

Research on Stick-Slip Noise around Hub Bearings in Driven Wheels

Mikio KASHIWAI*

Haruo SHINOHARA*

Nobuo NIWA**

Ikuo YAMAKAWA**

Shigeki OIDE**

Kunio MIZUNO**

ABSTRACT

Micro-slippage occurs in the metal contact surfaces between the hub bearings and surrounding parts of automotive driven wheels when driving torque is applied. A stick-slip noise can accompany this slip motion. Analysis of the occurrence of stick-slip has shown that it is caused by a combination of factors. The research described in this paper has discovered previously unknown causes. Excess insertion load or axial force causes non-uniform strain in the bearing inner race. This strain builds up even after the load is released. Changes occur in the lubrication conditions of the press-fit face of the hub and the bearing inner race with varying insertion speed and humidity conditions, leading to the generation of excess insertion load. An effective method for prevention of stick-slip is proposed on the basis of this analysis.

1. Introduction

The typical fastening structure around the hub bearings of automotive driven wheels is one where the hub unit bearings and the constant velocity joint (CVJ) are press-fit, serration-fit and then screw-fastened using a hub and spindle nuts.

When driving torque is transmitted from the CVJ, twisting and slipping occur in the fastening structure in accordance with the magnitude of that torque. In order to eliminate this twisting and slipping, an extremely thick serrated shaft must be selected and the serration must be fit snugly so there is no play. However, this method is limited in consideration of the space layout and ease of assembly and disassembly work. Therefore, the fastening structure must take into account twisting and slipping when driving force is applied.

The CVJ tends to rotate toward the direction of the driving torque due to the twisting of the CVJ spline and the gap between the CVJ spline and the hub spline. This shifting must be absorbed by the slipping of the metal contact surfaces. Slipping may occur in multiple locations, and these

slipping surfaces have various lubrication conditions. Normally, no special measures have been taken for this slipping surface lubrication.

In contrast to recent increases in the driving torque due to improved automotive engine output, the torsional rigidity of the serrated shaft has not increased, so slipping occurs more easily. If the lubrication conditions of these slipping surfaces cannot be controlled, stick-slip noise may occur. This stick-slip noise may on rare occasions be viewed as an abnormal noise (called “Paki” or “Kakkin” noise) during operation. This study investigated the conditions under which this noise occurs, and clarified the factors. An effective method for preventing this noise is proposed on the basis of this analysis.

2. Conditions under which Stick-Slip Noise Occurs

2.1. What is Stick-Slip Noise?

The noise that is the focus of this research is the stick-slip

* Tochigi R&D Center

** Honda Motor Co., Ltd.

noise produced when micro-slippage occurs in the metal contact surfaces. This slip motion occurs in the metal contact surfaces when driving torque is applied to the serrated CVJ shaft. The conditions under which slipping occurs can be broadly divided into an initial type noise, when stick-slip occurs in the new vehicle condition, and an enduring type noise produced by roughness of the slipping surface. This surface roughness can be due to repeated slipping in the metal contact surfaces or caused by a change in the lubrication conditions. In either case these noises are not symptomatic of a situation that might damage the fastening structure of the hub bearings.

2.2. Locations where Stick-Slip Occurs

Research has been performed for some time to determine the locations where stick-slip occurs. Stick-slip has been confirmed to occur in all locations that contact the inner race of the bearings. Analysis results showed that the stick-slip location that should be given the most attention is the contact face between the CVJ and the bearing inner race as shown in Fig. 1. When driving torque is applied, the hub and serration-fitted CVJ attempt to twist in the driving direction. The stick-slip produced by this twisting can be divided into two types. The first is stick-slip that occurs when the CVJ undergoes relative micro-motion at the contact face with the bearing inner race end. The second is stick-slip that occurs when there is large static frictional force at the contact face between the CVJ and the inboard bearing inner race end. In the second case there is relative movement at the contact face between the two bearing inner races, and at the press-fit face between the bearing inner race and the hub, causing high level stick-slip noise to occur at this time.

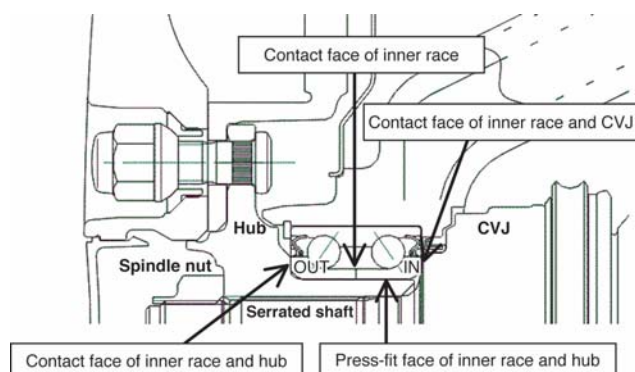


Fig. 1 Basic configuration around hub bearings in driven wheel

3. Factor Analysis of Noise Occurrence

3.1. Analysis of Initial Type Stick-Slip Noise

First, factor analysis was performed on the initial stick-slip noise that occurs in the new vehicle assembly condition. As a result, multiple factors were found.

