allows shifting from clutch to clutch by controlling the oil pressure supplied from the oil holes provided inside the rotating shaft. Focusing on the clutch structure (Fig. 2), the guide is fixed to the shaft via a spline, and the plates that mesh on the outer teeth rotate in sync with the guide. The disk has differential rotation from the plate before engagement starts, and this differential rotation reaches zero when engagement is finished. During this engagement process, the facing materials affixed to the disk transmit motive power by friction, but at the same time are damaged by heat generation⁽⁵⁾. When this damage is repeated over a long period, wear and burning may appear. Therefore, the goals of this study were set as follows.

- (1) To analyze the disk wear mechanism
- (2) To establish technology that can predict wear amounts in the initial stages of clutch design

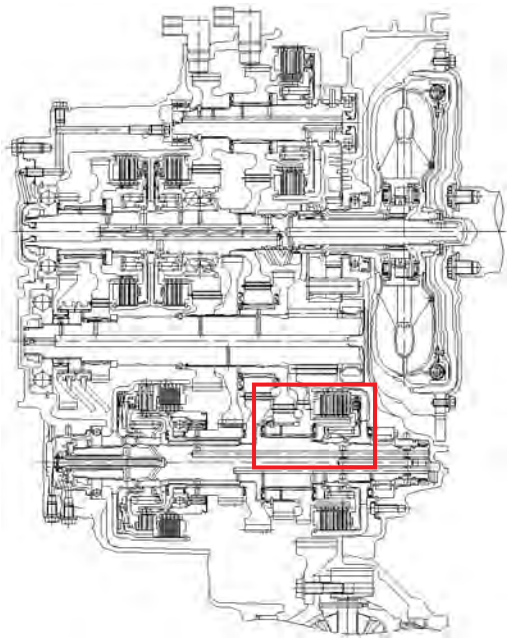


Fig. 1 Main section

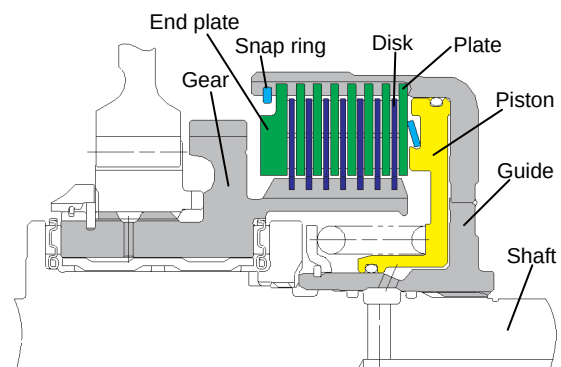


Fig. 2 Clutch detail

3. Analysis of Disk Wear Mechanism

Figure 3 shows the wear history obtained using a clutch pack durability test apparatus (Fig. 4). The horizontal axis shows the number of engagement cycles, and the vertical axis shows the wear amount. The wear amount was obtained by measuring the thickness of each disk and totaling the decrease in thickness. Note that the wear amount is known to be greatly influenced by the surface roughness of the disks and plates as well as by the amount of lubricant used, but these parameters were treated as constant values in this study. The figure clearly shows that the wear pattern is divided into an initial wear area in which wear progresses at a low number of engagement cycles, a steady wear area thereafter in which wear progresses at a gradual rate, and a transient wear area between the other two areas. Therefore, the wear patterns in each area were investigated.

3.1. Correlation between Initial Wear and Contact Pressure

The facing material structure consists of various fibers and inorganic matter bonded together by phenol resin with gaps, called pores, maintained between the various fibers. The facing materials ensure anti-wear performance while the clutch is engaged by absorbing and discharging lubricating oil through these pores. Facing materials generally have a Young's modulus of an order up to three digits smaller than that of steel or other materials, so there is significant deformation relative to the contact pressure load. In addition, the compression-displacement properties of the porous structure exhibit a response such as that shown in Fig. 5. Looking at the initial response, the displacement increases significantly under even the slightest contact pressure load. This indicates that large forces are not required to crush the aforementioned pores. This also means that there is little restorative force to return the porous structure to its original shape after a load is removed. Based on the above, the initial wear phenomenon is thought to be due to the yielding of the facing material under contact pressure loads.

