Method for Evaluating Brake Friction Materials Using High-temperature Friction Test Apparatus

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At the speedup of the railway vehicle, it is required to develop brake friction materials usable under a thermal load increased due to the improvement of braking force. A full-size bench test is essential for evaluating the performance of the mechanical brake conclusively, but it takes a lot of time and efforts to evaluate the friction coefficient of the brake friction materials at high temperature. Therefore, we investigate a method for evaluating the brake friction materials more easily than evaluating them using a full-size bench test. This paper introduces a method for quantitatively evaluating the friction coefficient at arbitrary temperature using a high-temperature friction test apparatus, and the availability of this method by comparing the results obtained by this method with that obtained by a full-size bench test.

**Keywords:** friction material, friction coefficient, high-temperature property, friction test apparatus

1. Introduction

Mechanical brakes on railway vehicles convert a vehicle’s kinetic energy into frictional heat. As brakes are applied, braking friction material (hereinafter “friction material”) is pressed onto the wheels and discs, generating frictional force, which decelerates the vehicle.

A vehicle’s maximum running speed depends heavily on the performance of the mechanical brakes used. Therefore, in order to allow faster rail services, new friction material capable of handling the increased thermal load resulting from the increased braking force needs to be found. The selection process to find appropriate friction material normally involves a full-size bench test (Fig. 1) for simulating the anticipated maximum braking loads (wheel load, speed, pressing force) and verifying the material’s performance, amongst others, to check if its friction coefficient under the higher thermal loads meets the target value; the target stopping distance and deceleration can be achieved by adjusting the brake cylinder pressure in the currently available range; and ensure the temperatures of the wheel, disc and friction material do not exceed the target values. If the material’s friction coefficient in high temperature conditions does not meet the target value, new material expected to meet the target value must be prepared and tested. This process must be repeated with a full-size bench test until a material that does meet the target braking performance is found.

While a full-size bench test is indispensable for final evaluation of braking performance, the method described above to evaluate material’s friction coefficients in high temperature conditions, is time and effort consuming. This paper discusses high-temperature friction test apparatus capable of measuring the friction coefficient of materials at given temperatures in a simpler way without requiring the full-size bench test, and compares the apparatus’s test results with corresponding results from a full-size bench test to clarify the apparatus’s applicability.

Fig. 1 Full-size bench test on a mechanical brake [1]

2. Study of method for measuring friction coefficient at arbitrary temperatures

2.1 Selection of a friction test method

Material friction and wear tests can be conducted in a range of ways based on the type of contact (point, line or surface) or motion (sliding or rolling) [2, 3]. JIS specifies wear tests on certain materials including fine ceramics and plastics. While JIS has no specified tests on metal materials, in 1999, the Japan Society of Mechanical Engineers proposed three standard methods for wear tests: block on ring type, pin on disc type and thrust cylinder type [4]. Figure 2 shows those three test methods.

The present study aims to evaluate friction materials for electric Shinkansen vehicles, where friction material is pressed onto the disc for surface-to-surface friction as shown in Figure 1, consequently, surface-contact friction tests were deemed preferable. Of the three test methods mentioned above, the pin-on-disc and thrust-cylinder methods are based on surface-to-surface contact. However, compared with the pin-on-disc method, the thrust-cylinder
method offers the following benefits: higher degrees of freedom for the shape and dimensions of test pieces and the facility to vary the set surface contact pressure by adjusting the applied load. Furthermore, the thrust-cylinder method allows high frequency induction heating coils to be installed easily: as such, friction tests in this study were conducted using the thrust-cylinder method.

![Diagram of induction heating](Image)

**Fig. 2 Standard Method for Wear Test specified by the Japan Society of Mechanical Engineers** (Source: Japanese Society of Tribologists: Wear and friction testers and their applications, Yokendo, pp.260, 2007)

2.2 Method for heating friction materials

Figure 3 outlines high frequency induction heating. High frequency induction heating works on the principle of electromagnetic induction where high frequency alternating current is sent through a coil wound around a conductor causing a change in the magnetic flux, which then brings about a potential difference on the conductor. Electromagnetic induction generates eddy currents through the conductor, and the eddy currents together with the resistance of the conductor generate Joule heat, which heats the conductor. The density of the current through the conductor is highest on the surface and tapers off towards the center. This is called the skin effect of current density. The effect is more significant with higher frequency alternating current [5].

