New Products

Development of New Brake Pads for Shinkansen

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Abstract

The Shinkansen has become increasingly faster for greater efficiency since its introduction. On the other hand, reducing stop distances is becoming essential since the Shinkansen must ensure safety even at higher speeds. The performance required of mechanical brakes that are activated during emergencies is extremely high in Japan that is an earthquake-prone country. New brake pads with a spring structure were developed for the Shinkansen disk brakes to solve the reduced braking performance caused by localized contact with the disk, which has been a problem with conventional rigid pads. The new brake pads have contributed to achieving higher speeds by reduction of the stopping distances of the Shinkansen.

1. Introduction

Since its opening in Japan, the Shinkansen has gradually increased its maximum speed[1] and has greatly improved the convenience of rail transport. As the speed has increased, the importance of safety assurance has increased, and technology development for this purpose has become essential. A mechanical braking system is one of the most important components that support the safety of the Shinkansen. Shinkansen brake systems[2] mainly use motorized regenerative brakes during normal operation. In emergencies such as an earthquake, however, mechanical braking systems must be used to stop the trains. Therefore, even if the speed increases, the braking distance with mechanical brakes must be made as short as possible, and improving the braking performance is essential from the perspective of maintaining safety.

Figure 1 shows the appearance and configuration of a disk brake system, which is a mechanical brake system adopted in the Shinkansen. The disk brake system is composed of a brake disk (hereinafter also called a disk), a brake pad (hereinafter also called a pad), and a caliper. The caliper pushes the pad against the rotating disk to brake the train. When the Shinkansen is running, the disk rotates together with the wheel at high speed. Therefore, when the Shinkansen is braked suddenly at high speed during an earthquake, for example, the friction heat between the disk and the pad causes the friction surface (also called the sliding surface) to become hot. If the contact between the disk and the pad becomes uneven and only partial, localized high-temperature regions (heat spots) occur and can exceed 1000°C.[3] High thermal stress occurs at the heat spots and may cause cracks on the disk surface and further cause various problems, such as decrease in braking force. Therefore, shortening the braking distance while increasing the speed requires the development of technology to make the contact between the disk and the pad as uniform as possible.

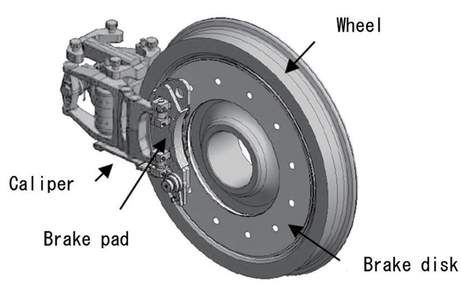

Fig. 1 Disk brake system for Shinkansen[5]

To solve the above problems, Nippon Steel Corporation focused on the pads among the components of the disk brake system and decided to develop a pad with a new structure that can make contact with the disk uniform.[4] This report summarizes the contents of our literature.[5]

2. Features of New Brake Pad

Before we explain Nippon Steel's new pad, we will provide an overview of the conventional pads and problems will be presented as a comparison. **Figure 2** shows the appearance of a conventional

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rigid pad. The rigid pad is constructed of eight sintered copper friction material sheets riveted to a single steel plate. Therefore, the rigid pad is pressed against the disk as a single plate. When friction heat is generated by sudden braking from a high speed, the disk is thermally deformed by several millimeters, but because the rigid pad is a single rigid plate, it only comes into localized contact with the disk, resulting in heat spots.

Considering the causes of heat spots as described above, the pad structure to suppress the heat spots becomes as shown in **Fig. 3**. As shown in Fig. 3, it is important to construct such a structure where the pad can move to follow the thermal deformation of the disk without locally contacting the thermally deforming disk. On the other hand, as the structure to make the pad movable is complicated, problems occur in terms of weight, durability, and space. Thus, Nippon Steel has devised such a structure where the new pad is divided into multiple friction materials, and each friction material is made movable by a spring. In particular, a structure with dish springs was adopted to obtain the necessary spring force while saving space. **Figure 4** shows the appearance of the new pad and a schematic cross-sectional diagram of the friction material block. The structure of the friction material block is such that two friction materials are joined on a steel plate called a back metal and each is connected to a rivet through a dish spring. Consequently, a simple and flexibly movable structure is obtained.

