Effects of Contact Conditions on the Connector Electrical Resistance of Direct Current Circuits

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ABSTRACT

Electric contacts serve the purpose of transmitting electric signals across two conducting components. In this paper, the effects of contact conditions such as surface roughness, oxidation, and contamination were investigated with respect to electrical resistance variation of a connector in a direct current circuit. Such change in the electrical resistance is particularly important for low power circuits. The experimental results showed that compared with the effects of contact surface scratch or oxidation, the effect of contamination on the resistance variation was the most significant. In order to minimize failure due to electrical resistance change at the contact region, proper sealing to prevent contamination from entering the interface is needed.

Key Words : Connector, Electric contact, Resistance, Signal

1. Introduction

Electric contacts are used for various applications including switches, relays, printed circuit boards, connectors, and many others. Ideally, the electric current should flow across the contacting surfaces without loss. However, due to the nature of the contact interface, some loss is incurred at the junction. This phenomenon is mainly due to the increase in the resistance at the contact point known as the contact resistance.[1] The change in the contact resistance can lead to variation in the circuit voltage, power loss, and signal variation which can result in system failure or a wrong diagnosis of a system condition in case of a system diagnosis using the signal monitoring.[2] Especially, in view of the trend of low power consumption, miniaturization, weight reduction, and computerization of mechanical systems, there are many circuits that must operate with low level electrical signals for communication with the electronic control system.[3] These systems are quite sensitive to the change in electrical signal and often lead to malfunction due to the increase in the contact resistance. Therefore, in order to minimize the loss of electric signal across the contacting point, high conduction materials should be used along with considerations to ensure minimum contact resistance.

The electrical contact resistance between two conducting materials depends on several factors. They include the inherent resistance of the materials, geometry of contact, surface roughness, oxidation film, real area of contact, and surface contamination.[4] Fig. 1 shows a magnified illustration of the contact region between two conducting parts.[5] Aa is the apparent area of contact and Ar is the real area of contact. The interface is not perfectly flat but consists of asperity junctions through which current must flow. This constriction effect of the junctions causes an increase in the electrical resistance at the contact region.

The contact resistance depends on the number and size of the junctions as well as the inherent resistance of the

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materials.[5] The actually contacting area or the real area of contact is significantly less than the apparent area of contact. The real area of contact increases with increasing normal contact force and decreasing material hardness.

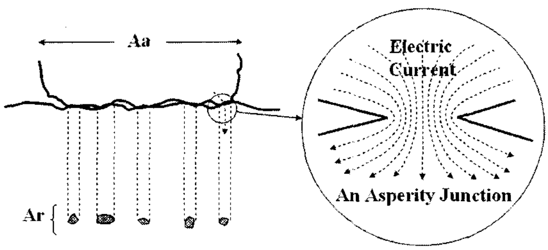


Fig. 1 Schematic of contact region between two conducting parts with surface roughness[5]

As can be readily imagined, surface contamination and oxidation can also cause a change in the inherent resistance. Also, external conditions such as temperature, humidity, vibration, and friction may affect the contact resistance, especially if the contact point is not rigid and experiences slight motion at the interface. Thus, the problem of electrical contact resistance variation is a very complex phenomenon which is system dependent in the sense that the operation condition also matters.[6] Despite its importance, the knowledge regarding the electrical contact resistance is not sufficient to overcome the problems that are reported in the field.

The aim of this work is to better understand the nature of electrical contact resistance of connectors that are typically used in automobile electrical systems. Particularly, the effects of surface scratch, oxidation due to heat application, and contamination from engine block on the change in the electric resistance of the connector in a direct current circuit are investigated to identify the most significant parameter that affects the electric contact resistance. The results of this work are expected to improve the electrical connector design for improved reliability and performance. The following sections describe the experimental work in detail.

2. Experimental Details

2.1 Specimens

A connector type as shown in Fig. 2 was used for the experiments. This type of a connector is used in many electric circuits including automobile Engine Control Unit (ECU).[7] It consists of male and female terminals to which electric wires are attached. The base materials for the connector are brass and copper alloy for male and female terminal, respectively. The terminals are coated with tin in order to provide adequate contact for electrical conduction. Electric current is transmitted through the contacting regions of the connector. A normal force is applied by the elasticity of the terminals as they are fitted into each other. If this elastic force is made to be high, a better contact can be achieved, at the expense of difficulty of assembly and disassembly. Therefore, the force should be optimized with respect to contact resistance and insertion force.

