The mechanism causing hydrogen embrittlement flaking of transmission bearings

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Abstract

There have been many research reports on hydrogen embrittlement flaking generated on bearing samples. However, there have been few reports of studies performed in actual operating environments. This paper clarifies the mechanism and influencing factors causing the hydrogen embrittlement flaking on pulley support bearings, taking into consideration the assembly and operating conditions of a continuously variable transmission unit.

1. Introduction

In recent years, the performance requirements for transmissions have been increasing year by year in order to reduce CO_2 emissions, which requires even lower friction and further reduction in size and weight of transmissions. For transmissions (e-Axles) used in electrified vehicles, motors are expected to become smaller to obtain higher rotational speeds in the future. For conventional continuously variable transmissions (CVTs), further expansion of ratio coverage and reduction of internal friction will be required. For bearings used in such transmissions, it is necessary to guarantee reliability considering how they are used in harsh environments.

Hydrogen embrittlement flaking is one of the various failure modes of bearings. There have been considerable researches(2) reporting on the mechanism causing hydrogen embrittlement flaking on bearing samples. However, there are few research reports on the actual transmission operating environment.

In a belt CVT, multiple bearings are used to support the pulley (Fig. 1). In tests using a bearing sample and a CVT unit under normal test conditions, the service life of the bearing is as designed. However, the bearings get damaged earlier than the service life calculated under the relevant conditions when a combined acceleration endurance test is conducted with combined operations such as start, stop, and high-speed driving (hereinafter referred to as the combined acceleration endurance test) at high oil temperatures.

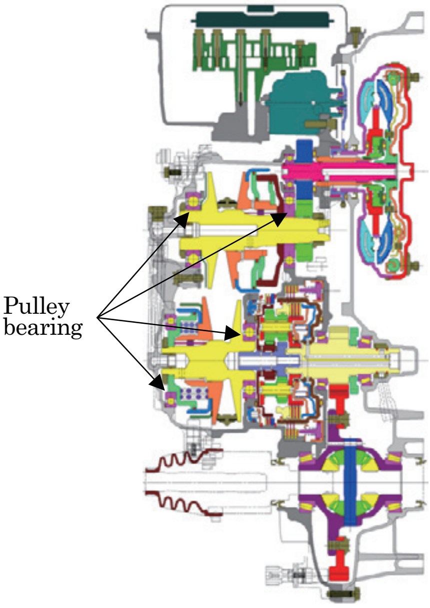

Fig. 1 Schematic structure of Jatco CVT 7

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As shown in Fig. 2, flaking occurs on the load area of the bearing outer ring's inner surface, whose inside contains a white layer. Further detailed analysis shows a larger than normal amount of hydrogen penetration, indicating the occurrence of hydrogen embrittlement flaking.

This paper clarifies the mechanism of hydrogen embrittlement flaking occurring on the pulley support bearings, taking into consideration the assembly and operating conditions of a CVT unit.

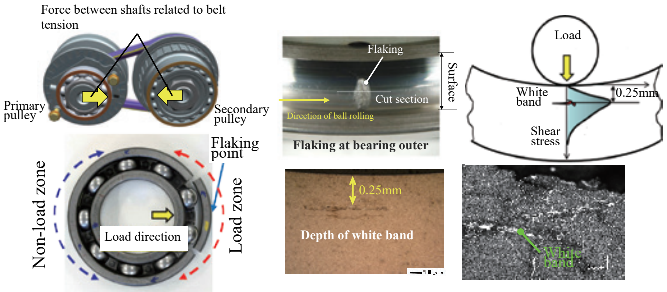

Fig. 2 Hydrogen embrittlement flaking

2. Mechanism causing the hydrogen embrittlement flaking

In general, hydrogen embrittlement flaking on a metal sliding part is considered to occur through the following mechanism (Fig. 3).

(1)The surface pressure, sliding velocity, and lubricant temperature of metal sliding surfaces are factors that influence the activation energy for decomposing hydrogen and other substances from hydrocarbons. They are also factors that influence the breakage of the oil film existing between metals. Thus, repeated sliding at high surface pressure, high sliding velocity, and high oil temperatures can easily generate hydrogen, causing oil film breakage to expose bare metal surfaces.

(2)The bare metal surface acts as a catalyst reducing the activation energy for decomposition into hydrogen atoms. Therefore, the bare metal surface becomes a factor accelerating the generation of hydrogen atoms, whose number increases.

(3)The hydrogen atoms are adsorbed on the bare metal surface where the oil film breakage occurred.