3. Study of Optimal Structure of New Brake Pad

In the new pad described in the previous section, the layout of the friction material blocks and the spring constant of the dish springs are important for achieving uniform contact between the disk and the pad. Here, we first show the results of our investigation into the optimal layout of the friction material blocks.

FEM simulation was used to study the layout of the friction material blocks. **Figure 5** shows the FEM simulation model developed by Nippon Steel for pad evaluation. In this model, ten types of parts, including the dish springs and rivets, are precisely recreated, making it possible to accurately simulate the contact state between the pad and the disk. As mentioned in the previous section, the disk is thermally deformed to cause uneven contact between the pad and the disk. It is thus important to simulate the contact when the disk is thermally deformed. A separate FEM simulation was conducted to evaluate the thermal deformation of the disk. The separate FEM simulation found that the disk during braking deforms to make its sliding surface convex as shown in Fig. 3. Therefore, the amount of disk deformation after the thermal deformation as determined by the separate FEM simulation is reflected in the disk shape of the model shown in Fig. 5, so that the contact of the thermally deformed disk with the pad is accurately reproduced.

To efficiently obtain an optimal solution for the layout of the friction material blocks, we must obtain the target results while minimizing the number of simulation conditions. For that purpose, it is best to consider the restrictions imposed by the system configuration and size, to limit the regions where the friction material blocks can be arranged, and to determine such a layout so as to ensure uniform contact between the disk and the lining. Specifically, we adopted the following ideas:

(1) If a friction block is placed at or near the piston (pressure) position of the caliper, the load acting on the friction block increases and causes uneven contact between the pad and the disk. Therefore, the friction block is placed to avoid the piston position.

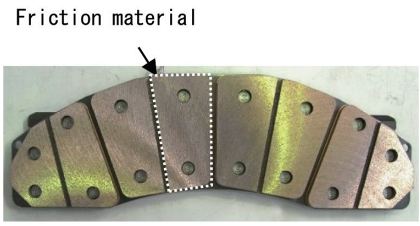

Fig. 2 Brake pad for Shinkansen (Rigid brake pad)[5)]

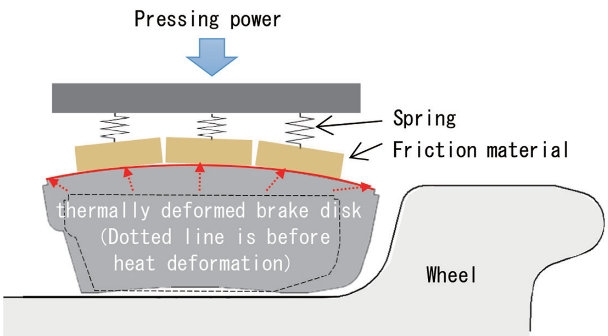

Fig. 3 Cross-sectional schematic illustration of contact between thermally deformed brake disk and new pad[5)]

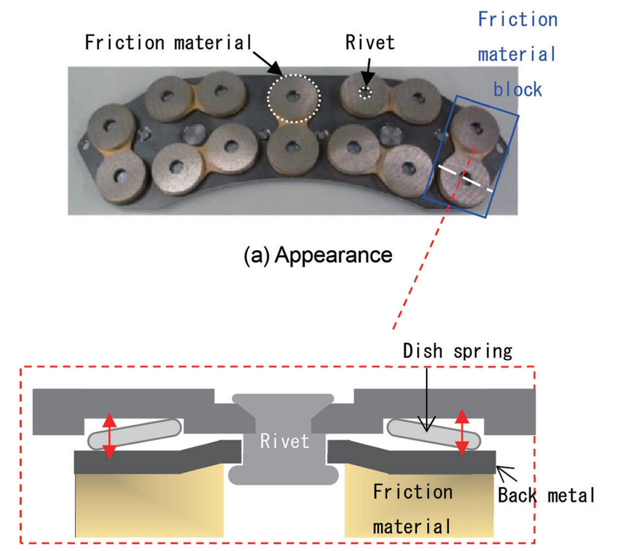

Fig. 4 New brake pad for Shinkansen[5)]

