Endurance Property of Rail Material for Ball Guide

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Abstract
Endurance properties of guide systems are investigated from the viewpoint of rail material selection. The application of a guide system on the various fields may lead to more severe operating conditions, for example a more corrosive environment. In that case we may need some anticorrosive material such as 18-8 stainless steel or titanium. We improved the surface hardness by roller burnishing and proved the possibility of using austenitic steel for rail material.
Keywords: linear guideways, roller burnishing, tribology, surface treatment, rolling fatigue

1 Introduction
Linear motion ball guide systems are widely used in machining centers, X-Y table, NC manufacturing stages and other precisely controlled moving equipment.

The linear guideways system was developed about 40 years ago by H. Teramachi. Until now, the concept of this device stays the same in principle, but many variations and improvements are made for various applications [1, 2]. The transparent schematic drawing is shown in **Fig.1**. The rotation of balls help to move the device with less force and it moves in an accurate manner.

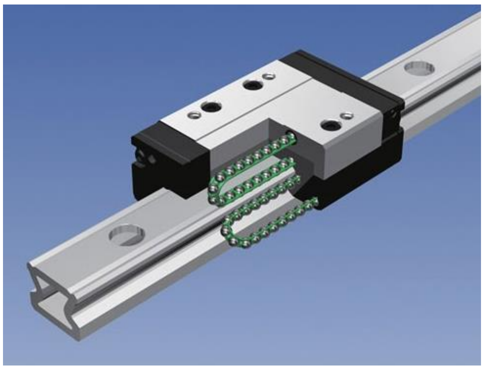


Fig. 1 The schematic view of LM guide system [3]

The principle of this equipment for easier and accurate movement is very simple. Simply the rotation of balls helps the reduction of the moving resistance. But the equipment and their endurance properties are not so very simple to design. Fundamentally systems are very similar to the conventional ball bearing system. However there are many different features in linear motion ball guide systems, for example reciprocal motion of ball rotation and the usually longer rail length, complicated load geometry and so on [4, 5, 6, 7].

At present, this device works well in the machining and semiconductor manufacturing industries. But in the future, this device will be applied to wider range of industries such as chemical, food processing or aerospace industry. That means we need to develop a device which could work in a more severe environment and has lighter weight. For example, 18-8 stainless steel and titanium alloy will be appropriate materials for the severe environment because of their anticorrosive properties, in addition, the latter is relatively lightweight. Hardening is common practice for rail material to improve endurance property, however, applying these materials as rail will cause technical issue. High carbon steel including chromium containing steels are very adequate by quenching for martensitic hardening, carburizing or induction furnace quenching. On the other hand, 18-8 stainless steel and titanium alloy could not use these methods because of their inherent material properties.

To overcome the issue, we propose applying roller burnishing as work hardening method. We tried to improve the surface hardness and tested to evaluate the effect of work hardening treatment. The scheme of this study is shown in **Fig. 2**.

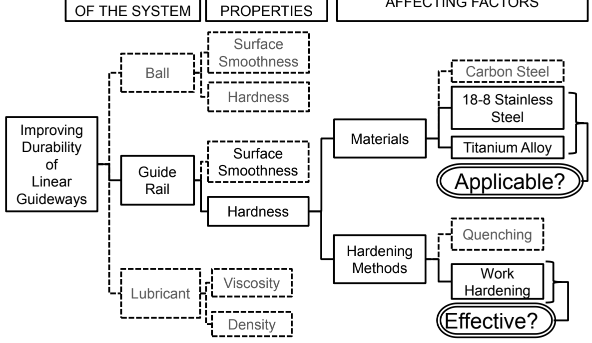


Fig. 2 The scheme of the experiment

2 Experimental procedure

2.1 Testing machine for endurance property

The endurance test is carried out by the originally designed testing machine, which consists of ceiling plate and floor plate.

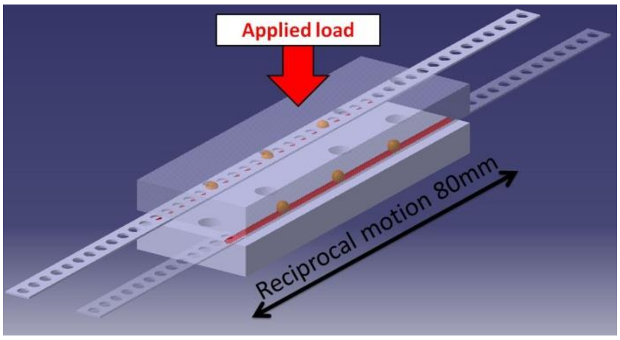


Fig. 3 Geometry of specimen plate and balls with retainer

Balls and their retainers are sandwiched by these plates. Both plates have 2 grooves with a radius of 3.09 mm, 3 percent larger than that of bearing balls. The geometry of test plates is shown in **Fig.3**. The floor plate moves along with groove direction driven by the servo motor. The ceiling plate is pressed by screw through upper frame of testing machine. The appearance of this testing machine and also polishing equipment are shown in **Fig.4**.

