Influence of Machined Surface on Transient Characteristics of Tangential Force at Wheel/Rail Interface

Daisuke YAMAMOTO
Computational Mechanics Laboratory, Railway Dynamics Division

This paper focuses on the size of the machined contact surface on the wheel flange to clarify its influence on wheel climb derailment after wheel turning. To investigate transient characteristics between machined contact surfaces and smooth contact surfaces, tangential force experiments were carried out using a pair of small cylindrical specimens. Experimental results show that the coefficient of friction on the contact surface increases due to repeated rolling and sliding frictional force. The tangential force coefficient on the machined contact surface is small in comparison with the smooth contact in the range of a slip ratio of less than about 1.0% due to the difference in the contact patch and surface properties, while the tangential force coefficient with both contact surfaces is almost the same in the range of a slip ratio of more than about 1.0%. This means that the influence of the machined contact surface on the steady and transient characteristics of the tangential force of the wheel/rail is small if only ordinary wheel turning is conducted.

Keywords: wheel/rail, machined contact surface, tangential force characteristics, contact patch, surface property, wheel climb derailment

1. Introduction

Wheel climb derailment after wheel turning sometimes occurs while shunting railway vehicle in a rolling stock depot. It has been reported that several factors are considered to be the causes of derailment: a decrease in wheel load due to track irregularity and rolling motion of the vehicle, the relatively large machined contact surface in circumferential direction generated by the wheel turning, and an increase of a frictional coefficient of the wheel/rail interface due to repeated running [1]. Among the causes of derailment, particular focus has been placed on the characteristics of tangential forces (frictional characteristics) acting on the wheel/rail interface shown in Fig. 1. One of the characteristics of derailment studied in this paper is the tendency for it to occur within a short running distance from wheel turning. This observation suggests that the coefficient of friction of the machined contact surface increases acting like a gear mesh, raising the chance of derailment. Therefore, wheel turning which does not generate large fine unevenness to the wheel flange should be carried out, and machining oil applied to the wheel flange after wheel turning at the rolling stock depot if necessary. Since the frictional mechanisms remain a difficult phenomenon to understand the frictional phenomena on wheel/rail contact surface should be investigated in detail.

In a previous study [2], the machined contact surface generated by wheel turning was examined, and a numerical analysis and experiment using a twin-disc rolling contact machine were conducted to investigate the difference in steady tangential force characteristics between the machined contact surface and rail and between the smooth contact surface and rail. The results revealed that the steady tangential forces acting on the machined contact surface were small compared with those on the smooth contact surface. This paper investigated the transient characteristics of the tangential force between the machined contact surface and the smooth contact surface. In an experiment, an actual wheel/rail interface was simulated using the contact surface between a pair of small cylindrical specimens, 30mm in diameter. An investigation was made of the transient characteristics of the tangential force which are the characteristics of changes from the contact surface after the wheel turning to the contact surface under steady frictional conditions. This showed that the machined contact surface generated by ordinary wheel turning did not significantly influence the characteristics of the tangential force acting on the wheel/rail interface, based on knowledge obtained from the previous experiment [2].

2. Steady characteristics of the wheel/rail tangential force

2.1 Relationship between the wheel/rail interface contact patch and tangential force characteristics

When a railway vehicle runs on rails with constant acceleration, steady tangential forces act on the wheel/rail interface. This wheel/rail interface is the status of the contact surface by elastic deformation because of the wheel load or the lateral force applied to the contact surface. According to Kalker’s rolling contact theory based on Hertzian theory
When a wheel tread profile and rail top shape are have their original shape, the contact surface for each wheel head/rail top combination or wheel flange/rail gauge corner combination, is elliptical. It is difficult to show the suitable rail shape where a gear engages with the machined contact surface on the wheel flange under the contact condition shown in Fig. 2.

When the frictional coefficient on the wheel/rail interface is constant, the tangential force acting on the wheel/rail interface is saturated with the frictional force. When the railway vehicle accelerates/decelerates, the sticking region and slipping region appear on the wheel/rail interface, and the tangential force rises due to the increase in the slip region because of greater acceleration/deceleration of the vehicle.

