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A Case Study of Abnormal Heat Generation of Automobile Engine Connectors during a Combined Environmental Test

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ABSTRACT

The electrical connector is an essential accessory component for sensor signals and power transmission within an automotive engine. Concern with regard to the durability of the electrical connectors in vehicles has increased in keeping with the significant increase in the number of electronic devices in modern vehicles for safety and comfort. The connectivity performance of electrical connectors is vulnerable to disturbances caused by external vibration or changing temperatures. In order to identify the cause of the abnormal heating of a connector during combined environmental testsof adistribution box, contact zones were observed using a scanning electron microscope (SEM) with EDS.The contact surfaceswith and without abnormal heat generation were compared. It is assumed that the fretting distance is longer than that of a connector with no abnormal heating under identical vibration conditions because the amount of contact force is relatively small in the case of an abnormal heating connector. Contact force less than an appropriate level causesan increase in the fretting distance. Resulting increased amount of oxide on the surfaces leads to high electrical contact resistance, generating abnormal heating at the contacts.

Key words: Fretting corrosion, Electric contact, Connector, Contact force

INTRODUCTION

The application of different advanced electrical and electronic systems for various advanced functions in automobiles is increasing rapidly. More than 500 connectors are now used in automobiles, with steady increases expected in future automobiles. High temperatures, thermal shocks, humidity, EMI, toxic gases, salinity, vibration, and mechanical shocks are factors that influence the failure of electrical and electronic components in automobiles [1]. More than 30% of such electrical failures are related to connectors, and these failures are known to be in the form of highand intermittent electrical contact resistance [2]. Connectors which link the electrical and electronic components of a vehicle have the lowest reliability, and poor electrical contact can seriously affect the safe operation of the vehicle.

Fretting corrosion, one of the main causes of connector contact failure, is a wear-related corrosion phenomenon caused bysmall movements of the contact point of a connector due to external vibration or changing temperatures [3-5]. The oxide film and debris generated due to fretting increase the contact resistance, distorting the value of the signal output from the related sensor and thus causing the vehicle ECU to output an erroneous output signal, finally resulting in an error in the actuator operation.

In this paper, we investigate the causes of the abnormal heating of a connector during combined environmental testsof adistribution box. In thecombined environmental test of a distribution box composed of various connectors for the electrical and electronic components mounted on an automobile, as shown in Figure 1, abnormal heating can occur in some connectors. Often, the cause of this problem cannot be found. In this study, to investigate the cause of the failure of an electrical contact, the connectors in question were disassembled and contact zones were observed using a SEM. In addition, the chemical compositions of the contact surfaces were investigated through EDS and the causes of the generation of the abnormal heat were identified. Finally, through this information, we provide informationwith which to improve the performance and quality control of electrical and electronic connectors.

BACKGROUND INFORMATION OF THE CONNECTORS

The combined environmental test of theelectrical distribution box, shown in Fig. 1, was carried out with it mounted onto a vibrating table installed in a temperature-controllable camber. The box was excited at 4.5 G acceleration with a frequency range of 20~50 Hz. During this test, the connector was electrically charged with an applied voltage of 14.5V for 360 cycles (=360 hours). One cycle was composed of a 45-minute power-on and a 15-minute power-off. The fifteen environmental thermal cycles were applied, as shown in Fig. 2. The material of the connector was $CuSn_4$, and the surface of the connector was coated with tin about 10 µm. The temperature of the connector was monitored by soldering the thermocouple as shown in Fig. 3.The test of the distribution box was carried out twice. In the first test, no failure occurred in the blower connector. However, there was abnormal heat generation in the same blower connector during the second test.Normally, the peak temperature of the connector rose in the 100 – 120 °C range during the test period, but for the connector in this study, the temperature rose abnormally to 193.8 °C after 191 hours.

