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The body can be viewed from the next page.

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Rails of monorail and guideway systems using rubber tires must maintain frictional resistance in wet conditions for safe driving. Especially this fact is particularly important when the rail has steel plates on its running surface and its longitudinal gradient is more than 3 %. Therefore, a nonslip type steel plate rail for above-mentioned systems has been newly developed. This plate has hot rolled semicircular grooves which are placed in the transverse and longitudinal directions, and can have the effective frictional function when the rubber tires come into contact with these lattice-shaped shallow grooves and deform elastically in their running. This paper describes experimental studies on the relationships between the groove shape, the coefficient of friction and fatigue strength in using this plate as the main member of the guideway girder.

1 Introduction

To relieve urban traffic congestion and secure simple and inexpensive commuting means between suburbs and urban areas, a new transportation system has been planned in many cities, with some of the projects already put into operation (see **Table 1**). Actually, the projects are classified largely into two types: one representated by guideway buses, and the other urban monorail system. With their similarity to subway as high-speed urban mass transporting system, their construction cost lower than in the subway, and their privilege of special granting of construction subsidy (as infrastructure subsidy under the national urban administration policy), these projects will further be accelerated in the future centering on major local cities.

The guideway buses and urban monorail systems are characterized by the use of high-pressurized rubber tires on the vehicles of exclusive railroads, thus ensuring running stability, safety, comfort and low noises. The railroads are of elevated structure for effective utilization of intraurban space, and they are usually made of concrete, but in the case of a long guideway span (25 m and over) or suspended monorail system, they are made of steel. Because of possible slippage of high-pressurized hard rubber tires running along steel railroads in wet conditions such as rain or dew, regulations in principle require appropriate nonslip measures[1]. For preventing slippage between the rubber tire and steel railroad surface, epoxy resin mortar using silica sand as aggregate is generally coated 8 to 15 mm thick on the steel railroad, as in the case of the Shonan Monorail (suspended type) and the Chiba Urban Monorail (suspended type). This engineering method is adopted not only on the steel railroad but also on the concrete railroad as in the Kobe New Transit Port Island Line. Though this method has useful effects such as in increasing friction coefficient between the rubber tire and the rail surface and in reducing running noise level, the mortar is susceptible to damage because of the aging of materials through repeated running load and ultraviolet rays, with broken pieces falling down off the elevated railroad onto the existing traffic directly under the railroad, posing serious safety problems. Also, necessary repair work on broken portions must be performed midnight in consideration of traffic services, leaving problems unsolved concerning workability and curing period. Moreover, portions once repaired tend to cause another weak points later at the risk of more frequent repairing needs.

On the other hand, the subways of Paris and Marseilles have arc-shaped machined-grooves on the surface of H-shaped steel railroads as nonslip technique. This method is to count on the friction force[2]

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Table 1 List of monorail and guideway system projects in Japan

City	Line name (Section)	Type	Line length (Km)	Total cost (Million yen)	Management	Construction period
Kitakyushu	Urban Monorail Kokura Line	Monorail (Mounted type)	8.7	68 714	Kitakyushu High Speed Rail Road Co., Ltd.	1974 ⁝ 1983
Chiba	Chiba Yamanote Line	Monorail (Suspended type)	17.7	85 000	Chiba Urban Monorail Co., Ltd.	1977 ⁝ 1987
Sakuramura (Ibaragi Pref.)	Traffic System of Tsukuba Academic City	Guideway system	1.5	4 200		1978 ⁝ 1984
Yokohama	Kanazawa Seaside Line	Guideway system	10.4	55 137		1979 ⁝ 1984
Ikeda Toyonaka Suita Ibaraki	Osaka Monorail	Monorail (Mounted type)	13.7	59 600	Osaka High Speed Rail Road Co., Ltd.	1980 ⁝ 1986
Komaki	Tohkadai Line	Guideway system	7.7	24 552	Tohkadai New Transist Co., Ltd.	1975 ⁝ 1985
Naha	Naha Urban Monorail	Monorail (Mounted type)	11.1	42 114		1981 ⁝ 1989

due to hysteresis loss in deformation of tire rubber bitten into machined grooves, with sufficient possibility of running into a maintenance-free rational method, if only right type of groove shape is selected. However, it is not deniable that manufacturing cost runs relatively high because of the machining.

With an eye on the advantage of the maintenance-free nonslip method among the existing nonslip methods mentioned above, the application of a rolled groove forming technique of Kawasaki Steel's own development in place of the machined groove method has been studied from the following points:

(1) the examination of manufacturing process of the plates,
(2) the study on the relationship of groove geometry to nonslipping characteristics, and
(3) the investigation into the effect of groove forming on the fatigue strength of the plates.

This paper proposes the Kawasaki Steel's method as the rational and economical nonslip method. The paper also touches upon the Kitakyushu Monorail Project as a representative urban monorail project as Kawasaki Steel system has been adopted to the steel railroad of its Kokura Line.

2 Steps of Development

2.1 Selection of Groove Geometry

The anti-slipping technique for steel plate involves securing the frictional resistance by arranging rolled projections over the surface, as exemplified by the epaisseur plate[3)] and floor plate. In the present study, this principle was expanded by the application of the Kawasaki Steel's roll forming method of small square projections, which was conceptually to make projections coarser and to secure slip-frictional resistance with grooves between projections. The products to be developed as rail faces to be run with rubber tire required to meet the following conditions:

(1) When running with large-sized, high-pressurized, hard rubber tire under wet conditions at a speed of 60 km/h, the slip-friction coefficient should be $\mu = 0.25$ or so.
(2) The running face should be used as the main structure member of runway girder, that is, the rail must have adequate fatigue strength despite groove formation.
(3) The traffic noises produced between the running tire and the groove should be minimized.
(4) Abnormal wear of rubber tire due to groove formation should be avoided as much as possible.
(5) The production cost should be as low as possible.