Fig. 2  Contact patch of wheel/rail interface and its characteristics of tangential force

2.2 Relationship between tangential force characteristics in the longitudinal/horizontal direction

The tangential force acting on the wheel/rail interface is called a creep force in the micro-slip region, and follows the principle of Coulomb’s friction in the slip region. When the wheelset runs with an attack angle, the tangential force on the wheel/rail interface acts in both the longitudinal and horizontal directions. \( F_x \) and \( F_y \) indicate the longitudinal tangential force and the horizontal tangential force respectively. There exists a relationship, shown in (1), between the combined force of \( F_x \) and \( F_y \) and the product of the frictional coefficient and the wheel load for each presence or absence of the machined surface. These relationships are called frictional circles with a radius of \( \mu F_z \) shown in the x-y plane.

\[
\sqrt{F_x^2 + F_y^2} \leq \mu F_z \tag{1}
\]

Equation (1) means that the tangential force in longitudinal direction is large so that the frictional circle increases without the attack angle. Therefore, the maximum horizontal tangential force can be evaluated under the condition of same attack angle by comparing the longitudinal tangential force between the machined contact surface and the smooth contact surface.

2.3 The machined contact surface and the steady characteristics of the tangential force

An actual wheel tread has a machined contact surface with triangular cross-sections from several \( \mu \)m to tens of \( \mu \)m in height, since wheel turning using a wheel lathe is carried out periodically. To investigate the relationship between both cases with/without the machined contact surface and the steady characteristics of tangential force, the experiment of tangential force was conducted. The experimental conditions were as follow; the vertical load is 450 N, the rotational velocity is 100 rpm, the temperature and the humidity around specimens are approximately 20°C and approximately 30% respectively, and the slip ratio is constant. The experimental results are shown in Fig. 3. Time history of Fig. 3(a) shows the coefficient of tangential force in the case of a smooth contact surface. This wheel specimen is defined as Type-W. The time history in Fig. 3(b) shows the coefficient of tangential force in the case of the machined contact surface which has triangular cross-section of 90 \( \mu \)m in height and 1mm in pitch. This wheel specimen is defined as Type-J. The specifications of all specimens are described in Section 3.3.

In the case of the smooth contact surface shown in Fig. 3(a), it was passed for approximately 15 minute until the saturation of the tangential force coefficient, which is the tangential force divided by the vertical load, under 0.3% constant slip ratio condition (blue line). The tangential force coefficient was large so that the slip ratio was large, and it confirmed that the saturation time of the tangential force coefficient tends to be shorter than under small slip ratio conditions. Under large slip ratio conditions, it was confirmed that the tangential force coefficient tended to decrease after saturation. This is due to changes in contact conditions from face contact to local contact at the protrusion of a surface roughness due to wear of the contact surface.

In the case of the machined contact surface as shown in Fig. 3(b), the tangential force coefficient with the machined contact surface is small compared with that with the smooth contact surface under small slip ratio condi-
tion. This is due to the contact area decrease due to the contact at protrusion of the machined contact surface, and the stiffness of the contact surface in shearing direction becomes small. The maximum value is measured under the condition where the tangential force coefficient is stable, and these measured values are divided into every slip ratio. Then the steady characteristics of tangential forces can be obtained under constant slip ratio conditions.

From the above experimental results, it was found that the maximum steady tangential force with the machined contact surface was small compared with a smooth contact surface under small slip ratio conditions, in both the longitudinal and horizontal directions. On the other hand, the transient characteristics of tangential forces, where the tangential force coefficient gradually increases from the start of the experiment to saturation as shown in Fig. 3, should be investigated. Therefore, the experimental investigation is described in Chapter 3 and Chapter 4.