Fig. 4 The endurance test machine (left) and polishing equipment for surface finish (right)

The feature of this testing machine is characterized by the attached load cells for measurement of applied load and driving force. Those values from load cells are continuously recorded by computer during testing.

The testing conditions are shown in Table 1. The bearing balls are made from high carbon steel SUJ2 and have a diameter of 6 mm. A steel ball retainer is used to maintain isolated ball action.

2.2 Rail materials and heat treatments

We selected SCM415 and SKS3 as reference plate material because of their popularity in general linear guideways system. SCM415 is carburized and treated with quenching and SKS3 is treated with high frequency quenching. In this experiment we evaluated 18-8 stainless steel (SUS304), pure titanium and beta-titanium alloy as a possible candidate for the rail material. The Vickers Hardness of SKS3, SCM415 and SUS304 were 750, 730 and 180, respectively.

Table 1 Experimental conditions

Stroke distance	80 mm
Frequency of reciprocal motion	1.3 Hz
Lubrication	Lithium grease
Number of supporting balls	6 or 8
Size of ball (radius)	3 mm
Testing temperature	Room temperature

2.3 Roller burnishing treatments

The roller burnishing method is used for hardening of specimen groove surface. The change of groove shape is shown in **Fig. 5**. Resulted surface of the groove is glossy and smooth (upper right). After roller burnishing treatment, the depth of the groove was increased about 0.2 to 0.5 mm.

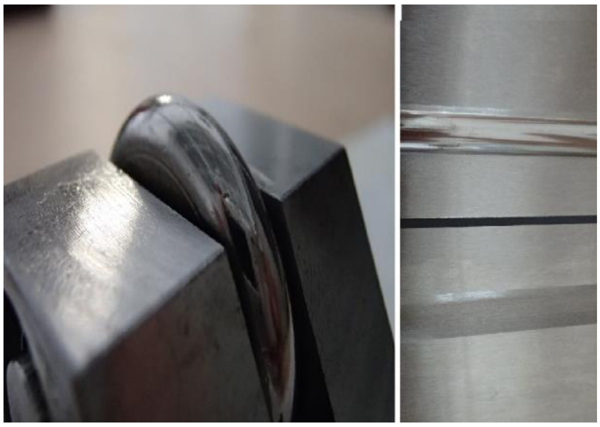


Fig. 5 The work hardening roller (burnishing roller) (left) and before (lower right) and after (upper right) of work hardened specimen

Fig. 6 The milling machine assembled with work hardening tooling (burnishing roller)

Figure 6 shows the milling machine and tooling equipment for hardening of specimen groove surface. It consists of a rotating hard wheel to press the specimen surface. By pressing the rotating hard wheel, the specimen is compressed and the hardness is increased, accordingly. The amount of work hardening is controlled by the depth of resulting groove.

2.4 The linear guideways and endurance testing

Equation 1 for rating life of linear guideways system suggests that when value C/P=1, 10% of test species will be disabled because of some breakage such as flaking, and the rest of them, 90% will continue to work without any deficiency. This equation is derived from the experience of ball bearing.

Equation 2 for durability of bearing, thought to be an original formula of equation 1, basic rating life L_{10} have a unit of 10^6, i.e. 1 million rotates. For example, L_{10}=1 means if the total number of revolutions of the inner ring reaches 1 million, 10% of species will be disabled and the rest of 90% will continue to work without any deficiency.

$$L = \left(\frac{C}{P}\right)^3 \cdot 50(km) \quad \cdot\cdot\cdot (1)$$

L: rating life (km)
C: basic dynamic load rating (N)
P: applied load (N)

$$L_{10} = \left(\frac{C}{P}\right)^3 \quad \cdot\cdot\cdot (2)$$

L_{10}: basic rating life (10^6 revolutions)
C: basic dynamic load rating (N)
P: dynamic equivalent load (N)

In case of linear motion system, analysis on durability life is relatively complicated compared to that of a conventional ball bearing system because of various factors such as enhanced deferential slipping or some other factors are multiply interacting.