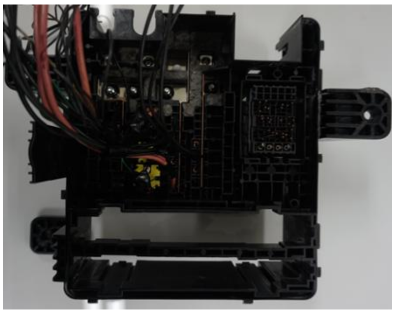


Fig. 1 Electrical distribution box for the complex environmental tests

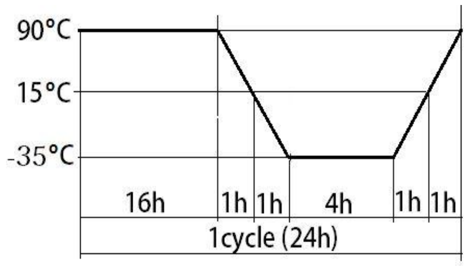


Fig. 2 Combined environmental test cycle condition

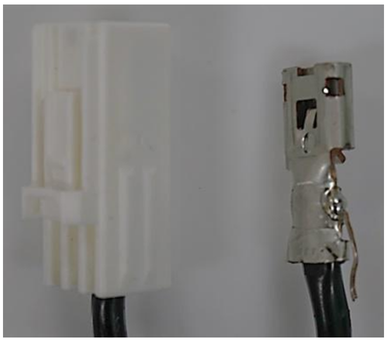


Fig. 3 Thermocouple attached to female connector for monitoring temperatures

FAILURE ANALYSIS

In this study, the causes of abnormal heat generation of the male and female connectors of the blower were analyzed. For this analysis, the contact surface between the blower connectors where the electrical contact failure occurred and the contact surface of another blower connectorwhich did not fail were initially compared. Contact areas of suchconnectors have various shapes. In the case of the blower connector analyzed in this study, the contacts of the connectors are composed of a bean (flat) to plane (flat) contact for the front side and a spherical (protuberance) to plane (flat) contact for the rear side, as shown in Fig. 4. The contact areas were observed on the flat surfaces of the male connector, as shown in Fig. 4, with and without abnormal heating, and the diameter of the contact area and the fretting distance were measured and compared.

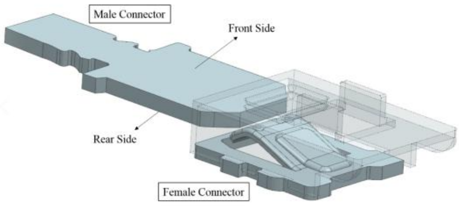
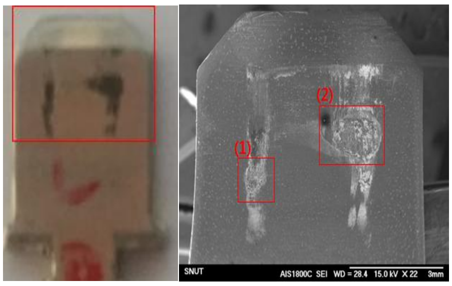


Fig. 4 Contact configuration of the blower connector

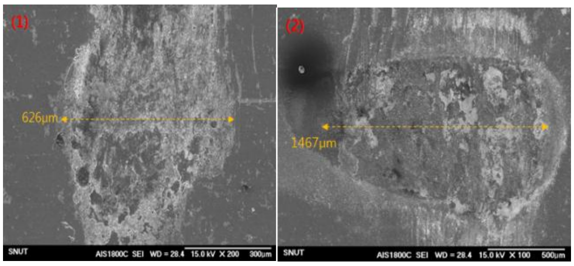
Failed connector observation

Fig. 5 is a photograph showing the surface condition of the front side of the male connector of the blower with abnormal heat generation during the complex environmental test. From Fig. 5(a), it is visually confirmed that fretting wear occurred. In addition, Fig. 5(b) shows clearly that fretting corrosion with white oxide particles occurred in two zones. Fig. 6 is SEM micrograph of locations (1) and (2) of thefront surface of the failed blower male connector in Fig.5.The widths of fretted zones (1) and (2) were measured and found to be 626 µm and 1467 µm, respectively. It was noted that a considerable amount of oxide debris was scattered around the contactarea where fretting corrosion had occurred.Fig.7 shows the rear surface of the male connector of the failed blower with fretting wear after the complex environmental test. The fretting distances were 1630 µm and 1555 µm, and for an average value of 1593 µm. Fig. 8 is an enlarged SEM photograph taken to measure the width of the fretting wear area with respect to positions (1-1), (1-2), (2-1), and (2-2) inFig.7. The widths of (1-1), (1-2), (2-1) and (2-2) were measured and determined to be 216 µm, 211 µm, 235 µm and 233 µm, respectively.The widths arenearly constant. From Fig.5 to Fig.8, it can be confirmed that fretting corrosion occurred in the longitudinal direction of the blower connector where abnormal heat generation occurred during the combined environmental test.



