

Research into the Reduction of Stick-Slip Noise in Exhaust System Joints

Masashi IWAI*

Mototaka MAEDA*

Etsuo TAKAKU*

Yasunori MURAKAMI*

Masanobu MIKI*

Takeshi FURUKIDO**

ABSTRACT

Ball joints, one type of joint applied as an automobile exhaust system joint, will often generate an abnormal noise upon oscillation. The noise generating mechanism of this phenomenon is explained using element analysis and friction characteristic analysis of the materials making up the surfaces of the joints. It was found that the roundness of the flare flange of ball joints which generate noise is imprecise. This causes the flange to come in partial contact with the spherical gasket eventually resulting in abnormal wear of the guard net in the gasket. The particles resulting from this wear accumulate on the gasket surface, where the stick-slip phenomenon then causes the noise. A study was also conducted to determine input frequency for oscillation angle and temperature of the ball joint during the use of an actual vehicle. The fabrication of a simple excitation device that could apply those input conditions made it possible to conduct a bench evaluation of the noise. This bench test method was used to conduct parameter studies of design variables that significantly affect the generation of the noise. The bench test was also used to determine the range of settings for set spring load and the flare roundness wherein the noise will not be generated.

1. Introduction

Currently, ball joints (referred to as joint hereafter) having an oscillation function are widely used in automobile exhaust systems. By locating these joints in the exhaust pipe, as shown in Fig. 1, the force applied to the exhaust pipe due to engine roll displacement is attenuated, making it possible to reduce vibration transmitted from the engine to the exhaust pipe. The basic structure, as shown in Fig. 2, is an exhaust pipe fitted with a spherical gasket (referred to as gasket hereafter) and an exhaust pipe with a flare-shaped flange (referred to as flare hereafter). These two parts are held together by a coil spring at a set load.

Ball joints often generate abnormal noise when they oscillate. However, this phenomenon is an early stage degradation phenomenon that occurs only in some vehicles after they have been driven several thousand kilometers under specific driving conditions. The cause and effect

relationship between the factors has not been clearly understood. Therefore, many countermeasures have been found through post-build trial and error. Many examples of these measures eventually become examples of suppression of the essential oscillation function.

Therefore, this project carried out cause analysis in order to understand this phenomenon from both a macro- and micro-perspective. The macro-perspective was based on the relationship of the factors to such input characteristics as the oscillation angle and the temperature of the joints. The micro-perspective was based on the implementation of material element analysis of the oscillation surface material and friction characteristics analysis. Based on these analyses, a bench noise evaluation method was constructed. An "evaluation map" was created from the numerical values determined through tests using this method for joint design parameters. This paper reports on the above.

* Tochigi R&D Center

** OILES CORPORATION

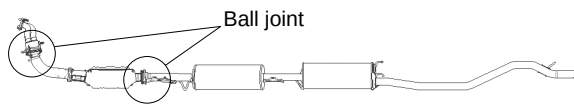


Fig. 1 Application example of a ball joint in an exhaust system

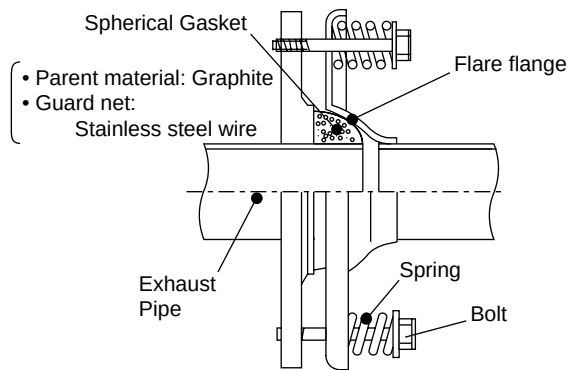


Fig. 2 Ball joint of an exhaust system

2. Noise Generation Factor Analysis

2.1 Noise Generation Condition in Vehicles

2.1.1 Measurement method

Measurements of noise generated by joints were made using actual vehicles. The measurement points, as shown in Fig. 3, were established in an adjacent area 100 mm below the joint. Driving conditions were fixed at a full load while idling after the engine is completely warmed up, the condition where the noise is most likely to occur. The oscillation angle and temperature were also simultaneously monitored at this time. Two sample joints were used for measurement: one normal part that does not generate noise, and one that does. Both joints were aged to an equivalent of the early stages of driving. The joints were not disassembled, but rather they were compared through use in the same vehicle, as assembled to the front and rear exhaust system components. This was done to reproduce, as closely as possible, the condition of the actual oscillation surface.

2.1.2 Measurement results

Fig. 4 shows the results of frequency analysis of noise near the joint, for both the normal parts and noise generating parts. The noise generating parts generated a metallic rubbing sound, "kyuru-kyuru", with the wide frequency range of 2 to 8 kHz.

Based on this data, the 2 to 8 kHz range was sampled, and Fig. 5 shows the noise level results in a time series graph. There was a clear difference between the two joints, and because there is a good correlation with the conventional feeling evaluation, this evaluation value will be used in the future as the noise level evaluation value.