(4)The adsorbed hydrogen atoms diffuse into the metal via their own kinetic energy.

(5)Hydrogen atoms diffused into the interior concentrate at the shear stress generation site just below the sliding surface.

(6)The continuous repetition of the phenomenon causes a white layer to form.

(7)The white layer is a hard and brittle structure. When internal stress is repeatedly applied, internal fracture progresses from the layer to generate cracks. These cracks eventually propagate to the sliding surface, leading to flaking.

(8)Hydrogen that penetrated into the metal, on the other hand, has the tendency to be released. Therefore, hydrogen embrittlement flaking is unlikely to occur because hydrogen is released in the stopped state and during intermittent operation, whereas hydrogen continues to penetrate in continuous operating environments.

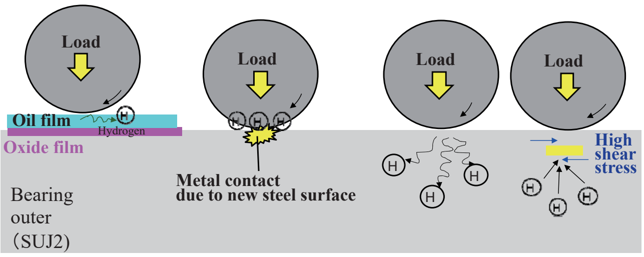

Fig. 3 Mechanism causing hydrogen embrittlement flaking

According to this mechanism, the following validation tests were performed:

- Sensitivity test for the amount of hydrogen penetration
- Measurement of bearing oil film thickness test using a CVT unit
- Test to confirm amount of hydrogen released while the vehicle is stopped

3. Methods used in validation tests

3.1 Sensitivity test for the amount of hydrogen penetration

Considering the mechanisms described in Chapter 2, the sensitivity of the factors influencing the amount of hydrogen penetration into bearings in a CVT unit was compared with the sensitivity obtained from tests using bearing samples.

The test machine for a bearing sample is shown in Fig. 4. Sensitivity tests were performed for influencing factors such as radial load, oil temperature, and rotational speed. The amount of hydrogen penetration into the bearing interior was examined after the tests were completed.

We also investigated the amount of hydrogen penetration depending on inputs such as torque and rotational speed of the bearings in a CVT unit. In the tests, the start and stop pattern and the constant input of loading were adopted (start–stop or constant load).

The test conditions are listed in Table 1.

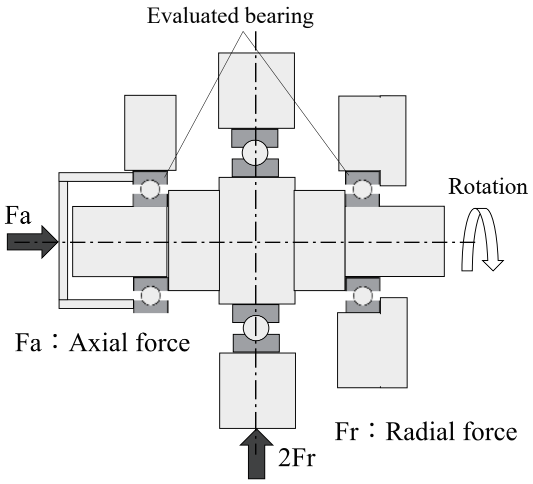

Fig. 4 Schematic of bearing unit test equipment

Table 1 Test conditions

	Influential factor	Radial load	Oil temperature	Input speed	Start-stop or constant loading
1	Radial load	2 conditions (medium and large)	High	High	Constant
2	Temperature	Large	2 conditions (medium and high)	High	Constant
3	Temperature	Large	High	3 conditions (small, medium, high)	Constant
4	Start-stop or constant loading	Medium	High	-	2 conditions (start-stop test pattern of triangular wave form)

Lubricant: CVTF (NS-3)

3.2 Bearing oil film thickness test using a CVT unit

There are various methods for measuring oil film thickness: optical, electrical, and ultrasonic methods, and methods using the properties of X-rays and neutron beams that penetrate the material. To measure oil film thickness in a CVT unit, these are necessary: minimizing changes to peripheral components, and installing the measurement instrument in a test facility that is capable of conducting endurance tests. Therefore, we used the electrical resistivity method with a bridge circuit. Figure 5 shows the measurement system of the electrical resistivity method. The inner and outer rings of the bearing are insulated by coating the surfaces other than their raceways with ceramic. While balls are rolling, contacting the oil film on the ring surface, the resistance in the circuit is infinite, meaning no electric current flows. Conversely, when balls are in direct contact with the metallic ring surface, current flows in the circuit. Thus we have developed a measurement system built in a CVT unit to determine the contact state between balls and the ring surface through changes in voltage.