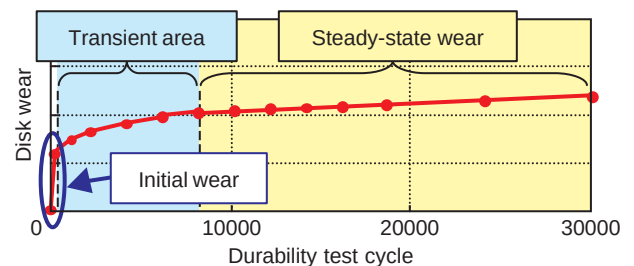


Fig. 3 Disk wear behavior

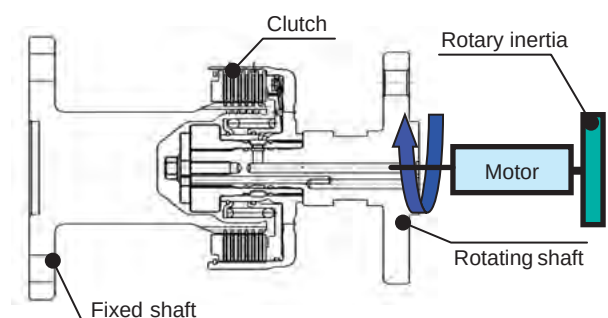


Fig. 4 Clutch fatigue test apparatus

Therefore, the correlation between the initial wear rate per cycle and the disk contact pressure was investigated using the clutch specifications shown in Fig. 6. Three-disk specifications were used to facilitate the clasp of pressure scaling paper between the disks. The disk contact pressure values in this figure are a visual representation of the color shade produced by the pressure scaling paper in the form of a contour chart. In addition, the initial wear rate was obtained by measuring the wear amount at two locations in the radial direction of each disk, and dividing the mean amount by the number of cycles. The wear amount was measured by conducting durability tests with operating conditions that varied the piston pressure F between two levels and the work energy Q/A between two levels. The resulting graph shows that the initial wear rate has a proportional relationship to the disk contact pressure and work energy (Fig. 7).

3.2. Correlation between Steady Wear and Temperature

The steady wear rate is smaller than the initial wear rate. That is to say, when operation enters the steady wear area, the damage per cycle becomes extremely small, and the facing material exhibits the wet clutch characteristic of maintaining long-term durability. However, even though there is only a slight increase, the wear curve still increases in the steady area (Fig. 3), so the influencing factors were investigated. As mentioned above, the facing materials include phenol resin, and have characteristics such that the weight decreases little by little as the temperature rises. In addition, it is known from thermogravimetry (TG) analysis and other methods that the weight decreases significantly at a certain temperature.

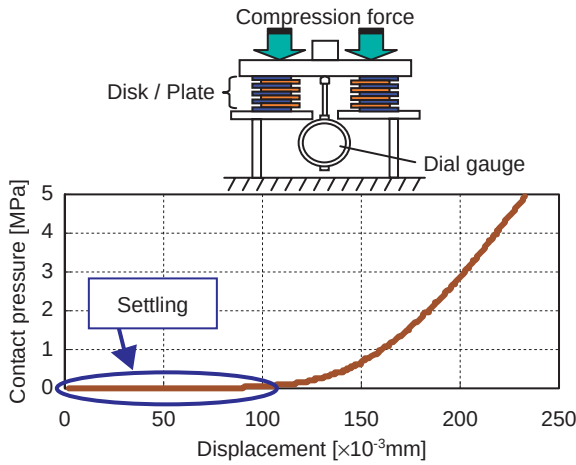


Fig. 5 Compression-displacement property

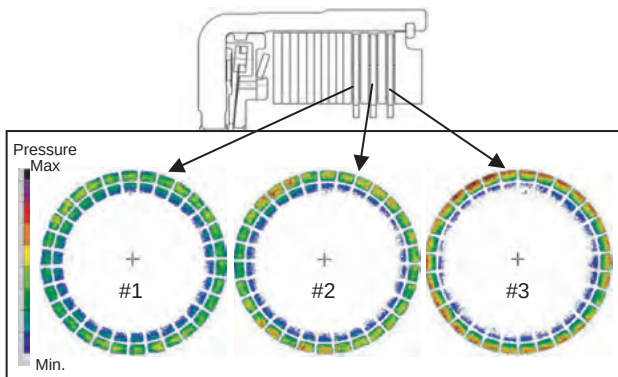


Fig. 6 Measured 3-disk clutch pressure distribution

Therefore, temperature was thought to have some relationship with steady wear, and the steady wear amounts obtained as a result of the durability tests with three-disk specifications were organized according to the maximum temperature during engagement. The temperatures were measured using thermocouples embedded in each plate (Fig. 8). As operating conditions, the piston pressure was fixed and the work energy was varied between three levels. The results showed an excellent correlation between the steady wear rate and the maximum temperature under high work energy conditions, but the wear amounts sampled in the lower work energy areas were smaller, so somewhat ambiguous results were obtained (Fig. 9).