3.1.1. Finished condition of the bearing contact faces (1) Lathe turning and grinding

There are two types of machining processes for the contact face between the CVJ and the bearing inner race: lathe turning and grinding. This contact face is generally used as the reference surface for machining the inside of the CVJ, and in this case the finished surface roughness after lathe

turning or grinding must be 6.3 S or less. However, some CVJ are known to provide a separate CVJ machining reference surface, so the roughness of the contact face with the bearing inner race is increased up to approximately 25 S, and concentric lathe turning finish lines (Fig. 2) remain.

Figure 3 compares the effect on stick-slip of the difference in the above two types of contact face finished conditions. The contact faces were degreased to eliminate the influence of lubrication, and torque equivalent to the driving torque was applied from the CVJ at a cycle of one time each in the forward and reverse directions to produce repeated twisting. The degree of acceleration of the vibration produced at that time was measured and compared up to 1,000 cycles. The results confirmed that the concentric finish lines were advantageous with respect to stick-slip. This showed that grinding processed parts had a high noise level in the initial condition when the lubrication condition was poor.

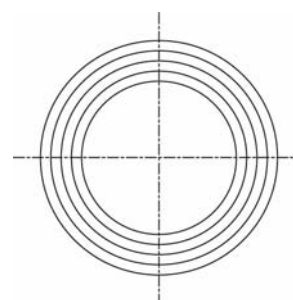


Fig. 2 Concentric finish line

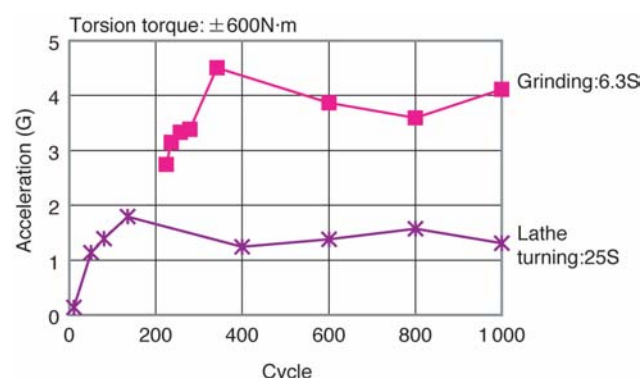


Fig. 3 Acceleration level for stick-slip and the machining process of CVJ

(2) Grinding waves

In the grinding process, care must be taken to manage the bearing play of the grinder main spindle and the grinding wheel feed rate. Depending on these management conditions, waves appear on the above-mentioned CVJ grinding finished surface, and the number and height of these waves varies. The true contact area changes according to the number and height of the waves, causing the static frictional force of the contact face to also change. As a result, stick-slip may occur at the contact face with the bearing inner race, and the CVJ and bearing inner race may also slip together. When the CVJ and bearing inner race slip together, stick-slip occurs at the press-fit face of the bearing inner race and the hub. Thus, factors causing stick-slip were found to be the CVJ waves, and the static frictional force between the hub and the bearing inner race that prevents the bearing inner race from slipping together with the CVJ.

Figure 4 shows an example of the number of waves on the contact face between the CVJ and the bearing inner race produced by different grinding conditions. To ensure a flat surface, the bearing play of the grinder main spindle and the grinding feed rate must be reduced. The wave height was greatest when there were seven waves.

Figure 5 shows the change in the slipping location due to the differences in the number of CVJ waves and the press-fit interference of the bearing inner race and the hub. When there were seven waves, the static frictional force at the contact face between the CVJ and the bearing inner race exceeded the frictional force provided by a press-fit interference of $25\text{ }\mu\text{m}$ or less between the bearing inner race and the hub, causing slipping to occur at the press-fit face. Setting a press-fit interference of $40\text{ }\mu\text{m}$ increased the static frictional force of the press-fit face, and slipping occurred at the contact face between the CVJ and the bearing inner race.



Fig. 4 Surface condition of CVJ

H : Slip at inner race and hub C : Slip at inner race and CVJ			
Interference of hub/bearings	Number of waves		
	Flat	21	7
$10\text{ }\mu\text{m}$	C	H	H
$25\text{ }\mu\text{m}$	C	C	H
$40\text{ }\mu\text{m}$	C	C	C

Fig. 5 Waves and interference for various fitting dimension of hub/bearings

3.1.2. Changes in the dynamic frictional force due to the lubricant

The fastening structure around the hub bearings of the driven wheels shown in Fig. 1 is generally assembled in the condition with only cutting oil or rust-proof oil applied to the metal contact surfaces, and without using lubricant. However, the following test results showed that stick-slip prevention effects cannot be expected for some types of applied oils with regards to slipping at the metal contact surfaces.

