Rails function as guide ways for the trains that run on them. Differing from roads for automobiles, rails are characterized by how they linearly support the load of trains on extremely small contact points (only the size of a one-yen coin). They are track components that have little redundancy and are required to meet very high standards of reliability to fulfill their role.

Repeated heavy loads of trains facilitate symptoms such as a rail defect, wear and fatigue, and rails have finished their roles when reaching a point that they are no longer usable and need replacing. Rails are maintained through regular inspections to prevent rail breakdown; but in rare cases, approx. 10 times a year in JR East’s operation area, rail breakdown occurs during service life of rails and leads to the state that trains cannot run on them. That threatens stable transport.

When a crack occurs, grows and finally breaks a rail to make a gap, the signal current carried by that rail is broken and relevant blocking signals are displayed to stop trains. In such a case, operational restriction procedures are taken, and stable transport consequently is inhibited. Past tests showed that there are no risks of derailment by a rail gap of up to 70 mm, but rules for strict operation restriction are set down in control standards. That assures safe operation, but concurrently threatens stable transport, causing troubles for passengers.

As rails are extremely linear components, they cannot avoid suffering axial compressive force. So, they may buckle when temperature rises in summer (Fig. 1).

Continuously welded rails (CWR, rails longer than 200 m made by welding multiple 25 m rails) in particular require appropriate control over thermal axis force and strength against buckling. CWR are characterized by having a smaller safety margin compared to other material.

As described above, rails are track components that are used in severe environments assuming that they are appropriately controlled; thus, they account for 10 billion yen in maintenance expenses per year. This amount accounts for 10% or more of total track maintenance expenses, and such maintenance puts a heavy load on the global environment according to life cycle assessment (LCA) regarding CO2. It is also estimated that rails account for 80% of track maintenance work. Hence, we have been conducting various R&D in sections related to tracks on improving reliability and extending service life of rails to improve transport stability and reduce maintenance costs. In this paper, we will introduce outlines of that R&D.
Rails are classified as high carbon steel. The carbon content is as high as 0.4 to 0.8%; so, while it is reliable in terms of high wear resistance and high strength, it is more fragile and lower in weldability compared to usual mild steel. The load conditions for rails are quite severe as seen by how rails support wheel loads as heavy as several tons on a contact point only as big as a one-yen coin. The pressure at that contact point exceeds 1,000 MPa, which is more than the yield stress, and sometimes causes partial plastic deformation of rails. As for shape, rails need appropriate curvature for sharp curves. If rails are easily deformed, that causes problems in terms of safety and comfort. So they require the appropriate cross sectional area and weight. However, if rails are too big, they become expensive and difficult to handle in maintenance. Thus, rails have a shape and cross sectional area decided from a comprehensive perspective.

The coefficient of linear expansion of rail is around $10^{-5}/^\circ C$. So, if a 1,000 m rail freely expands, it would expand by more than 10 cm as temperature rises by $10^\circ C$. CWR, with expansion controlled and welded with many rails to not move, has advantages in terms of passenger comfort and maintenance. On the other hand, nearly 60 tons of axial compression force is accumulated in CWR at midsummer.

As just described, rails with practical shape and weight are used almost to their limits in severe environments. Since they have smaller safety margins compared to other track components, we need to assure safety and quality of rails based on appropriate maintenance.

### Service Life of Rails

Multiple factors determine the service life of rails. Main factors are fatigue from repeated tensile stress at rail joints (including welded joints), wear from friction between wheels and rails, defects (cracks) caused in use, chemical corrosion where iron is oxidized by water, oxygen or acid and rust grows, and electric corrosion where leaking of current carried in the rails to the ground causes loss of electrons and iron gets thinner. We replace rails due to these causes.

A comparison of numbers of rails causes for rail replacement at JR East is as shown in Fig. 2.

Some defects, the largest cause of replacement, in the past were caused during manufacture; but now, most defects are caused and grow in use due to improvements in quality control technologies for rail manufacturing. Among such defects while in use, the most typical one in Japan is squat caused by rolling contact fatigue, a kind of fatigue damage from the wheel’s rolling contact (Fig. 3).

Fatigue, the second largest cause, is assessed by million gross tonnage which means accumulated loads of trains that pass the location (hereinafter "MGT"), and standards for replacement are specified per type of rail and type of rail joint. According to the specifications set just before the Japan National Railways was privatized, the standard is for tonnage to be 400 MGT for joints and 600 MGT for welded joints of 50 N rails, and 600 MGT for usual joints and 800 MGT for welded joints of 60kg rails. That corresponds to approx. 20 years for the Yamanote loop that circles central Tokyo. These tonnage standards are based on the number of times tensile stress that occurs at a rail base when impact load is applied to a joint is repeated; and those can be determined using a S-N diagram on metal fatigue of rails (a diagram that shows the relationship between stress amplitude and the number of times a load is applied).