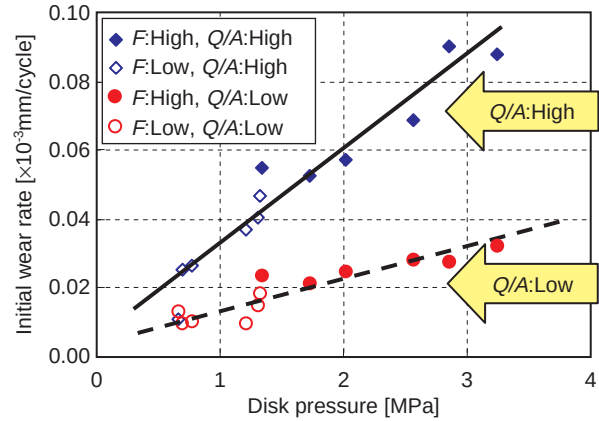


Fig. 7 Correlation of initial wear and disk pressure

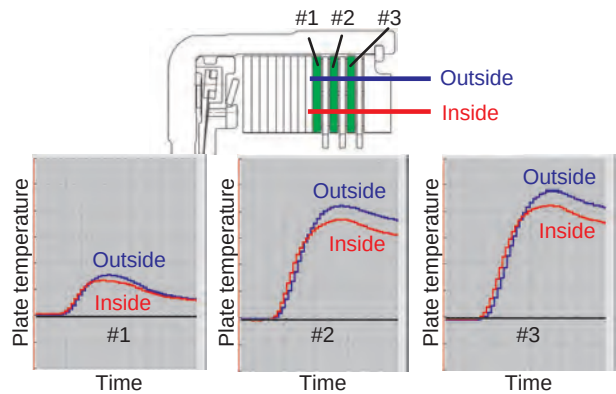


Fig. 8 Measured 3-disk clutch plate temperature

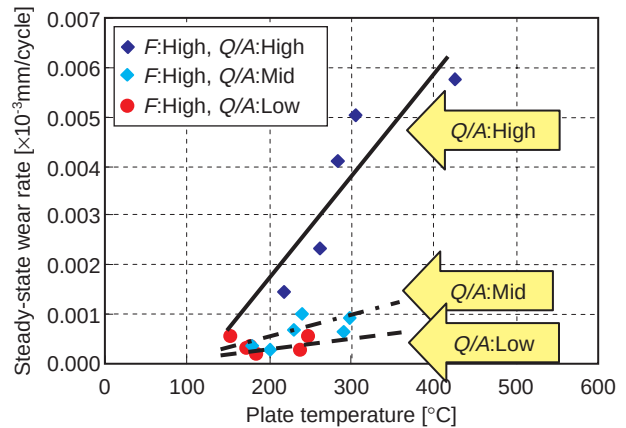


Fig. 9 Correlation of steady state wear and plate temperature

4. Development of Simulation Technology

Analysis of the disk wear mechanism showed a correlation between the initial wear rate and the contact pressure, and the steady wear rate is thought to be related to the maximum temperature. Therefore, the contact pressure distribution and the temperature distribution were quantified using structural analysis.

4.1. Disk Contact Pressure Simulation

Figure 10 shows the structural analysis model used to simulate the contact pressure distribution.

The analysis model is a cyclic, symmetric elastic model, and the angle was selected so that an integer multiple of this model produces the complete clutch shape. The disks are composed of a core plate and facing materials, so contact pressure analysis needed to accurately reproduce the facing material area. Therefore, the facing materials were modeled using shell elements and were attached to the disk surface. In addition, the compression-displacement properties of the facing materials were introduced to the analysis as a property of the contact surface. Figure 11 shows the contact pressure distribution results for typical facing material segment shapes. The contact pressure distribution of each disk changes according to the piston pressing position, the snap ring receiving position, the number of disks, the disk thickness, and other factors, so the distributions are non-uniform.

Next, the simulation results were compared with contact pressure values measured using a tactile sensor to verify the simulation accuracy (Fig. 12). The compared positions were the two locations at which the wear amount was measured for each disk. As shown in Fig. 13, the resulting difference was found to be within $\pm 15\%$.

4.2. Plate Temperature Simulation

The temperature distribution was simulated using the heat transient analysis method. However, to use this method various thermal physical property values must be identified. These values are the thermal conductivity that represents the rate of heat transfer within the same material, the heat transfer coefficient that determines the rate at which heat is transferred and received via a contact surface, and the thermal diffusion coefficient that represents heat dissipation due to lubrication and the air. Therefore, temperature measurements and simulations were performed to identify each of these thermal physical properties individually. The identification method for one of these thermal physical properties, the heat transfer coefficient, is described below.