3. Transient characteristics of wheel/rail interface tangential force

3.1 Outline of tangential force experiment using a pair of small cylindrical specimens

When an actual vehicle runs on rails, the tangential force of the wheel/rail interface is not always steady. To investigate the transient characteristics of tangential forces on the wheel/rail interface, a tangential force experiment was carried out using a pair of small cylindrical specimens

![Fig. 4](image)

(a) Twin-disk sliding-frictional rolling machine equipped with environmental device in RTRI

![Fig. 4](image)

(b) Inside chamber

Fig. 4 Experiment of tangential force using a pair of small cylindrical specimens

In the experiment, a twin-disk sliding-frictional rolling machine equipped with an environmental device in RTRI was used as shown in Fig. 4. This device has a new function which can change the slip ratio from a small value to a large value continuously. The experimental conditions were as follows: the maximum diameters of the specimens were 30 mm, the vertical load was 450 N (in the case of the smooth contact surface, the calculated contact pressure was approximately 1 GPa.), the rotational velocity was 100 rpm, the attack angle was zero, the slip ratio was changed successively five times simulating the powering of an actual railway vehicle. In addition, to make the frictional coefficient of the wheel/rail interface large and stable, the temperature and the humidity around specimens were controlled and kept at approximately 20°C and approximately 30% respectively using the environmental device.

3.2 Experimental conditions of the slip change rate

In the case of powered running, the braking and the wheel slip etc., the slip ratio of the wheel/rail interface changed continuously. However, it was difficult to show the change in slip ratio in detail. In this paper, to simulate actual running condition, the slip ratio pattern, defined as "a slip change rate" in this paper, was set to increase from 0.1% to 3.0% at three different rates of change, and the three patterns were defined as "a condition of running simulation." The patterns of slip change rates were shown in Fig. 5. For example, in the case of the CASE 1, an average slip change rate is approximately 0.003%/sec., since the slip ratio increases from 0.1% to 3.0% in approximately 970 sec. The experiments described in this Chapter are based on the conditions of the running simulations (CASE 1 to 3) shown in Fig.5. Each experiment was performed 5 times.

| Slip ratio change rate | Duration of slip ratio change | Slip change rate (Average%/sec) |
|------------------------|-------------------------------|--------------------------------|
| CASE 1: 0.1→3.0         | Approx. 970                   | Approx. 0.003                  |
| CASE 2: 0.1→3.0         | Approx. 98                    | Approx. 0.03                   |
| CASE 3: 0.1→3.0         | Approx. 11                    | Approx. 0.26                   |

![Fig. 5](image)

Fig. 5 Simulated running conditions used in tangential force measurement experiments

3.3 Specifications of specimens

The wheel specimen and rail specimen are shown in Fig. 6. These specimens were cut down from the actual wheel and the actual rail respectively, and its contact surface was manufactured to the desired shape using a numerically controlled lathe. The wheel specimen of Type-W
shown in Fig. 6(a) has smooth contact surface which has approximately 0.2 to 0.5 $\mu$m in arithmetic mean roughness $Ra$. The wheel specimen of Type-J shown in Fig. 6(b) has machined contact surface of 90 $\mu$m in height and 1 mm in pitch. In order to make the contact patch between specimens elliptic, the shape of the contact surface of the rail specimens was made into an arc with a radius of 300 mm, and the roughness of the contact surface was approximately 0.3 to 0.6 $\mu$m in arithmetic mean roughness $Ra$.

To remove fat and dirt from the contact surface of the specimen, all specimens were processed by performing ultrasonic cleaning for 15 minutes by dipping them completely into petroleum ether. The specimens were dried completely and then used in the experiment.

3.4 The relationship between the slip change rate and the transient characteristics of tangential force

3.4.1 Time history of the tangential force coefficient

The time history of the experimental results under simulated running conditions of CASE 1 (approximately 0.003%/sec. slip change rate condition) are shown in Fig. 7. The time history of Type-W which had the smooth contact surface and Type-J which with the machined contact surface are indicated with a blue line and red line respectively.