For wear, the third largest cause, we have standards for wearing depth from the upper corner of a rail called the "gauge corner" and for wearing depth from the rail head. The former is specified to prevent gauge-widening derailment and the latter is to prevent increase of stress or displacement by deterioration of rigidity of rails due to decrease of cross sectional area. Wear occurs particularly at curves and it is the largest factor that affects service life of rails in curved sections with small radii. Tongue rails in turnouts and rails at curves also wear fast, and when we replace these rails, we also replace stock rails, lead rails and rails for curves that may need not to be replaced according to standards. This is to avoid unevenness between new rails and previously laid rails, taking continuity of their sectional shape into account. Replacement related to turnouts, the fourth cause, includes such replacements.

We have explained service life and the current situation of rails as above. Next we will introduce some examples of R&D for further
improvement of transport stability and reduction of maintenance cost.
To improve transport stability, it is essential to find any defect without fail and keep appropriate control of those according to type and size to prevent rail defects from growing into breakdown of rails that might cause suspension of operations. As shown in Fig. 2, the largest cause of replacement of rails is defects; hence, we have to make efforts to prevent the occurrence of rail defects themselves.

4.1 Detecting Rail Defects
Rail defects are detected by a rail defect detecting car using ultrasound (Fig. 4). Recently, as performance of the detecting cars has been improved, we have tried to improve detection stability, expand detection area, and increase types of defects to be detected. But, still we cannot detect defects on the complete cross section of a rail. In defect detection, we apply ultrasound from the rail head; but, because of the sectional shape of rails, the ultrasound does not reach to the rail base. Thus, the rail base is a part where defects cannot be detected. There have been cases where defects occurred, grew and lead to rail breakdown in rail bases.

![Fig.4: Rail Defect Detecting Car](image)

Rail defects that often occur at rail bases are electric corrosion and chemical corrosion (Fig. 5). Rail bases have contact with rail fastenings that fix rails to sleepers (sometimes to ballast also). Water leaking in a tunnel or water pooled in a road crossing that flows through such contact points might cause a leak of current carried in the rail into the ground. In such a case, iron atoms of rails are ionized and rails become thinner. In places where the whole cross section of a rail is exposed, we can find electric corrosion or chemical corrosion by visual inspection at foot patrols; but such inspection is difficult in road crossings etc. where rails are covered.

For rail bases where defect detection is difficult, we are carrying out R&D on detection technology using “guided waves”, low frequency ultrasound. Guided waves have recently attracted attention as a mean for high-speed nondestructive testing for long and massive structures with simple sectional shape such as flat plates and piping.

4.2 Predicting Growth of Rail Defects
Since the mechanism of growth from crack occurrence to rail breakdown has not been clarified yet, methods for rail defect control are still based on experience of maintenance. But that mechanism needs to be clarified to reduce costs of replacement of defective rails and to improve inspections by reviewing inspection intervals, criteria etc. Fig. 6 shows a detailed breakdown of types of rail defects that account for the largest percentage of causes of rail replacement shown in Fig. 2. As indicated, much of rail replacement is carried out due to squat.

![Fig.6: Breakdown of Defect as Causes for Rail Replacement](image)

Hence, accurate prediction of growth of squat will enable us to achieve improved safety and more efficient rail maintenance. In squat, there are horizontal cracks under the dark hollow shown in Fig. 3. As time passes, some of these horizontal cracks may branch into the rail. Such a branch crack is called a transverse crack (Fig. 7).

For transverse cracks, if a transverse crack grows, that deteriorates the strength of the rail and finally might cause rail breakdown.

![Fig.7: Pattern Diagram for Squat](image)

Now we can predict growth of transverse cracks to some extent in the laboratory. But various factors apply in the field, so we need to further improve precision of prediction for analysis of crack growth by testing crack growth with defective rails that are replaced.
4.3 Preventing Rail Defects

We need to make efforts to reduce the occurrence of squat that accounts for a large percentage of causes for rail replacement. To accomplish that, we have been carrying out many studies to clarify the mechanism of squat occurrence. For rails for Shinkansen, by analyzing the metal structure under the contact surface of rails from a material science perspective, we found that the layer that is affected by contact with wheels is very shallow. Therefore, it has been proposed to remove the layer where contact effects are accumulated and squat is caused by grinding (hereinafter noted as "grinding"). On the other hand, the layer of rails for low-speed lines that is affected by contact with wheels is deep, and preventing squat by grinding is said to be difficult for that.