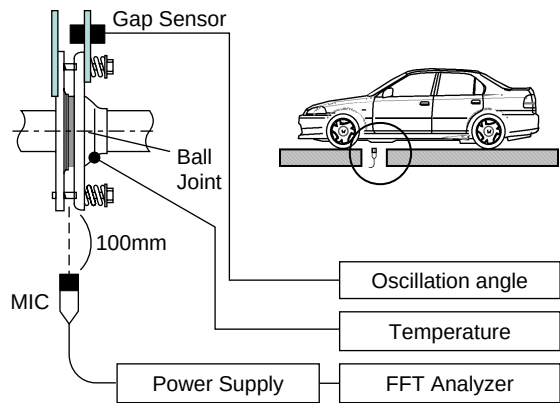


Fig. 3 Measurement system for noise in a vehicle

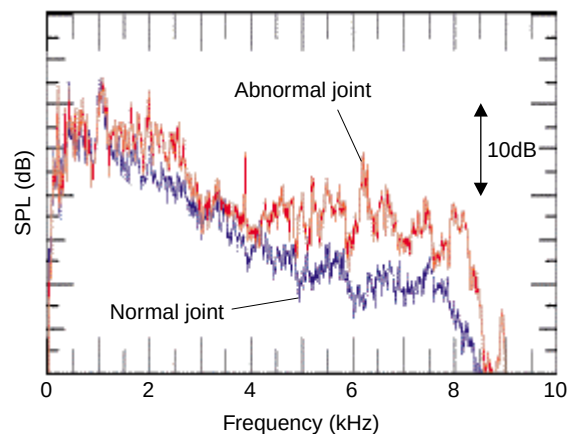


Fig. 4 Noise level frequency characteristics

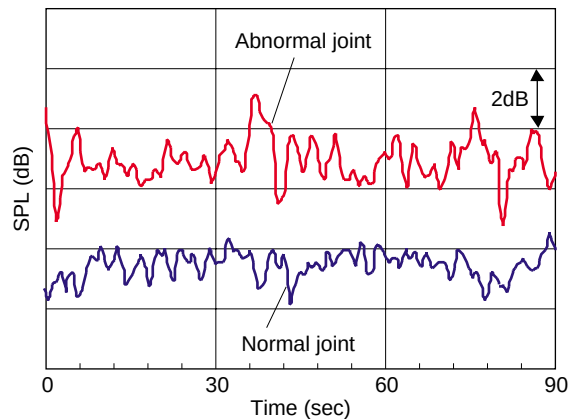


Fig. 5 Noise level time domain band pass data

2.2 Changes to Noise Level due to Differences in Driving Condition

2.2.1 Measurement method

In the previous section 2.1, the vehicle driving conditions were fixed at those where noise is generated most easily, but it is known that the noise level of noise generating parts changes according to differences in driving conditions. However, because it is difficult to take stable measurements when there are fine changes to driving

conditions, as shown in Fig. 6, confirmation was made using bench vibration tests. Under actual vehicle driving conditions, the joint oscillation angle and temperature fluctuate. Thus, the two parameters were changed slightly in the same way on the bench, and the relationship with surrounding noise levels was checked. The measurement method used was exactly the same as with the actual vehicle. In addition, the joints used were the same two samples as in the vehicle measurements, a normal part and an abnormal part. The joints were not disassembled, but rather vibrated together with the front and rear exhaust system components.

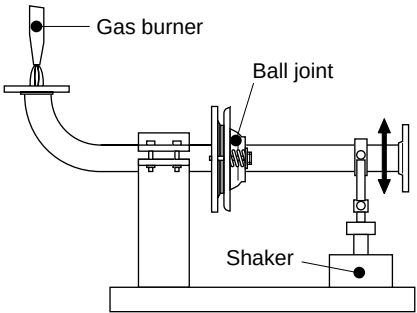


Fig. 6 Bench oscillation test (component parts of ball joint)

2.2.2 Measurement results

Fig. 7 shows the noise measurement results during the bench vibration test, when the oscillation angle and temperature are changed. With normal parts, there are no large changes to surrounding sound, even when the oscillation angle and temperature are changed, and no abnormal noise is generated. The maximum oscillation angle on the vehicle is 0.15° under full-load, idling conditions, but even if the oscillation angle is increased to 0.25° , no abnormal noise is generated. In comparison, surrounding noise tends to increase in noise-generating parts with greater oscillation angles and higher temperatures. The noise generation boundary line is at the point when the oscillation angle is 0.15° and temperature is 200°C . It was learned that when conditions are more severe than this, abnormal noise would, without fail, be generated.

From this, it was also confirmed through bench vibration tests that the conditions under which a vehicle generates the maximum abnormal noise levels, that is, with an oscillation angle of 0.15° and a temperature of 260°C , clearly fall within the noise generation range.