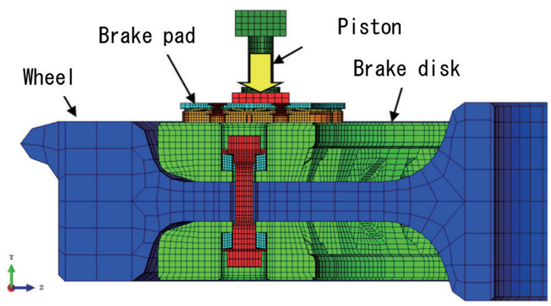

Fig. 5 FEM simulation model[5)]

(2) When the disk is thermally deformed, its sliding surface becomes convex. There is a height difference of several millimeters between the apex and both ends of the convex surface. Therefore, if a friction material block is placed at the apex of the convex surface, the deformation of the dish spring alone cannot keep up with the deformation of the disk, and uniform contact is not obtained. Therefore, we decided not to place a friction material block at the position corresponding to the apex of the thermally deformed convex surface.
(3) It is best to arrange the friction material blocks at equal distances from each other so that they are equally loaded. Arranging the friction material blocks at equal distances while satisfying the conditions (1) and (2) above makes it possible to obtain uniform contact between the disk and the pad.
(4) The above are the restrictions that must be considered to ensure uniform contact between the disk and the pad. There are other restrictions as well. An especially important restriction is the size of the friction material blocks. The disk has a through hole on the sliding surface for bolt fastening. If the friction material is smaller than the bolt hole, it may fall into the bolt hole during braking. For this reason, the size of each friction material must be larger than the bolt hole of the disk so that it does not fall into the bolt hole.

When the layouts of the friction material blocks to satisfy the conditions (1) to (4) above are narrowed down, there remain a few layouts that need to be considered. FEM simulation of the remaining layouts provides the layout where the contact between the pad and the disk becomes most uniform. The study process is omitted here. The layout shown in **Fig. 6** was obtained as the optimal solution.

To verify the validity of this evaluation, we created models of layouts that did not satisfy any or more of the conditions (1) to (4) above and compared them with the results of the optimal layout. The results are shown in **Fig. 7**. Layout 4 in Fig. 7 corresponds to the layout shown in Fig. 6. The pros and cons of the respective layouts were evaluated based on the scatter of the load acting on the friction materials. Specifically, the standard deviation of the load acting on the 14 friction materials was used as an index. The smaller the standard deviation, the more uniform the contact between the pad and the disk was judged to be. Compared to Layouts 1 and 2, which do not satisfy the conditions (1) and (2) above, Layouts 3 and 4, which satisfy the conditions (1) and (2) above, have a significantly reduced standard deviation and a smaller scatter of the load. Furthermore, Layout 4, which satisfies condition (3), has the effect of reducing the scatter of the load compared to Layout 3. In this way, it can be said that the friction material layout was determined efficiently by applying the above-mentioned approach.

Another important study item is the spring constant. If their spring constant is small, the dish springs deform excessively, cannot withstand the pressing load from the caliper, and collapse. If their spring constant is large, on the other hand, the dish springs cannot deform sufficiently, do not allow the pad to follow the thermal deformation of the disk, and cause the pad to contact the disk only locally. Because the spring constant of the dish springs depends on their shape,[6] we studied the optimal dish spring shape by using the FEM simulation technique, just as we did when we studied the friction material layout. The details of the results are omitted here. We designed the optimal dish spring shape to maximize the contact area of the dish spring with the thermally deformed disk.

