Deterioration Analysis of Automotive Connectors Used in High Mileage Vehicles

Shigeru SAWADA*, Atsushi SHIMIZU and Yasushi SAITOH

Automotive electronics have developed significantly in recent years. This trend has increased the number of connectors used, has promoted multi-way connectors, and has required that connector reliability be secured. For the development of highly reliable automotive connectors, it is important to understand the deterioration state of connectors that are actually used in vehicles. In this study connectors were collected from high mileage vehicles (one with 100,000 km mileage, another with 150,000 km mileage) and their deterioration state and possible deterioration factors were investigated. The results showed that the deterioration of terminals progresses in proportion to mileage, but the deterioration level was not on the level that leads to insufficient reliability. In addition, from the observation results of collected terminal surface, the main promoter of deterioration was determined to be fretting wear. Based on this determination, the number of fretting cycles that is equivalent to 100,000 km in mileage was estimated by comparing with the fretting wear test on the bench. As a result, the number of fretting cycles was extremely smaller than expected and its level was sufficient to keep the reliability of connectors.

Keywords: connector, fretting corrosion, contact resistance, vehicle environment, terminal deterioration

1. Introduction

Various electrically controlled systems are used in newer vehicles, such as the automated driving system, precise engine control, automatic brake system, and automatic doors. This trend increases the number of electronic devices mounted in the vehicle. The number of wiring harnesses that connect electrical devices has been increasing year by year. Thus, understanding connector deterioration used in high mileage vehicles is important when developing vehicle connectors.

In this study, used connectors were collected from used vehicles, and investigated for deterioration and possible deterioration factors. In addition, the investigation results were comparatively evaluated with the results of a fretting corrosion*1 bench test in order to determine the number of fretting cycles that is equivalent to the actual vehicle mileage. The terminal resistance with high mileage was also determined.

2. Investigation Method and Results

2-1 Method to investigate collected connectors

Two D-segment sedans were selected for collecting connectors: a vehicle manufactured in 2002, driven for 8 years with 100,000 km in mileage, and a vehicle manufactured in 1997, driven for 13 years with 150,000 km in mileage. Both vehicles were driven in Japan.

From these vehicles, the wiring harnesses were removed with the connectors mated. **Table 1** shows the number of connectors collected. The collected connectors were categorized into two categories: sealed connectors mainly used in the engine compartment, and unsealed connectors used in the vehicle cabin. **Figure 1** shows a sample of the wiring harness and the collected connector. The collected connectors that were kept mated were used to measure terminal resistance with a four-terminal method. The terminals were all tin-plated for medium current application. The terminal resistance was determined by deducting the resistance value that corresponds to the wire length from the measured value. For comparison, the new terminal resistance of the same type was also measured.

After having measured the terminal resistance, some terminals were disassembled and observed at the contact with a scanning electron microscope (SEM).[1]

Table 1. The number of connectors collected from the vehicles investigated

	100,000 km	150,000 km
Sealed Connector (Engine Room)	34	31
Unsealed Connector (Indoor)	67	69
Total	101	100

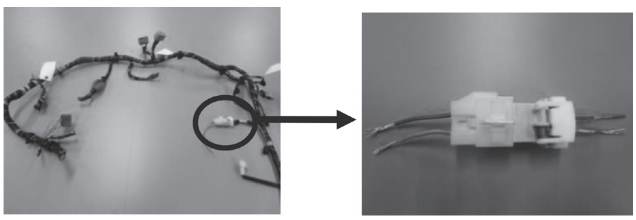
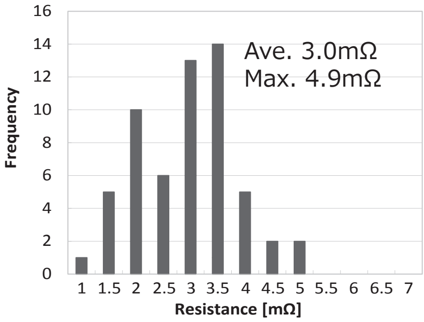