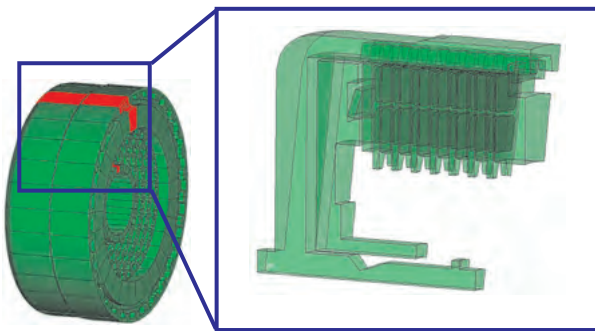


Fig. 10 Analysis model for contact pressure distribution

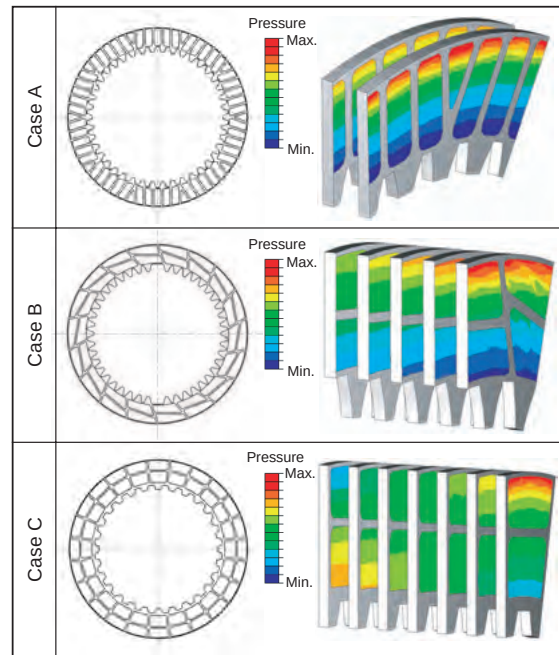


Fig. 11 Results of contact pressure distribution analysis

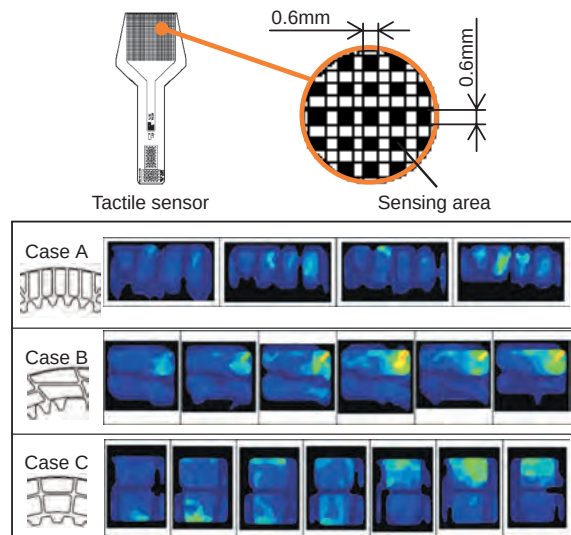


Fig. 12 Contact pressure distribution measurements

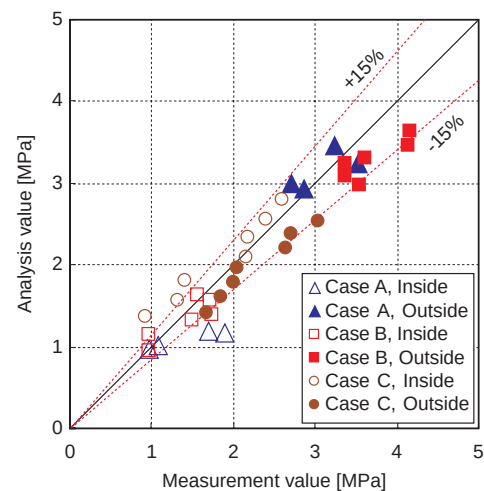


Fig. 13 Accuracy of contact pressure distribution analyses

Figure 14 shows the test apparatus used to obtain the heat transfer coefficient. Plates and wet disks were stacked alternately on top of the testing table, and pressure was then applied to reach the specified contact pressure. In addition, the uppermost plate was heated using a heater, and the temperature of the middle plates was measured using thermocouples. The measurement results shown in Fig. 15 clearly indicate that the temperature rises more slowly for the lower plates.

A heat transient analysis model that includes the testing table was created to simulate this heat transfer, and the heat transfer coefficients were adjusted to provide the same temperature history for each plate. The dotted line in Fig. 15 shows the temperature history ultimately obtained from these calculations. The measurement and simulation results match closely, thus verifying the accuracy of the identified heat transfer coefficient.

The temperature distribution during clutch engagement was simulated using the three thermal physical property values identified in this manner. At this time, it is necessary to apply the heat flux to the entire disk surface as a load condition. The heat flux q_i at an arbitrary position is calculated by the following equation.

