Development of Third-Generation Electronically Controlled AWD Coupling with New High-Performance Electromagnetic Clutch

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This paper describes the development of the new third-generation electronically controlled all-wheel drive (AWD) coupling that achieves drastically improved drag torque performance and torque accuracy at low temperatures and contributes to higher fuel efficiency through weight reduction in the driveline. One issue for electronically controlled AWD couplings is an increase in torque due to higher lubricant viscosity at low temperatures, especially below 0℃ because of clutch slide with the lubricant sealed inside the couplings. The developed third-generation electronically controlled AWD coupling addresses this issue by focusing on the surface texture of the electromagnetic clutch. The third-generation coupling also restricts the torque increase by actively utilizing the dynamic pressure between the clutch plates and increasing the clearance of the clutch plates at low temperatures where viscosity increases. This enables further weight reduction in the driveline. In order to reduce drag torque at low temperatures, a macroscopic sliding surface profile in the order of tens of micrometers is provided on the electromagnetic clutch under fluid lubrication. In addition, to reduce control torque at low temperatures when electric current is applied, the microscopic sliding surface profile on the electromagnetic clutch, which is in the order of several micrometers, was optimized under boundary lubrication. This results in stable torque accuracy at both low and high temperatures.

***Key Words**: All-Wheel Drive System, Third-Generation ITCC, Electromagnetic clutch, Surface Texture*

1. Introduction

In the field of vehicle driveline components, the development of new products that contribute to improved fuel efficiency while maintaining driving stability and safety has become an urgent need from the standpoint of helping to protect the global environment. Improving fuel efficiency through weight reduction and higher driveline efficiency is particularly important for vehicles installed with an all-wheel drive (AWD) system such as that shown in **Fig 1**.

Minivans and sports utility vehicles (SUVs) based on the chassis of passenger cars have become popular all over the world. Furthermore, AWD systems are increasingly adopting couplings capable of electronically controlling the transmission torque as shown in **Fig. 2**.

The Intelligent Torque Controlled Coupling (ITCC) is an electronically controlled AWD coupling that distributes optimum torque as needed. This coupling enables excellent AWD performance and high fuel efficiency, and also allows for a high degree of matching with other control systems, such as brake and electronic stability control systems. In addition, ITCC is being further developed to achieve both higher AWD performance and fuel efficiency. It is important to stabilize torque especially under low temperature conditions, and improving this performance may help to reduce the weight of the driveline. The torque derived from clutch drag when the ITCC control current is not applied (i.e., when the clutch is not pressed) and the control torque when the control current is applied (i.e., when the clutch is pressed) increases in low temperature conditions due to higher lubricant viscosity. Improving this torque change may enable further weight reduction in the entire driveline through reviewing the driveline from the aspect of strength design.

The third-generation ITCC has been developed to achieve this aim by focusing on the surface texture of the electromagnetic clutch. It expands the clearance between the clutch plates to restrict excess increases in torque by actively utilizing the dynamic pressure between the clutch plates at low temperatures where the viscosity of lubricant increases. This enables weight reduction of the driveline and contributes to an improvement in fuel efficiency. This paper describes the high-performance technology of the electromagnetic clutch used in the third-generation ITCC.