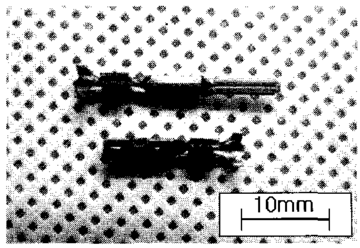


Fig. 2 Photographs of male and female connector terminals used for the experiments

2.2 Experimental method

The electrical contact resistance of the connector shown in Fig. 2 was investigated with respect to surface scratch, oxidation due to heating, and contamination. The parameters and the methods of varying those parameters are summarized in Table 1.

Table 1 Parameters and methods for electrical contact resistance experiments

Parameter	Control method
Roughness	Scratching the male terminal surface
Oxidation	Baking in an oven (1 week, at 100℃) Heating (max. 7min., at 400℃)
Contamination	Hydrocarbon particle insertion into the contact interface

2.2.1 Surface roughness

In order to see the effect of surface roughness on the contact resistance, a simple method of scratching the terminal surface was used. Scratching was done to represent a very rough surface. Intuitively, it may be thought that the roughness of the surface has a direct effect on the contact area, and therefore, if the surfaces are smooth, it is expected that the contact resistance will decrease. However, this may not necessarily be the case since for most engineering surfaces with micro-asperities, the real area of contact for a given normal force is determined by the ratio of the normal force and the hardness of the softer of the two contacting materials.[8] Hence, in the equation that determines the real area of contact, the surface roughness does not appear as a variable. Nevertheless, in order to verify this view, the surface roughness was chosen as one of the parameters to be investigated. The surface roughness was varied by scratching the surface of the male terminal using a hard tip. The terminals were assembled after scratching the surface.

2.2.2 Oxidation due to heating

As a means to oxidize the terminal surfaces, the terminals were heated inside an oven or by a direct heat source. The metal surface of the terminals reacts with oxygen in air to form an oxide film. Oxidation is expected to increase the contact resistance and can occur naturally during operation of the circuit as the interface gets heated.[9,10] The oxidation conditions used in this work were designed to accelerate the oxidation process.[11] Several oxidized specimens were prepared. One was heated inside an oven at 100℃ for one week and the others were heated by a direct heat source at 400℃ up to seven minutes. These conditions were selected after many preliminary oxidation experiments to provide a wide spectrum of surface oxidation state.

2.2.3 Contamination of contact interface

The electric connectors are subject to contamination from the surrounding. Particularly, in the case of connectors used for automobile ECU, combustion products as well as other hydrocarbons from other sources may contaminate the connector interface. The contact region of the terminals was contaminated with hydrocarbon residues sampled from a severely burnt metal surface by inserting the residues into the contact interface.

2.3 Experimental set-up

A simple circuitry was designed and used for measurement of the electrical contact resistance of the connectors. Fig. 3 shows the schematic of the measurement circuit. R1 and R2 are variable resistors. The electrical contact resistances at the normal (Rn) and contaminated (Rc) terminals were calculated by using the Ohm's law from the voltage loss (V_l) and the current (I) measured by a multimeter. Source voltage (Vs) was set to about 9 V in order that the current I would be 100 mA for convenience of the contact resistance calculation.

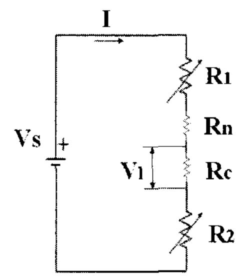


Fig. 3 Schematic of the electric circuit for measuring the electric contact resistance of the connectors

3. Results and Discussion

3.1 Effect of surface roughness

Connectors with and without the surface scratch were investigated with respect to their contact resistance. Fig. 4 shows the 3-dimensional optical profiler image of the connector male terminal surface before (normal) and after scratching. Table 2 summarizes the surface topography parameters for the two surfaces shown in Fig. 4.