Steel and other magnetic materials are often used as the conductor for high frequency induction heating. In high frequency induction heating, magnetic materials generate heat due to hysteresis loss associated with changes in the magnetic flux [6]. This heat generation and the Joule heat mentioned earlier are an effective means for heating the conductor.

This study specifically looks at copper-based sintered alloys that are used as brake friction material on electric Shinkansen vehicles. Copper-based sintered alloys are difficult to heat through induction (due to their resistance and magnetic permeability both being low). Accordingly, the friction material test piece was configured as shown in Fig. 3 (b). The test piece measured 80 mm in outside diameter and 40 mm in overall length and was placed inside an induction heating coil. In high frequency induction heating, heat generated in the steel material is transmitted to the friction material, thus helping it to heat up more easily. The test piece shown in Fig. 3 (c), consisted of a piece of steel material and a 10-millimeter-thick piece of copper-based sintered alloy, joined together by diffusion sintering.

Figure 4 shows a piece of friction material being induction heated. Figure 4 (a) shows the friction material before induction heating started. In Fig. 4 (b), which shows the material 500 seconds after induction heating started, the periphery of the material was glowing red. In Fig. 4 (c), which shows the material 600 seconds after induction heating started, the entire piece was glowing with the periphery glowing more brightly. Fig. 4 (d) shows that 700 seconds after heating, compared to 600 seconds after heating began, the brightly shining portion has spread further towards the center. This demonstrates that heat transmitted from the steel material helps the friction material to heat up. It was also observed that in induction heating the outside and center areas of the friction material glowed with different levels of brightness. This indicates that with conductors the surface can heat up more easily than the center due to the skin effect mentioned earlier, meaning that there are temperature gradients in friction materials.

![Friction material in induction heating](Image)

(a) Principle of high frequency induction heating  
(b) Method for heating friction material test pieces  
(c) Friction material test piece

![Friction material in induction heating](Image)

(a) Before heating  
(b) After 500 seconds  
(c) After 600 seconds  
(d) After 700 seconds

**Fig. 3 Outline of high frequency induction heating**

**Fig. 4 Friction material in induction heating**
friction material as it heats up more easily. Accordingly, the example in Fig. 5 (c), a ring measuring 75 mm in outside diameter and 65 mm in inside diameter, was selected as the test piece (hereinafter friction test “mating material”).

Figure 6 shows the measured temperature of the friction material as it was induction heated from room temperature to 1100°C. The friction material was heated at a rate of 100°C per minute and the material’s temperature was measured using a type K thermocouple installed directly below the sliding periphery’s middle point (at 70 mm from the center of the friction material). Figure 6 shows that the friction material heated up in accordance with the heating rate and reached 1100°C at 660 seconds after heating started, the maximum temperature that can be preset on the high frequency induction heating system. Thus it is verified that by using the friction material test piece profile and the high frequency induction heating system, friction materials can be heated to desired temperatures.

![Fig. 5 Examples of test pieces with the same slide area](image)

The high-temperature friction test apparatus, which is based on a combination of friction test using the thrust-cylinder method and the high frequency induction heating system, will be outlined below.

Figure 7 provides an overview of the high-temperature friction test apparatus. The rotating part driven by an electric motor moves back and forth on a rail as the cylinder is retracted and extended by air pressure. As the cylinder is extended, the mating material at the end of the rotating part is pressed onto the friction material installed on a fixed stand that has been heated to a desired temperature by the induction heating system. The pressing force \( P \) [N] is set by adjusting the air pressure regulator. The friction coefficient \( f \) is calculated using (1).

\[
f = \frac{T}{r_d \times P}
\]

Where \( T \) is torque [N \cdot m] and \( r_d \) is the effective radius of the contact surface [m] (hereafter “preset effective radius”).

It is assumed that the axle load is distributed evenly over the friction surface and that any impact of difference in relative radial slide on the friction coefficient is ignored [7]. Based on those assumptions, the preset effective radius is calculated using (2).

\[
r_d = \frac{\int_{r_1}^{r_2} r^2 \, dr}{\int_{r_1}^{r_2} r \, dr}
\]

Where \( r_1 \) is the inside diameter [m] and \( r_2 \) is the outside diameter [m] of a contact surface. Table 1 lists the specifications of the high-temperature friction test apparatus.