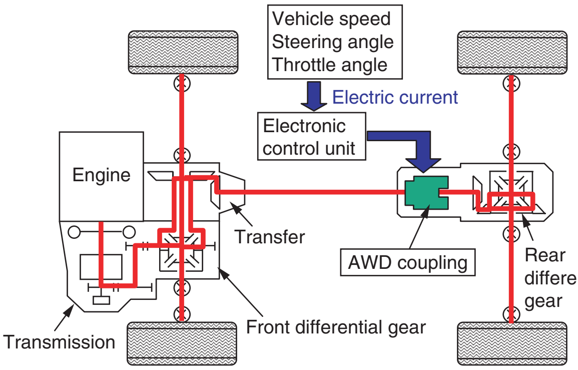

Fig. 1 Example of ITCC application

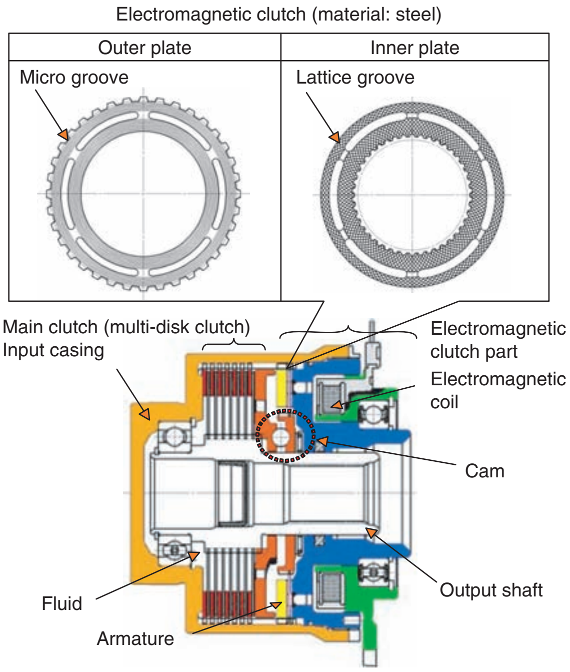

Fig. 2 Structure of ITCC

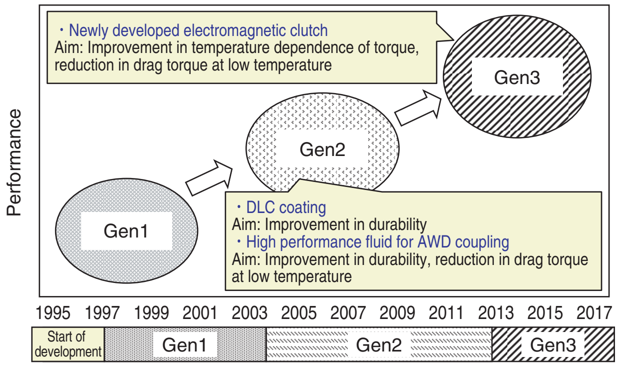

Fig. 3 History of ITCC

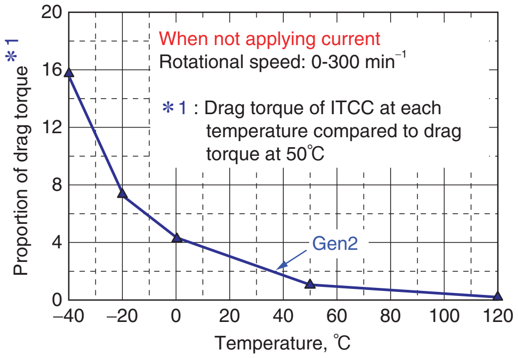

Fig. 4 Temperature dependence of drag torque of ITCC

2. History of ITCC development

Figure 3 shows the history of ITCC development. The first-generation ITCC, an electronically controlled AWD coupling, was developed in 1997 (Gen1)[1], featuring the first use of its distinct structure with an electromagnetic clutch in the world. The second-generation ITCC was released in 2004 (Gen2). Durability was significantly improved by the use of diamond-like carbon (DLC) coating[2)-4)] on the electromagnetic clutch and a special lubricant[5]. These measures expanded the usable boundary area of the AWD coupling and greatly enhanced the competitiveness of the product. In addition, improving the durability increased the clutch capacity, thereby reducing the number of clutch plates and helping to reduce size and cost.

This paper describes the third-generation ITCC (Gen3), in which the drag torque performance and torque accuracy at low temperatures were drastically improved by modifying the surface texture of the electromagnetic clutch. The third-generation ITCC is now in production.

3. High performance technology

3. 1 Reduction in drag torque at low temperatures

As shown in **Fig. 4**, the drag torque of the ITCC increases under low temperature conditions. This is caused by increased lubricant viscosity. The second-generation ITCC uses a special lubricant with a synthetic base oil. This reduces the increase in viscosity under low temperature conditions compared with a general mineral series lubricant. However, it was necessary to modify the sliding surface to further reduce the drag torque.

Figure 5 shows the Stribeck curve. The range of lubrication examined in this study is in the hydrodynamic lubrication region as shown in **Fig. 5**. **Figure 6** indicates the influence of each component on the drag torque of the ITCC. The electromagnetic clutch alone contributes five percent of the ITCC drag torque. However, considering torque amplification by cam mechanism, this is equivalent to 88 percent of the overall total drag torque. Therefore, reducing the drag torque depends largely on improving the electromagnetic clutch.