A reciprocating type friction tester (Fig. 7) was used with a $\phi 10$ steel ball (Fig. 6) as the test piece to measure the coefficient of dynamic friction under high surface pressure.

Tested lubricants

Rust-proof oil A : Refined kerosene used as the base oil

Rust-proof oil B : Lubricant used as the base oil

When the contact face load was 300 N in the degreased condition (Fig. 8), the coefficient of dynamic friction was confirmed to increase over time. Unlike rust-proof oil B (Fig.10), the coefficient of dynamic friction increased over time for rust-proof oil A (Fig. 9), which does not contain a lubricant. This resulted in an unstable lubrication condition that produces dynamic frictional force similar to the degreased condition (Fig. 8).

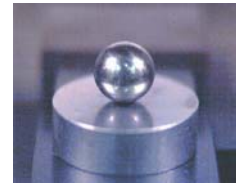


Fig. 6 Test piece for dynamic friction

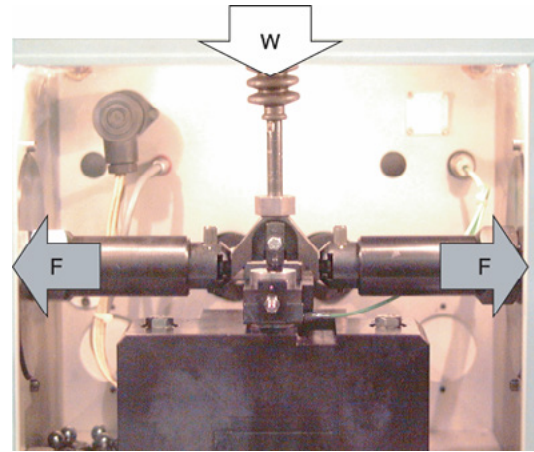


Fig. 7 Coefficient of dynamic friction

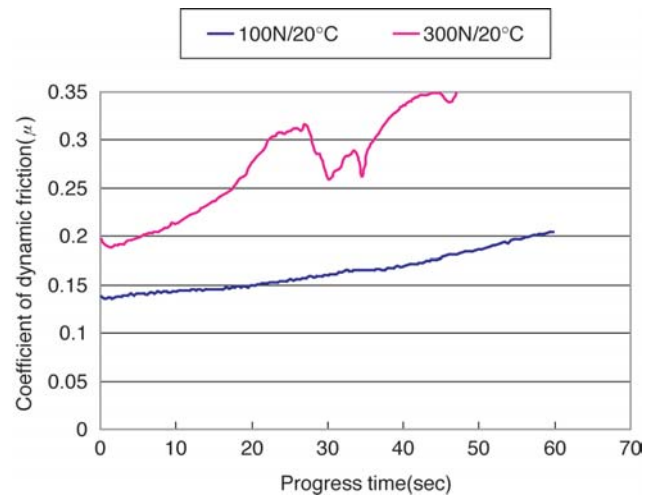


Fig. 8 Coefficient of dynamic friction when degreased

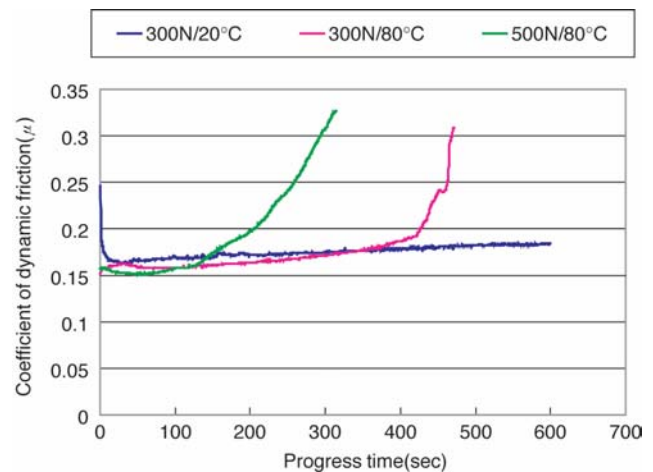


Fig. 9 Coefficient of dynamic friction with rust-proof lubricant type A

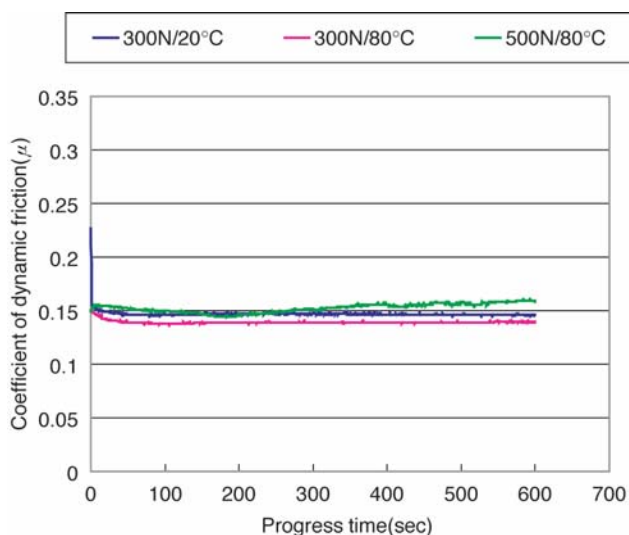


Fig. 10 Coefficient of dynamic friction with rust-proof lubricant type B

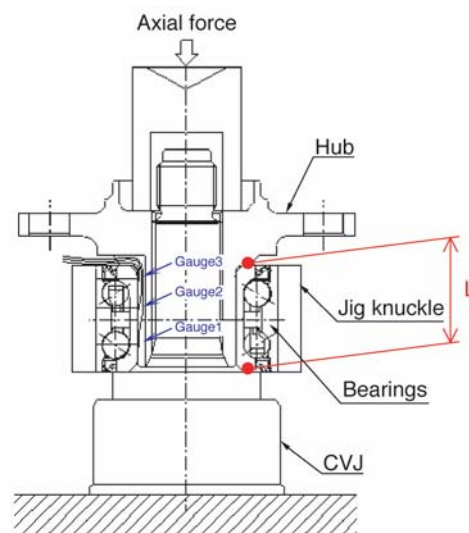


Fig. 12 Measuring strain of inner race of bearings

3.1.3. Non-uniform strain at the bearing inner race

Figure 11 shows the results of measuring the inner race length (L in Fig. 12) in the no-load condition after press-fitting the hub to the bearing inner race and applying a load equivalent to the axial force. The inner race length of 40.96 in Fig. 11 is the length after contact of the inboard and outboard inner races, and a length shorter than 40.96 represents the accumulation of strain in the no-load condition. In addition, Fig. 12 and Fig. 13 show the strain of the bearing inner race measured by attaching strain gauges to the bearing inner race and applying a load equivalent to the axial force. Figure 13 shows that gauge 3 changes toward the tension side regardless of whether a load is applied. In addition, the strain was confirmed not to change even when the load was removed. When this type of non-uniform strain of the bearing inner race occurs, the true contact area at the contact face between the inner race and the hub decreases, so the static frictional force drops and slipping is thought to occur more easily. Figure 14 shows a CAE representation of non-uniform strain of the bearing inner race. The bearing inner race is normally a non-uniform thickness, so when an excessive load is applied, the strain easily becomes non-uniform.