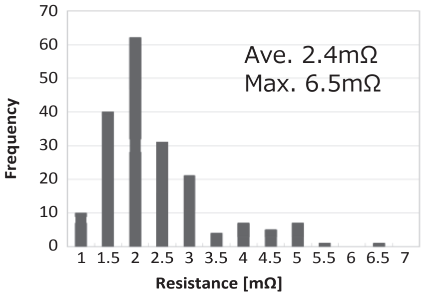
Fig. 1. Sample of wiring harness and connector

2-2 Investigation results of collected connectors

The investigation was performed with a widely-used tin-plated terminal for intermediate level current application (the maximum 26 A) that is the most popular type among the connectors collected from the vehicle with 100,000 km in mileage. **Figure 2** shows the results of measured resistance of the medium current terminal. The highest resistance with sealed connectors was 4.9mΩ, which does not have an influence on connection reliability. The highest resistance terminal was in the ignition connector located close to the engine. Among unsealed connectors, the wire-to-wire connector terminal that was directly connected to the engine wiring harness showed the highest resistance of 6.5mΩ. This resistance does not have an influence on connection reliability as well.



a) Sealed connector

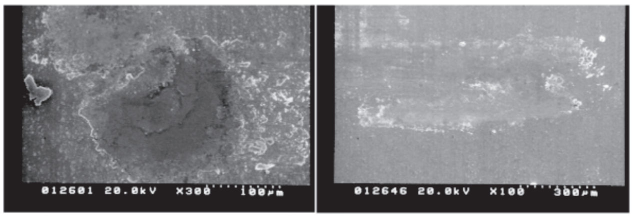


b) Unsealed connector

Fig. 2. Resistance of terminal with 100,000 km mileage vehicle

A high resistance terminal and a low resistance terminal of the sealed connector were disassembled and their contact surfaces were observed. **Figure 3** shows the observation results. With the high resistance terminal (4.9mΩ) severe contact wear was observed.[1] With the low resistance terminal (0.7mΩ) the contact surface was quite smooth and little wear had occurred. The displacement reaction force was measured at the spring of high resistance terminal because contact resistance possibly increases due to smaller contact force. The measurement results showed almost the same value as the initial value, and no reduced contact force was identified. No large increase of resistance at the crimped area was identified as well. According to these results, fretting corrosion is considered to be the main promoter of increased terminal resistance.

Figure 4 shows the results of measured resistance of medium current terminal collected from the 150,000 km mileage vehicle. Similar to the results from the terminal collected from the 100,000 km mileage vehicle, the maximum terminal resistance was 7.9mΩ, which was not a value that has an influence on the connection