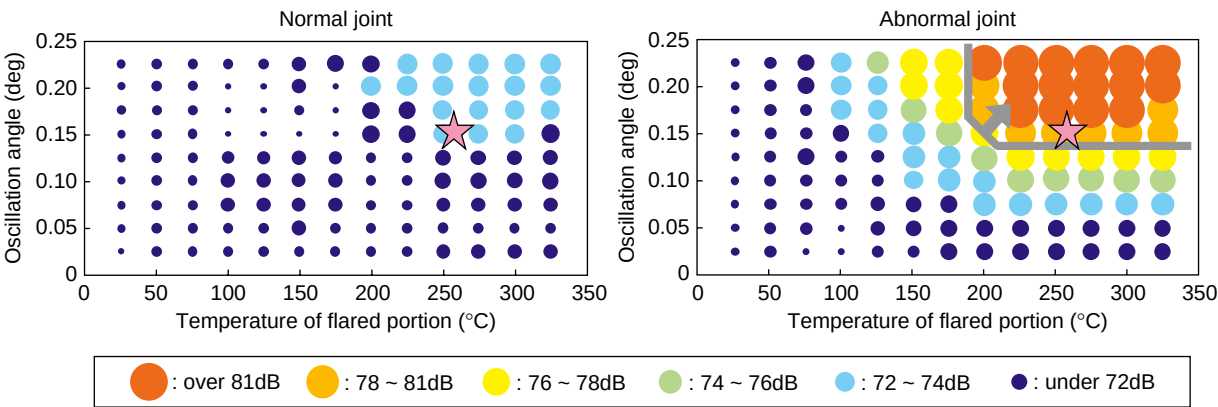


Fig. 7 Noise level during the bench oscillation test

	Normal joint	Abnormal joint
Appearance		
Roundness		

Fig. 8 Characteristics of the flare flange

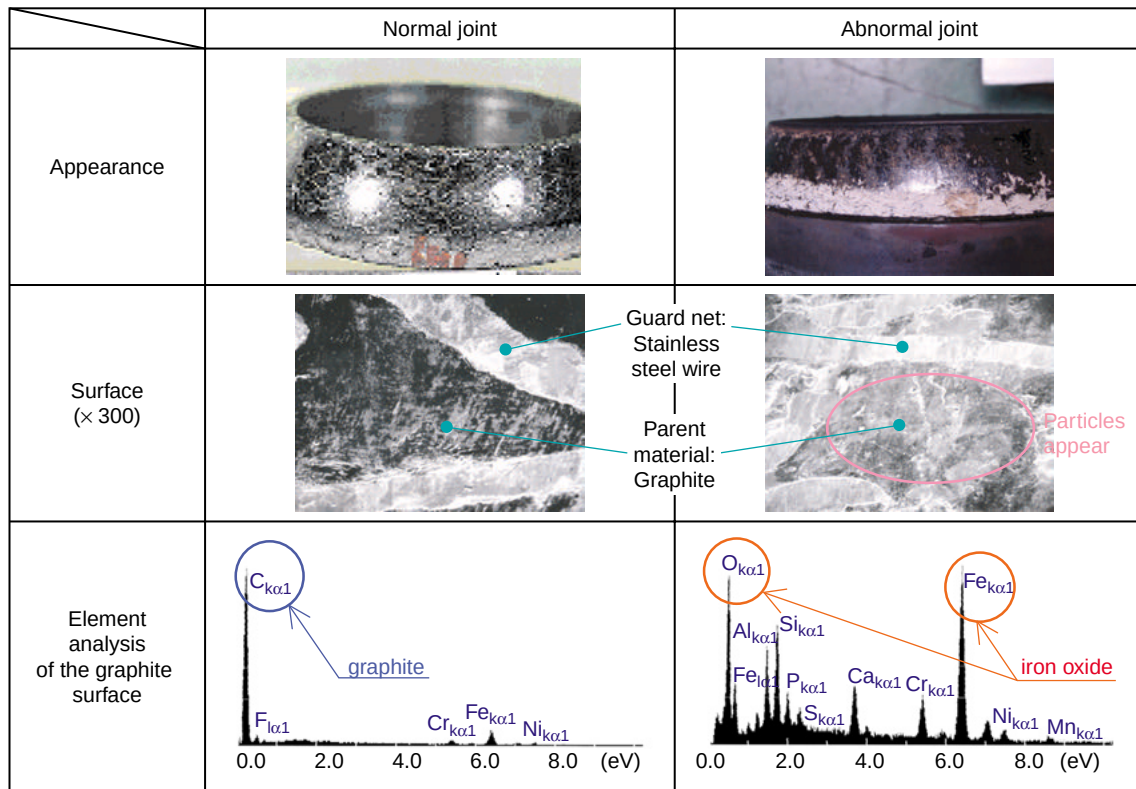


Fig. 9 Characteristics of the spherical gasket

2.3 Joint Contact Surface Investigation Results

2.3.1 Flare

A contact surface investigation was carried out for the two types of flare used in the noise confirmation tests. Those results are shown in Fig. 8. Looking at a photographic image of their appearances, it was learned that noise-generating parts have extremely uneven contact compared with normal parts. The results of flare roundness measurements show that normal parts have much better accuracy, 280 μm , than noise-generating parts, 450 μm .

2.3.2 Gasket

Next, an investigation was made of contact surface with the two types of spherical gaskets used in noise confirmation testing. The results are shown in Fig. 9.

With only photographic images of their appearances, no clear difference could be seen between them. Thus, the images were enlarged 300 times and reconfirmed. At this magnification a clear distinction could be made between the parent material graphite and the core stainless-steel wire. On the normal parts, the parent material was black, and the core material was white. However, with the noise-generating parts, there were many areas that gleam white on the parent material that originally looked black. It was confirmed that a contaminant had accumulated on the parent material.

Element analysis was carried out on the parent material surface for both parts. The major element of the normal parts was graphite. However, the major elements of the abnormal parts were iron and oxygen – that is, iron oxide. Therefore, it was learned that the accumulated contaminant is the powder generated by the core stainless-steel wire wear.