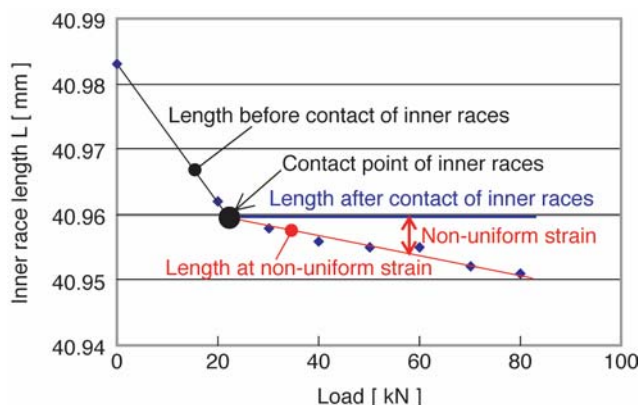


Fig. 11 Insertion load and inner race length

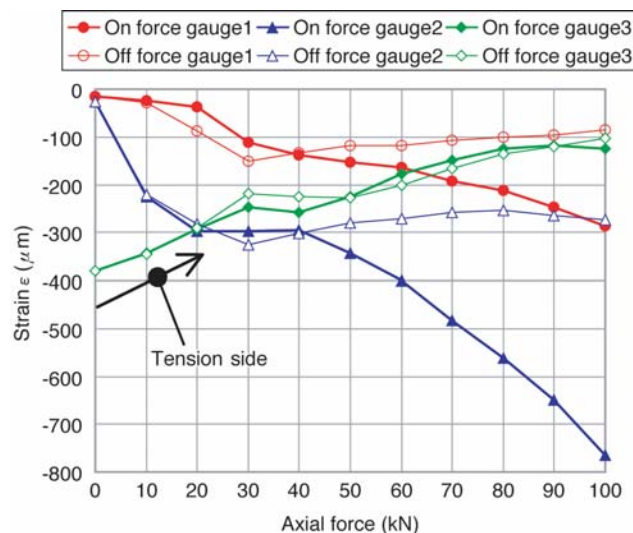


Fig. 13 Axial force and strain

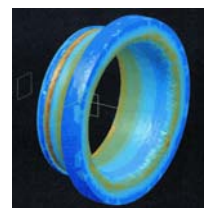


Fig. 14 Non-uniform strain of inner race

3.1.4. Effects of humidity

(1) Humidity and torque coefficient

A phenomenon was reported where stick-slip noise occurred when this fastening structure was manufactured during rainy weather. Investigations of vehicles exhibiting this phenomenon showed that the spindle nut tightening torque had changed, so factor analysis was performed.

First, the change in the torque coefficient with respect to humidity was investigated. The torque coefficient was found to change according to the tapered shape of the spindle nut seat and the humidity as shown in Fig. 15. In the humid condition the torque coefficient tended to become higher and the axial force tended to drop.

However, a clear correlation between the weather and the rotation angle of the spindle nut after contact was confirmed as shown in Fig. 16. Factories where this phenomenon occurred used a press-fitting machine structure where the maximum load was set by hydraulic control. This led to the hypothesis that, like the above-mentioned correlation between the insertion load and the strain of the bearing inner race, the effects of humidity caused an excessive load in the process to press-fit the hub to the bearing inner race, which resulted in non-uniform strain of the bearing inner race.

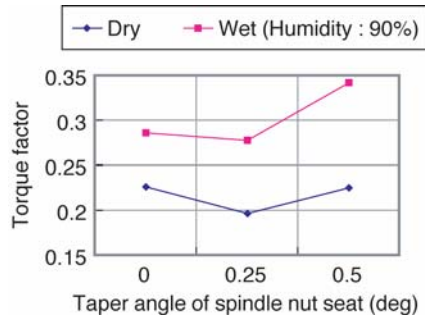


Fig. 15 Torque factor with variation in nut seat angle

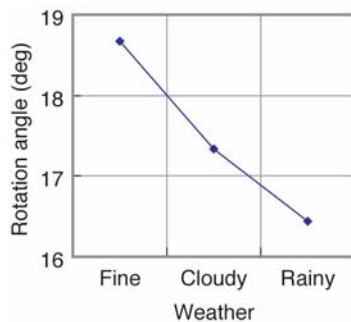


Fig. 16 Change of spindle nut rotation angle with change in weather

(2) Humidity and lubrication condition

Based on this hypothesis, the humidity and the insertion load were measured. This measurement used a mass produced press-fitting machine and changes in the insertion load over time were recorded as shown in Fig. 17. The hub was press-fit to the bearing inner race and the change in the load due to humidity was compared, focusing on the load (contact load) at the load rise point when the hub contacts the inner race and the peak insertion load.

The humidity around the press-fitting machine during rainy weather was approximately 60% and the measurement results confirmed a high correlation (coefficient of correlation: -0.912) between the contact load and the peak insertion load as shown in Fig. 18. Here, the peak insertion load increases as the contact load decreases. The humidity around the press-fitting machine during fine weather was approximately 20% and the coefficient of correlation at this time dropped to a level that was hardly noticeable (coefficient of correlation: -0.280), as shown in Fig. 19.

These results show that the dynamic frictional force drops when the humidity is high and the bearing inner race contacts the hub with a small insertion load. The cause for this is thought to be that the lubrication performance of the water-soluble cutting oil used when machining the hub changes according to the humidity. The contact load is small, but the insertion load control has a time lag, which causes the

peak load to increase. The dynamic frictional force drops so the actual load applied to the bearing inner race increases. This causes the strain of the bearing inner race to increase and assembly enters the next spindle nut tightening process with this strain accumulated even in the no-load condition. Tightening is performed at the reference torque, but the bearing inner race which contracts with the tightening already has strain due to the excessive insertion load so the specified torque is reached with a small rotation angle. This fastening condition is thought to be the same as excessive tightening of the spindle nut. If the parts are assembled into a vehicle in that fastening condition, the application of driving torque from the CVJ causes the bearing inner race to move together with the CVJ so slipping occurs at the press-fit face between the bearing inner race and the hub. This slipping phenomenon produces stick-slip noise.