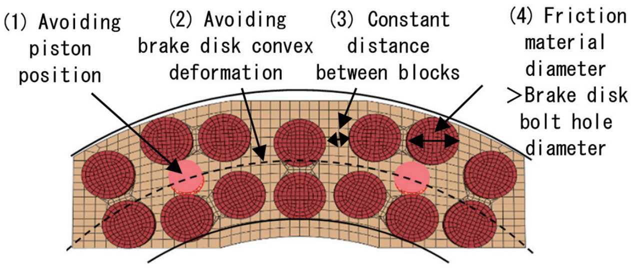

Fig. 6 Layout of developed friction material blocks[5]

Layout	(1) Block at piston position	(2) Block at brake disk convex deformation position	(3) Distance between blocks	(4) Friction material diameter
1	With	Without	Not constant	Diameter larger than brake disk bolt hole
2	Without	With	Not constant	
3	Without	Without	Not constant	
4	Without	Without	Constant	

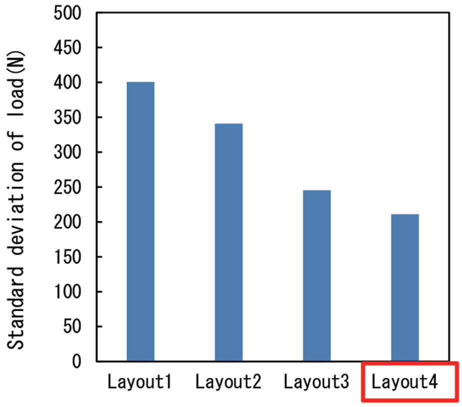

Fig. 7 Standard deviation of load for each friction material block[5]

4. Development of Brake Squeal Control Pad

The studies in the previous sections aimed to improve braking performance and durability by making the contact between the disk and pad uniform. On the other hand, another performance required of the disk brake system is quietness. The reduction of noise, especially when called brake squeal, is a challenge. The brake squeal is a high-pitched noise that occurs during braking.[7] It is necessary to reduce the brake squeal from the standpoint of reducing the environmental impact and ensuring passenger comfort.

To efficiently study measures to reduce the brake squeal, it is a good idea to utilize the FEM simulation technique as described in Section 3. However, methods for evaluating the brake squeal, especially from railroad disk brake systems, have not been fully established. Therefore, following the evaluation methods traditionally used in the automobile sector, we first tried to obtain the attenuation ratio from FEM complex eigenvalue analysis and evaluate the brake squeal using the obtained values.[8] The attenuation ratio is an index that indicates the degree to which the vibration changes over time. A positive value means that the vibration gradually subsides, and a negative value means that the vibration diverges and squeals occur.

Figure 8 plots the negative attenuation ratios at each input frequency obtained by analysis of the new pad (base shape) proposed in the previous sections and the countermeasure shape described later. In Fig. 8, each plot point indicates the frequency at which the brake squeal occurs. As shown in Fig. 8, the new pad has many divergent frequencies due to its structure. It is difficult to judge the brake squeal magnitude relationship between the base shape and the countermeasure shape from Fig. 8. Therefore, the sound pressure for each 1/3 octave band, which is often used in noise evaluation, was added up. The noise level at the representative frequency was used as an index of the quietness of the pad.[9] The sum of the attenuation ratios within the frequency band (defined as the squeal index) was calculated, and a comparative evaluation was performed using this index. When we compared the squeal index and the experimentally obtained noise level, we found that the squeal index becomes maximum at the frequency where the noise level is highest. The maximum value of this squeal index was defined as the "maximum squeal index" and was used as the evaluation index of brake squeal.

As a result of various studies we conducted using the established evaluation method, we found that increasing the rigidity of the friction material block is effective in reducing the brake squeal. **Figure 9** shows the brake squeal control friction material block shape developed based on the study results. **Figure 10** compares the countermeasure shape and the base shape in the maximum squeal index. The countermeasure shape reduced the maximum squeal index by 13% compared to the base shape. **Figure 11** shows the results of the brake squeal noise level measured using the base and countermeasure brake pads. These results also show that the countermeasure shape can reduce the brake squeal.