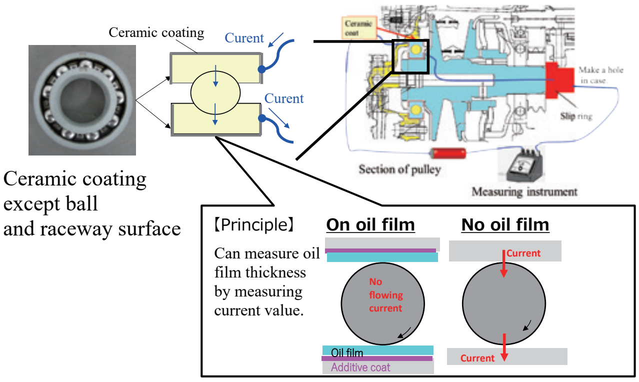

Fig. 5 Test method for measuring oil film

The bridge circuit diagram for obtaining voltage is shown in Fig. 6. The combined resistance R of the circuit is:

$$R = R1 + (R2 \times Rx / (R2 + Rx)) \tag{1}$$

where Rx is resistance between balls and the outer ring raceway. When the oil film between balls and the outer ring breaks, allowing the balls to come into metal-metal contact, Rx = 0 Ω. Then, the voltage of the circuit is V = I × 0 from Eq. (1), and the value read on the voltmeter is 0 V.

When an oil film is formed between balls and the outer ring to eliminate the direct metal-to-metal contact, they are insulated from each other. Then, the combined resistance is R = ∞ Ω from Eq. (1). Then, the voltage is V = I × ∞, which equals ∞ given the equation, but the voltmeter value indicates 1 V because the voltage of power supply applied to the circuit is 1 V.

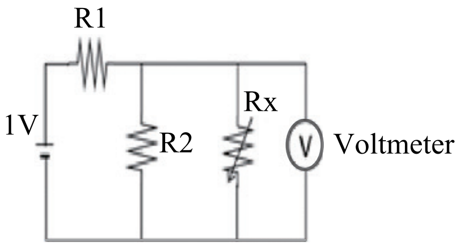

Fig. 6 Circuit for measuring oil film

The maximum acceleration start condition was extracted from the combined accelerated endurance test to measure with two oil temperature levels. The test conditions are listed in Table 2.

Table 2 Test condition for measuring oil film thickness

	Oil temperature	Input torque	Input speed	Primary pressure	Secondary pressure
Combined durability test conditions (Full acceleration start)	2 conditions (medium and high)	High	～medium	～medium	～high

3.3 Test to confirm amount of hydrogen released while the vehicle is stopped

Hydrogen was charged at 25 mA/cm^2 for 120 minutes in the electrolytic cathodic hydrogen charging test. Gas chromatography analysis was then used to measure the rate and amount of hydrogen released under high oil temperature isothermal condition simulating the stopped state of a vehicle (Fig. 7).

Conditions

Solvent: 3%NaCl, 0.3%NH_4SCN

Time: 120min,

Input: 25mA/cm^2

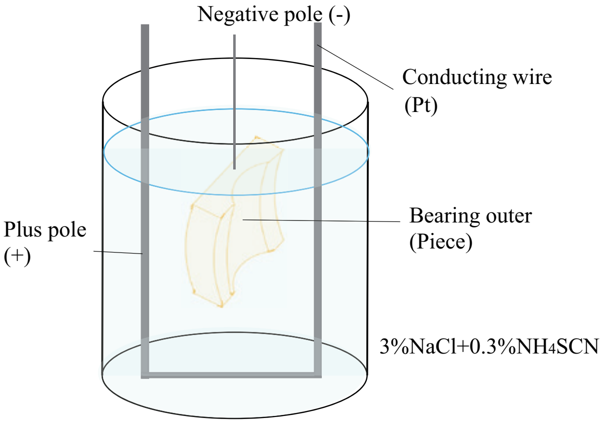

Fig. 7 Test for charging hydrogen

4. Test results

4.1 Results of the test of sensitivity to the amount of hydrogen penetration

Figure 8 shows the test results.

- A positive correlation was obtained for hydrogen penetration, load, and oil temperature, whereas a negative correlation was obtained for rotational speed.
- The test with repeated start–stop inputs in the CVT unit shows more hydrogen penetration than the case with a constant input.

The magnitude of sensitivity to the factors affecting hydrogen penetration is in the order of load, oil temperature, and start–stop pattern.