2.4 Joint Contact Surface Material Unit Analysis

2.4.1 Test method

From the results outlined in section 2.3 above, it is assumed that the core stainless-steel (JIS SUS310S-W1) powder (major element: iron oxide) that accumulates on the gasket parent material surface comes into partial contact with material equivalent to the flare material (JIS SUS304S-HP), and that the stick-slip phenomena during oscillation

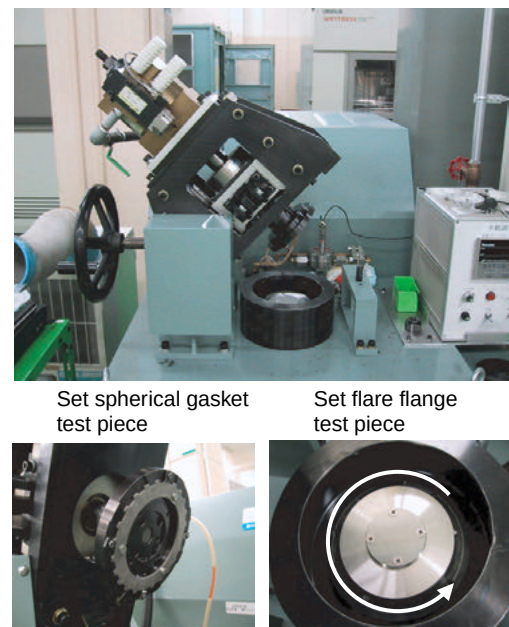


Fig. 10 Low velocity friction apparatus

is the origin of the abnormal noise. A friction test was implemented for each component material of the joint sliding surface to identify the causes of the noise generation.

As shown in Fig. 10, using a low velocity friction apparatus, the stainless-steel (JIS SUS304-HP) plate selected for the flare and the tip selected as the gasket raw material (core = JIS SUS310S-CB, parent material = graphite) were checked for friction behavior by sliding in the axial direction. Verifications were performed for the stick-slip phenomenon that occurs at high temperatures from the friction characteristics with combinations of these materials.

Also, test conditions were established based on conditions of actual vehicle use.

2.4.2 Test results

The results obtained with the low velocity friction apparatus are shown in Fig. 11.

First, a test was implemented with the combination of a stainless steel plate equivalent to the flare, and a graphite tip. The friction coefficient was in the 0.1 to 0.25 range, and even with a temperature rise the sliding state was stable in the normal wear range.

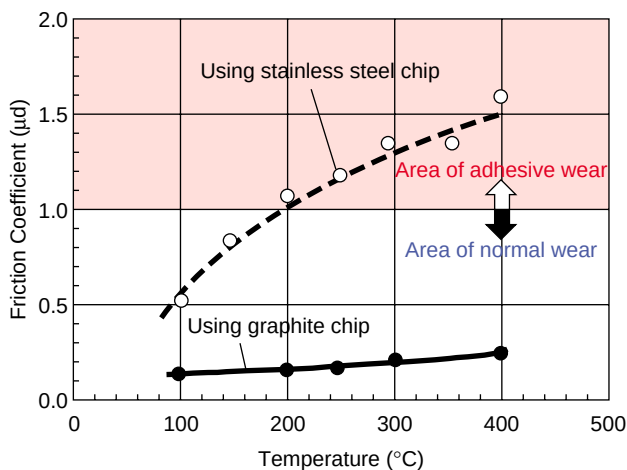


Fig. 11 Characteristics of the friction coefficient

Next, a test was implemented with a combination of stainless-steel plate equivalent to the flare and a stainless-steel tip equivalent to the gasket guard net. The friction coefficient was very high for the results using the graphite tip, and rose with a rise in temperature such that at a temperature of 200°C or more, it exceeds 1.0. That is to say, the shearing force of the sliding surface exceeds the contact load, and the sliding status is in the adhesive wear range.

Fig. 12 shows the results of a comparison of the friction coefficient change levels and the surface conditions of the core-equivalent stainless steel tip in the normal and adhesive wear ranges. The friction coefficient change level is small with normal wear, but it is extremely large with adhesive wear. Also, at this time, adhesion marks on the sliding surface were clear. That is, in the condition whereby the core stainless steel wire wear powder is accumulated on the graphite surface of the gasket material, there is partial contact with a material equivalent to that of the flare, creating an adhesive wear state, and causing the occurrence of the stick-slip phenomenon. The abnormal noise is generated from this phenomenon.

2.5 Abnormal Noise Generation Analysis during Vehicle Use

2.5.1 Test method

From the results of section 2.4 above, noise is generated when core material wear powder has accumulated on the gasket surface and the stick-slip phenomenon occurs. Next, an analysis was carried out for this phenomenon on how the gasket surface state changes from the new part state through use, and how it arrives at noise generation. First, giving full consideration to patterns of use, we looked into degradation input factors to the joint during operation, such as oscillation angle and temperature, in order to establish a vehicle verification mode. Next, the vehicle was driven in this verification mode in order to understand the relationship between the condition of the gasket surface changes and abnormal noise generation. The continuous verification flow is provided in Fig. 13.

First, data concerning oscillation angle and temperature applied to the joint was measured while driving for 500 km