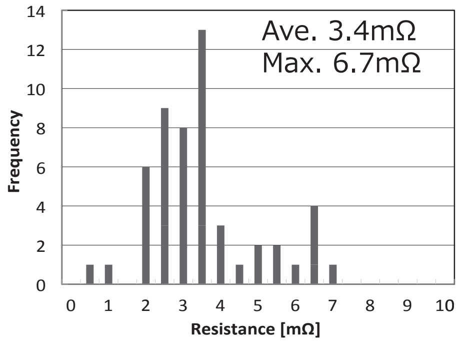
Female terminal　Male terminal

a) High resistance terminal（4.9mΩ）

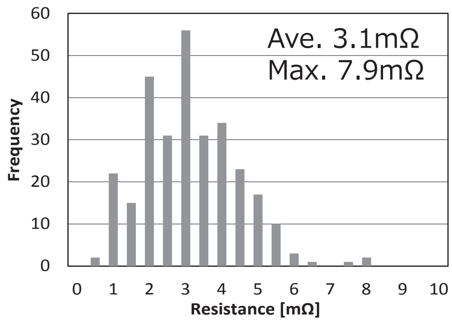
Female terminal　Male terminal

b) Low resistance terminal（0.7mΩ）

Fig. 3. Scanned images of terminal contact



a) Sealed connector

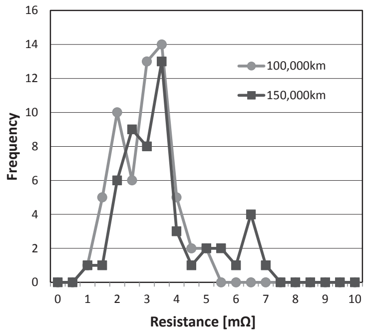


b) Unsealed connector

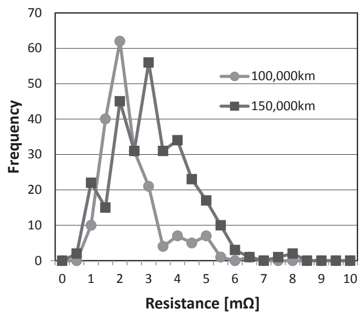
Fig. 4. Resistance of terminal with 150,000 km mileage vehicle

reliability problem. With unsealed connectors the terminal that showed the highest resistance was the one with the ignition connector located closest to the engine. The same results had occurred as with the 100,000 km mileage vehicle. With unsealed connectors the highest resistant terminal was in the wire-to-wire connector that is directly connected to the engine wiring harness.

Figure 5 shows the comparison of distribution in resistance with both the sealed connectors and unsealed connectors for medium current applications. As shown in this figure, both connector types increase in resistance in proportion to mileage.



a) Sealed connector



b) Unsealed connector

Fig. 5. Comparison of distributed resistance of terminals

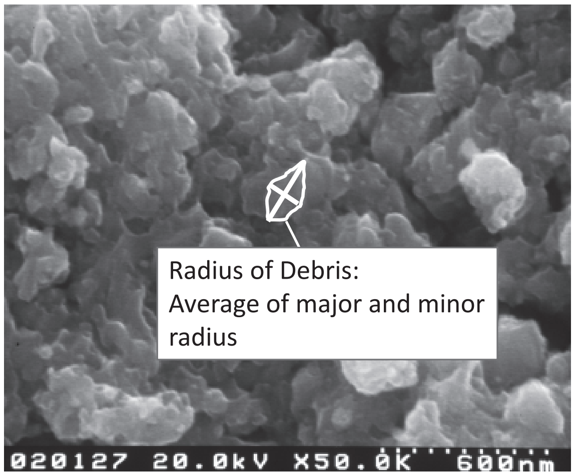


Fig. 6. Example of the radius of debris in the fretting corrosion test

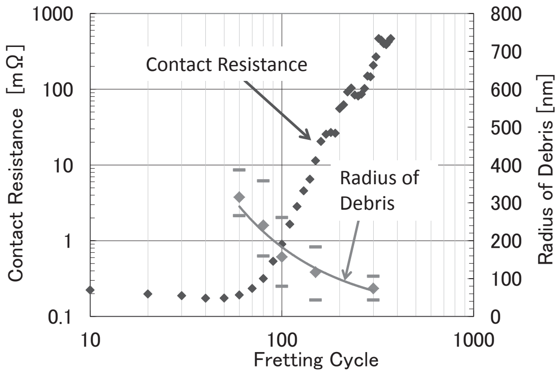
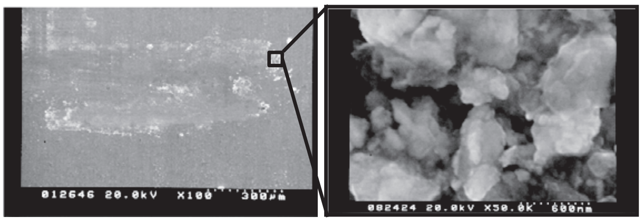


Fig. 7. Radius of debris and contact resistance measured in the fretting corrosion test

