Abstracts:
A reduction in the number of pantographs of a train-set or in the number of contact strips of a pantograph to improve the performance of the pantograph-catenary system results in an increase in the collecting current density per strip. The wear of contact strip is governed mainly by arc discharge occurring simultaneously with contact break between the contact strip and contact wire. Due to the increase in the collecting current density, the effect of arc discharge on the contact strip becomes more significant than ever and the existing metallized carbon contact strips cannot cope with such a severe condition. We have improved the electrical conductivity of the existing contact strips, tested them for wear in a laboratory, mounted them on a pantograph of electric vehicle and investigated their resistance to wear and contact break arc discharge. This paper describes the results of laboratory and field tests.

Keywords: Current collection; pantograph; contact strip; carbon material; wear; arc discharge
1. INTRODUCTION

It is well known that the use of carbon materials as pantograph contact strips is much effective to reduce the wear of contact wire. Many railways in Europe use carbon contact strips not only for local trains but also for high speed trains like French TGV, German ICE or English IC.

In Japan, the former Japanese National Railways had never used carbon materials since the late 1940s because of its high electrical resistivity and small mechanical strength. They had used the copper based sintered metal alloy for four decades. Since just before the privatization of Japanese National Railways in 1987, however major efforts have been devoted to reducing costs to maintain facilities. To decrease the wear of contact wire, carbon based contact strips of lower resistivity than that of existing ones were developed and had been tested in DC electrified railways in Japan.

To use carbon materials safely as the contact strips for the pantographs of DC electric vehicles, which are predominantly used on narrow gauge lines of Japan Railways (JR) companies, the temperature of contact wire at the contact at standstill is required to be less than the maximum limit of 90 degrees Centigrade under the following conditions.

(1) The maximum electric current of about 100 A per pantograph at standstill
(2) The maximum atmospheric temperature of 40 degrees Centigrade
(3) The pantograph uplift force of 59 N
(4) The use of simple catenary

To keep the temperature of the contact wire at contact point under 90 degrees Centigrade, the allowable temperature rise is limited to only 50 degrees.

Any of these conditions is so severe for carbon materials when compared with those in conventional cases that the impregnated carbon materials which have electric resistivity of about 700 μΩcm and are widely used in European railways are difficult to use in JR companies. Table 1 shows typical carbon-based contact strip used in Japan and Europe classified with regard to its resistivity.

<table>
<thead>
<tr>
<th>Resistivity (μΩcm)</th>
<th>Typical material</th>
<th>Voltage</th>
<th>Use in sh J.R. companies</th>
<th>cf. European equivalents in terms of resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher than 1000</td>
<td>SW</td>
<td>DC 1.5 kV</td>
<td>(not used)</td>
<td>CY3TA, AR129</td>
</tr>
<tr>
<td>300–1000</td>
<td>MC15</td>
<td>AC 20 kV</td>
<td>JR Hokkaido</td>
<td>MY7D, P5279</td>
</tr>
<tr>
<td>100–300</td>
<td>PC78</td>
<td>DC 1.5 kV</td>
<td>JR East, JR Shikoku</td>
<td>MY258</td>
</tr>
<tr>
<td></td>
<td>PC78A</td>
<td>DC 1.5 kV</td>
<td>JR West</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PC58</td>
<td>DC 1.5 kV</td>
<td>JR Central</td>
<td></td>
</tr>
<tr>
<td>Lower than 100</td>
<td><strong>To be developed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Carbon-based contact strip materials used in Japan

According to the past consideration and experiments, the electrical resistivity of the contact strip material must be under 300 μΩcm to control the temperature rise below 50 degrees. This required resistivity is about one-third of that used in Europe. Fig. 1 shows some experimental results of temperature rise near contact point when direct current of 100 A flows through the contact between a strip and the wire. As shown in the Fig. 1, strip materials with the resistivity larger than 290 μΩcm cause a considerable temperature rise in several minutes of current collection.
As a result of these considerations and experiments, the carbon materials with resistivity less than 300 $\mu\Omega \cdot$cm were developed and tested in the latter half of the 1980s, and replaced with the sintered metal alloy since then. Recently, these materials are used for more than 60% of the DC electric vehicles of six JR companies.

Most of the pantographs used for DC electric vehicles have had four contact strips in the direction of the contact wire. However, the number of contact strips on a pantograph has been reduced recently by half and, therefore, the current density through a contact strip has doubled in a certain JR company.

When the current density at the contact doubles, it might be difficult to suppress the temperature rise of contact wire at standstill to less than the limit. A larger effect of arc discharge at a contact break might cause larger wear of contact strip and heavier damage on the strip surface, which could bring about the metal migration on the strip surface.