3 Results and discussion

3.1 On the work hardening of SUS304

At first we tested the SUS304 stainless steel "as received" condition. That means no hardening treatment on the groove surface. In this case the specimen could not be applied with high load, because of plastic deformation on the groove surface. The indentation of the balls might disturb their rolling. To avoid this defect, we tried to start the test with low load. **Figure 7** shows the relationship between drag force and rotating distance for SUS304. For this experiment, the load was increased in a step-by-step manner. Increased drag force was shown for a relatively short period just after application of increased load, and soon decreased and stabilized. We think, that work hardening will be the cause of the phenomenon, and if so, hardness of the material which quenching could not be applied will be improved by controlling this phenomena appropriately.

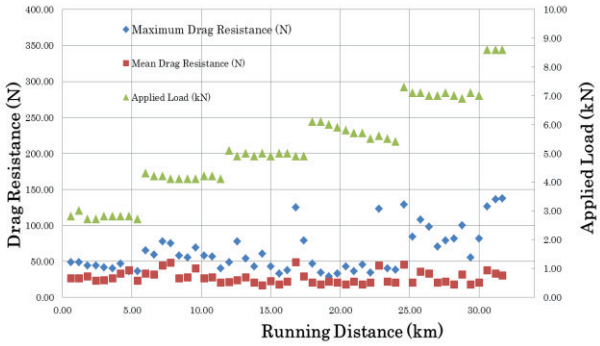


Fig.7 Changes of drag force in endurance test for SUS304

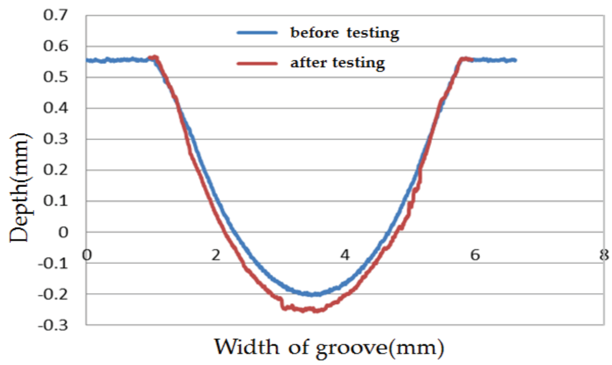


Fig. 8 Changes of cross-sectional shape of the groove for as received SUS304 after testing

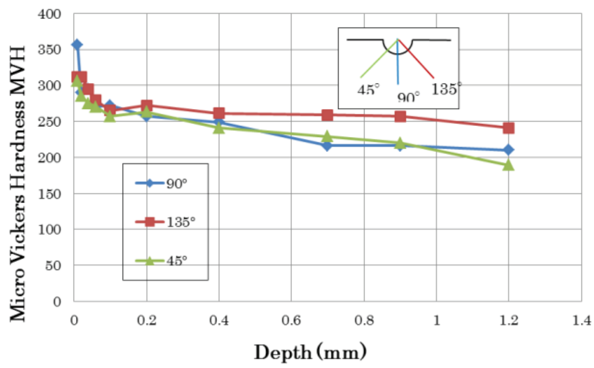


Fig.9 Changes of Micro Vickers hardness of 18-8 stainless steel vicinity of the groove in radial direction after roller burnishing

Figure 8 shows changes of cross-sectional shape of the groove before and after SUS304 endurance test. Compared with quenched material, relatively deeper groove is observed due to relatively high plastic deformability.

After roller burnishing, the Micro Vickers hardness in the vicinity of surface area are measured and the results are shown in **Fig. 9**. The roller burnished groove of specimen has higher hardness. The effective depth of hardened layer is about 0.1 mm. This value may respond to the Hertz's maximum shear stress range. That means, if we could evaluate the contact diameter between the ball and the bottom of the groove to be about 1 mm, then the 0.1 mm depth of the groove is in the range of maximum shear stress.

We will proceed in the consideration more precisely in the future. And we also suggest that the thickness of the hardened layer will be controlled by the setting of the milling machine accordingly, and it can be used to control the hardness of the rail material.