3. Comparison with Fretting Corrosion Test

From the investigation of the collected connectors, fretting corrosion was determined as the main factor for deterioration damage in connectors. Therefore, the results were compared with the fretting corrosion*1 test. The wear particle diameter of collected terminals was observed with a scanning electron microscope was compared with the radius of debris gotten in the fretting corrosion test. **Figure 6** shows an example of measured wear particles generated in the fretting wear test. The radius is defined as the mean value of the longest and shortest radius. **Figure 7** shows the relation between the radius of debris in the fretting corrosion test and the resistance value.(2) The fretting corrosion test was conducted with tin-plated samples under the load of 3 N, at 50 μm fretting distance, and at 1 Hz frequency. The larger the number of fretting cycles, the more the contact resistance increases, and the smaller the radius of debris becomes. This result indicates that the debris radius becomes small due to tin debris being progressively oxidized. **Figure 8** shows a sample scanned image of the contact area and debris of the collected high-resistance terminal with 100,000 km in mileage. The average radius of debris was 169.9 nm. **Figure 9** shows the relation between debris radius and terminal resistance in collected terminals. These results show that the smaller the debris radius, the higher the terminal resistance becomes the same as the results of the fretting corrosion test shown in **Fig. 7**. This clearly indicates that there is a relation between the debris radius and deterioration in terminals. **Figure 10** shows the comparison between the radius of debris in the collected connectors and the number of fretting cycles in the fretting corrosion test. This comparison shows that the terminal deterioration level at 100,000 km mileage is equivalent to the fretting corrosion cycle average of 75 or up to 150 cycles in the laboratory fretting corrosion test. When compared to the fretting wear test that is performed under the load of 3 N and at the fretting distance of 50 µm, however, the contact load of intermediate current terminals is around 10 N and the fretting distance is not stable. These differences will be future research agenda.



(a) Contact surface of the male terminal (b) Enlarged view

Fig. 8. Scanned image of the debris of collected terminals

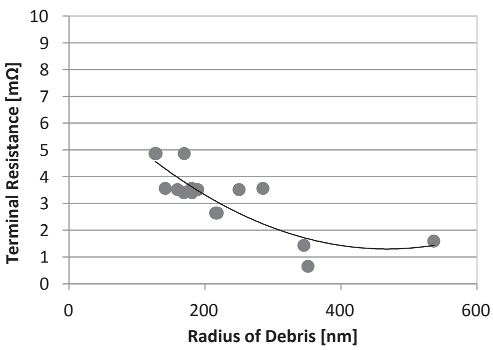


Fig. 9. The relation between radius of debris and terminal resistance in collected terminals

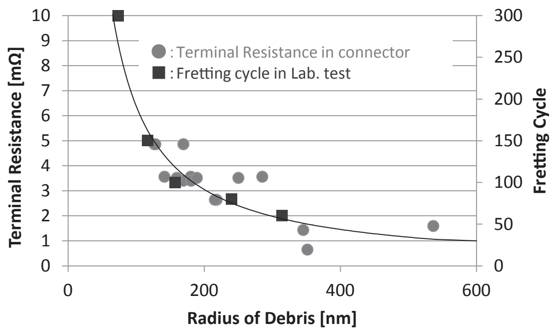


Fig. 10. The relation between the radius of debris, the number of fretting cycles, and the terminal resistance

4. Prediction of Deterioration by Statistical Weibull Analysis

4-1 Probability of high-resistance terminal

According to the investigation results of terminal resistance with 100,000 km and 150,000 km mileage vehicles, some terminals suffered deterioration due to wear. Moreover, it was determined that resistance was not a value that has an influence on connection reliability. However, this does not guarantee that the resistance of all the terminals is low. Therefore, the probability of the terminal being high in resistance was calculated with the Weibull distribution function. The Weibull distribution function is shown as the **Formula (1)** with the resistance as *t*, and the cumulative probability below *t* as *f*(*t*).[3),(4)]

$$f(t) = \frac{m}{\eta}\left(\frac{t}{\eta}\right)^{m-1} \exp\left\{\left(-\frac{t}{\eta}\right)^{m}\right\} \quad \cdots\cdots (1)$$

Here, *m* is the Weibull modulus and *η* is the scale parameter.