![Fig. 6 Measured temperature of the friction material in induction heating](image)

![Fig. 7 Overview of the high-temperature friction test apparatus](image)

| Table 1 Specifications of the high-temperature friction test apparatus [1] |
|-----------------|-----------------|-----------------|
| Type            | Thrust-cylinder method |
| Loading method  | Air pressure method | Maximum pressing force: 5 kN |
| Rotation method | AC servo motor    | Rotational speed: 30–1500 rpm Maximum torque: 100 Nm |
| Heating method  | High frequency induction heating | Maximum temperature: 1100°C |
| Measured parameters | Temperature, air pressure, torque, rotational speed, vibrational acceleration of the test apparatus |
3. Results of high-temperature friction test

Friction test was conducted using the high-temperature friction test apparatus (hereinafter “the high-temperature friction test”) on four types of copper-based sintered alloy friction material, Materials A to D shown in Fig. 8, and mating material. Table 2 shows conditions in which the high-temperature friction test was conducted. To minimize any impact of frictional heat generated by friction slide on the materials’ frictional characteristics, friction speed was set to 0.11 m/s (rotational speed of 30 rpm), the lowest speed that can be set on the test apparatus. Figure 8 shows the external appearances of the friction materials after the high-temperature friction test. Figure 9 shows the mean friction coefficients of the friction materials observed in the friction test.

### Table 2 Conditions for high-temperature friction test [1]

| Surface contact pressure | 1.1 MPa |
|--------------------------|---------|
| Friction speed           | 0.11 m/s (Slide radius: 35 mm) |
| Test temperature         | *50°C – 1100°C* |
|                          | *Raised in stages of 100°C or 200°C |
| Test duration            | 60 seconds |
| Test session             | 3 times* |
|                          | *3 sessions after the friction coefficient stabilized |

During the test, the following characteristics were observed on Materials A to D.

(1) Material A

The mean friction coefficient stayed nearly flat from 200°C to 600°C and peaked at 0.38 at 700°C. After 800°C, the mean friction coefficient declined and reached 0.19 at 900°C. After the test reaching 900°C, the friction material showed deformation: the periphery appeared pushed outwards. Chips and cracks were also observed in many locations of the periphery. As it deformed, the friction material interfered with the induction heating coil and the test was stopped there.

(2) Material B

The mean friction coefficient stayed nearly flat from 200°C to 600°C, peaking at 0.44 at 800°C. After 900°C, the mean friction coefficient declined and reached 0.25 at the maximum temperature of 1100°C. After the test reaching 1100°C, the friction material showed deformation: the periphery appeared pushed outwards. Chips and cracks were also observed in many locations of the periphery as well as a minor deformation from the heat and pressing force.

(3) Material C

The mean friction coefficient kept a moderate decline up to 600°C and after 800°C started to rise, peaking at 0.59 at 900°C. The parameter was still above 0.5 at 1000°C and then declined sharply, reaching 0.26 at 1100°C. After the test reaching 1100°C, the friction material showed chips and cracks on the periphery as well as a minor deformation from the heat and pressing force.

(4) Material D

The mean friction coefficient continued to decline up to 400°C and started to rise after 600°C, peaking at 0.52 at 800°C. It then fell sharply, reaching 0.17 at 900°C and 0.16 at 1000°C. At 900°C during the test, dents were observed on the sliding surface as well as deformation, chips and cracks on the periphery of the friction material. At 1000°C, the dents on the sliding surface and the deformation on the periphery had advanced and numerous chips and cracks were also observed. As it deformed, the friction material interfered with the induction heating coil and the test was stopped there.

As discussed above, the high-temperature friction test provided clear indications of thermal behavior of the friction coefficient for each friction material that was tested. This means that by using the test method, it is possible to measure the friction coefficient of friction material at a given temperature. The high-temperature friction test which was conducted with a friction coefficient of 0.3 showed that the approximate maximum adaptable temperature was 800°C for Materials A and D and 1000°C for Materials B and C.
This means that by using the test method, it is possible to determine the approximate maximum adaptable temperature of friction materials for a given friction coefficient.

4. Comparison of results from the full-size bench test with those from the high-temperature friction test

As mentioned in the introduction of this paper, the full-size bench test is indispensable for final evaluation of braking performance. Braking force plays a key role in achieving required braking performance. Braking force is derived from the frictional force of mechanical brakes. The force with which a friction material is pressed, or pressing force, is set based on the friction coefficient of the friction material. Figure 10 shows the behavior, observed in the full-size bench tests, of the instantaneous friction coefficient of the friction material with different initial speeds of braking. The instantaneous friction coefficient with initial speed A and that with initial speed B both meet the target value, shown as a dotted line, across the entire speed range. This means the target braking force has been achieved with those initial speeds. On the other hand, with initial speed C, which reflects anticipated faster running speed, the instantaneous friction coefficient does not reach the target value in part of the speed range where the required braking force and performance are not achieved.