(a) (b)

Fig. 5(a) Front surface of the failed male connector of the blower and (b) a magnified image of its surface with fretting wear after the complex environmental test



(a)(b)

Fig. 6 SEM micrograph of (a) location (1) and (b) location (2) onthe front surface of the failed blower male connector shown in Fig. 5

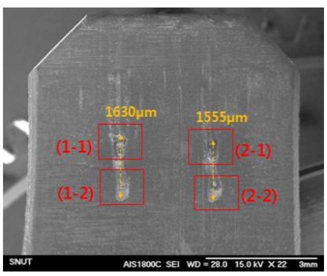
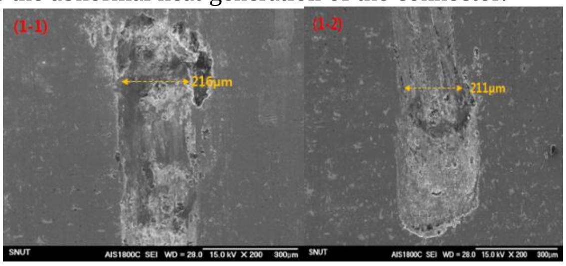
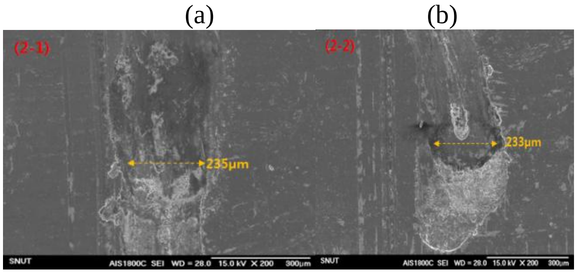


Fig. 7 Rear surface of the failed blower male connector with fretting wear after the combined environmental test

A chemical composition analysis was conducted by means of EDS of the connector contact area and on the non-contact area of the connector where abnormal heat generation occurred. Fig. 9 shows the EDS results of several points on surface area (1-1) of the rear surface of the blower male connector shown in Fig. 8. Table 1 summarizes these test results. Table 1 shows that at point (3), which is located at the center of the fretting corrosion zone, the concentration of oxygen is very high at approximately 54% while that of tin is very low at about 3%. In addition, the concentration of oxygen at point (5), where no contact occurred, is about 14.5%, which is very low compared to those of the other points where fretting corrosion occurred.Additionally, the concentration of tin at the same point is close to 31%, indicating that the tin plating remains. The small amount of tin at point (3) indicates that the tin plating is mostly worn down and that the underlying copper is exposed. Except for the point at whichno contact occurred, the concentrations of oxygen at positions (1), (2), (3), (4), and (6) are in the range of 30~50%, suggesting that these points are covered with oxide film or oxide debris. It can be assumed that the electrical contact resistance is increased due to these nonconductive oxides. Therefore, the oxides which accumulate due to fretting corrosion may increase the resistance at the connector contact area, and the increased resistance may influence the abnormal heat generation of the connector.



(a) (b)



(c) (d)

Fig. 8 SEM micrographs of the fretting wear surfaces of (a) location (1-1), (b) location (1-2), (c) location (2-1) and (d) location (2-2) on the rear surface of the blower male connector shown in Fig. 7