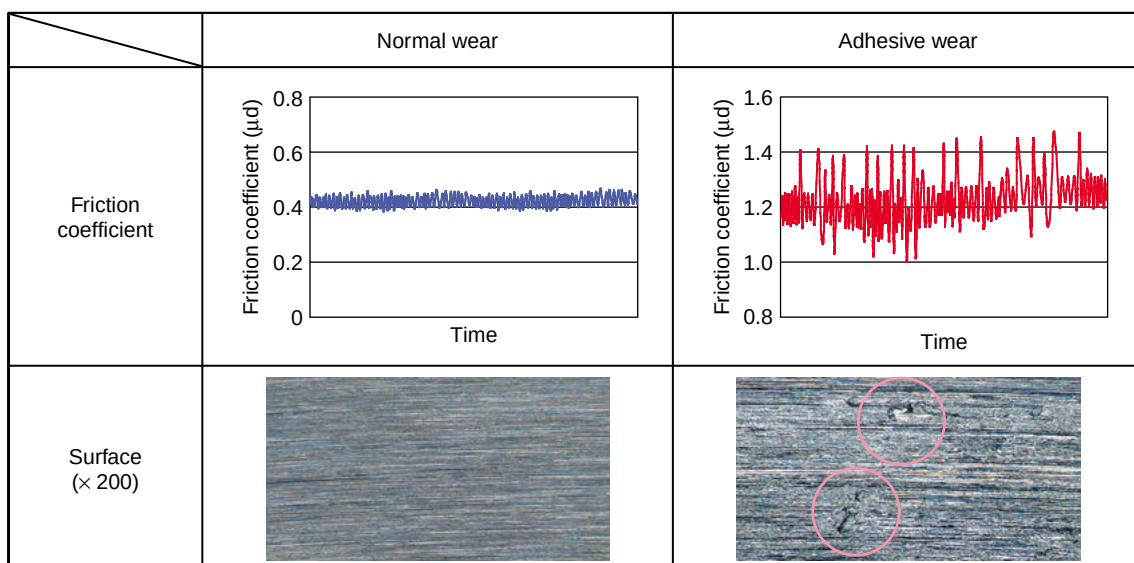


Fig. 12 Comparison between normal wear and adhesive wear

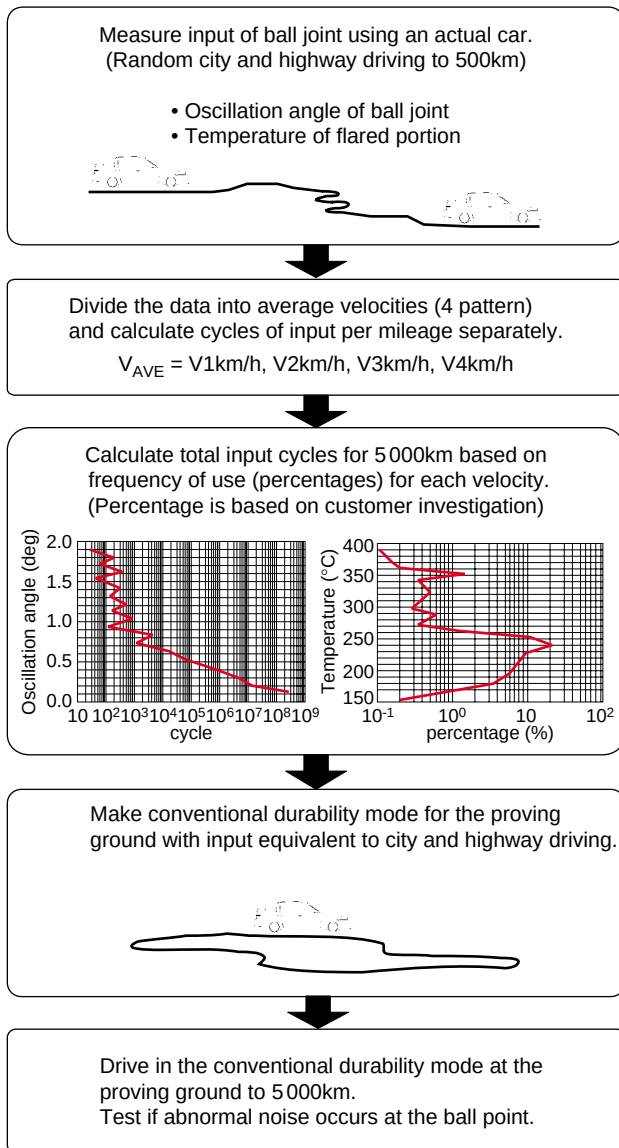


Fig. 13 Verification flow through noise occurrence

on a normal road. The measurement method used was the same as when performing the abnormal noise confirmation. Also, information on vehicle speed, engine speed, throttle angle, and gear position was gathered simultaneously, in order to understand the operating conditions. Next, the actual use vehicle speed range was divided into four patterns according to average vehicle speed, and input frequency data for each unit distance was calculated for each driving pattern.

Then, based on results of a user survey, wherein customers were asked how often they drove in each speed range, oscillation angle and temperature input frequencies were determined in proportion to frequency of use for each speed range for 5,000 km.

Further, based on results of input frequency obtained from driving on ordinary roads, a test course reproduction mode was created. This mode is a driving mode that provides input frequencies for oscillation angle and temperature that are equivalent to those on ordinary roads by having standardized the input levels for temperature and oscillation angle while driving on normal roads.

2.5.2 Driving results from the vehicle abnormal noise reproduction mode

A vehicle was driven 5,000 km in this mode. A new joint having the same flare roundness, 450 μm , as the part confirmed to produce the abnormal noise was used. Results of abnormal noise level changes in terms of driving distance are shown in Fig. 14. The abnormal noise was first confirmed at 2,950 km. The noise level reached its maximum at 3,700 km and it remained at approximately the same level until the 5,000 km. The gasket surface state changes that occurred at this time are shown in Fig. 15. With the new part (0 km) the gasket surface is covered with a layer of lubricant, and no noise is generated. According to the results of the element analysis of the parent material surface, the major element was iron, and the surface lubricant was PTFE.