For solving these problems, the reasoning was advanced in the following way. Since there was no previous data with regard to the selection of groove geometry, and the time limit for the application of the products to the actual project, Kitakyushu Urban Monorail Kokura Line was imminent, the groove geometry was decided daringly on the basis of the Kawasaki Steel's technical data with epaisseur plates provided with small square projections[4)] and the results of indoor friction test with a simple passenger car, to be described later. According to the reference 4), following data are available with regard to slip-

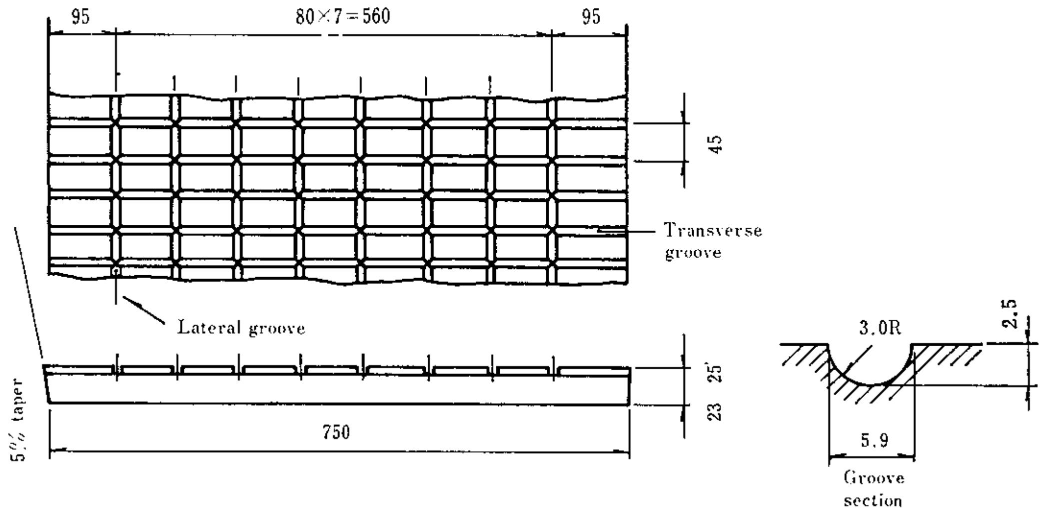


Fig. 1 Shapes and dimensions of developed nonslip plates

frictional resistance under wet conditions between the steel plate provided with projection and the rubber tire of passenger car.

(i) Within the ranges of projection width 3–12 mm, groove width 4–9 mm and groove depth 3 mm, the friction coefficient under wet conditions (μ) tends to decrease to 0.7–0.5 as the ratio of projection width to groove pitch, K, which is one of parameters representing the projection geometry and called aspect ratio, increases.

(ii) With steel plate of $K = 0.5$, the friction coefficient obtained from slip resistance test in actual running in the field is smaller than that of indoor slip resistance test with a passenger car, to owing to the difference in the experimental techniques.

Therefore, the aspect ratio K, for the required μ-value (0.25) in requirement (1) described above was determined on the basis of the friction coefficient in wet field $\mu = 0.4$ for $K = 0.5$ and that with ordinary as-rolled flat plate under wet conditions $\mu = 0.18$ obtained from the reference 5), on a straight line simply connecting these two points, as $K_1 = 0.82$. Moreover, through the similar operation with a straight line assigning gradient $\Delta\mu/\Delta K$ obtained experimentally in (i) to point $K = 0.5$, $\mu = 0.4$, another value of aspect ratio, $K_2 = 0.92$ was determined. While K_1 is more advantageous than K_2 with respect to friction, and K_2 is more favorable than K_1 in regard to noise, $K = 0.867$ was obtained because it is close to the mean of those two values as a measure for approaching to the required μ, and because it makes groove pitch an integral value. Thus, groove pitch was determined to be 45 mm. The cross section of groove was made semicircular with 3 mm radius, because of limitations due to machining of roll and rolling technique, as well as the requirement (2) mentioned above. The width and depth of groove were decided to be about 6 mm and 2.5 mm, respectively. While improvement in dimensional accuracy of groove and the product itself was emphasized in selecting the plan shape of groove, the lattice pattern was selected because of the desirability of simple geometric shape for rolling, and its connection to the solving of requirements (3), (4) and (5). That is, as shown in **Fig. 1**, tranverse grooves were crossed with longitudinal grooves so as to augment the friction and to exert the following effects. The pitch of longitudinal grooves was set to 80 mm so as to avoid duplication with the tread pattern of tire used. The effects of the longitudinal grooves are listed below.

(1) The longitudinal grooves make it easy to drain in the longitudinal direction of rail and reduce splashing noise of running tire.
(2) Compressed air is readily led away at the contact area between the tire and the rail, which leads to the reduction of the noise.
(3) The formation of water layer is prevented owing to the effect (1), with the secondary effect of avoiding the reduction of slip resistance.
(4) The stability of running tire is enhanced.
(5) The finishing accuracy of rolled products is improved.