The prediction procedure was as follows: the cumulative probability distribution was calculated based on the measured resistance of medium current terminals. The Weibull modulus (*m*) and scale parameter (*η*) were calculated in such a way that the difference between the cumulative probability distribution and the calculated results would be the minimum. **Figure 11** shows the results. The values *η* and *m* with respect to respective sealed and unsealed terminals were applied to the **Formula (1)** to calculate the probable number of

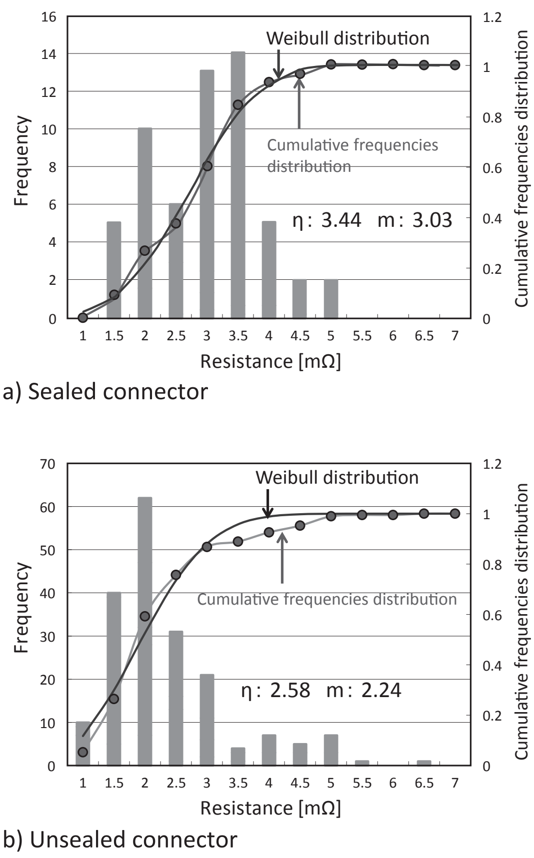


Fig. 11. Analysis result of terminals used in the vehicle with 100,000 km in mileage

terminals out of 100 million terminals at 100,000 km. **Table 2** shows the calculation results. No single terminal out of 100 million terminals is 10mΩ or higher in resistance at 100,000 km.

Table 2. The number of terminals possible out of 100 million terminals using the vehicle with 100,000 km in mileage

Resistance (mΩ)	Appearance number	
	Middle current Non-Sealed	Middle current Sealed
6.0	304	2,788
6.5	17	100
7.0	1	2
7.5	0	0
8.0	0	0
8.5	0	0
9.0	0	0
9.5	0	0
10.0	0	0

4-2 Prediction of resistance value with the vehicle with 200,000 km in mileage

In this investigation, the relation of terminal resistance at 100,000 km and 150,000 km was clarified. Therefore, there was an attempt to determine terminal resistance of the connector at 200,000 km. The resistance was estimated to increase exponentially (**Formula (2)**).

$$R_{ave} = Ae^{Bx} \quad \cdots\cdots (2)$$

Here, R_{ave} indicates the average terminal resistance, x indicates mileage, and A and B are constant numbers. **Figure 12** shows estimated results gained with the least squares method. It was expected that the progression tendency in deterioration was different between the sealed connector and the unsealed connector, even though their initial resistance was the same 1.5mΩ. At 200,000 km, the resistance was expected to be 3.9mΩ with the unsealed connector and 4.9mΩ with the sealed connector. The progression in deterioration with the sealed connector is 1.25 times faster than that of the unsealed connector. This result indicates that the sealed connector is, compared with the unsealed connector, more susceptible to deterioration due to more severe temperatures and a high vibration environment.