After driving 1,700 km, contact occurred. The gasket surface lubricant was stripped, and the results of element analysis of the parent material surface show that the major element was carbon, which indicates that the parent material is graphite. Again, no abnormal noise is generated.

After driving 3,700 km, wear was more advanced, and looking at an enlarged photographic image, it was clear that the core stainless steel wire has been scraped.

According to the results of element analysis of parent material surface, the major elements were iron and oxygen – iron oxide – which indicated that the wear powder from the core stainless steel wire had accumulated on the surface. At this time, there was a noticeable abnormal noise. Also, it was confirmed that the state of the surface was the same as the noise-generating part described in section 2.3.

Based on the results above, because the flare roundness was poor (450 μm), partial contact occurred so that the core stainless steel wire was scraped. The resulting powder covered the parent material graphite surface. Consequently, the stick-slip phenomenon occurs and an abnormal noise was generated.

2.5.3 Comparison of the abnormal noise reproduction mode and conventional durability modes

As outlined above, abnormal noise generation was confirmed with the abnormal noise verification mode established with due consideration to the way users drive on an ordinary road. However, no abnormal noise occurred

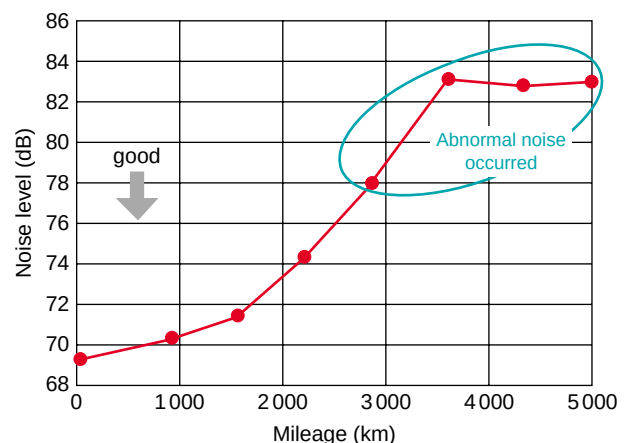


Fig. 14 Results of driving in the conventional durability mode at the proving ground

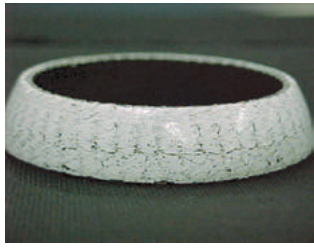
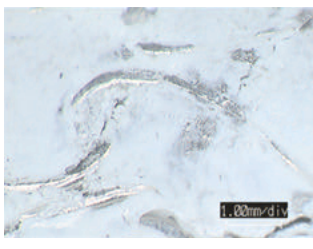
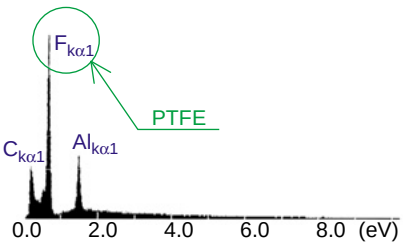
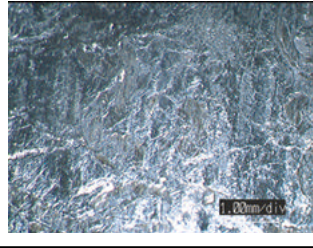
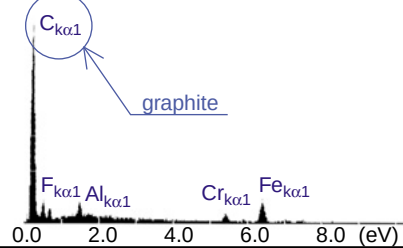
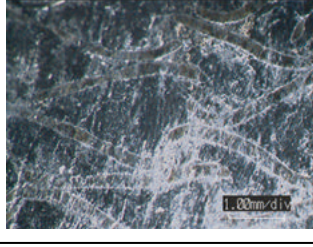
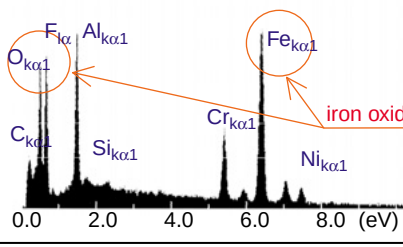
Mileage (km)	Appearance	Surface	Element analysis of the graphite surface
0			
1600			
3700			

Fig. 15 Transition of the spherical gasket surface

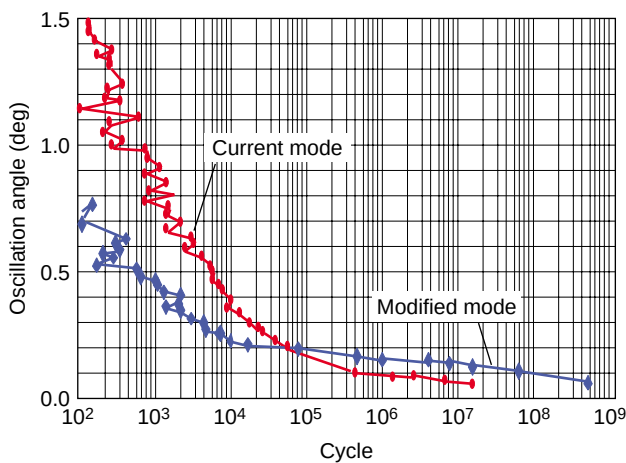


Fig. 16 Difference in oscillation angle for each driving mode

in the other durability modes implemented. These durability modes simulate driving situations where input is mainly concentrated on input to the chassis and body.