To reduce the drag torque of the electromagnetic clutch, this study focused on the surface texture of the clutch. **Figure 7** shows a general equation of shear stress, which indicates how to reduce the drag torque. The drag torque increases due to higher lubricant viscosity especially under low temperature conditions, but can be reduced by expanding the clearance between the clutch plates. Therefore, crowning of several tens of micrometers (μm) was provided on each land portion of the inner plate surface as shown in **Figs. 8** and **9**. As a result, it was found that the drag torque at –40℃ decreases linearly with the increase in the amount of crowning as indicated in **Fig. 10**. This has a remarkable effect, especially when lubricant viscosity increases under low temperature conditions. The crowning allows the active use of high-viscosity lubricant to effectively leverage the hydraulic reaction force in the direction that expands the clearance between the clutch plates. In contrast, in above-normal temperatures, this hydraulic reaction force is adjusted to prevent a trade-off relationship. Without this adjustment, an excess increase in the hydraulic reaction force due to greater slip velocity would create a negative μ-v characteristic slope (index of vibration resistance: dependence of friction coefficient on velocity) and generate shudder.

Figure 11 compares the drag torque of the second and third generation ITCC units. Especially below 0℃, the drag torque of the third-generation ITCC is approximately 50 percent lower than the second-generation ITCC.

The crowning provided on the inner plate surface allows for a significant reduction in the drag torque.

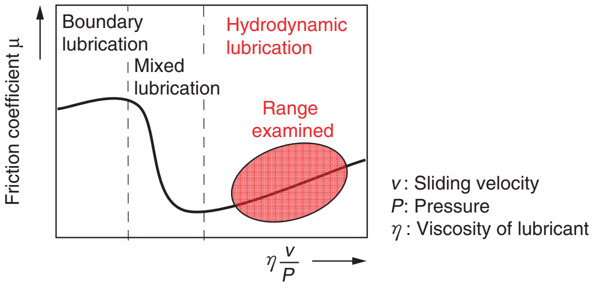

Fig. 5 Illustration of range examined using Stribeck curve (drag torque)

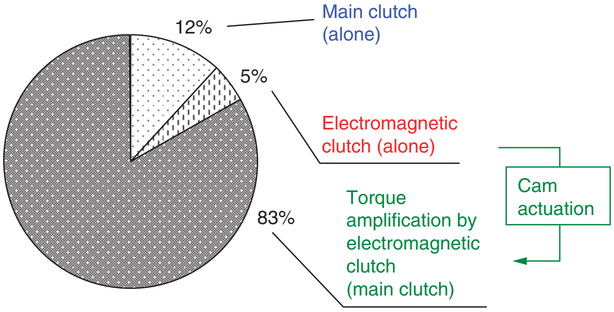

Fig. 6 Contribution of ITCC components to drag torque

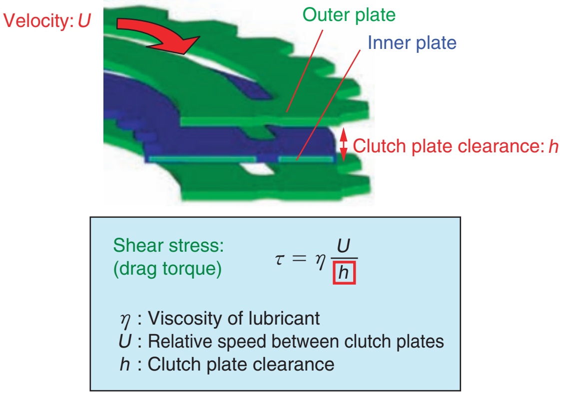

Fig. 7 Method of reducing drag torque

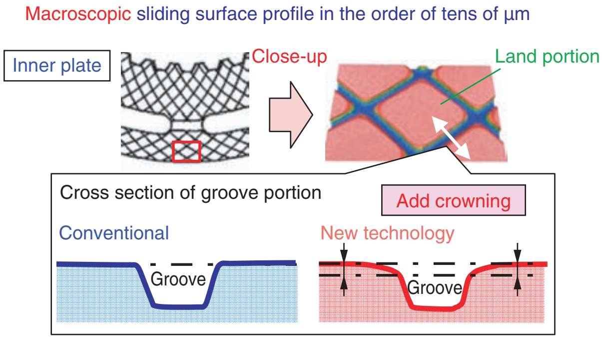

Fig. 8 Reducing drag torque by adopting macroscopic sliding surface profile (crowning)