2.2 Rolling Method

In rolling the products specified in 2.1, a method was taken in which the shaping of longitudinal grooves was separated from that of transverse grooves so that rolling was performed by using two different passes. This was to lower manufacturing cost and secure the

Table 2 Chemical composition of test materials

(wt%)

Materials	C	Si	Mn	P	S	Nb	Al
A	0.15	0.20	0.90	0.014	0.005	—	0.029
B	0.16	0.34	1.30	0.015	0.07	0.032	0.030

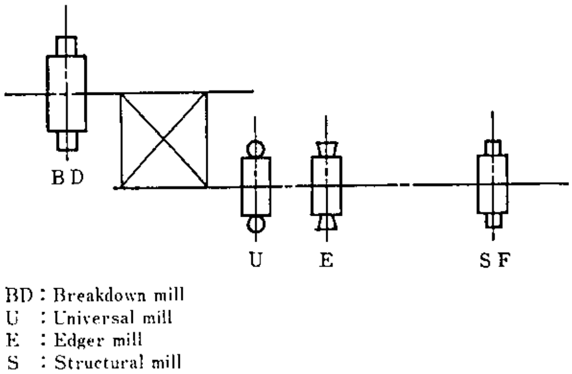


Fig. 2 Mill layout

Table 3 Mechanical properties

Materials	σ_Y (kgf/mm^2)	σ_B (kgf/mm^2)	El (%)	vE_0 (kgf·m)
A	35	48	29	18
B	42	55	29	20

σ_Y : Yeild strength σ_B : Tensile strength
El : Elongation vE_0 : Absorbed energy at 0°C
Plate thickness $t=25$ mm

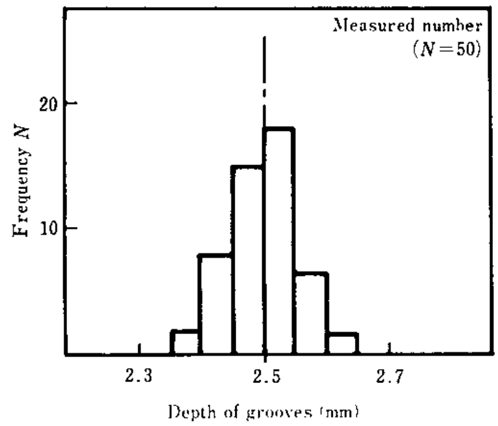


Fig. 3 Dimensional results of rolled groove depth

product accuracy. This is because in the conventional one-finishing-pass-method, the rolls which had the lattice-shaped projections corresponding to the grooves had to be machined by the use of a special machine tool, so the manufacturing cost increased and also "pull down" at the intersection between longitudinal and transverse grooves tended to become larger so as to make it difficult to secure the accuracy of groove geometry.

Figure 2 shows the layout of the rolling mill. The chemical composition of rolling materials and the mechanical properties of a 25 mm thick steel plate are shown in **Tables 2** and 3, respectively, as the manufacturing data of the present products. **Figure 3** shows, as a representative example, the actual data of groove depth (2.5 mm) which is required of utmost accuracy because of its extensive effect on fatigue strength over and beyond any other dimensional factors. It is evident that favorable results were obtained owing to the adoption of rolling method mentioned above. An appearance of the product is shown in **Photo 1**.

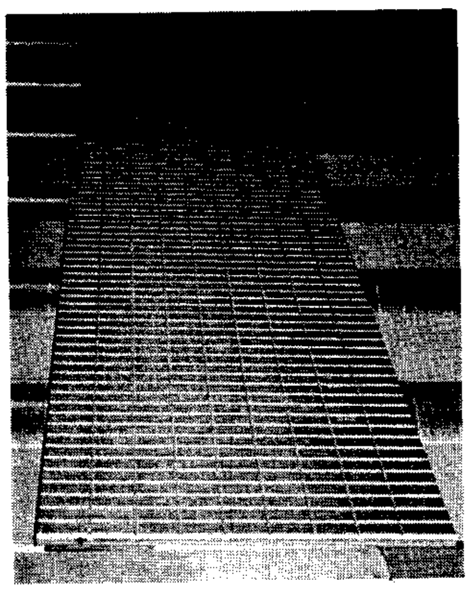


Photo 1 Produced nonslip plate with rolled lattice-shape grooves

3 Characteristics of Nonslip Steel Plate

3.1 Coefficient of Slip Friction

3.1.1 Simplified indoor test

(1) Experimental method

In order to examine the frictional resistance of roll-formed grooved steel plate with groove shape as described in Section 2, an indoor experiment