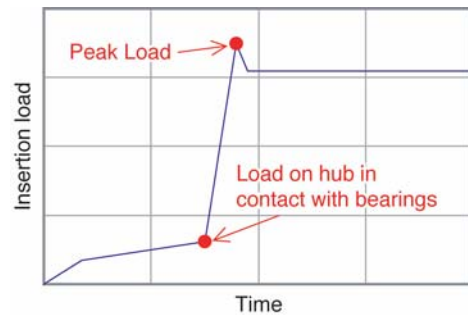


Fig. 17 Insertion load with time

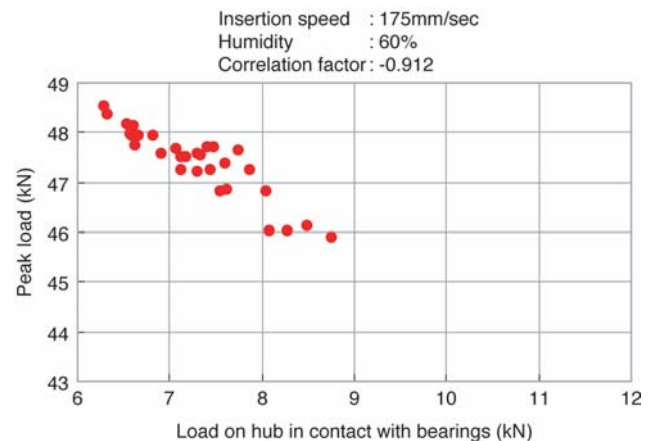


Fig. 18 Peak load and load on hub in contact with bearings in the case of a rainy day

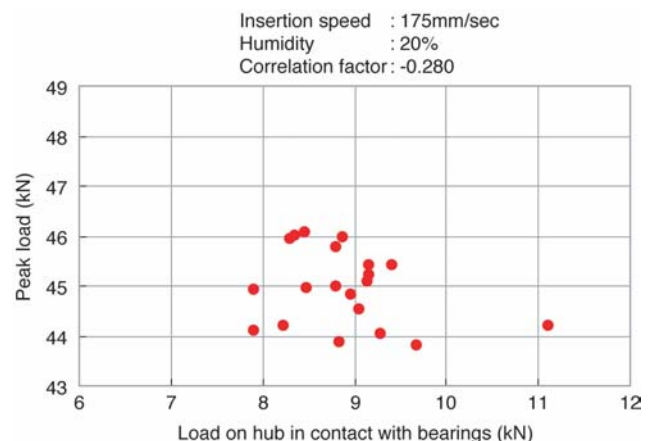


Fig. 19 Peak load and load on the hub in contact with bearings in the case of a fine day

(3) Maximum set insertion load and insertion speed

The peak load of the above-mentioned press-fitting machine can be set, but normally that setting is not changed even if the size of the bearings flowing along the line changes. Therefore, the set load becomes larger than the required insertion load as the bearing size decreases and the insertion speed also increases in this case.

The experiment shown in Fig. 20 compared the coefficient of correlation between humidity and the contact and peak loads at insertion speeds of 175 mm/s and 80 mm/s. At an insertion speed of 80 mm/s, a stable press-fit condition was obtained for all humidity ranges. In contrast, the correlation with humidity was confirmed to change greatly at an insertion speed of 175 mm/s. At an insertion speed of 175 mm/s, the lubricant was found to spread to the press-fit face, which is thought to have changed the lubrication condition.

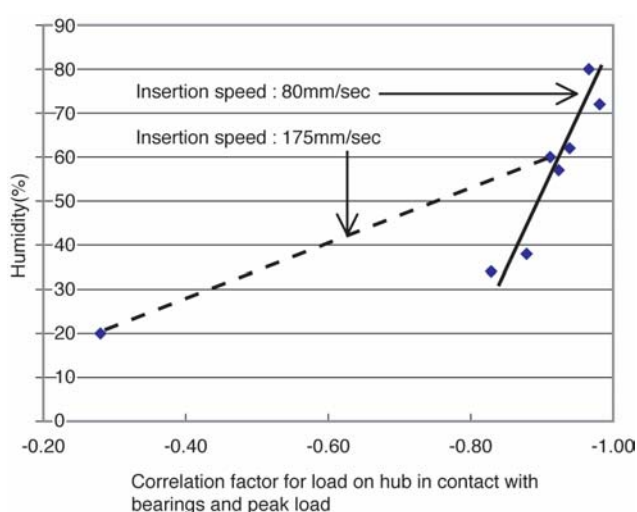


Fig. 20 Humidity and correlation factor

3.2. Enduring Type Stick-Slip Noise

3.2.1. Surface roughness

Stick-slip noise includes noise produced when running for long periods causes the contact face to become rough due to slipping of the contact face between the CVJ and the bearing inner race. Figure 21 shows a contact face that has been roughened by actual running. When the contact face becomes rough, stick-slip may occur at this face, or it may occur at the press-fit face between the bearing inner race and the hub when the CVJ and the bearing inner race move together because the roughness increases the static frictional force of this face.