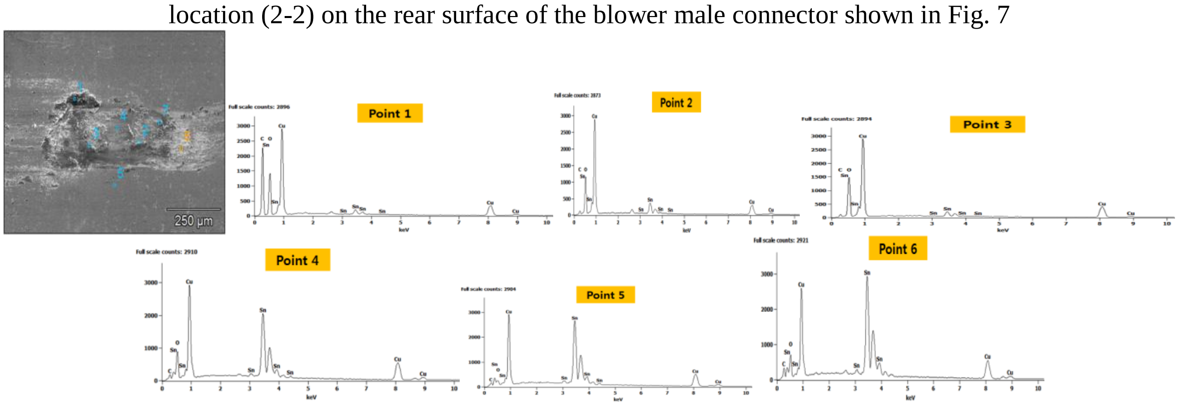


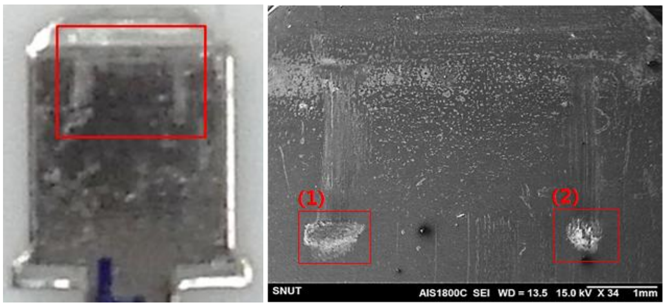
Fig. 9 SEM micrographs of location (1-1) of the rear surface of the male connector of the blower shown in Fig. 8 and EDS results of several points on the surface

Table -1 EDS results of several points at location (1-1) on the rear surface ofthe male connector of the blower shown in Fig. 8

	C at%	O at%	Cl at%	Cu at%	Sn at%
Point 1	49.16	31.76		18.03	1.04
Point 2	6.19	47.33		41.28	5.20
Point 3	5.50	54.15		37.65	2.70
Point 4	5.13	35.19		39.26	20.43
Point 5	5.92	14.46		48.69	30.92
Point 6	7.88	29.23		35.32	27.56
Point 7	30.33	39.67	2.20	23.92	3.88

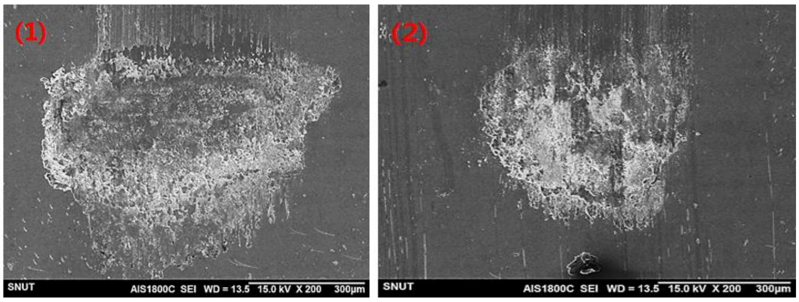
Passed connector observation

Fig. 10 shows the front surface of a male connector of a blower which passedthe combined environmental test without abnormal heating and a magnified image of its surfaces showing fretting wear. It can also be seen that there are two zones of fretting wear at the contact points. Fig. 11 is SEM micrograph of locations (1) and (2) on the front surface of the male connector of the passed blowershown in Fig. 10. However, it can be seen that the size of the fretted zone is smaller than that of the connector where abnormal heat was generated. Fig. 12 shows the rear surface of a male connector of a passed bower, which is the same connector shown in Fig. 11. A magnified image of a surface with fretting wear after combined environmental test is also shown. The two vertical scratches in Fig. 12 are judged to have occurred during the removal of the connector, and two small fretted zones can be observed in this figure. Fig. 13 shows SEM micrographs of location (1) and location (2) on the rear surface of the male connector of the passed blower in Fig.12. The width and the length of the fretted zone (1) are 283 μm and 518 μm, respectively, and the corresponding width and length of zone (2) are measured and found to be 262 μm and 445 μm. That is, the average width and length of the fretted zonesare 272.5 μm and 481.5 μm, respectively.