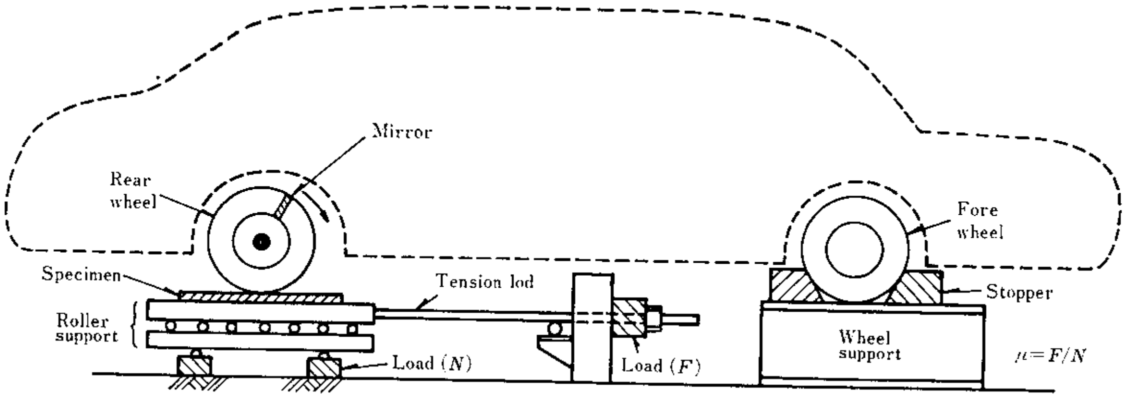
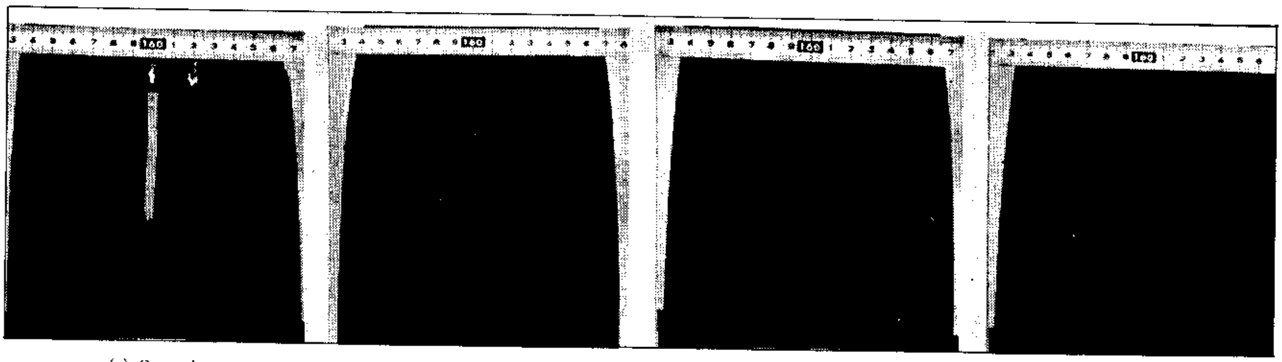


Fig. 4 Experimental equipment of friction resistance test in wet condition



(a) Smooth (b) Straight rib (c) Zigzag rib (d) Normal type

Photo 2 Tire tread patterns used in laboratory test

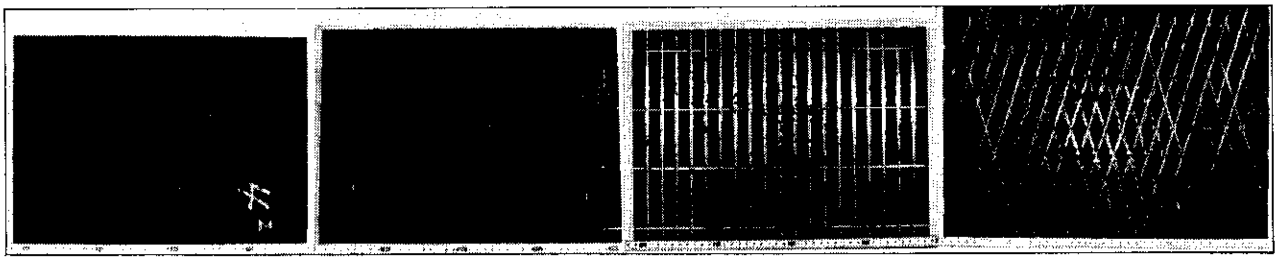
was carried out with an ordinary passenger car as shown in **Fig. 4**. For the experiment, the passenger car was anchored on the floor with stoppers applied to the front wheels with the rear wheels suspended by a crane. As the engine is started and the rotation of rear wheels is stabilized, the wheels are placed on the test specimen installed at a specified location. The specimen is supported vertically with three vertical load cells and rollers of insignificant frictional resistance and horizontally with a tension rod including a longitudinal load cell inbetween, as illustrated in **Fig. 4**. The vertical force N exerted by the weight of rear wheels, and the horizontal kickout force F created by idling rubber tires in contact with the specimen were measured. The friction coefficient was calculated as $\mu = N/F$ from two measured values. The rotational speed of the rear wheel tire was determined by measuring with a pulse meter intermittent light reflections from a piece of metal foil fixed on the tire. The running speed (km/hr) was calculated on the basis of the number of revolutions per unit time and the tire perimeter. Since the friction coefficient under the wet conditions is to be sought for, the whole surface of the specimen was sprayed uniformly and continuously with 13.4 l/min water, so as to form a sufficient water layer between the specimen and the tire. Bridgestone's 5.60-13 tires were used for the experiment. Tires were provided with four types of tread patterns: (a) smooth tire with no tread pattern, two patterns (b) and (c) expected to be adopted in the urban monorail, and (d) normal tire for the passenger car, as shown in **Photo 2**. Throughout the experiment, the rear wheel load and the internal pressure of tire were held constant at 220 kgf and 1.7 kgf/cm^2, respectively.

(2) Specimens

Types of specimens and experimental conditions are listed in **Table 4**. Grooves were cut on the surface of as-rolled steel plates by machine tolls except for plates with rolled grooves. The primer

Table 4 Types of specimens and experimental conditions

Experiment No.	Varieties	Specimen						Remarks
1	Groove pitch	No.	1-1	1-2	1-3	1-4	1-5	Machined groove Groove radius : 3 mm Groove depth : 2.5 mm
		Pitch (mm)	45	30	20	15	12	
2	Groove width	No.	2-1	2-2	2-3	2-4		Machined groove Groove depth : 2.5 mm Groove width:8.7 mm (R5 mm),10.7 mm (R7 mm)
		Pitch (mm)	45	45	20	20		
		width (mm)	8.7	10.7	8.7	10.7		
3	Plate surface	No.	3-1	3-2	3-3	3-4		Rolled groove Groove pitch : 45 mm Groove radius : 3 mm, Groove depth : 2.5 mm
		Condition	As rolled	Shot blasted Rz 55 μm	Painted (Primer)	Painted (Epoxy)		
4	Flat plate	No.	4-1					As rolled plate (SS41)
5	Groove pattern (Skewed lattice)	No.	5-1	5-2				Machined groove Groove radius : 3 mm Groove depth : 2.5 mm Intersect angle between grooves : 36°
		Pitch (mm)	30	20				