$$q_i = r_i \times \mu_i \times p_i \times \omega$$

r : Radial position, μ : Dynamic friction coefficient,

p : Contact pressure, ω : Slip velocity, i : Position variable

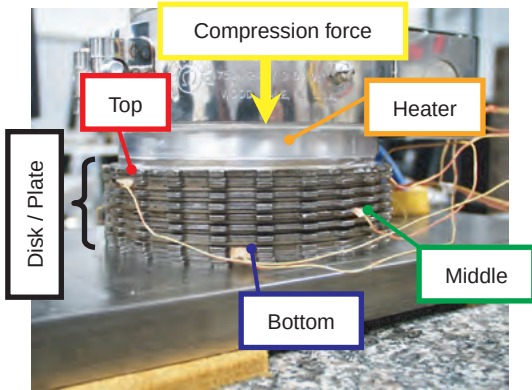


Fig. 14 Measurement apparatus for identifying heat transfer coefficient

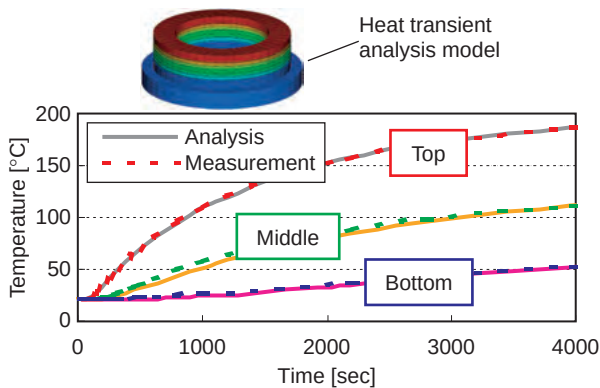


Fig. 15 Identification of heat transfer coefficient

Here, the dynamic friction coefficient used the values obtained by the SAE #2 function test, and was treated as a function of the contact pressure, slip velocity and temperature (Fig. 16).

In addition, the contact pressure used the results of the contact pressure distribution simulation. Figure 17 shows that the maximum temperature of each plate during the engagement process when varying Q/A could be accurately reproduced. However, detailed examination shows that the temperature error increases for plates #6 and #7, counted from the piston.

Therefore, the plate temperature rise error was investigated, and was found to be approximately $\pm 20\%$ (Fig. 18). This is thought to be because the same thermal diffusion coefficient that represents the effects of heat dissipation due to the lubricating oil was used for all the plates in the simulation. It is thought that this error can be reduced in the future by clarifying the flow of lubricating oil inside the clutch.

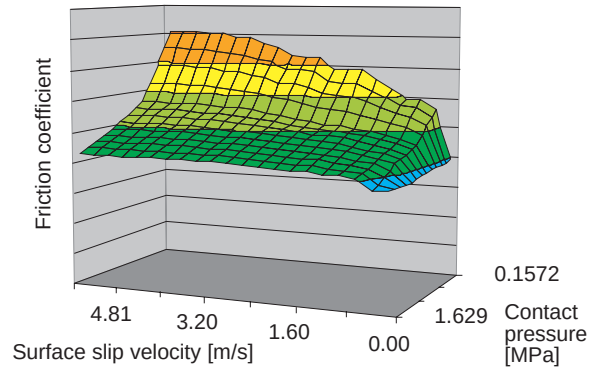


Fig. 16 Dynamic friction coefficient

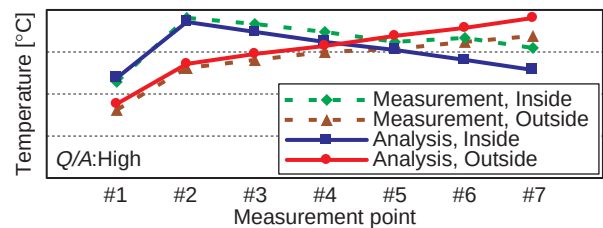
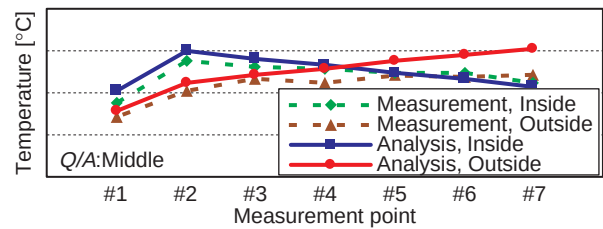
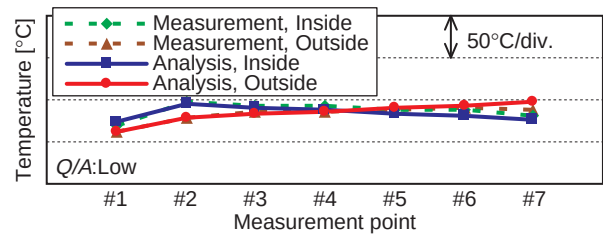


Fig. 17 Plate temperature distribution

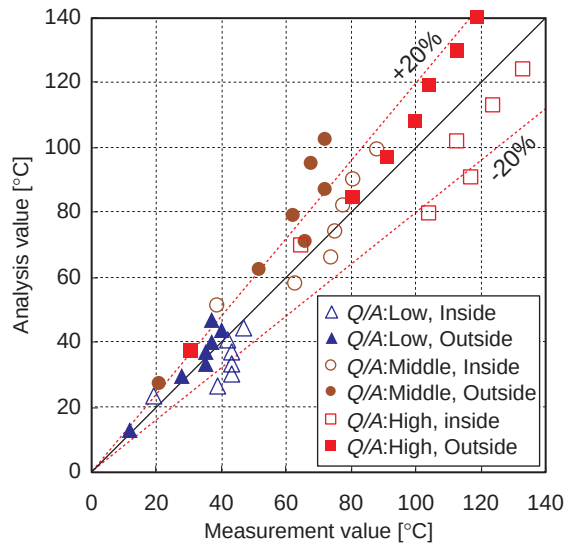


Fig. 18 Accuracy of temperature distribution analyses

5. Development of Wear Amount Prediction Technology

5.1. Wear History Calculation Method

The development of simulation technology enabled quantization of the disk contact pressure distribution and the plate temperature distribution during engagement. Therefore, the correlation with the durable wear amount (dotted line in Fig. 19) was investigated once again using actual clutch specifications.