Fig. 21 Rough face of CVJ

3.2.2. Contact face lubrication

Methods for preventing stick-slip based on the adhesion theory of friction were investigated. The conditions for selecting the lubrication method for the contact face between the CVJ and the bearing inner race were as follows.

Selection conditions

- The lubricant should not attack the bearing seals or other rubber materials.
- Performance should be maintained even under conditions of a poor protective environment for the contact face.
- The lubricant should be easy to obtain and allow refilling after its life span is reached.

In consideration of the above conditions, solid lubrication utilizing the molecular level shearing of molybdenum disulfide (MoS_2) interposed on the contact face was deemed suitable.

Figure 22⁽¹⁾ shows a photograph of shearing in the MoS_2 crystal orientation viewed at a magnification of 6 million times. MoS_2 has a micaceous molecular structure, so when the metals move relative to each other, the MoS_2 interposed between the metal contact surfaces shears and reduces the adhesive force between the metals.

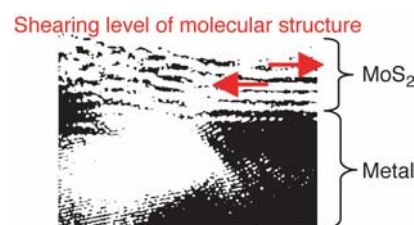


Fig. 22 Crystal structure orientation

The coefficient of dynamic friction of the MoS_2 grease was measured using the method described in section 3.1.2 above. The results confirmed that a stable coefficient of dynamic friction can be obtained even when the temperature changes under high surface pressure.

The coefficient of dynamic friction was confirmed to drop slightly when the contact face load was raised from 100 N to 300 N at a temperature condition of 20°C as shown in Fig. 23. The coefficient of dynamic friction at a contact face load of 300 N was also confirmed to drop at a temperature condition of 80°C as compared to a temperature condition of 20°C. Likewise, the coefficient of dynamic friction at a temperature condition of 80°C was confirmed to drop further and stabilize at 0.05 after 200 s when the contact

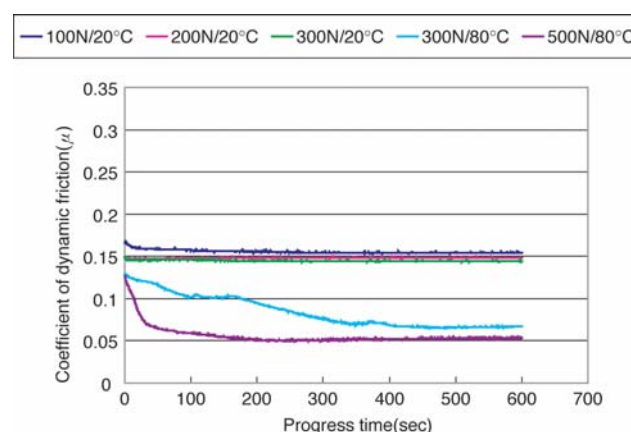


Fig. 23 Coefficient of dynamic friction with MoS_2 grease

face load was raised to 500 N. The high surface pressure and temperature rise are thought to improve the fluidity of the grease, so the MoS_2 spreads over a wide area and reduces the coefficient of dynamic friction.

Summarizing the above results, the easy-to-shear characteristic of MoS_2 is strongly manifested when the MoS_2 grease spreads widely over the metal contact faces. This easy-to-shear characteristic can be used to prevent stick-slip around the hub bearings of driven wheels.

3.2.3. Lubrication and surface roughness

When fastening portions experience repeated slipping, the contact face becomes rough. These limit conditions and the effects of lubricants were confirmed using a torsion tester.

Torsion test conditions

- Lubricants applied to the contact face

- (1) MoS_2 grease
- (2) Rust-proof oil
- (3) Degreased

- Torsion torque : $\pm 1,300 \text{ N}$

- Number of repeated cycles : 8,000 cycles

Figures 24, 25 and 26 show the test results.

- (1) MoS_2 grease : No roughness
- (2) Rust-proof oil : Roughness
- (3) Degreased condition : Surface roughness of a worse degree than (2) above.

This confirmed that use of a lubricant was effective even under life operating conditions.