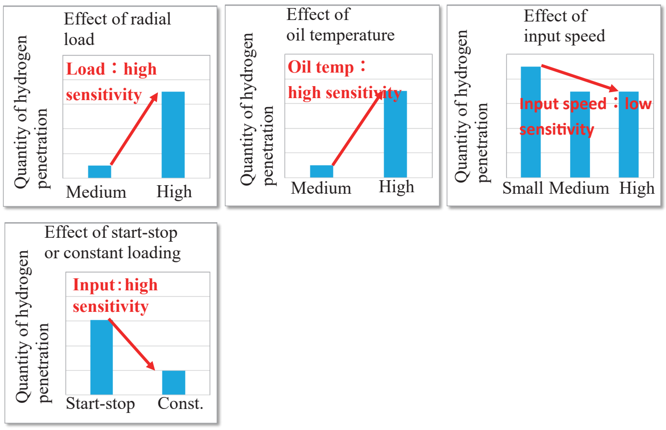

Fig. 8 Sensibility of hydrogen penetration for bearing

4.2 Results of oil film thickness measurement using a CVT unit

Figures 9 and 10 show the measurement results of the bearing's oil film thickness using a CVT unit. The stages in the profile are classified by the input conditions into three: section (a) is the stage before the rise of primary oil pressure, primary torque and primary rotational speed, section (b) is the stage during the rise, and section (c) is the stable stage after the rise.

- In section (a), representing the stop state, the voltage is 0 V regardless of the oil temperature. The result indicates that no oil film is formed between the balls and the ring raceways.
- At normal oil temperature, the voltage is 0 to 0.6 V in the former half of section (b), indicating an oil film is formed intermittently. In section (c), the voltage is about 1 V, which indicates that an oil film is formed.
- At high oil temperatures, the voltage is 0 V in the former half of section (b), indicating that no oil film is formed. In the following section (c), the voltage is about 1 V, which indicates that an oil film is formed, as in the case of normal oil temperature.

These results indicate that no oil film is formed in section (a), corresponding to the pre-start state regardless of the oil temperature. In section (b), no oil film is formed when the oil temperature is high. On the other hand, under normal conditions with low oil temperatures, an oil film forms intermittently. In section (c), an oil film is formed regardless of the oil temperature. Thus, in the former half of section (b), when the input of the influencing factor is rising, a significant difference is observed in the formation of the oil film depending on oil temperatures.

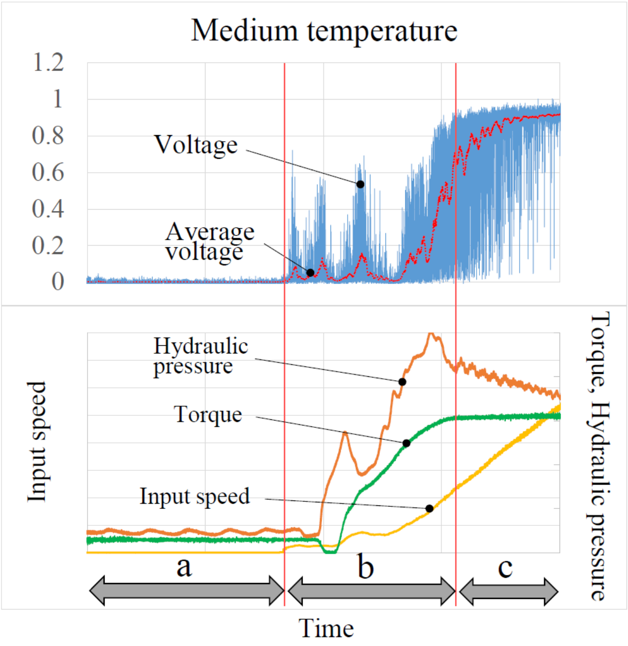

Fig. 9 Measured oil film thickness (medium temperature)