The tangential force coefficient of Type-W (blue line) decreased immediately from approximately 0.6 to approximately 0.3 after approximately 6 minutes. The change occurred because of the contact conditions between the specimens became discontinuous due to the flats generated on the contact surface. After approximately 3 minutes, the periodic collision noise diminished, and the tangential force coefficient increased again, becoming saturated from approximately 0.5 to approximately 0.6 when the slip ratio exceeded approximately 2.0%. When experiments were carried more than twice, no new flats were generated on the contact surface. The tangential force coefficient increased in linear fashion until the slip ratio reached approximately 1.0%, and was saturated at approximately 0.5 when the slip ratio exceeded 1.0%.

The tangential force coefficient of Type-J (red line) increased by small increments in first experiment and was saturated at approximately 0.6, equivalent to Type-W when the slip ratio exceeded 2.0%. Assuming that the contact surface of Type-W did not have a flat, it was estimated that the tangential force coefficient of Type-J would be smaller than that of Type-W (blue line) up to a slip ratio of approximately 2.0% for reasons described later. After the second experiment, when the slip ratio was below approximately 1.0%, the tangential force coefficient of Type-J was consistently smaller than Type-W.

From the above experimental results, it was found that the tangential force coefficient of the machined contact surface was smaller than with the smooth contact surface when the slip ratio was less than approximately 1.0% at least. The difference in the tangential force coefficient between the machined contact surface and rail and between the smooth contact surface and rail was very small when the slip ratio was more than about 1.0%.

3.4.2 Relationship between the tangential force coefficient and the slip ratio

Figures 8 to 10 show the characteristics of tangential forces in the experimental conditions of CASES 1 to 3. The vertical and the horizontal axes indicate the tangential force coefficient and the slip ratio, respectively. The symbol ○ indicates the tangential force coefficients under experimental conditions of CASE 1 to 3, and each color of each symbol indicates the experimental order. For example, the blue and the red symbols indicate the results of the first
and second experiment, respectively. The symbol × indicates the maximum tangential force coefficients obtained in the steady range shown in Fig. 3 in Chapter 2 under constant slip ratio conditions (0.3%, 0.5%, 0.8%, and 2.0%).

(1) CASE 1 (under approximately 0.003%/sec. slip change rate condition)

In the case of Type-W shown in Fig. 8(a), the tangential force coefficient in the first experiment diminishes when the slip ratio is about 1.0% to approximately 1.5% due to a flat generated on the contact surface. The gradient of the tangential force coefficient in the second experiment is smaller than that in the first experiment. Furthermore, the maximum tangential force coefficient in the first experiment is a smaller from approximately 0.1 to approximately 0.2 than in the second experiment. In order to confirm the relationship between the abrupt decrease in the tangential force coefficient and the wear of the contact surface due to the flat, a reproduction experiment was performed under the same conditions as in CASE 1. As a result, when no flat was generated on the contact surface, the tangential force coefficient was close to the coefficient under the constant slip ratio condition (Symbol ×). From this experimental result, it was found that the flat on the contact surface reduced the tangential force coefficient.

Although it was confirmed that the tangential force coefficient (Type-J shown in Fig. 8(b)) in the first experiment tended to decrease when the slip ratio was about 0.7% to approximately 0.9%, no flat was generated on the contact surface. As the experiment was repeated the tangential force coefficient increased when the slip ratio was more or less below 1.0% and tended to approach the tangential force coefficient in the steady condition.

(2) CASE 2 (under approximately 0.030%/sec. slip change rate condition)

The gradient of the tangential force coefficient of Type-W, which is shown in Fig. 9(a), is smaller compared with that of CASE 1 in the first experiment. The tangential force coefficient slowly increased as the experiment was repeated, and tended to be saturated when the slip ratio was constant (Symbol ×). However, the tangential force coefficient does not reach the saturated value after the fifth experiment.

The tangential force coefficient of Type-J, shown in Fig. 9(b), was also the smallest of all CASEs, with a maximum value of less than 0.2. In addition, even when the experiment was repeated, the change in tangential force coefficient remained small in all 5 consecutive experiments.