The results yielded the proportional relationship between the initial wear rate and the disk contact pressure shown in Fig. 20, and the proportional relationship between the steady wear rate and the plate temperature shown in Fig. 21. This substantiates the results of the previous wear mechanism analysis.

The important point here is that proportional relationships were obtained, and since the slope (K_i and K_s) of each relationship is known, the wear histories can be reproduced using the following simple equations.

$$W_i = P \times K_i \times N$$

$$W_s = T \times K_s \times N$$

W_i : Initial wear amount, W_s : Steady wear amount

P : Contact pressure, T : Temperature, N : Number of cycles

In addition, the average value of these wear histories is used as the wear amount W_T in the transient area that lies between the initial wear area and the steady wear area.

$$W_T = (W_i + W_s) / 2$$

The solid lines in Fig. 19 are the wear histories calculated using the above equations. They match closely, both qualitatively and quantitatively, with the actual measurements. This shows that when the results of durability tests are available, the wear histories can be expressed by obtaining the slopes K_i and K_s . However, a remaining issue was that wear amounts could not be predicted unless the durability test results were available.

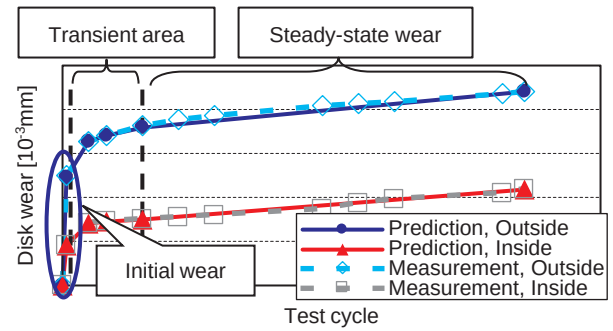


Fig. 19 Wear prediction for clutch disk

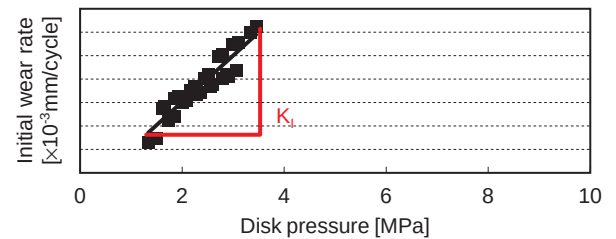


Fig. 20 Relationship between initial wear rate and pressure

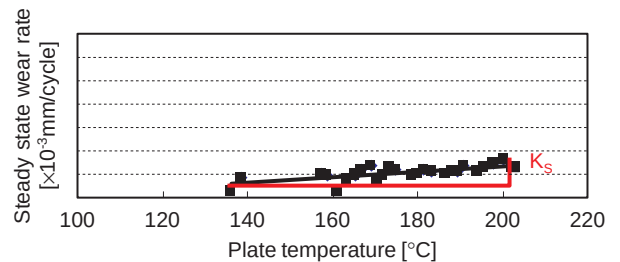


Fig. 21 Relationship between steady-state wear rate and temperature

5.2. Facing Material Wear Property Maps

Therefore, these relational equations were applied to various durability test results using different clutch specifications and Q/A. In these calculations the segment shape was allowed to differ, but only the facing materials used the same materials in all cases. The results clearly showed that while the slopes K_i and K_s differed in each durability test, the slopes changed in the order of the work energy. Figures 22 and 23 show this relationship in the form of 3-D graphs. These graphs include the durability test results using ten different sampling clutch specifications. These two graphs show 3-D maps of the specific wear properties of the facing materials.

The ability to obtain facing material wear property maps made it possible to obtain the slopes K_i and K_s , which are needed to calculate the wear amounts for arbitrary clutch specifications and operating conditions by interpolating the data from these wear property maps.