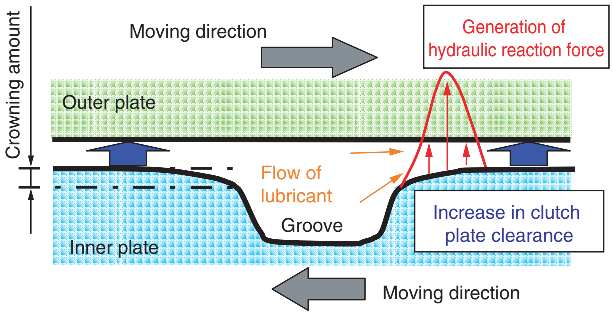

Fig. 9 Mechanism of drag torque reduction at low temperature with crowning

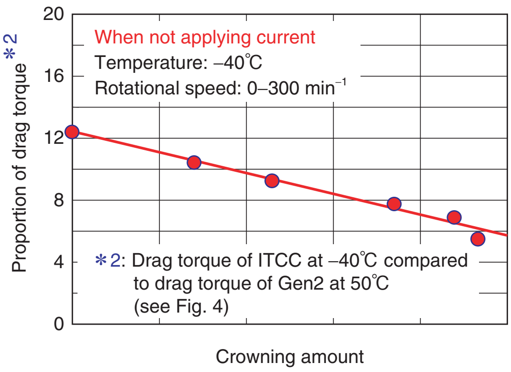

Fig. 10 Effect of crowning on reduction in drag torque at low temperature

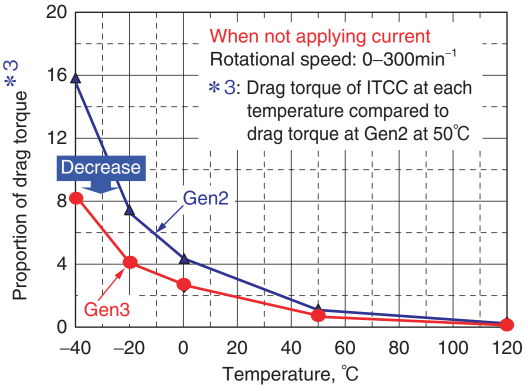

Fig. 11 Temperature dependence of proportion of drag torque in actual ITCC units

3. 2 Improvement in torque accuracy at low temperatures

The range of lubrication examined in this study lies in the boundary lubrication region on the Stribeck curve as shown in **Fig. 12**. In order to control this boundary friction, the optimization of the microscopic sliding surface profile of the electromagnetic clutch was examined theoretically and experimentally. **Figure 13** illustrates the friction between the sliding materials (i.e., the inner and outer plates) in oil. The friction is considered to be a mixture of fluid friction due to the shearing resistance of the lubricant and boundary friction due to solid contact 6).

Figures 14 and **15** show the simplified models of the friction interface between the outer and inner plates used for theoretical analysis.

The normal force F_1 of the boundary friction area caused by the clutch pressing force F_0 is represented in Equation (1)

$$F_1 = F_0 - \iint P r dr d\theta \qquad (1)$$

where, P is the hydraulic reaction force of the lubricant, and r and θ indicate the radial direction to the sliding direction, and the circumferential direction (the sliding direction), respectively, as shown in **Fig. 14**.

The torque T_F caused by solid friction is expressed in Equation (2)

$$T_F = \int \frac{2\pi r^2 F_1 \mu_b}{A} dr \qquad (2)$$

where, A represents the apparent contact area of the sliding portions, and μ_b represents the coefficient of boundary friction between solids.

Next, the torque T_f caused by the viscosity of the lubricant is expressed as follows.

$$T_f = \iint \tau r dr d\theta \qquad (3)$$

where, τ is the shear stress of the lubricant working on wall surfaces. As the following equations show, P is

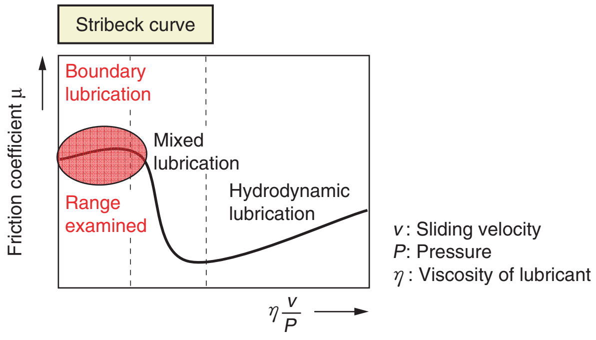

Fig. 12 Illustration of range examined using Stribeck curve (control torque)