It can be seen that the average surface roughness increased by more than five times due to scratching. Significant burrs can be also observed along the periphery of the scratched track. Compared with the normal surface, it is plausible that the protruded regions of the scratched surface will prevent the two surfaces from making full contact, thus causing an increase in the electrical resistance. The resistance measurement results showed that the change in the electrical contact resistance due to scratching was about 0.2 mΩ . This value is only a fraction of the nominal resistance of about 3 mΩ . This suggests that surface roughness is not a significant factor in determining the contact resistance.

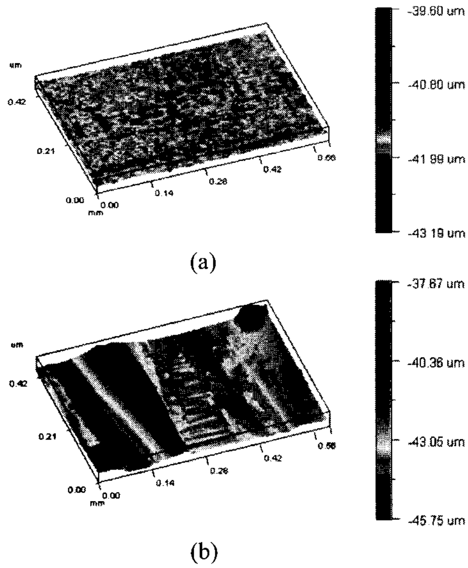


Fig. 4 3-dimensional optical profiler image of (a) normal and (b) scratched surface of the male terminal

Table 2 Surface topography parameters for normal and scratched connector surfaces

Roughness (μm)	Average (Ra)	Root-Mean-Square (RMS) (Rq)	Peak-to-valley (Rmax)
Normal surface	0.18	0.24	3.59
Scratched surface	1.03	1.29	8.08

This outcome may be explained by two views. The first is that the high protrusions of the scratched surface burrs get flattened out during the terminal assembly process. Thus, the actual surface state of the scratched terminal may be much smoother than what it appears to be before being assembled with the female terminal. The other view is that even though the average surface roughness of the scratched surface is more than five times that of the normal surface, the real area of contact for both surfaces is similar. This view is consistent with the contact theory that the real area of contact is not a function of surface roughness.[5] Unless the surfaces are atomically smooth, contact between two solids under an applied load will never be perfectly flat. Hence, even the normal surface used in this work must form isolated contact junctions when assembled. Though surface roughness does not have a direct effect on the electrical contact resistance, it may have an effect on the integrity of the coating material and frictional resistance during insertion, and therefore, it should be kept low as long as the cost is not significant.

3.2 Effect of oxidation due to heating

As mentioned in the previous section, the connector specimens were heated to form a layer of oxide on their surfaces. In the first batch of experiments, male and female terminals were baked inside an oven for one week at 100℃. Fig. 5 shows the electrical resistance of the terminals and the connector in its assembled form before and after the baking process. It was found that for the connector used in this set of tests, the resistance of the individual terminals was about 3.5 mΩ before baking. However, after the baking process, the resistance increased by about 1 mΩ, which corresponds to about 30% increase. It is suggested that the increase in the resistance is due to the oxidation of the terminal materials due to heating. Metallic oxides, in general, have higher inherent electrical resistance than oxide-free metals.

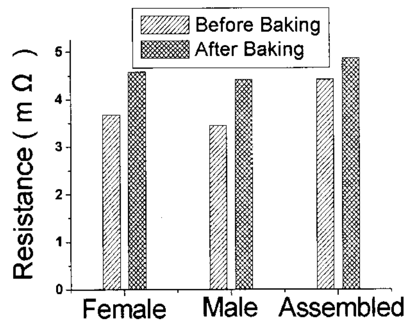
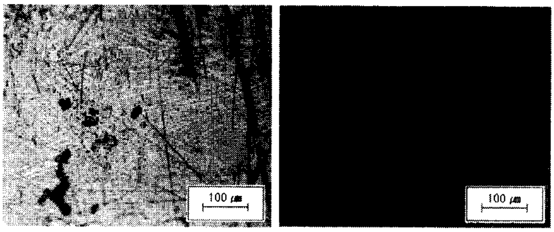


Fig. 5 Electrical resistance of terminals before and after baking in the oven at 100℃ for one week

The significance of the 1 mΩ increase in the electrical resistance would depend on the electric circuit system. For very low power circuits, 1 mΩ variation in the resistance value may lead to undesirable effects.