Therefore, joint input frequency was also measured in these conventional durability modes, and a comparative verification was made with this new abnormal reproduction mode. Oscillation angle input frequency measurement results are shown in Fig. 16.

From these results, we know that the abnormal noise

reproduction mode is a low input, high frequency model, while conventional durability modes focus on high input. Comparing the range with an oscillation angle of approximately 0.1° , the abnormal noise reproduction mode shows a frequency approximately 10 times that of the conventional durability modes.

Because the cause of this phenomenon is the gasket guard net wear and the resulting wear contaminants accumulating on the surface, the abnormal noise reproduction mode (which has a high frequency with a fine amplitude) can be said to have more severe conditions than the conventional durability modes. Accordingly, when converting the actual driving abnormal noise reproduction mode to a bench test, the key points in setting the input conditions were low force input, high frequency conditions.

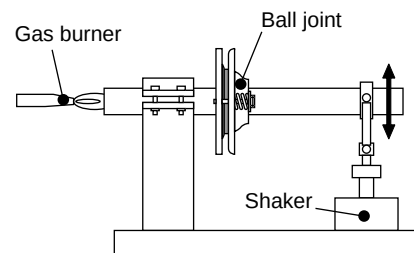


Fig. 17 Bench oscillation test (Ball joint test piece)

3. Creating a Bench Evaluation Method

An investigation was carried out for the conversion of the driving in the abnormal noise reproduction mode, which simulates input obtained from an ordinary road as obtained in section 2.5, into a bench test.

3.1 Bench Test Method

3.1.1 Shaker device

An outline of the bench shaker system is shown in Fig. 17. This system was constructed so that the oscillation angle and temperature inputs that are applied to the joint during actual driving can be set, facilitating verification of abnormal noise. In Fig. 3, the sample part joints are not disassembled but rather vibrated while connected to the front and rear exhaust system components in order to faithfully reproduce the abnormal noise of the recovered parts. However in this investigation, the tests were implemented with a test piece created by cutting out the joint and welding it to a pipe. This was done to prevent any constraints due to joint size or location, and to increase the versatility of the system.

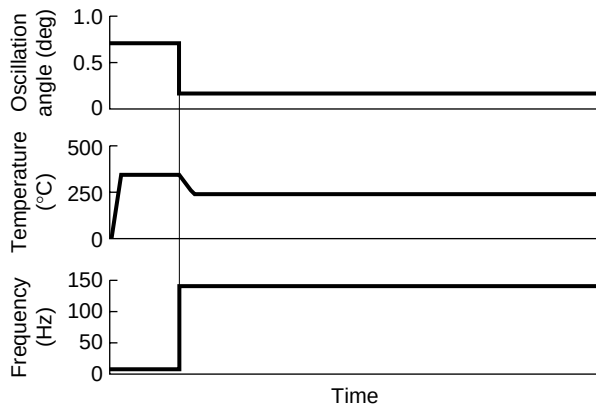


Fig. 18 Bench oscillation test conditions

3.1.2 Establishing oscillation input conditions

As explained in section 2.5.3, abnormal noise reproduction mode is a low input high frequency model. Thus, focus was placed on this point, and simplified input conditions were set. Fig. 18 shows these details. As for the input conditions, the focus was on low input with an oscillation angle of 0.10° , and temperature was set at the greatest temperature proportional to time. The oscillation frequency was set higher than with a vehicle, from the point of view of shortening the time period. Also, because the new gasket has a surface lubricant that includes PTFE, both the oscillation angle and temperature were set higher for the initial period only, with the idea of quickly removing the lubricant layer so that there is partial contact with the parent graphite material. In this investigation, the oscillation angle was set at the average value for the input in a vehicle, and the temperature was set at 300°C or more, a temperature which vaporizes PTFE. As the oscillation angle is large, the frequency is determined by the shaker capability.

Based on the above details, a bench mode equivalent to driving 5,000 km was established.

3.2 Results of Bench Evaluation Method Verification

In order to verify that this bench test method is appropriate, confirmation tests were carried out with new test pieces having an accuracy equivalent to the flare roundness of $450\text{ }\mu\text{m}$ used in the driving abnormal noise reproduction mode.

The test results are shown in Fig. 19. In the bench test, too, it was confirmed that abnormal noise occurs after 3,200 km of use. This is approximately an 8% difference from the 2,950 km at which noise occurred during driving, and is judged to be an adequate simulation of driving.