(a) 3-1 (b) 1-2 (c) 1-3 (d) 5-2

Photo 3 external appearances of typical specimen shown in Table 4

painting treatment after shot blasting in experiment No. 3 comprises two layers of epoxy zinc primer (65 μm) and a layer of epoxy M10 paint (100 μm). The painted surface was cured in air for 14 days or longer. The experiment No. 4 is to obtain a reference data in the flat plate with no grooves. The experiment No. 5 is to study the characteristic values with skewed lattice plate which has grooves machined 18° with respect to the transverse direction for tire running, in place of orthogonal lattice grooves.

Typical examples of specimens are shown in **Photo 3**.

(3) Experimental results

The relationship of friction coefficient between the rolled-grooved plate and four types of tires under wet condition to tire speed in Experiment No. 3 which is the primary purpose of this study is shown in **Fig. 5**. In these figures, the results with machined-grooved plate (1-1) of the same pattern as rolled-grooved one and with flat plate (4-1) are also presented for the purpose of comparison. As in the case of concrete or asphalt pavement, the friction coefficient tended to decrease monotonously with the increase of rotational speed, and was largest with a tire of antislip zigzag rib pattern tread, and nearly equal for a straight rib tire and and a smooth tire. The friction coefficient on rolled-grooved plate at the tire speed 60 km/h with tires of non-zigzag rib pattern was between 0.18 and 0.21, about 20% less than the aimed value, 0.25, while that with tire of zigzag rib pattern was 0.33, about 30% greater than the desired value. The friction coefficient of rolled-grooved plate was higher than that of machined-grooved one, which might be attributed to higher surface roughness and slightly lower flatness in the vicinity of rolled grooves. When comparing grooved plate with that plate, tires having less frictional function of its own, such as those with smooth surface or

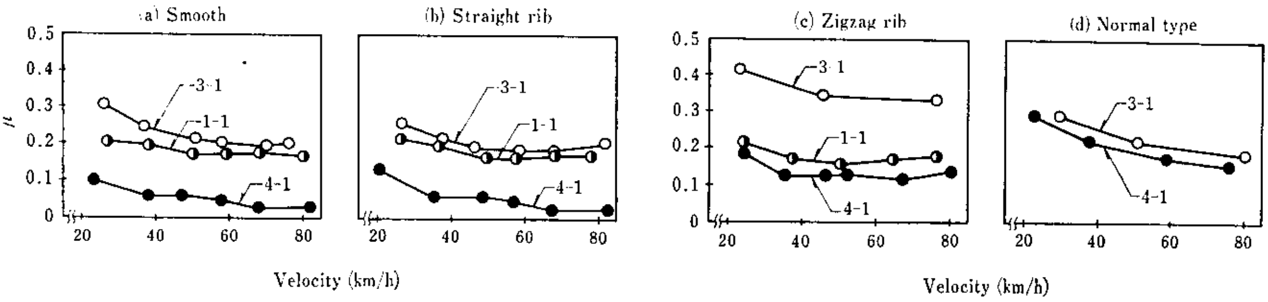


Fig. 5 Friction coefficients, μ, between rubber tires and steel plates with semicircular grooves in wet condition

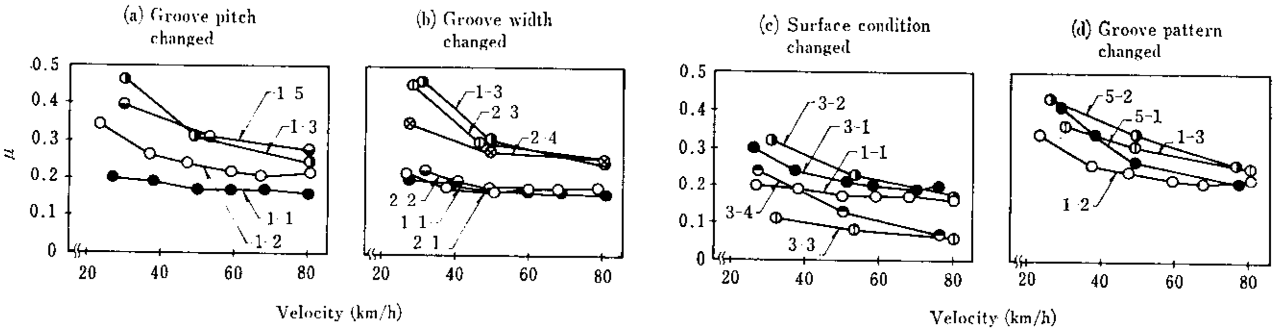


Fig. 6 Friction coefficients, μ, corresponding to the variation of groove shapes and plate surface condition when smooth rubber tire used

straight-ribbed pattern, gave widely different friction coefficients for two kinds of plate, clearly demonstrating the effects of grooving. On the other hand, zigzag-ribbed and normal tires which have antislip function in themselves, gave nearly equal values for two plates, showing little effects of grooving.

As is evident from the results mentioned above, and particularly, in **Fig. 5** (a), it should be noted that, even when the tire is worn out to be close to a smooth tire, the friction coefficient under wet conditions on the rolled-grooved plate is kept as high as 0.2 or so at 60 km/h speed.