Another point to note from Fig. 5 is the change in the electrical resistance of the terminals after the assembly. There is an increase of about 1 mΩ, which is attributed to the resistance increase due to contact between the male and female terminals. Also, in the case of the assembled connector, the resistance increased slightly after baking.

In order to investigate the effect of heavily oxidizing the connector on the electrical resistance, a heat source of 400℃ in temperature was directly applied to the connector for different time intervals. By doing so, mild to severe surface oxidation of the terminals could be achieved. The connector was heated in the assembled form for one to seven minutes. Fig. 6 shows the optical micrographs of the connector surface before and after heating it at 400℃ for seven minutes. The darkened surface is evidence of severe surface oxidation.



(a) (b)

Fig. 6 Optical micrographs of connector surface (a) before heating and (b) after heating at 400℃ for seven minutes

Fig. 7 shows the electrical resistance of the connector with respect to heating time at 400℃. It can be seen that there is a sudden increase in the resistance after four minutes of heating. Before that time, surface oxidation due to heat did not affect the resistance. Also, it is interesting to note that once the resistance increased sharply by about 2 to 3 mΩ, the value did not continue to rise with heating time. The decreasing resistance for 300 and 360 seconds cannot be definitely explained. It may be due to the non-uniform heating of the connector from specimen to specimen.

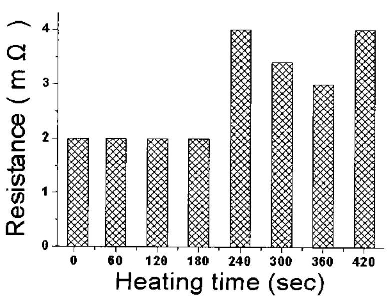


Fig. 7 Electrical resistance of the connector with respect to heating time at 400℃

In any case, it is clear that heating which leads to surface oxidation can contribute to the increase in connector resistance by a few milliohms. Again, the significance of this magnitude would depend on the circuit system.

3.3 Effect of contamination

In the next set of experiments, the effects of hydrocarbon contaminants in the contacting interface of the connector on the electrical resistance were investigated. Such contaminants can be introduced to the connector from residues on the engine block and other sources under the hood of an automobile. Hydrocarbon residues were collected from a severely burnt metal surface and a slight amount was coated on the terminal surfaces. Then, the terminals were assembled. Such sequence may happen if a technician were to disassemble the connector for service and re-assemble it without ensuring cleanliness of the connector terminals. Another possibility is that engine block residues may be introduced to the connector due to splashing by water stream or oil leakage. Introduction of the contaminants into the connector resulted in the electrical resistance increase of about 1 Ω, which is three orders of magnitude higher than the surface roughness or the oxidation case. This magnitude would certainly lead to malfunctioning of the electric circuit.

One difficulty regarding this experiment was in controlling the amount of contamination introduced to the connector interface. Though it was certain that a drastic change in the electrical resistance of the connector can occur due to contamination, the critical amount was difficult to identify. As a means to vary the amount of contaminant in the connector interface, the connector was repeatedly disassembled and assembled. During this process, the contaminant amount was randomly introduced to the connector interface. This resulted in the resistance increase of about 4.85 Ω for some instances, which is also a very large magnitude. It may be stated that hydrocarbon contaminants cause the most significant increase in the connector electrical contact resistance. Hence, precautions must be taken to ensure proper sealing and cleanliness of the connectors to prevent the contaminations from entering the interface.

4. Conclusions

In this work, the effects of surface roughness, surface oxidation, and hydrocarbon contamination on the electrical resistance variation of a connector in a direct current circuit were investigated. From the research results, the following conclusions may be drawn:

(1) Surface roughness variation by scratching resulted in about 0.2 mΩ increase in the electrical resistance, which is not considered to be significant.

(2) Oxidation of the connector by heating resulted in about 1 to 2 mΩ increase in the electrical resistance depending on the degree of oxidation. This increase is more than 30% of the initial state and may be significant for low power circuits.

(3) Slight amount of hydrocarbon contaminants introduced to the connector interface can cause a drastic increase in the electrical resistance which will most likely lead to malfunctioning of the electric circuit. Therefore, care must be taken to properly seal the connector from outside contaminants and maintain its cleanliness for proper operation.

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