Recent studies, however, suggest the possibility of preventing squat by grinding rails, because it has been proved that the layer on the contact surface of rails affected by contact with wheels lies on the surface with the depth of around 0.1 mm. This applies even when the condition of laying rails differs. And, since squat in rails for low-speed lines begins to occur from approx. 50 MGT, we expect squat reduction effects by grinding at intervals of approx. 50 MGT, based on the results of experimental research.

Based on the above-mentioned study results, we started grinding to reduce squat on lines and sections with large annual tonnage in Tokyo area from 2005. Such grinding is carried out by rail grinding vehicles that have been used mainly for grinding of corrugated rails and roughness at welded joints. Those rail grinding vehicles grind the surface of rails by rotating grindstones directly connected to drive shafts of motors (Fig. 8).

![Fig. 8: Rail Grinding with a Rail Grinding Vehicle](image)

Passing of a grinding vehicle only once does not complete grinding the surface of a rail. Grinding by passing of a grinding vehicle multiple times finished the rail to its proper shape. We call passing of a grinding vehicle over an area one time "a pass", and the distance and efficiency of grinding at the limited interval of train operation depends on the number of passes. It is an economic issue for us to assure the required grinding with fewer passes. The necessary number of passes depends on the number of grindstones equipped to a grinding vehicle. Repeated test grinding has proved that we can achieve the required grinding with four passes using a basic grinding car with 16 heads (with 16 grindstones) currently in operation. Fig. 9 shows appearance of the contact surface of a rail before and after grinding.

![Marking](image)

We can see marking put before grinding removed after four passes of grinding. That confirms that grindstones evenly contact the surface of the rail. Now we carry out grinding combined with additional passes for surface finishing. Grinding for squat reduction has a short history; so we have to keep checking whether squat control is achieved as expected.

![Before grinding and After four-pass grinding](image)

**Fig. 9: Contact Surface of a Rail Before and After Grinding**

4.4 Changing Material Quality of Rails

In addition to grinding of rails for squat reduction as explained above, we are conducting studies from the perspective of changing the material rails are made of. In order to prevent squat and achieve longer service life of rails, bainitic steel rails have been developed. Those are rails that facilitate appropriate wear so that rails can themselves remove the layer affected by contact that can be the origin of rail defect. The development concept for those differs from the concept of stronger rails, which was traditionally been considered a principle for development of rails. Bainitic steel rails are now undergoing performance checks by laying test track.

4.5 Struggling with a New Type of Rail Defects

As stated above, there have been many studies on squat reduction such as changing rail maintenance and changing the material rails are made of. The breakdown of rail defects shown in Fig. 6 includes head checks that are the next most common type of defect after squat and battering. In recent years, many head checks involving breakout (spalling) shown in Fig. 10 have been found mainly in the Tokyo area on gauge corners of high rails at shallow curves and transitions. Although head checks have traditionally been considered defects to be taken care of in rail maintenance, care by checking the length of cracks was enough, because cracks involving spalling were hardly found, except in sections where rolling stock lubricates rails. But in recent years we have found head checks involving spalling at curves that have relatively large radii and do not cause heavy wear. We are concerned that they could result in rail breakdown.

There have been various studies on squat as it is a typical form rail defect; but not so many have been performed on head checks, because there have been few cases of head checks causing rail breakdown. Now we are analyzing the occurrence of head checks and growth to spalling, and are carrying out studies on means to counter that while referring to previous research reports.
Under head checks with heavy spalling, horizontal cracks are linked along the rail, and we found that some types of such links might cause cracks that grow into the rail base (Fig. 11).

This is the same kind of growth as of squat described above. We also found that some horizontal cracks that occur under head checks at the gauge corner grow in the direction of the field corner and might penetrate the rail. In such a case, we should expect that whole rail head may break off. In other words, when head checks only remain cracks, the possibility that it causes rail breakdown is very small; but if spalling occurs and a horizontal crack grows from that, there is a risk that whole surface of the rail head peels off or that the horizontal crack causes rail breakdown as in squat.

Since spalling that originates in head checks has some kind of relationship with factors such as faster trains, changes in rolling stock structure, and changes in shape of contact surface, we are carrying out experiments using rolling test machine manufactured to evaluate phenomenon related to fatigue and wear between rails and wheels. We plan to analyze factors for occurrence of head checks focusing on the shape of wear of wheels and rails; and concurrently we will try to find a material for rails that is effective against head checks by testing rails of different materials.