The friction coefficient for plates of various groove pitches, as examined in Experiment No. 1, are shown in **Fig. 6** (a). In this case, smooth tires which are most unfavorable with respect to slip are used. As is evident from the figure, the smaller the groove pitch is, the greater the hysteresis loss in deformation of tire is, and hence, the greater the friction coefficient tends to become. **Figure 6** (b) shows the friction coefficient of plates with various width of groove, while keeping the groove pitch and depth constant (Experiment No. 2). Since the friction coefficient changed very little for groove widths 6.0, 8.7 and 10.7 mm in both cases of groove pitches 45 mm and 25 mm, it is infered that the contribution of groove width to the friction coefficient is extremely small.

Figure 6 (c) shows the friction coefficient for different surface conditions of rolled-grooved plate (Experiment No. 3). Particularly, the surface roughness exerts marked effects on the frictional resistance. For four kinds of grooved plate, the magnitude of friction coefficient is in the following order: shot-blasted surface (Rz 55 μm) > as-rolled surface (Rz 40 μm) > painted surface > primer-coated surface.

Figure 6 (d) shows the friction coefficient on plates with groove patterns changed from orthogonal to skewed lattice, with the cross section of groove held constant (Experiment No. 5). As the coefficient for plate of skewed lattice pattern was slightly greater than that of orthogonal lattice pattern in both groove pitches 30 mm and 20 mm, it was observed that the former had favorable trend for slip prevention. This may be attributed to the fact that grooves in the skewed latttice pattern always fit and grip the tire continuously.

It seems that this experimental finding is to be taken into consideration in case of commercial production together with the rolling technique.

In view of the surface conditions of rolled plate, it is expected that a particular part of rail plate is ground down as rubber tires pass over enormous number of times in many years of service period. For this reason, the surface roughness was examined for running portion and non-running portion of rubber tire with steel finger joint of the monorail guideway currently in use.

The subject portions examined had been installed for about 16 years and passed over by approximately 760 000 trains. The results prove that the surface roughness of the running portion of the finger joint is Rz 20–25 μm which is about 20 μm smaller than that of non-running portion.

The friction coefficient in an extremely unfavorable situation with regard to slip was, therefore, examined as an extra experiment by the use of plate buff-polished to roughness Rz 2–5 μm. While the test conditions were essentially identical to those in the preceding experiments, the rear wheel axle load was a little increased to 315 kgf. For the purpose of comparison, the same experiment was conducted with flat plate of the same roughness as rolled plate. Throughout these experiments, normal tires (560–13) for passenger car were used. The results are shown in **Fig. 7**. Each curve in **Fig. 7** was derived from measured values in 4–6 identical tests through the method of least squares. In case of as-rolled plates, both grooved and smooth, the friction coefficient was fairly greater than the value given in **Fig. 5** (d), as the rear wheel axle load was increased (curves ① and ②). However, when the surface roughness was reduced to Rz 2–5μm, the frictional resistance declined as indicated by curve ③ for grooved plates and by curve ④ for flat plates. In the extreme case of tire abrasion, frictional resistance fell drastically as in curves ⑤ and ⑥ for grooved and flat plates, respectively.

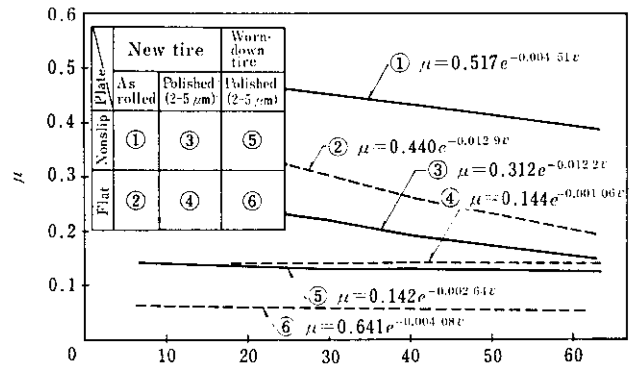


Fig. 7 Friction coefficients between steel plate surface and rubber tires by changing both conditions

As is evident from these curves, the grooved plates were most favorable with respect to friction in every situation, and even in the extreme case of tire abrasion, grooved plates of 45 mm pitch ensured friction coefficient about 0.1 higher than at flat plate.

3.1.2 Field experiment with actual monorail tires

(1) Experimental method

Factors on the part of tire affecting friction coefficient between rubber tire and steel plate involve not only tire tread pattern described in the preceding subsection, but also tire size, wheel axle load, internal pressure of tire, tire structure and properties of tire rubber. In order to study all of these factors, a field experiment was conducted on rolled-grooved plates by the use of a testing trailer which was applied with actual axle load 5.5 tf, equipped with tires used in actual monorail operation (See **Photo 4**). That is, rolled plates 750 mm wide, 24 mm thick and 50 m long were laid on the road, and a truck equipped with a loading device with hydraulic jack, disk brake and actual monorail tires (diameter 1 006 mm, width 341 mm, internal pressure 10 kgf/cm^2 and steel radial structure) was trailed by a trailer to run in acceleration on them. When the truck came to steel plate, test tires only were braked to stop rotation, and while keeping trailed, traction force, vertical load and running speed at every time point were measured to determine friction coefficient. In order to reproduce wet road surface conditions, an adequate amount of water was sprayed on the surface of test railway immediately after starting the above test run. For the purpose of comparison, test tires of smooth, straight ribbed and zigzag ribbed tread patterns, as used in the indoor experiment were used. For the test railway, rolled-grooved and flat steel plates and concrete pavement were used, with the surface of steel plate always shot-blased (Rz 55 μm) and coated with zink-rich primer (15 μm thick).