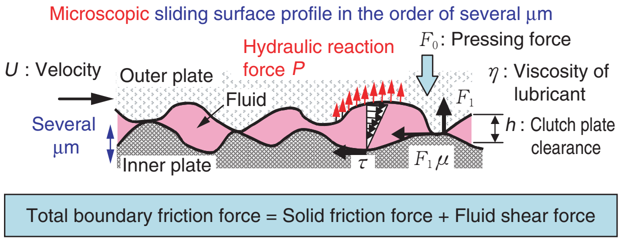

Fig. 13 Control of boundary friction on microscopic sliding surface profile

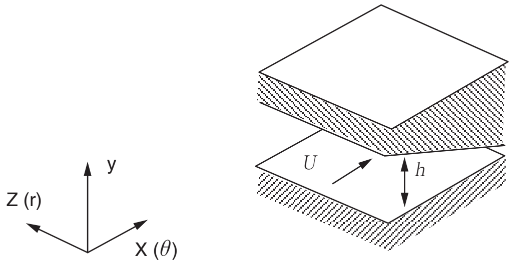

Fig. 14 Wedge-shaped clearance

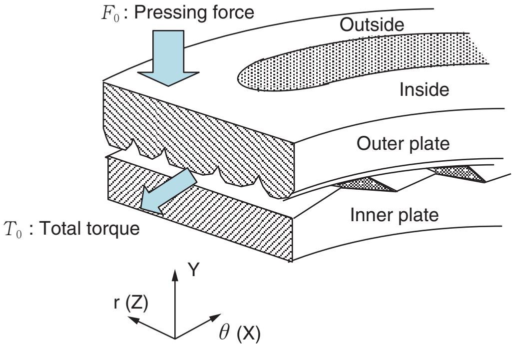

Fig. 15 Friction surface profile model of electromagnetic clutch

expressed by a simplified hydrodynamic motion equation and τ is expressed by a Newtonian viscosity equation.

$$h^3 \frac{\partial^2 P}{\partial x^2} + h^3 \frac{\partial^2 P}{\partial z^2} = 6MU \frac{dh}{dx} \tag{4}$$

$$\tau = \frac{h}{2}\frac{dP}{dx} + M\frac{U}{h} \tag{5}$$

where, M represents the viscosity of the lubricant and U represents the sliding velocity. The total torque T_0 is as follows.

$$T_0 = T_F + T_f \tag{6}$$

Thus, the optimum total friction, including the boundary friction, was examined considering the hydraulic reaction force and the fluid friction due to the shearing resistance of the lubricant.

Under low temperature conditions where the viscosity of the lubricant increases, an excess increase in control torque is restricted by actively utilizing the hydraulic reaction force and increasing the microscopic oil film. **Figure 16** shows the three-dimensional shape of the micro-grooves provided on the outer plate. The micro-groove is a microscopic surface profile in the order of several µm. This microscopic sliding surface profile controls the boundary friction.

The optimum micro-groove pitch of the outer plate obtained by the theoretical analysis described above was examined. **Figure 17** indicates the micro-groove pitch and rate of torque change (i.e., the proportion of the change in the control torque at –40℃ compared to that at 50℃). The solid line shows the calculated values, and the points are the experimental values. Both the experiment and analysis were conducted with crowning (fixed) provided on the inner plate. **Figure 17** indicates that the calculated values accurately simulated the experimental values. As the micro-groove pitch of the outer plate increases, the torque change rate decreases and there exists an optimal pitch where the control torques at 50℃ and –40℃ become equal. If the micro-groove pitch is expanded further the thickness of the macroscopic oil film in accordance with the increase in sliding velocity become too large, a negative μ-v characteristic slope is created and eventually shudder occurs. Based on these results, the micro-groove pitch is expanded on the third-generation ITCC to adjust the control torque at low temperatures so as not to increase significantly over the control torque at 50℃. Since the adoption of a DLC-Si coating in the second-generation ITCC already improved the wear resistance of the clutch considerably, the micro-groove pitch can be expanded.