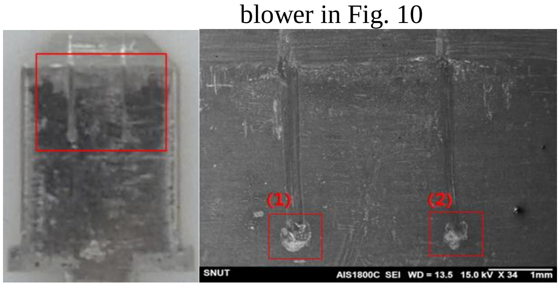
(a) (b)

Fig. 10 (a) Front surface of the passed male connector of blower and (b) magnified image of its surfaces with fretting wear after the combined environmental test



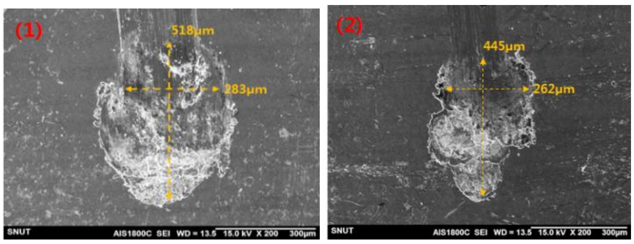
(a) (b)

Fig. 11 SEM micrographs of (a) location (1) and (b) location (2) on the front surface of thepassed male connector of blower in Fig. 10



(a) (b)

Fig. 12(a) Rear surface of the male connector of a passed blower and (b) magnified image of its surfaces showing fretting wear after the combined environmental test



(a) (b)

Fig. 13 SEM micrographs of (a) location (1) and (b) location (2) on the rear surface of the passed male connector of blower shown in Fig. 12

The average diameter of the contact zone is 223.8 µm on the rear side of the connector, as shown in Fig.8, where the abnormal heat occurred. In addition, it was confirmed that the average contact diameter of the connector without abnormal heat generation is 272.5 µm, which was approximately 49 µm smaller than the connector with abnormal heat generation. Assuming that fretting wear is mainly generated in the longitudinal direction of the connector, the contact diameter of the connector can be assumed to be proportional to the width of the fretting wear region. The contact diameter is proportional to one-third of the power of the contact force according to the Hertz equation [6]. Therefore, it can be assumed that the connector with abnormal heat generation has less contact force than the connector without abnormal heat generation.In addition, it was confirmed that the fretting zone length in the longitudinal direction of the connector is approximately 1600 µm, which is approximately 1125 µm longer than that (= about 475 µm) of the connector having no abnormal heat generation. It is also assumed that the fretting distance is longer than that of the connector with no abnormal heating under identical vibration conditions because the contact force is relatively lowfor the abnormal heating connector, as less contact force leads to a longer sliding distance under the same vibration conditions. In general, the fretting distance when fretting corrosion occurs is inversely proportional to the fretting lifetime [7,8]. That is, the longer the fretting distance is, the greater the accumulation of oxides becomes on the contact part, which shortens the fretting lifetime.

A chemical composition analysis was also conducted using EDS on the fretted zone and the non-contact zone of the connector where abnormal heat generation did not occur. Fig. 14 shows SEM micrographs of location (1) of the rear surface of the male connector of the passed blowershown in Fig. 12. Also shown are EDS results of several points of the surface. Table 2 summarizes these EDS test results.Table 2 shows that the oxygen concentration at location (3), which is the surface withoutcontact, is about 19%, which is much lower than those of other locations where fretting corrosion occurs. The tin concentration at location (3) is 65%, suggesting that the tin plating remains intact. At position (2), where white oxide debris has accumulated, the oxygen concentration is 48%, the copper concentration is 2%, and the tin concentration is 44%. This debris deposited around the frettingzone is judged to be tin oxide, which is an electrical insulator.Atlocation (5), at the center of the zone where fretting corrosion occurred, the oxygen concentration is very low at about 9%, the tin concentration is approximately 9%, and the copper concentration is about 74%, indicating that the tin plating is mostly worn away, leading to metal-to-metal contact. Therefore, it is considered that less heat was not generated due to metal-to-metal contact compared to the connector which did undergo abnormal heat generation.