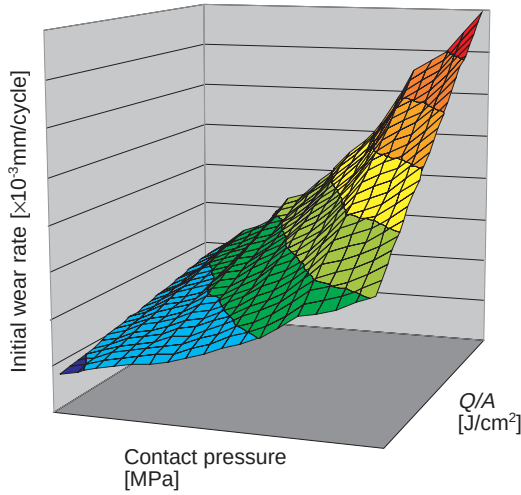


Fig. 22 Initial wear properties map

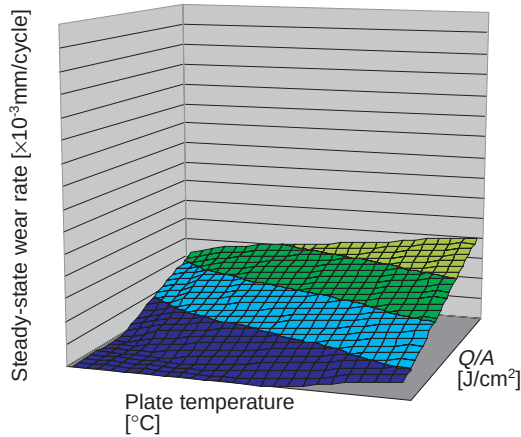


Fig. 23 Steady-state wear properties map

6. Application to the Initial Stages of Clutch Design

Changing the piston shape to increase the effective clutch diameter is often considered a means of increasing the torque capacity without increasing the clutch size. Figure 24 shows three typical formats for the piston pressing position. Viewed simply in terms of the effective clutch diameter, the torque capacity increases in the order of inner, flat and outer pressing types. However, even though the torque capacity increases, it may not be possible to use these methods if the wear amounts would also increase accordingly.

Therefore, the newly developed technology for predicting wear history was applied to these three piston formats. Figure 24 shows that the disk contact pressure distribution varies greatly depending on the piston pressing position. The inner pressing piston exhibits an even contact pressure distribution over the entire disk, but the contact pressure tends to decrease on the inside of the disk and shift towards the outside as the piston format shifts towards the flat and outer pressing types. Also, the plate temperature distribution basically shows the same tendency as the contact pressure distribution, in which the maximum temperature tends to increase as well (Fig. 25).

Next, Fig. 26 shows the results of predicting the wear history using the simulated disk contact pressure distribution, plate temperature distribution, and the facing material wear properties. The two lines in each graph represent the wear amounts in the center of the facing material inner segment as well as in the center of the facing material outer segment. The wear amounts were compared using the disks with the greatest wear amounts. The number of cycles until the maximum allowable wear amount was reached was determined for each specification. The inner pressing type was found to have the longest life, followed by the flat pressing type and outer pressing type, in that order. In addition, judging by the number of cycles required by this clutch, the outer pressing type specifications cannot be used. Examination of the gap between the two lines shows that the inner pressing type uses the entire disk surface, but there is little wear on the inside of the disk for the outer pressing type, indicating that this area is not used.