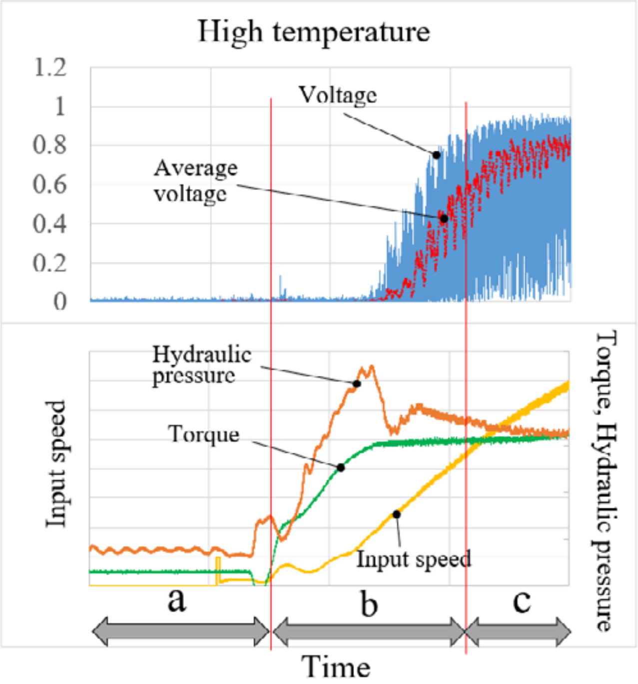

Fig. 10 Measured oil film thickness (high temperature)

4.3 Results of test to confirm amount of hydrogen released while the vehicle is stopped

In the electrolytic, cathodic charge test, hydrogen was charged, and then the amount of hydrogen release was measured after a period of time to simulate a vehicle's stopped state. Figure 11 shows the measurement result of the amount of hydrogen released. The effect of the stop time is significant. In particular, hydrogen is rapidly released in the initial 60 minutes.

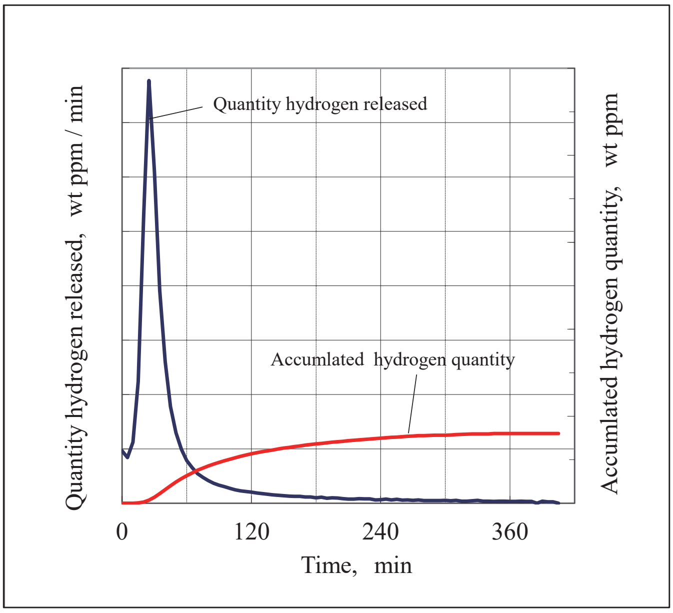

Fig. 11 Measured quantity of hydrogen released (high temperature)

5. Discussion on the hydrogen embrittlement flaking mechanism in the CVT unit

In the former half of section (b), where a significant difference in oil film thickness was observed in the measurement using a CVT unit, oil film breakage occurred at temperatures higher than the normal temperature. We suppose that the high oil temperature lowered the viscosity of the oil, causing the oil film to break at start, and that this condition was maintained until the rotational speed became high. The results are consistent with those obtained from the sensitivity tests performed with bearing samples to measure the amount of hydrogen penetration depending on oil temperature.

In the test using a CVT unit, the belt is tensioned at all times from the stopped state. Therefore, a high load is also applied to the bearing. Considering the results of the sensitivity to influencing factors in the tests using bearing samples, bearings in CVT units are susceptible to hydrogen penetration.

In the combined accelerated endurance test using a CVT unit, the hydrogen embrittlement flaking occurred only with high oil temperatures. The fact suggests that the hydrogen embrittlement flaking occurs with the following mechanisms: 1) A high oil temperature produces a low oil viscosity; 2)

With the low viscosity, the oil film is easily broken when a high load is continuously applied from the start state to the state with a high rotational speed; and 3) The sustained oil film breakage lets hydrogen penetrate into bearings easily. Furthermore, in the combined accelerated endurance test, no interval was set in order to shorten the test time. Therefore, hydrogen was unlikely to be released. In that test, the conditions were more likely to cause hydrogen embrittlement flaking than the actual operating environment.

6. Summary

Sensitivity tests and oil film measurements were performed for factors influencing hydrogen penetration considering the operating conditions of the CVT unit. We clarified the mechanism causing the occurrence of hydrogen embrittlement flaking in the CVT unit environment. Hydrogen embrittlement flaking is a phenomenon that occurs only in continuous operation at high oil temperatures in combined accelerated endurance tests.

7. References

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