Fig. 24 Damage of contact face with MoS_2 grease



Fig. 25 Damage of contact face with rust-proof lubricant

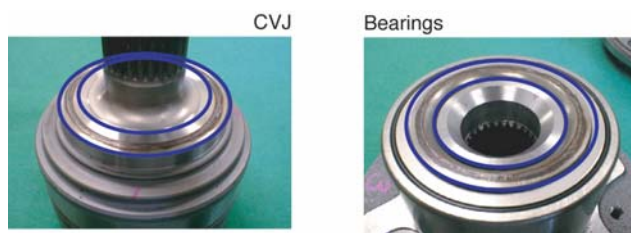


Fig. 26 Damage of contact face when degreased

4. Methods for Preventing Stick-Slip

Stick-slip around the hub bearings of driven wheels occurs due to an increase in the static frictional force at the contact face between the CVJ and the bearing inner race, and a decrease in the static frictional force at the press-fit face between the bearing inner race and the hub. Therefore, methods for preventing stick-slip include reducing the static frictional force at the contact face between the CVJ and the bearing inner race to ensure slipping, and ensuring that the static frictional force at the press-fit face between the bearing inner race and the hub exceeds the static frictional force at the contact face.

4.1. Ensuring Slipping at the Contact Face between the CVJ and the Bearing Inner Race

The static frictional force can be reduced by managing the finishing process for the contact face between the CVJ and the bearing inner race to prevent waves and by leaving concentric lathe turning finishing lines. In addition, when applying rust-proof oil to the contact face between the CVJ and the bearing inner race, excellent lubrication conditions can be obtained by selecting an oil that uses a lubricant as its base oil. As a more active measure, applying MoS_2 grease can ensure sliding at the contact face between the CVJ and the bearing inner race. When the lubrication condition deteriorates after long periods of use, the lubrication condition can be improved by refilling the MoS_2 grease.

4.2. Ensuring Static Frictional Force at the Press-fit Face between the Bearing Inner Race and the Hub

Increasing the press-fit interference between the bearing inner race and the hub can elevate the static frictional force at the press-fit face. In addition, increasing the rigidity of the bearing inner race also increases the static frictional force at the press-fit face that is obtained from the interference. When the load used to insert the hub to the bearing inner race is excessive, or when the axial force produced by tightening the spindle nuts is excessive, non-uniform strain occurs in the bearing inner race. In this case the true contact area at the press-fit face between the bearing inner race with non-uniform strain and the hub decreases, and the static frictional force also decreases. Increasing the rigidity of the bearing inner race suppresses the occurrence of non-uniform strain and ensures static frictional force at the press-fit face between the bearing inner race and the hub.

5. Summary

Factor analysis of stick-slip noise around the hub bearings of driven wheels revealed multiple factors and the following previously unknown special factors were found.

- (1) Excessive axial force due to spindle nut tightening and an excessive insertion load produced non-uniform strain in the bearing inner race and this strain accumulated even when the load was removed. This non-uniform strain of the bearing inner race was a factor causing stick-slip at the press-fit face between the bearing inner race and the hub.
- (2) If a fast insertion speed is used when inserting the hub to the bearing inner race, the coefficient of dynamic friction of the press-fit face (friction face) is easily

affected by a rise in humidity during insertion. When the humidity rises, the coefficient of dynamic friction falls. When fast insertion is performed in a high humidity environment, the coefficient of dynamic friction decreases and insertion is possible with a small load. This results in the same excessive insertion load condition as in (1) above, and is a factor causing stick-slip.

Stick-slip noise can be prevented by eliminating the above special stick-slip factors, managing the finishing process of the contact face between the CVJ and the bearing inner race, and increasing the press-fit interference with the hub after first ensuring the rigidity of the bearing inner race. However, the most effective method for preventing stick-slip noise proposed by this paper is to ensure an excellent lubrication condition at the contact face between the CVJ and the bearing inner race. As a concrete method, an excellent lubrication condition can be maintained and stick-slip noise can be prevented by applying MoS₂ grease to the contact face between the CVJ and the bearing inner race.

Afterword

With regards to the stick-slip around the hub bearings of driven wheels that is the subject of this research, in addition to the noise level, the noise recognition level also changes depending on differences in automotive sound insulation performance. Even when it is not recognized as abnormal noise, if the structure is such that slipping occurs at the contact face between the CVJ and the bearing inner race when driving torque is applied, MoS₂ grease should be applied to that contact surface to maintain an excellent lubrication condition and prevent changes in the stick-slip noise level.

Acknowledgements

The authors wish to express their deepest thanks to all related parties at Yanagawa Seiki Co., Ltd., NTN Corp., Fuserashi Co., Ltd., and Sumiko Lubricant Co., Ltd. for their immense cooperation with this research.

Reference

- (1) Takahashi, N., Kashiwaya, S.: High resolution transmission electron microscopy observation of the MoS₂-Au interface formed due to Stick-Slip of MoS₂ sliding on Au in relation to the friction trace, *Wear*, 206, p. 8-14 (1997)

■ Authors ■



Mikio KASHIWAI



Haruo SHINOHARA



Nobuo NIWA



Ikuo YAMAKAWA



Shigeki OIDE



Kunio MIZUNO