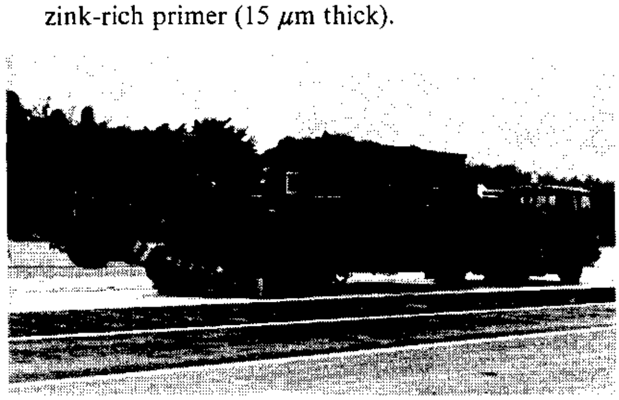


Photo 4 Trailer and specimen tire used in field test

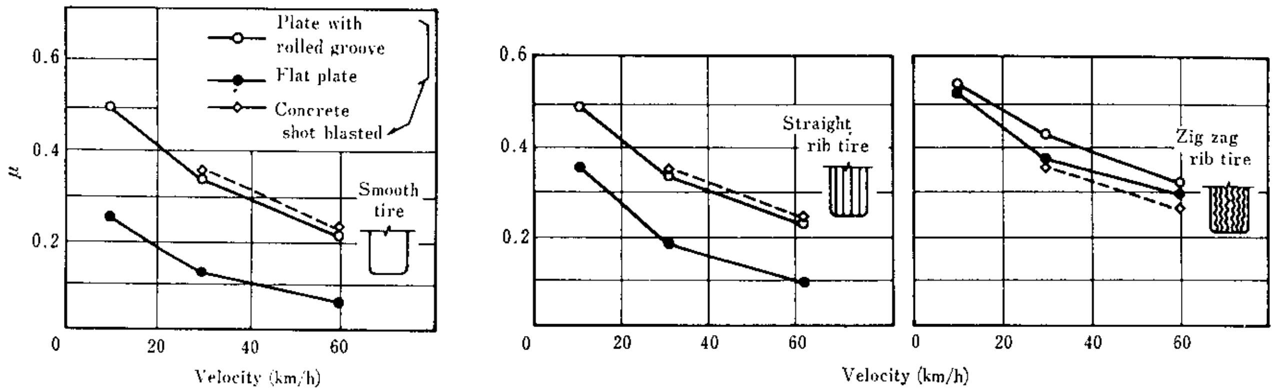


Fig. 8 Field test results corresponding to the various type tires

(2) Experimental results

The friction coefficients measured of various types of tire are shown in **Fig. 8**. While these results were qualitatively agreed with those obtained in the indoor experiment described above, the former values were rather always greater than the latter. Though straight ribbed and zigzag ribbed tires gave an aimed value of 0.25 at 60 km/h as a friction coefficient to rolled-grooved plate, it was found that a friction coefficient greater than 0.20 can be ensured on smooth tires which can be assumed to be the abraded condition of these tires. The measured values obtained from rolled-grooved plate were naturally greater than those obtained from flat plate, and nearly equal to those from concrete surface.

3.2 Fatigue Strength

Another point to be examined of the present product is to ensure the fatigue strength as a structural member. While the fatigue strength is mainly affected by transverse grooves, a complicated notch effect occures at the cross point to longitudinal grooves. With two kinds of specimen, base metal and T-type specimen with ribs on one side, of dimensions shown in **Fig. 9**, the pulsating tensile test was conducted by using an electro-hydraulic fatigue testing machine at the lower limit of load 1 tf, with cyclic speed 10 Hz and sinusoidal testing waveform. The mechanical properties and chemical composition of specimens are shown in **Table 5**. As shown in **Fig. 9**, the specimen includes no parallel segment at the test area which is bordered by circular arcs of 390 mm radius. While the stress concentration factor of this specimen at the time of applying tensile load was assumed to be about 1.14, no particular correction was made to the fatigue test results. The results are shown in **Fig. 10**. The S-N curve for the base metal is obtained by applying the method of least squares to the experimental results as represented by the formula given below.

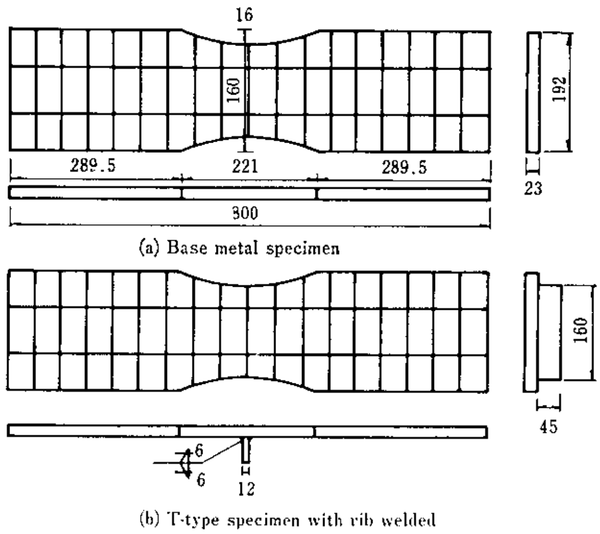


Fig. 9 Specimens of fatigue test

Table 5 Chemical composition and mechanical properties of fatigue test specimen

Elements	C	Si	Mn	P	S
Weight (%)	0.15	0.18	0.65	0.019	0.010

Plate	Y.S. (kgf/mm²)	T.S. (kgf/mm²)	El (%)	$_vE_0$ (kgf·m)
With rolled grooves	35.6	49.6	21 A	15.6, 13.0, 15.2
Rib	35.4	47.0	26 A	—

$$\sigma_r = 90\,200\,N_F^{-0.2856}\ (\mathrm{kgf/cm^2}) \quad \cdots\cdots\cdots (1)$$