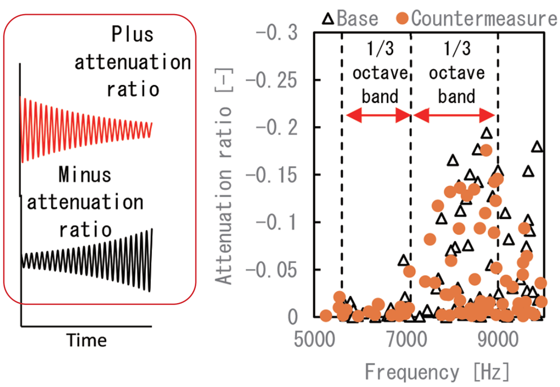

Fig. 8 Results of brake squeal evaluation by conventional method[5]

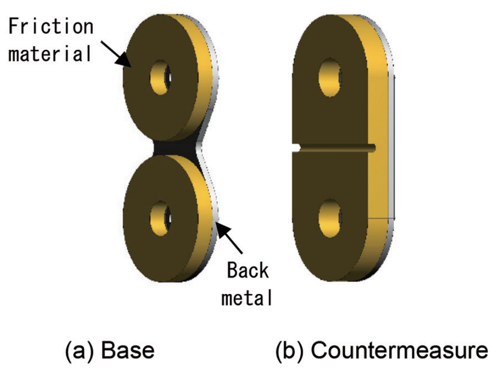

Fig. 9 Shape of improved friction material block for brake squeal[5]

5. Performance Evaluation of Prototype

As described above, using the FEM simulation, we succeeded in proposing a new brake pad structure that can reduce the brake squeal while keeping the contact between the disk and the pad uniform. To evaluate the actual braking performance of the new brake pads, we prototyped new brake pads and conducted a braking test with the prototype new pads. **Figure 12** shows the appearance of the new brake pad. The most expected effect of the new brake pad is reduction of the temperature of the disk during braking. For this purpose, we measured the temperature of the disk sliding surface with an infrared camera. This infrared camera can take pictures at high speed and is designed to take pictures synchronized with the rotation of the disk. The infrared camera makes it possible to observe the change in the temperature distribution on the disk surface always at the same position. As an example of the obtained results, **Fig. 13** shows the temperature distribution at the time when the disk temperature is highest. For comparison, Fig. 13 also shows the brake surface temperature when a conventional rigid pad is used. A comparison of the disk sliding surface shows that the disk sliding surface temperature is more than 100°C lower for the new brake pad than

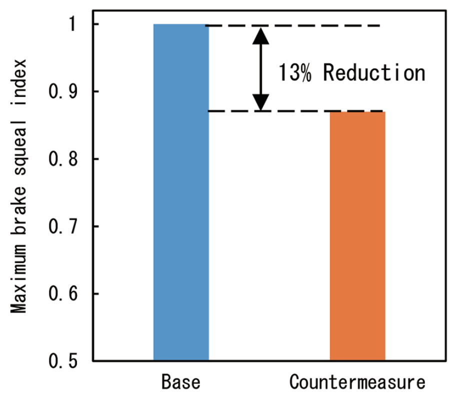

Fig. 10 Results of brake squeal evaluation by the devised method[5]

Item	Before brake squeal improvement	After brake squeal improvement
Noise level (dB)	94	86
Friction material shape		

Fig. 11 Brake squeal evaluation results[5]

Fig. 12 New brake pad[5]