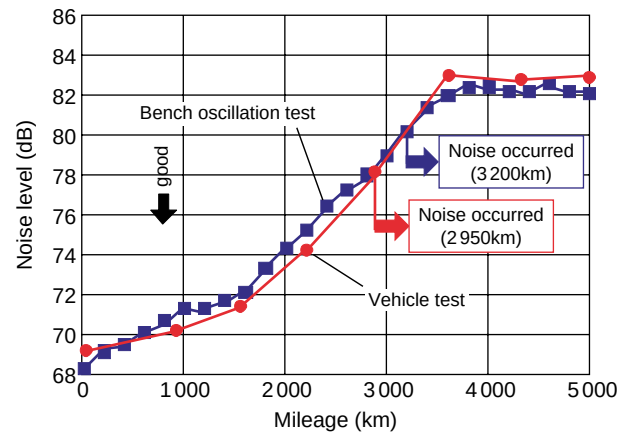


Fig. 19 Comparison between bench test and vehicle test

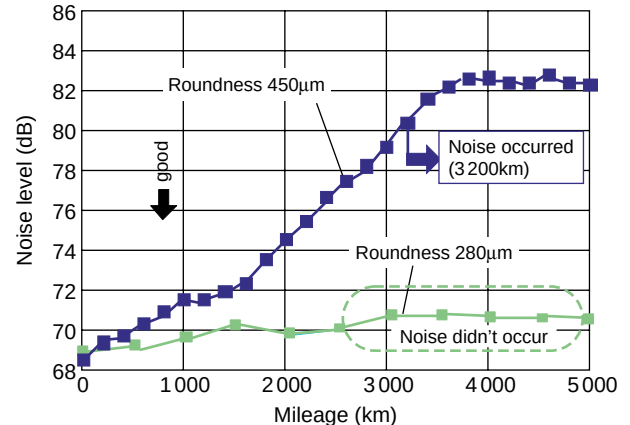


Fig. 20 Results of bench oscillation test

Next, verification was made of any abnormal noise generated by implementing testing on the bench using two types of new test pieces having different new part flare roundness.

According to the results in section 2.3.1, we know there is a clear difference in flare roundness accuracy for the normal part and noise-generating part. The flare roundness of the test pieces used in this case matched that of the test pieces used earlier, were $280\text{ }\mu\text{m}$, equivalent to the normal part, and $450\text{ }\mu\text{m}$, equivalent to the noise generating part.

The results of the above comparison are shown in Fig. 20. From these test results, we were able to confirm that the part specification with the poor flare roundness

accuracy of $450\text{ }\mu\text{m}$ resulted in the generation of abnormal noise at approximately 3,000 km. The flare with good roundness accuracy of $280\text{ }\mu\text{m}$ was confirmed to cause no abnormal noise even at 5,000 km.

From the results above, it can be said that the established bench test method can be applied to evaluate abnormal joint noise in vehicle driving.

4. Creation of Abnormal Noise Standards

Utilizing the bench evaluation method outlined above, the range of use wherein no abnormal noise is generated was investigated by looking into ball joint design variables. Because this phenomena is a problem of gasket guard net wear caused by gasket and flare partial contact, we limited our investigation to the main design variables that affect this contact, flare roundness and spring set load. Abnormal noise was judged with various combinations of oscillation angle, in a range of 0 to 0.50° , and temperature, in a range of 20 to 350°C , converting to driving distance, for every 1,000 km (up to 5,000 km), with the greatest noise levels plotted. Confirmation of noise levels was made according to the bench evaluation method when these parameters were changed, and the results mapped. These results are shown in Fig. 21.

5. Summary

A detailed analysis of the causes of abnormal noise generation during ball joint oscillation was made, and the following results were attained.

- (1) If the joint flare roundness accuracy is poor, there is abnormal wear due to partial contact between the gasket and the flare. This leads to powder formed from the wear of the thus exposed gasket guard net on the surface to adhere to the gasket surface. The gasket guard net is made of stainless steel, which means that when there is contact with the flare, which is also stainless steel, there is stainless-to-stainless contact. With oscillation, this results in an adhesion wear state, and when the parts slide, abnormal noise is generated due to the stick-slip phenomena.
- (2) Based on the patterns of use on ordinary roads, data on the input frequency for the oscillation angle and temperature was simulated, and a simple bench test method was created. This makes it possible to evaluate abnormal noise.
- (3) Using the bench evaluation method, a map was created from combinations of joint flare roundness and spring set load settings. This map can be used to judge abnormal noise.

From the above, it is now possible to prevent abnormal noise, by determining the appropriate joint flare roundness accuracy and spring set load in the early design stage of development.

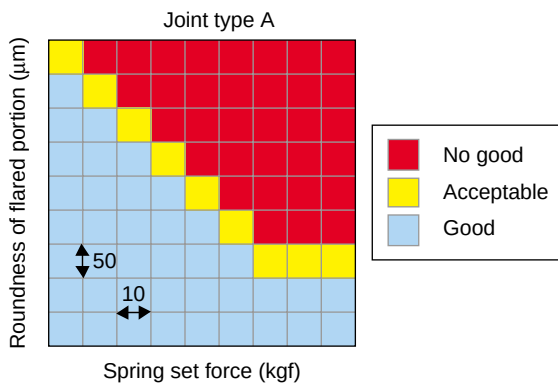
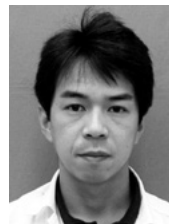


Fig. 21 Map of abnormal noise evaluation for ball joint

From this map it was learned that in order to restrict abnormal noise generation, it is most effective to have good roundness and a low spring set load. Also, even with the same spring set load, abnormal noise is generated in the range where flare roundness is large, shown in red, but no abnormal noise is generated in the low roundness range, shown in blue.

In the area of the map shown in blue, where abnormal noise is not generated, core wear powder contaminants have not accumulated on the surface and the normal surface state is maintained. That is to say, improving roundness accuracy and reducing spring set load actually reduces surface pressure on the contact surface, and is effective in restricting abnormal wear due to partial contact. Also, if roundness accuracy is established at a set value or less, abnormal noise will not be generated even if spring set load is increased. Thus, an improvement in roundness accuracy is thought to be effective at suppressing wear contaminant accumulation.

■ Authors ■



Masashi IWAI



Mototaka MAEDA



Etsuo TAKAKU



Yasunori MURAKAMI



Masanobu MIKI



Takeshi FURUKIDO