The authors have improved the electrical conductivity of the existing materials, developed materials with resistivity of less than 100 $\mu\Omega \cdot$cm, subjected them to laboratory wear tests, mounted them on a real pantograph and investigated their performance against wear and arc discharge. According to the results of laboratory and field tests, it has been confirmed that the developed materials have been improved from the existing materials with regard to the resistance to the metal migration and wear.

This paper describes the development of a lower resistivity carbon contact strip and laboratory and field test results.
2. DEVELOPMENT OF METALLIZED CARBON OF LOWER RESISTIVITY

2.1 Major problems when used of a high collecting current density

A reduction in the number of pantographs of a train-set or in the number of contact strips of a pantograph to improve the dynamic performance of the pantograph-catenary system results in an increase in the collecting current density per strip. The current collecting conditions for a variety of electric multiple-units (EMUs) are plotted in Fig. 2 with regard to the collecting current density at running and at standstill of vehicle. The numbers in Fig. 2 represent the type of EMU and “1-P.” means that a train-set has one pantograph, that is, “207-0 (1-P.)” means “207-0 Series EMU train with a pantograph.” With a two-contact-strip pantograph, the current density at running has almost doubled or tripled when compared with a four-contact-strip pantograph.

The wear of contact strip is governed mainly by arc discharge occurring simultaneously with contact break between the contact strip and contact wire. Due to the increase in the collecting current density, the effect of arc discharge on the contact strip has become more significant than ever. The existing metallized carbon contact strips cannot cope with such a severe condition.

The existing carbon contact strip material made by copper alloy impregnation has a problem of the migration of metal particles contained inside. When the material is used under the condition where contact break between contact strip and contact wire often occurs with arc discharge, the impregnated metal content of the material “migrates” from the strip surface to outside the material.
This migration of metal could degrade the electrical conductivity on the surface and wear resistance of the strip material.

Frequent and continuous occurrence of arc discharge between the contact strip and contact wire might cause “migration” of impregnated metal contents from the sliding surface to outside the strip material. The contact resistance between metal-migrated surface and contact wire could become high enough to raise the temperature at the contact point under stationary conditions beyond the allowable limit (90 degrees Centigrade for pure copper wires). Consequently, the electrical resistivity at the strip surface must remain low in spite of metal migration. Therefore, the initial resistivity must be much lower.

2.2 Design of contact strip materials

To control the migration of contained metal particles, the following countermeasures are considered to be effective.

(1) Increase of metal particles contained in the material
(2) Use of metal species which are more wettable with carbon
(3) Increase of the conductivity of carbon material itself
(4) Addition of heatresisting metal particles

We have developed two types of contact strip materials. One is the existing material improved by the above countermeasures (1) and (3), the other is a copper-titanium alloy impregnated carbon-carbon composite (C/C composite) according to above (2).

The Grade “PC78A” made by impregnation of copper into porous carbon is used as a standard. The grade “A0” are modified from “PC78A,” and the grade “A1” are further improved from “A0.” Each developed material has an increased content of copper and graphite to increase electrical conductivity.

The grade “C1” is made of carbon/carbon composite (C/C composite) into which Cu-Ti alloy is impregnated. Because carbon is not wetted with but repels melted copper, when it is impregnated into the pores of baked carbon, it is necessary to apply a high pressure in order to uniformly impregnate melted copper into the carbon. But when copper is used in conjunction with Ti, on the other hand, the wettability of carbon with copper is much improved. As a result, baked carbon is easily impregnated with melted copper uniformly. The melted copper and Ti form an alloy and are tightly bound to carbon walls, so that the Ti- and Cu-containing C/C composite material has higher mechanical strength and electrical conductivity than the existing copper alloy impregnated carbon materials have.

The physical properties of three developed contact strip materials “A0,” “A1” and “C1” are compared with those of the existing contact strip material “PC78A” in Table 2.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>PC78A</th>
<th>A0</th>
<th>A1</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.9</td>
<td>3.1</td>
<td>3.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Resistivity (µΩcm)</td>
<td>180</td>
<td>90</td>
<td>90</td>
<td>110</td>
</tr>
<tr>
<td>Flexural strength (MPa)</td>
<td>120</td>
<td>105</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Charpy impact value (kJ/m²)</td>
<td>4.2</td>
<td>4.0</td>
<td>4.2</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Table 2: The physical properties of contact strip materials