3.2 Work hardening of titanium alloy

The hardness of titanium alloy is usually improved by alloying or work hardening. The endurance property of rail material depends on the hardness of the rail surface. Therefor we evaluated if cold working is applicable to the material for improvement of hardness. **Figure 10** shows the effect of cold rolling on the hardness of titanium alloy. The hardness of titanium was increased by cold rolling. The work hardening ratio means the reduced thickness compared to the original thickness. The specimen was cold rolled to 80 % of its original thickness. Vickers hardness of pure titanium was improved by up to 75%, and for beta-titanium by up to 30%, respectively. It is not easy to draw a definitive conclusion from this sole experiment, it may be possible to use this alloy as rail material similar to the process described in the previous section 3.1 on the austenitic stainless steel.

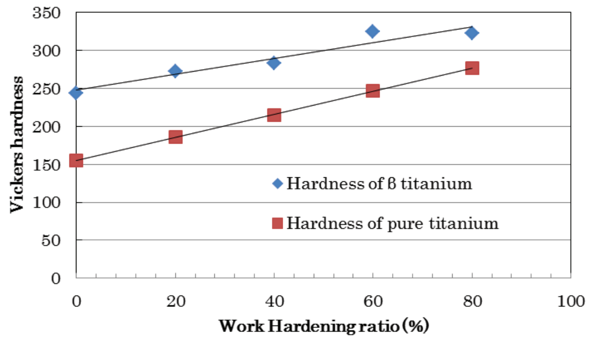


Fig.10 Changes of Vickers hardness of titanium by work hardening

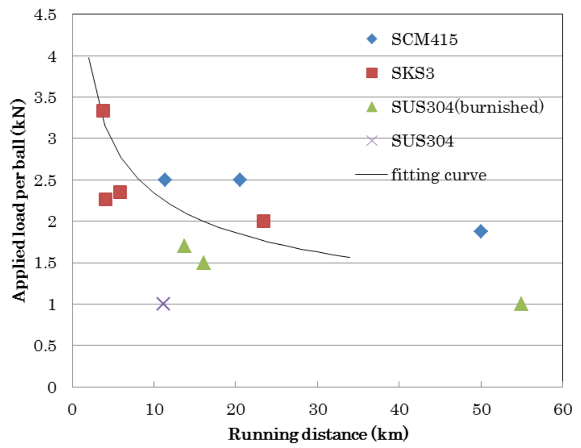


Fig.11 Life of rolling distance for miscellaneous materials

3.3 The endurance property of rail materials

Figure 11 shows the relationship between applied load and running distance till breakage of the system. That mean, testing machine shut down if the current of servo motor exceed 200% more than 4 minutes. Comparing with SCM415, case hardening steel material, relatively short running distance is shown for SKS3. As described in previously the hardness of SCM415 and SKS3 is not so differentiated, and durability of the system will be proportional to the surface hardness of the rail, so the reason of this difference of running distance is not clear for now. Further investigation will be required for the cause of the differences among them.

For untreated SUS304, an endurance distance of 10.5 km under a load of 1 kN is achieved and the roller burnished specimen has an improved property to 16.0 km under 1.5 kN. It corresponds to about 70 % higher applied load. However, this value is relatively small compared to general SKS3 or SCM415 materials under this experimental condition. It is assumed that SUS304 will be utilized in a severe environment such as corrosive atmosphere under relatively light work condition, and further consideration on development of effective method for work hardening will be investigated.

Figure 12 shows the relationship between drag force denoted by rolling resistance coefficient and rotating distance for SKS steel. Drag force is affected by the surface texture. During continuous measurement of drag force, spiked drag force is observed when the direction of the movement is reversed and relatively huge drag force is shown for steady movement. With drag force increased during testing, damage of the surface of material was observed, and finally the system failed. We defined the point as end of life of the test material. In most cases, the test equipment will be stopped during the endurance test because of increased drag force, caused by damaged surface texture, and exceeded driving force of servo motor, though the specimen will continue to work when applied external force to move. Analysis of data suggests that possible a reason for the recovery of drag force will be surface flattening by the continuous movement of the ball.

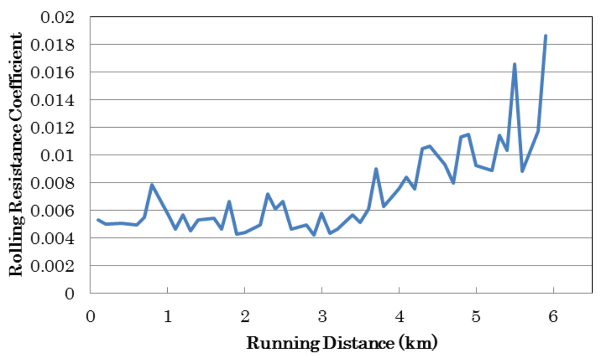


Fig.12 Changes of maximum drag force during endurance test for SKS3 steel

3.4 Surface damage and flaking

Invisible defects built up under the surface of the material will be the cause of visible the defects such as flaking, pitting or spalling. There are few studies on defect under the surface of the material before spalling. With this experiment, we cut the test species with a fine cutter, and observed defects under the surface with optical and scanning electron microscope (SEM).