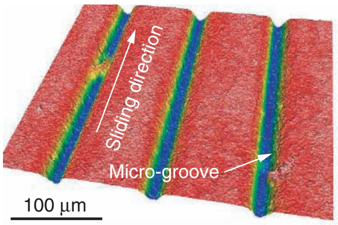

Fig. 16 Three-dimensional image of micro-groove

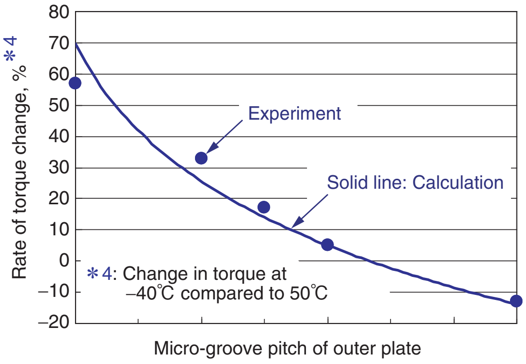

Fig. 17 Effect of micro-groove pitch on rate of torque change

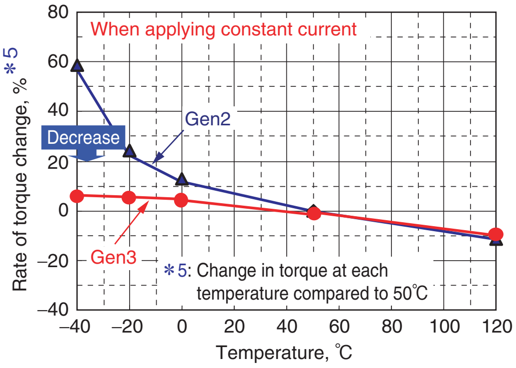

Fig. 18 Temperature dependence of rate of torque change in actual ITCC units

Figure 18 shows the proportion of control torque change at each temperature for the second and third generation ITCC units based on the torque at 50℃. Especially below 0℃ the third-generation ITCC dramatically reduces the control torque. When both change rates are compared at –40℃, the third-generation ITCC improves by about 85 percent over the second-generation unit.

4. Conclusion

Figure 19 summarizes and compares the surface profiles of the second and third generation clutches. For the third-generation clutch, the inner plate is provided with macroscopic crowning in the order of tens of µm, and on the outer plate, the pitch of the micro-groove with the microscopic surface profils in the order of several µm is adjusted. This drastically improves drag torque and torque accuracy at low temperatures.

Therefore, the ITCC performance is enhanced remarkably by optimizing the surface texture of the electromagnetic clutch. It is hoped that the third-generation ITCC can further contribute to the protection of the global environment in the future by helping to reduce the size and weight of the vehicle driveline.

The major findings from this research and development are described as follows:

(1) By focusing on the hydraulic reaction force derived from the macroscopic sliding surface profile and providing crowning on the sliding surface, the drag torque at low temperatures was reduced by about 50 percent.

(2) By optimizing the micro-groove pitch of the sliding surface, which controls the boundary friction force, the temperature dependence of torque was improved by about 85 percent.

(3) The newly developed third-generation ITCC drastically improved drag torque performance and torque accuracy at low temperatures, and can contribute to higher fuel efficiency and weight reduction in the driveline.

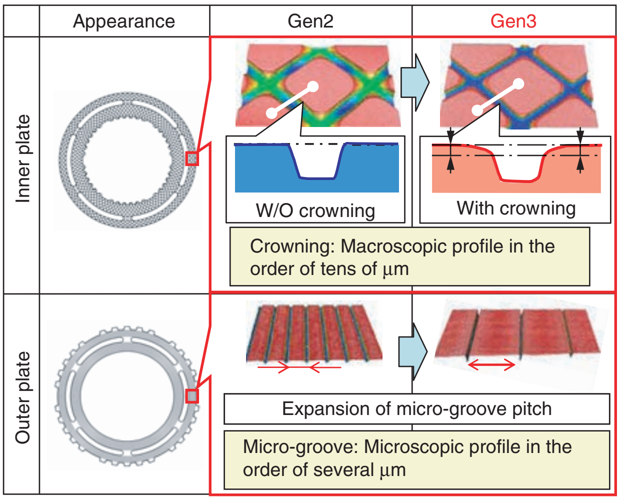

Fig. 19 Comparison of surface profiles of second and third generation electromagnetic cluthes

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