This indicates the tremendous impact that an increase in thermal load would have as a result of faster rail services on friction material performance. Especially noteworthy is that the sharp decline in instantaneous friction coefficient, as observed in full-size bench tests often occurs near the maximum temperature of friction materials. Assuming that this phenomenon occurs as a result of friction materials losing friction coefficient at high temperatures, it appears likely that there is a correlation between the decline in the friction coefficient at high temperature, as observed in the high-temperature friction test, and the decline in instantaneous friction coefficient, as measured in the full-size bench tests, and between the temperatures at which these phenomena occur.

To verify this assumption, and focusing on Material C and Material D whose maximum usable temperatures were evaluated as 1000°C and 800°C respectively, with a friction coefficient, as measured in the full-size bench tests, of 0.30, which is below the reference friction coefficient does not reach the target value in part of the speed range where the required braking force and performance are not achieved.

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Fig. 9  Change in mean friction coefficient at different temperatures [1]

Fig. 10 Behavior observed in full-size bench tests of instantaneous friction coefficient with different initial braking speeds [1]
coefficient of 0.30 in the high-temperature friction tests, as discussed in Section 3, a comparison was made between the instantaneous friction coefficients at the materials’ maximum temperatures observed in full-size bench tests and the results from high-temperature friction tests.

Figure 11 shows the instantaneous friction coefficients of the materials at their maximum temperatures observed in full-size bench tests, superimposed on the results of high-temperature friction tests. With Material D, the maximum temperature in the full-size bench tests ranged between around 840°C to around 900°C and the instantaneous friction coefficient at that temperature ranged between 0.20 and 0.30, which is below the reference friction coefficient of 0.30. This is presumably because Material D passed its maximum usable temperature of 800°C, which caused its friction coefficient to decline. This shows high degrees of agreement between the results of the full-size bench test and those of the high-temperature friction test. Consequently, it is presumed that high-temperature friction tests identified the characteristics of friction materials as accurately as those of the full-size bench test.

With Material C, the maximum temperature in the full-size bench tests ranged between around 940°C to around 1010°C and the instantaneous friction coefficient at that temperature ranged between 0.39 and 0.49, which meets the reference friction coefficient of 0.30. This is presumably because Material C did not reach temperatures in the full-size bench tests that would have caused the friction coefficient to decline as in the high-temperature friction tests. This indicates that it is difficult to adjust the friction temperature in a full-size bench test, and that it is impossible to make satisfactory evaluations when finding the adaptable reference temperature at which the performance of the friction material is secured, i.e. the critical temperature. On the other hand, by using the high-temperature friction test, it is possible to evaluate to a satisfactory level, the maximum adaptable temperature of friction materials with respect to any given test temperature.

The above has shown a correlation between the results of high-temperature friction tests, a method proposed in this paper, and those of full-size bench tests, making it likely that the proposed test method will be applicable for the evaluation of the friction coefficient of friction materials at high temperature. The method appears useful as basic test to select candidate friction materials for full-size bench test as part of the development process of friction materials.

5. Conclusions

This paper discussed high-temperature friction test apparatus capable of measuring the friction coefficient of friction materials for brakes at given temperatures in a simpler way than the full-size bench test. Furthermore, the applicability of the apparatus was verified by comparing its results with those of full-size bench tests. This led to the following findings:

1. A combination of thrust cylinder-type friction test apparatus and selected induction heating methods, test piece shapes and test conditions offers the capability, with high repeatability, to measure the friction coefficient of friction materials at given temperatures.
2. Based on the results of high-temperature friction tests, it is possible to determine the approximate maximum usable temperature of friction materials for a given friction coefficient.
3. Comparison of the instantaneous friction coefficient of friction materials at their maximum temperature as observed in full-size bench tests, with the friction coefficient observed in high-temperature friction tests, showed a correlation between the results of those tests, making it likely that the high-temperature friction test can be applied to evaluate the friction coefficient of friction materials at high temperature.
4. The evaluation method proposed in this paper appears useful as basic test to select candidate friction materials for a full-size bench test.

The results of the high-temperature friction and full-size bench tests will be used to improve the accuracy of the proposed method and work will continue to establish it as basic test for selecting candidate friction materials.

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