Based on these results, three things were found. First, for each presence or absence of the machined contact surface, the transient tangential force coefficient of the wheel/rail interface slowly increase when the experiment was repeated and tended to saturate at the steady tangential force coefficient. Secondly, the tangential force coefficient in the case of the machined contact surface was smaller than that in the case of the smooth contact surface when the slip ratio was less than approximately 1.0%, at least. Finally, the tangential force coefficient of both contact surfaces was almost the same when the slip ratio was more than approximately 1.0%.

It is clear that the maximum tangential force coefficient with the machined contact surface generated by ordinary wheel turning does not increase anymore than with a smooth contact surface.
4. Relationship between the surface properties on the contact surface and the increase /decrease mechanism of tangential force

There is a correlation between the frequency of contact and the degree of the micro peeling on the contact surface. This is because the smaller the slip change rate in the experiment, the longer the rolling-sliding frictional force acts on the contact surface. Therefore, the viewpoint for experimental evaluation is changed from the slip change rate to the surface properties on the contact surface.

4.1 Surface condition after the experiment and the tangential force coefficient

To consider the relationship between contact surface conditions and the transient characteristics of tangential forces, the cross-sectional shape of the specimen was measured by a surface roughness measuring instrument, type SE3500 made by the Kosaka Laboratory Ltd. The cross-sectional shape of the wheel specimen and the photograph of contact surface are shown in Fig. 11. The cross-sectional shape of Type-W measured after the fifth experiment of CASE 3 and that of Type-J measured after the fifth experiment of CASE 2 are shown in Fig. 11(a) and Fig. 11(b) respectively. In this paper, the cross-sectional shape of Type-J, which was measured after the fifth experiment of CASE 3, was not used for comparison before/after experiment, since it was not confirmed that the contact surface of CASE 3 was dark brown.

In the case of Type-W shown in Fig.11(a), the difference of the cross-sectional shape before and after experiment was not clearly confirmed, and the surface roughness of contact width after the fifth experiment (green line) was less than before experiment (blue line). However, it is confirmed that the contact surface after the fifth experiment shown in the left side of Fig. 11(a) was dark brown. From these comparisons, it is considered that the increase in the tangential force coefficient due to the repetition of the experiment was caused by a change in surface properties, not the change in cross-sectional shape due to wear.

In the case of Type-J shown in Fig. 11(b), although the difference in the height of the contact width before and after the experiment was approximately 30 μm, it is considered that the change of the cross-sectional shape is small. This is because the increase in contact area was limited because the change in ratio of the cross-sectional shape of the triangular section was small. Furthermore, it confirmed that the contact surface after the fifth experiment shown in the left side of Fig. 11(b) was dark brown like in Fig. 11(a).

From the above, it is estimated that the change in surface properties has a significant influence on the increase in the tangential force coefficient (the frictional coefficient).

4.2 Tangential force increase/decrease mechanisms

The change process in surface properties observed in the experiment described in Section 3 was considered by comparing the literature describing mechanisms for increasing friction coefficient [4]. The schematic figure about the change process of the contact surface observed in the experiment is shown in Fig. 12.

The contact surface of new specimens before the experiment shown on the left side of Fig. 12 was a silver color shown in Fig. 6. When the rolling sliding-frictional force acted on the contact surface, the color of contact surface changed from silver to brown immediately, and the tangential force coefficient increased following the change in the contact surface. At the beginning of the change process, contact pressure is high, the slip ratio is large, and the contact frequency is high. When the contact surface changes dark brown, the tangential force coefficient reached a maximum value during the experiment and tended to be saturated at maximum value until the contact surface changed back to a silver color due to micro peeling on the contact surface. The increase process of the tangential force coefficient was not caused by a change in the cross-sectional shape of specimens based on the consideration described in Section 4.1. The change in color was clearly confirmed on the contact surface during the long-term experiment with a small slip ratio. It is thought that this change of color is the oxide of the metal powder which was peeled from the contact surface and trod down on. The diameter of the specimen after the experiment increased to several μm when the cross-sectional shape of specimen was measured.
According to previous literature [4], when a contact surface is damaged by friction, the metal matrix emerges on the surface due to micro peeling of the metal, and the friction coefficient rises because of greater adhesion at the contact surface. However, the friction coefficient of the contact surface was saturated at a constant value due to the lubrication effect of the oxidation film produced on the contact surface. Because the oxidation film which is produced through a process in which the metal matrix is combined with atmospheric oxygen it appears momentarily on the contact surface. This increased friction coefficient agrees well with the change process on the contact surface from new specimen as shown in Fig. 12. Therefore, it can be understood that the change in surface properties is deeply related to the increase in friction coefficient. The process of micro peeling on the contact surface varies with contact pressure, slip ratio, and contact frequency. Therefore, although the saturation times of the tangential force of Type-W and Type-J are different, it is considered that the mechanisms leading to its increase in both cases are essentially the same.