Figure13 shows the damaged groove and cross cut section of specimen plate.

Figure 14 is SEM image of the observed defect built under the surface of the test material. In many cases, defects on the bottom surface of the groove are integrated with under the surface defects, and could not be clearly distinguished with crack caused by defects under the surface, namely cracks generated by Hertz's maximum stress [8].

Figure 15 is SEM image of rolling contact surface and severely damaged rail guide. On the rolling contact surface, flaking is observed. It will be common that defects under the surface are hard to distinguish from enlarged defects, so care should be taken on selecting the test piece. As expected, SUS304 does not endure high load conditions. However our study reveals some improvement of withstanding load are achieved during endurance experiments for work hardening by roller burnishing treatment.

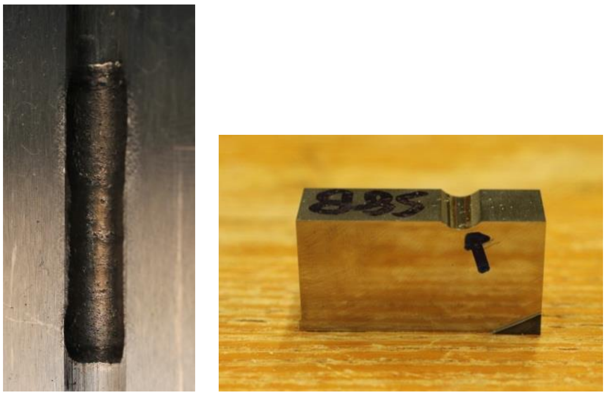
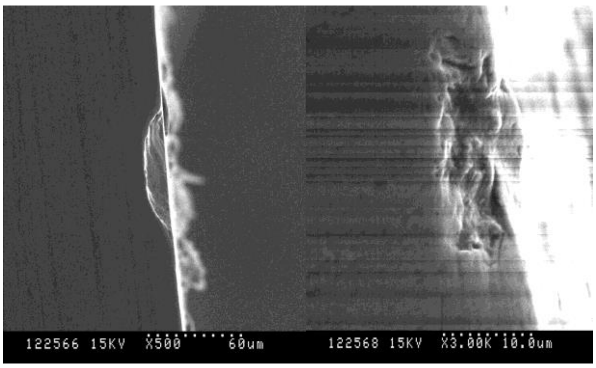
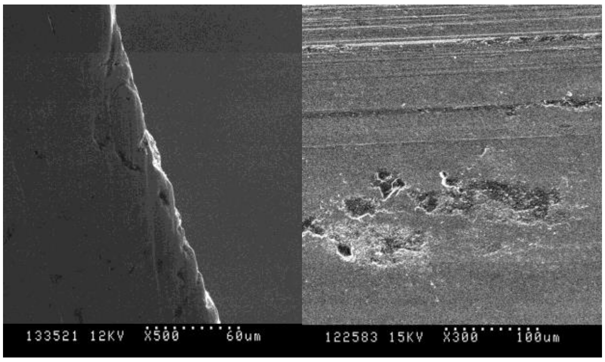


Fig. 13 Damages on the groove(left) and cross-cut of the groove(right)



a) SUS304 ×500 b) SKS3 ×3000

Fig.14 SEM image of flaking on the bottom of the groove



a) Rolling contact surface b) Severely damaged rail guide

Fig. 15 Rolling contact surface and severely damaged rail guide of SUS304 steel

We will investigate whether other materials with formation of hardened layer by quenching shows the same phenomenon as SUS304, and would like to deepen our knowledge on these materials.

In this study, we did not find a clear result of internal crack described in Hertz contact theory. In the meantime, we observed some prospective results of crack generated by Hertz's maximum stress, and we would like to study if internal crack exists.

4 Conclusions

1. The property of rolling fatigue was investigated for SCM415, SKS3 and SUS304 (18-8 stainless) steels.
2. 18-8 stainless steel was work hardened by roller burnishing.
3. The endurance property of 18-8 stainless steel was improved by roller burnishing about 70%.
4. The hardness of titanium was increased by cold rolling.

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