3. LABORATORY WEAR TESTS

3.1 Experimental procedure

The testing apparatus and procedure are the same as those in our previous work. A tested strip is pressed with the normal load of 49 N on the periphery of a rotating copper disk which is 1000 mm in diameter. A direct current is fed from disk to strip at 100 V. The electric current and the voltage...
drop between the disk and strip are measured throughout the test. Tests of the carbon material lasted for 10 min at 100 km/h. The electric current was 100 to 400 A per strip. Prior to sliding the metallized carbon strip, the wear surface of the copper disk was slid and abraded by a copper-based sintered metal alloy at 25 km/h for 10 min under an electric current of 100 A. This abrasion gives a roughness value of $60 \sim 120 \mu m R_{max}$ to the surface. After this treatment, the metallized carbon strip was slid and tested. The weight loss of the strip was measured after three times of repetition of above procedure. The accumulated energy of arc discharge was calculated through the voltage drop and current.

3.2 Results

Fig. 3 shows the relation between the wear rate of strip and the accumulated discharge energy. The wear rate of strip in sliding under occurrence of arc discharge has a linear relationship with the accumulated discharge energy in logarithmic coordinates. In Fig. 3 the wear performance of “A0” and “A1” is slightly improved from that of “PC78A” and the performance of “C1” is considerably better than that of “PC78A.”

![Fig. 3: The relation between the wear rate and the accumulated discharge energy](image)

4. FIELD TESTS

4.1 Test procedure

The contact strip “A0” or “PC78A” was installed on the pantograph of a 207-0 Series EMU train. The wear rate of each strip was measured after a test run of 310 to 390 km. The maximum electric current at running was 820 A per strip and the maximum sliding speed was 130 km/h. The contact strips detached from the pantograph after the test run were investigated with respect to the variation of electrical resistivity on the sliding surface.

After the test run of “A0” and “PC78A,” “A1” and “C1” were further developed and prepared for field tests in ordinary operation. “A1” and “C1” were installed on the pantograph of the 201 and 207-0 Series EMU trains. The wear rate of each strip was measured after ordinary operation (up to about 30,000 km of sliding distance). The maximum electric current per strip at running is set at about 790 A for 201 Series EMUs and about 840 A for 207-0 Series EMUs. The contact strips detached after operation were investigated in the same manner as in the test run of “A0” and “PC78A.”
4.2 Results

The wear rate of the developed material is improved as shown in Fig. 4. Fig. 5 shows the variation of the electrical resistivity on the surface, represented by the ratio of the resistivity before and after the test run at the same point on the surface. For “PC78A,” the resistivity varied up to 10 to 20 times at 11% of the whole area of the strip surface. On the other hand, the areas of the same increase were 4% for “A0.” The resistance to metal migration of “A0” is improved from that of “PC78A.”

Fig. 4: The wear rate of strip measured after a test run of 310 to 390 km on 207-0 Series EMU

Fig. 5: The variation of resistivity on strip surface after a test run of 310 to 390 km on 207-0 Series EMU
Fig. 6 shows the wear rate of the developed materials used for 201 and 207-0 Series EMUs at a high current collecting density. This wear rate is normalized by that of “PC78A" used for a normal current collecting vehicle. In spite of the severe condition, the wear rate of “A1” is significantly improved from that of “PC78A.” The wear rate of “C1” is not so improved.

Figs. 7 and 8 show the variation of the electric resistivity on the surface, represented by the ratio of the resistivity before and after ordinary operation at the same point on the strip surface.

The resistivity of “A1” after the test run varied mainly from 5 to 23 times that of bulk material on 201 Series EMUs and from 8 to 45 times that of 207-0 Series EMUs. On the other hand, contrary to the results in the wear rate, the resistivity variation of “C1” is smaller than that of “A1.” The resistivity of “C1” varied from only 1 to 4 times that of bulk material on 201 Series EMU and from 3 to 10 times that of 207-0 Series EMU. Consequently, the resistance to metal migration of “C1” is considerably higher than that of “A1.” Because “A1” was improved from “A0,” the resistance to metal migration of “A1” is considered to be higher than that of “A0” or “PC78A.” Therefore, “C1” is concluded to have high resistance to metal migration.
5. CONCLUSIONS

(1) According to the results of laboratory and field tests, the developed contact strip materials “A1” and “C1” are improved from the existing material with regard to the resistance to the metal migration and wear rate.

(2) In particular, a copper and titanium alloy impregnated C/C composite “C1” showed a considerable improvement in the resistance to the metal migration.

These developed materials are expected to be applied to the contact strips of DC electrified electric locomotives or DC electrified high speed electric vehicles because of its lower resistivity and higher performance against wear and contact break arc discharge.

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REFERENCES