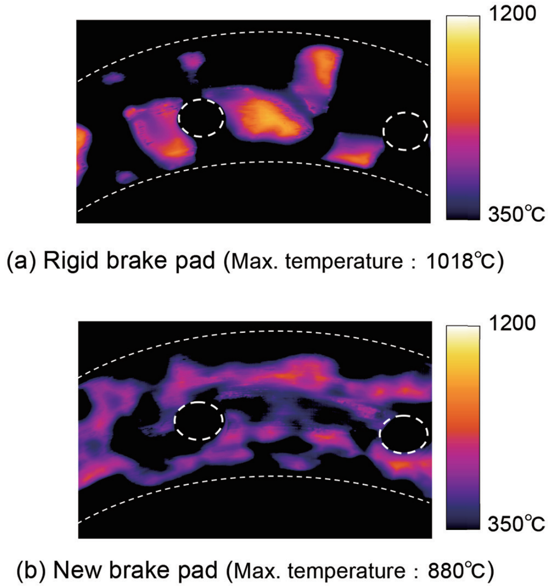

Fig. 13 Measured brake disk surface temperature during braking[5)]

Table 1 Comparison of performance of brake pads[5)]

Item		Rigid brake pad	New brake pad	Difference
Brake disk	Max. surface temperature (°C)	1018	880	−14%
	Warpage of outer side (mm)	0.17	0.09	−47%
Brake pad	Max. temperature (°C)	932	852	−9%
	Reduction of thickness by wear (mm)	0.23	0.10	−57%
Brake force	Average coefficient of friction	0.26	0.29	+12%

for the rigid brake pad. It can also be seen that the sliding surface temperature distribution is wider for the new brake pad than for the rigid brake pad. As described in this section, we have been able to avoid local contact using the new brake pad and to achieve reduction of the disk temperature using the new brake pad as initially targeted.

Table 1 shows the results of the comparison of performance parameters between the new pad and the rigid pad as evaluated in actual brake tests. The new pad not only reduces the temperature of the disk and the pad, but also has other noteworthy advantages. One such advantage is the increase in the average coefficient of friction. This result shows that it is possible to stabilize the coefficient of friction at a high value by optimizing the layout of the friction materials of the same type. Both characteristics are necessary for shortening the braking distance. We can say that the new pad has made a significant contribution to this achievement.

6. Summary and Future Prospects

To shorten the braking distance to ensure safety in an emergency as the speed of the Shinkansen increases, we investigated a new type of pad that can ensure uniform contact between the disk and the pad in the disk brake system. By dividing the friction material into several pieces and supporting each piece with a dish spring, we were able to make the friction material uniformly contact the disk by utilizing the deformation of the dish spring even when the disk is thermally deformed during braking. By making full use of the FEM simulation model developed by Nippon Steel, we clarified the optimal layout of the friction materials and the optimal spring constant of the dish springs to maximize the performance of the brake pad. In addition, we proposed a friction material block shape that can reduce the brake squeal to ensure quietness. We prototyped the new brake pad devised as described above and evaluated its performance in a full-scale brake test. We confirmed that the maximum temperature during braking is reduced by more than 100°C compared to the conventional rigid pad and that the coefficient of friction increases and stabilizes. These results greatly contribute to shortening the braking distance. We have succeeded in developing a new pad that can accommodate the increase in the speed of the Shinkansen.

The new pad adopts an extremely simple structure in which the dish springs are fastened with rivets. The new pad is, therefore, advantageous not only in terms of performance, as mentioned above, but also in terms of cost. In addition, a space-saving spring structure allows the new brake pads to be installed in current vehicles without changing their specifications, making it possible to minimize the investment required when adopting the new brake pads. Needless to say, the adoption of the new pads will have a significant effect on improving convenience when the speed of the Shinkansen is increased. In addition to shortening the braking distance, the thermal load on the disk is made uniform. The uniform thermal load is expected to suppress the occurrence of disk cracks and reduce the disk replacement frequency.

It has already been decided that the new brake pads we have developed will be adopted in all vehicles of the Tokaido Shinkansen. The new brake pads are expected to be installed in more vehicles. Achieving both higher speed and shorter braking distance will remain one of the most important issues in the future. As the application of new brake pads to next-generation Shinkansen trains is also on the horizon, we would like to continue the development of even more evolved and advanced brake pads based on the knowledge gained in this development project.

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