However, as mentioned in Section 2.3, if a rolling-sliding frictional force is applied to the contact surface repeatedly, the tangential force coefficient decreases a little. This is because the contact condition changes from a uniform surface contact to contact with protrusions due to wear progression on the contact surface. It also confirmed the decrease in the tangential force coefficient due to contact surface wear observed in previous experiments [5].

From the above discussion, it is considered that the mechanism that causes an increase in the tangential force coefficient is due to greater adhesion. This is because a rolling-sliding frictional force is applied to the contact surface repeatedly, and a metal matrix emerges on the contact surface due to continuous micro peeling. On the other hand, it is considered that the mechanism leading to a decrease in the tangential force coefficient is due to changes in the contact conditions from a uniform surface contact to contact with protrusions caused by to wear progression on the contact surface, that is, a decrease in the contact area.

5. Conclusions

This paper focused on the size of the machined contact surface on a wheel flange to clarify its influence on wheel climb derailment after wheel turning. In order to investigate the transient characteristics between a machined contact surface and rail and between a smooth contact surface and rail, tangential force experiments were carried out using a pair of small cylindrical specimens. As a result, regardless of the machined contact surface, the tangential force acting on the contact surface was smallest just after the wheel turning. Furthermore, when a rolling-sliding frictional force was applied to the contact surface repeatedly, the tangential force slowly increased due to changes in surface properties. During the transition from the contact surface after wheel turning to the contact surface under steady frictional conditions, the maximum tangential force coefficient with the machined contact surface was smaller than that with the smooth contact surface in the slip ratio range of less than approximately 1.0% at least. However, the maximum tangential force coefficient of both contact surfaces was almost same when the slip ratio exceeded approximately 1.0%.

From the above experimental results, it is considered that the machined contact surface generated by ordinary wheel turning work does not have a significant influence on the overall tangential force characteristics of the wheel/rail interface.

References

[1] Momosaki, S., et.al.: “A study on flange climbing derailment at low speed on a tight curve and the switch,” Journal of the 13th railway mechanics, Japan Society of Civil Engineers Committee for Structure Engineering Liaison Committee on Railway Mechanics, 2009, pp.37-42(in Japanese).
[2] Yamamoto, D.: “Technique of reducing steady lateral force by providing micro-ribbed wheel tread profile,” Proceedings of the 9th International Conference on Railway Bogies and Running Gears (BOGIE’13), Budapest, 2013, pp.135-143.
[3] Kalker J.J.: Three-Dimensional Elastic Bodies in Rolling Contact, KLUWER ACADEMIC PUBLISHERS, 1990.
[4] Suzuki, M.: “Tribology experiments in space,” Journal of the Vacuum Society of Japan, Vol.51, No.8 (2007), pp.542-545(in Japanese).
[5] Yamamoto, D.: “Characteristics of tangential force at the wheel/rail under non-steady slip ratio,” 11th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2018), Delft, The Netherlands, 2018, pp.1147-1155.

Authors

Daisuke YAMAMOTO
Senior Researcher, Computational Mechanics Laboratory, Railway Dynamics Division
Research Areas: Vehicle Dynamics, Contact Mechanics, Wheel/Rail

QR of RTRI, Vol. 61, No. 2, May 2020