4.6. Controlling Fatigue of Rails

As shown in Fig. 2, the second most common cause for rail replacement is fatigue. The standards for replacement are specified according to the limit for fatigue that is caused by tensile stress at the base of welded joints of rails. Most of the tensile stress is generated by bending stress that occurs when trains pass on rails. As that standard is based on accumulated tonnage, the replacement is called “tonnage replacement”. At welded joints of rails, there is a difference in hardness between softened area generated by heat during welding and the welded metal material; so, repeated passing of wheels causes roughness on the contact surface of rails that gradually develops. That roughness generates more stress too. But previous studies revealed that it is possible to extend fatigue life by appropriate maintenance such roughness at welded joints of rails.

Specifically, it has proved possible to extend the life of rails longer than twice the standard for current tonnage replacement by grinding rails in four passes with the above-mentioned 16-head rail grinding vehicles to make the average grinding interval 50 MGT after laying rails. Yet we plan to extend the replacement interval for the time being only by 200 MGT in field examination to review actual intervals. For already-laid rails that have received tonnage to some extent, it has been found that lives of 50 N rails with an accumulated tonnage of less than 500 MGT and 60 kg rails with less than 700 MGT at the start of grinding can be extended by 200 MGT unless there is large roughness on such rails. Grinding of rails with the aim to extend fatigue life enables us not only to improve of reliability of rails, but also to reduce tonnage replacement of rails, i.e. to reduce costs.

4.7. Improving Wear Resistance of Rails

Lateral force is loaded to rails when trains pass through a sharp curve. This is not only a factor for flange climbing derailment, but also a main factor for side wear of rails and corrugation on contact surface of low rails at curves. Wear is, as shown in Fig. 2, the third most common cause for rail replacement. As a countermeasure against such wear, we have studied use of rail material that has a wear reduction effect and use of lubricant etc.

As a kind of wear-resistant rail, HH rail (rails with the whole cross section of rail head heat hardened) have been used. And recently, an HE rail (hypereutectoid rail), a type of heat treated rail that has better wear resistance and surface defect resistance has been developed and manufactured. As transversal load causes hard side wear of high rails, rail replacement due to wear is mainly carried out according to replacement standards (Fig. 12). Accordingly, we have taken actions for high rails at sharp curves such as use of HH rails and installation of track lubricators.

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We are evaluating wear when lubricant is used and examining the wear mechanism. Using lubricant on gauge corners of high rails decreases the friction coefficient and reduces wear, but we have found that this increases transversal load both to low and high rails. On the contrary, using lubricant only on low rails decreases transversal load both to low and high rails. Thus, we expect reduction of corrugation, an issue regarding the contact surface of low rails, and reduction of wear on flanges of wheels contacting high rails and side wear of rails, an issue regarding high rails.

We are also studying development of lubricants. Current lubricants have a problem where applying them to the contact surface of low rails increases the risk of causing wheel slip and skid. Generally speaking, the friction coefficient of lubricant with mineral oil is extremely low. In contrast, it has been found that solid lubricant has a friction coefficient appropriate for rails; hence, we are carrying out R&D on that as a material for new lubricant (friction moderator).

4.8. Preventing Buckling of Rails
The explanation up to this point that been on our efforts against rail defect and wear. But, accidents can occur even when rail material is maintained in good condition. Rail buckling is an example of such an accident. As temperature of rails rises in summer, axial compression force at rails increases, and that increases the risk of buckling. Buckling causes large deformation of track; but unlike with rail breakdown where blocking signals are displayed to stop trains, a train might pass over a section with large deformation resulting in derailment. In order to prevent such accidents, appropriate control of axis force of rails is required. But at present, such control is actually carried out using the traditional method of measuring the length of expansion or compression of rails between poles set at specified intervals relying on marking put in advance.

Compared to inspection of track irregularity of usual rails that has been evolved from manual inspection to inspection with a high-speed track inspection vehicle, inspection of CWR is not that far advanced. Additionally, this method still has some room of measurement error and we cannot measure localized axial force.

Although we conducted many studies on measurement methods of axial force for CWR, no practical methods have been suggested. There were suggestions of methods such as directly attaching a strain gauge to a rail, focusing on change in magnetic characteristic when stress occurs, as well as focusing on change in ultrasound velocity according to stress. But those still have issues to be dealt with such as identifying initial values when stress is not applied and receiving the effect by residual stress in rails.

But, thanks to recent tremendous technological innovation and advance of information technology, some of the studies that were suspended could possibly be successful if tried again. Currently we are studying methods to estimate axial force by making use of a characteristic of guided waves stated above whereby they change in velocity in a rail according to axial force; but at the same time, we consider it important to continue reviewing previous studies.