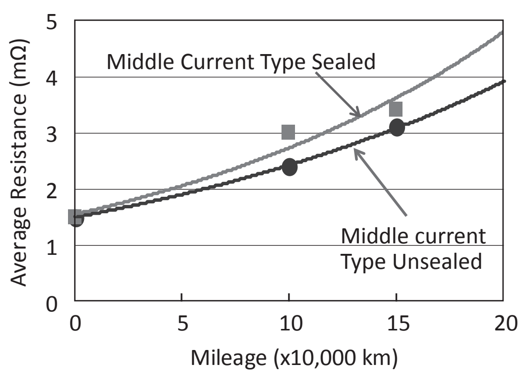


Fig. 12. The relation of average terminal resistances with mileage

5. Conclusion

An investigation of connector's resistance was conducted to investigate the deterioration behavior of automotive connectors used in high mileage vehicles. In this investigation, connectors used in vehicles driven 100,000 km and 150,000 km in Japan were collected to investigate the terminal resistance of terminals for medium current applications. The investigation results showed the following:

1. The higher the mileage, the higher the terminal resistance. Both the average terminal resistance and the maximum terminal resistance of the vehicle with 150,000 km in mileage are higher than those of the vehicle with 100,000 km in mileage. These values, however, were not values that have an influence on connection reliability.
2. The results of contact observation determine that the deterioration due to fretting corrosion is the main promoter of higher terminal resistance. When comparing the debris radius in the fretting corrosion test and that of collected terminals, the wear level of the collected terminals is equivalent to the fretting wear cycle average of 75 or up to 150 cycles of the fretting corrosion test.
3. The failure analysis showed that the probability of terminals that are insufficient in reliability at 100,000 km was extremely small. Furthermore, the average resistance value of connectors at 200,000 km was determined to be about three times as high as the initial resistance value.

6. Acknowledgment

We would like to express our sincere gratitude to Professor Kazuo Iida, Department of Electrical and Electronic Engineering, Graduate School of Engineering, Mie University, for his major support in the disassembly and investigation of collected vehicles throughout this research.

Technical Term

∗1 Fretting corrosion: Fretting corrosion is caused by the repeated cyclical rubbing between two surfaces at a quite small μm-distance. Wear particles that are generated by fretting, oxidized in air, and deposited on the surfaces in contact cause contact failure. Fretting corrosion possibly occurs due to the difference in coefficient of thermal expansion attributable to thermal cycle, as well as outside vibration and displaced contact due to mechanical impact.

References

(1) Yuya Saruwatari, Yasushi Saitoh, Terutaka Tamai, Kazuo Iida and Yasuhiro Hattori, "Investigation of environments for connectors on vehicle," IEICE Technical Report, Vol. 111, No. 254, EMD2011–59, pp. 13–18, Oct. (2011)

(2) Daiji Ito, Yasushi Saitoh, Terutaka Tamai, Kazuo Iida and Yasuhiro Hattori, "Examination by the nanoscale surface observation and the contact resistance in the fretting corrosion," Research and Engineering Society for Electromechanical Components and Contact Technology in Japan, No. 122-3, (2010) in Japanese.

(3) Chi. H. Leung, E. Streicher and D. Fitzgerald, "Weibull analysis of switching contact resistance in laboratory and commercial circuit breakers," Proc. 53rd IEEE Holm conf. on electrical contacts, pp. 56-61 (2007)

(4) M. Hasegawa and Y. Tabagitani, "Analysis of contact resistance data with Weibull distribution function," Proc. 54th IEEE Holm conf. on electrical contacts, pp. 344349 (2008)

Contributors (The lead author is indicated by an asterisk (∗).)

S. SAWADA∗

- Ph.D. in Engineering
  Assistant General Manager, Circuits and Connection R&D Division, AutoNetworks Technologies, Ltd.

A. SHIMIZU

- Ph.D. in Engineering
  Assistant Senior Manager, Circuits and Connection R&D Division, AutoNetworks Technologies, Ltd.

Y. SAITOH

- General Manager, Circuits and Connection R&D Division, AutoNetworks Technologies, Ltd.