The probability of 95% nondestruction for eq. **(1)** is given by

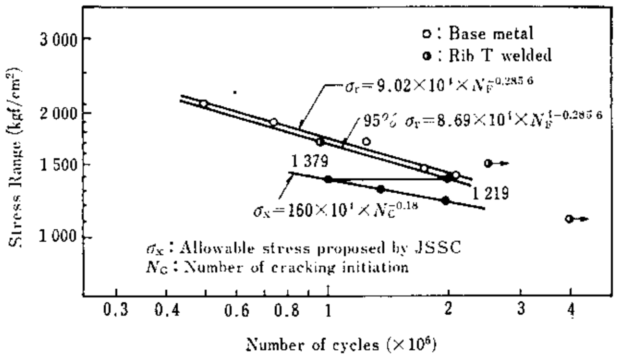


Fig. 10 Fatigue test results

$$\sigma_r = 86\,900\, N_F^{-0.2856}\ (\text{kgf/cm}^2) \cdots\cdots\cdots\cdots (2)$$

σ_r: Stress amplitude
N_F: Number of cycles to failure

The fatigue strength of 2×10^6 cycles derived from eq. **(2)** is about 1 380 kgf/cm². The allowable stress not causing fatigue cracks at 2×10^6 cycles, as calculated on the basis of the guide to fatigue design[6] issued by the JSSC (Japan Society of Steel Construction), is about 1 219 kgf/cm². It is proposed, therefore, that the allowable fatigue stress of the base metal of present product be 1 200 kgf/cm². On the other hand, for T type specimens with rib, of which only three data points were available, the fatigue strength was nearly equal to that of base metal. Hence, the allowable value for the ordinary T type ribbed specimens with no grooves can be applied, and about 1 060 kgf/cm² may be proposed as a measure for the allowable fatigue stress at 2×10^6 cycles.

As is evident from the foregoing considerations, it may be concluded that the present product may be used as main structural members, so long as the welding process control is perfect.

4 Conclusions

The rolled-grooved steel plate to be used as nonslip plate for the railway of urban monorail with rubber tires has been developed, and its friction coefficient and fatigue strength required for ensuring the safety running of vehicles have been determined experimentally. The results obtained are summarized below:

(1) In the indoor experiment to measure the friction coefficient, it was found that the coefficient of grooved plate increased as the groove pitch was reduced.
(2) As the friction coefficient was not affected by changing the groove width within a range from 6 mm to 10.7 mm, groove width contributes little to frictional resistance.

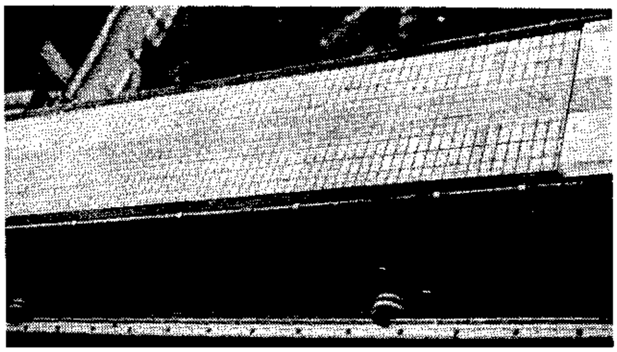


Photo 5 Monorail runway girder using the nonslip plate with rolled lattice-shape grooves

(3) The frictional resistance was extensively affected not only by the groove layout pattern but also by the roughness of steel plate surface. In order to obtain the ideal nonslip steel plate, therefore, it is necessary to develop a product provided not only with grooves but also with adequate surface roughness.
(4) While the product developed here is steel plate provided with orthogonal lattice grooves, it seems that the skewed lattice pattern is a more rational solution. This point should be studied hereafter in view of the rolling technique and cost.
(5) The aimed value of friction coefficient 0.25 between the developed steel plate and the actual monorail tire can nearly be secured by selecting an appropriate tread pattern of tire. Though the tire tread was worn away, the friction coefficient can be secured at a level of 0.20 at 60 km/h velocity on the rolled-grooved steel plate.
(6) When both tire and railway worn away, the friction coefficient at 60 km/h velocity can be held at a level of 0.12 or higher, which was 0.1 or so higher than that on the grooveless flat steel plate.
(7) The fall of fatigue strength due to the presence of grooves was smaller than that due to the presence of T-type rib fixed by welding, and the guaranteed allowable stress at 2×10^6 cycles was 1 200 kgf/cm².
(8) The allowable fatigue stress of T-type ribbed specimens made from the rolled-grooved steel plate was about 1 060 kgf/cm² at 2×10^6 cycles, which was equal to the strength of similar specimen made from ordinary steel plate. It is evident, therefore, that the present product can be used as the main structural member of the elevated railway.

About 200 tons of developed product has been used in the sections of 3% or greater gradient in the elevated steel runway of the Kitakushu Urban Monorail Kokura Line, of which outline is shown in **Photo 5**.

While the developed product has characteristics described above, further improvement may be required. The study will be advanced in consideration of the results of running test with actual vehicles in the Kokura Line so as to obtain more rational solution and to expand the application positively to the subsequent projects.

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