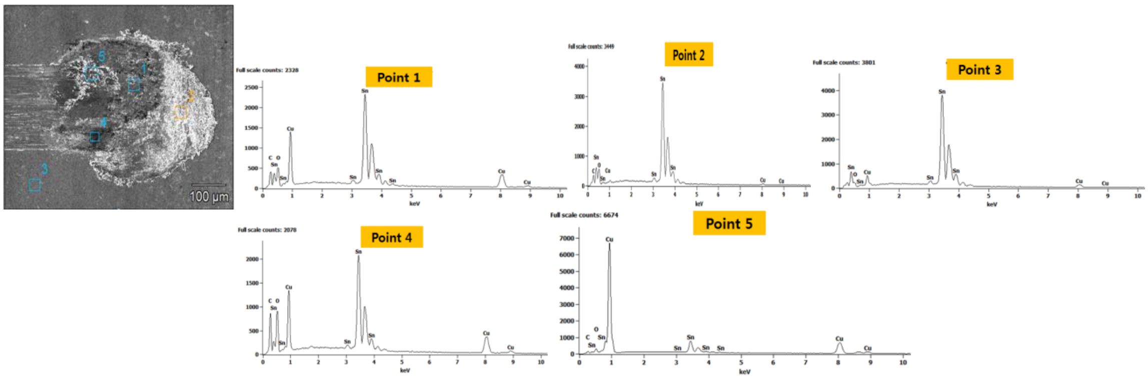


Fig. 14 SEM micrographs of location (1) on the rear surface of the male connector of the passed blower shown in Fig. 12 and EDS results of several points on the surface

Table -2 EDS results of several points at the surface of location (1) on the rear surface of the male connector of the blower shown in Fig. 12

	C at%	O at%	Cu at%	Sn at%
Point 1	12.75	32.35	27.59	27.31
Point 2	6.22	47.50	1.97	44.31
Point 3		18.80	16.19	65.01
Point 4	20.09	40.87	20.50	18.54
Point 5	7.59	9.11	74.31	8.99

Thus, the contact force between the female and male connectors of the blower subject to abnormal heat generation is reduced until it is under the reference level, increasing the fretting distance of the connector in the vibration environment. Therefore, if the contact force is less than an appropriate level, the fretting distance becomes longer. As a result, the generation of oxide increases, and the electrical contact resistance between the connectors is increased. This is expected to result in additional joule heat at the contacts. Differences in connector contact forces arise during the manufacturing or assembly process of the connectors. The findings of this study suggest the importance of the contact force at the connections of electrical connectors.

CONCLUSION

The cause of abnormal heating according to combined environmental testsof connectorscan vary. In this study, it is considered that one of the causes of the abnormal heating of blower connectors is that the contact force of the connectors is lower than the reference value.The connector is manufactured by an automated process, implying thatits dimensions should be constant. However, there is a possibility of errorwhen the contact force is less than the reference contact force during the fabrication or assembly process.It is impossible to find such a problem with the connector contact force when the connector is assembled.One of the important factors to consider when manufacturing these types of connector is the contact force. If the contact force exceeds the reference value, the fretting distance decreases but the insertion force of the connector becomes excessive and the contact wear rate increases. On the other hand, if it is less than the reference value, the fretting distance is increased, thus, shortening the fretting lifetime of the connector.However, connector manufacturers or automobile companies generally have little information about the contact force of connectors. For some companies, tin-plated connectors are defined as an ambiguous standard with a contact force of 1.2 N regardless of the size and/or contact area of the connectors.Through this study, it is proved that the contact force of these connectors has a great influence on the resultingfretting lifetime.Therefore, it is important to compile data by which to determine the standard deviation of the actual contact forces of these connectors for better quality control. In addition, it is necessary to develop a system for measuring the connector contact force as well as to study and determine the optimal connector contact force.

Acknowledgements

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