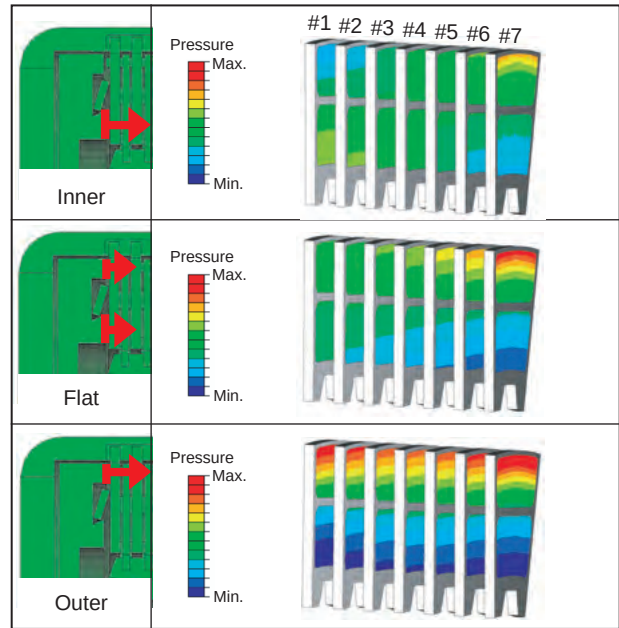


Fig. 24 Difference of contact pressure distribution

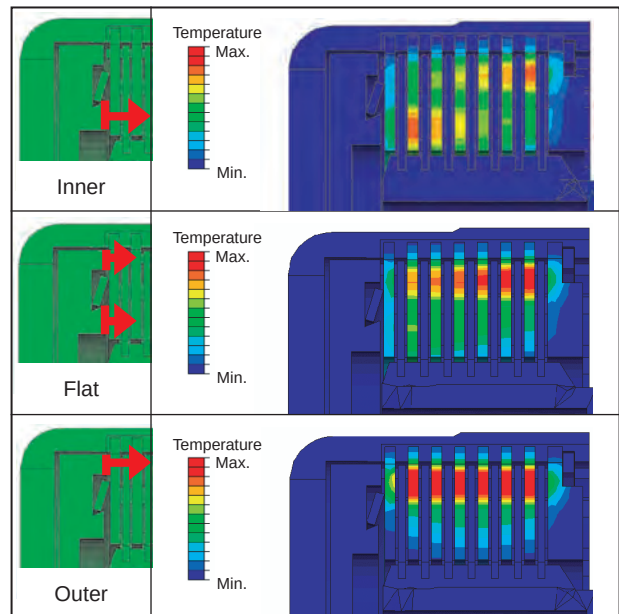


Fig. 25 Difference of temperature distribution

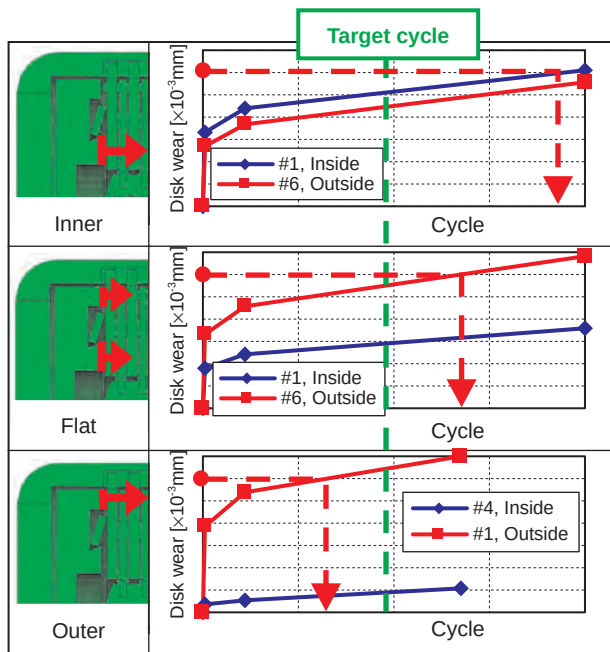


Fig. 26 Difference of amounts of wear

Thus as shown above, the newly developed technology makes it possible to set specifications, including clutch durability, in the initial design stages.

7. Conclusion

Detailed analysis of disk wear amounts in a clutch pack yielded the following information, which is needed to set specifications, including clutch durability, in the initial design stages.

- (1) Contact pressure was found to be the main factor for the initial wear amount, and maximum temperature for the steady wear amount.
- (2) Analysis technology was developed for simulating the disk contact pressure distribution and plate temperature distribution, and the disk surface status during engagement was quantified.
- (3) Wear amounts could be predicted for optional clutch specifications and operating conditions by obtaining the unique wear properties of the facing materials.

8. Afterword

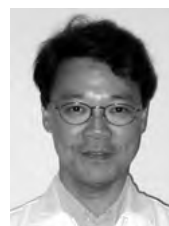
The multiple plate clutch structure has existed for a number of decades, but the manifestation of the wear properties^{(6),(7)}, vibration issues, lubricating oil flows⁽⁸⁾ and other characteristics have not yet been completely explained. Multiple plate clutches are a typical tribological mechanism, so complete quantization is difficult, but the authors hope to continue applying practical engineering approaches in the future.

References

- (1) Kato, Y., Shibayama, T.: Mechanism of Automatic Transmissions and Their Requirements for Wet Clutches and Wet Brakes, *Tribologist*, Vol. 39, No. 12, p. 6-11 (1994)

- (2) Uchida, Y., Miyamoto, O., Otani, T., Maruyama, T., Sakai, K., Tanimoto, S.: Development of New Compact 4-speed Automatic Transmission for Honda LIFE, *Honda R&D Technical Review*, Vol. 16, No. 2, p. 79-86
- (3) Inoue, M., Arai, Y., Azegami, T., Hirao, Y.: Research on Reduction of Unusual Noise in Wet Multiple Disk Clutch for 4WD, *Honda R&D Technical Review*, Vol. 15, No. 2, p. 133-138
- (4) Kato, Y., Akasaka, R., Chiba, N., Mori, Y.: Analysis on the Friction Characteristics of a Paper-Based Facing for a Wet Clutch of an Automatic Transmission, *Tribologist*, Vol. 39, No. 12, p. 71-78 (1994)
- (5) Natsumeda, S.: On the Engagement Mechanism of a Friction Plate, *NSK Technical Journal*, No. 655, p. 32-38 (1993)
- (6) Haj-Fraj, A., Pfeiffer, F.: Modeling of Wet Clutches in Automatic Transmissions, *The 2nd International Conference on Recent Advances in Mechatronics*, p. 9-15 (1999)
- (7) Miyoshi, T.: Friction Characteristics and Porosity of Friction Plate, *NSK Technical Journal*, No. 655, p. 25-31 (1993)
- (8) Miura, T., Sekine, N., Azegami, T., Murakami, Y.: Friction Property of Segment Bonded-type Wet Clutches for Automatic Transmission, *HONDA R&D Technical Review*, Vol. 10, p. 142-149

■ Authors ■



Toshihiro SAITO



Tamotsu KOTEGAWA



Yoshiteru MATSUURA



Seiichi TANAKA



Kimikazu OHTSUKI