Electrical contact resistance for a conductive Velcro system

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Abstract

Conductive Velcro fasteners are employed as a joining material for various types of connections due to their detachable properties, especially when an electrical connection is established. Due to microscopic actual contact spots between the fibers and hooks in the Velcro joints, a large electrical contact resistance is established that could cause heat and potentially short-circuit. In this study, the electrical contact resistance behaviors in the conductive Velcro are estimated according to the electrical load, frequency and load amplitude. The wear behavior due to these effects is investigated after long exposure to dynamic loading under a specific frequency at a low load amplitude.

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1. Introduction

Velcro (hook & loop) fasteners are employed as a joining material for various types of connections due to their detachable properties. Velcro fasteners consist of two fabric strips featuring fiber-like loops, which are attached to the opposing hook surfaces. This structure allows two pieces to be easily fastened or detached. The hook and loop setup has traditionally been used as a fabric fastener, but recently its uses have expanded to mechanical, medical and construction devices [1–4]. More recently, the increasing focus on smart fabric has led many researchers to notice the potential for a fabric electrical connector [5–10]. Among these attempts, the application of conductive Velcro as an energy storage system, such as a battery assembly in an automotive or transportation environment, has also been introduced [11].

The application of a conductive Velcro fastener is usually hindered by large electrical contact resistance, since the electrical conduction in the Velcro system occurs in the actual microscopic contact spots between the fiber-like loops and hooks, establishing large electrical contact resistance, which can generate heat and cause a short-circuit [12]. Thus, the estimation of electrical contact resistance is important for understanding the performance of an electrical connector [13].

To properly apply the conductive Velcro system to the automotive or transportation field, the effect of dynamic loading on the electrical contact resistance must be understood. Specifically, the effects of dynamic loading due to the frequency and load amplitude usually affect the life of an electrical connector in the form of fretting wear or corrosion [14–17]. Furthermore, since the conductive Velcro system is much more flexible and the dynamic response is significant, adverse effects may cause an increase in the electrical contact resistance. Even though there have been many works on electrical contact resistance and the effect of dynamic loading in an electrical connector [18–25], previous studies have not yet been conducted on the electrical contact resistance of a conductive Velcro system. Therefore, our research objective is to understand the electrical contact resistance behavior in a conductive Velcro system under dynamic loading conditions, which may help to extend the application to dynamic loading systems.

In this paper, we perform experiments to understand the characteristics of electrical contact resistance at the interface of the hook and loop connection in a conductive Velcro system. Specifically, experiments are performed under a low-frequency vibration condition to show the characteristics of contact and the corresponding fretting behavior. In addition, the analysis is focused on the changes in the contact resistance according to several important variables in an electrical and mechanical system, such as the vibration frequency, electrical load, and load amplitude.

2. Experimental details

2.1. Materials

The conductive Velcro system used in these experiments was manufactured by APLIX, consisting of a pair of silver-coated nylon

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fibers and hooks, as shown in Fig. 1. The dimensions of the specimen are 20 mm × 20 mm.

2.2. Micro-sliding tester

The micro-sliding tester is designed to measure the electrical contact resistance at the interface of the hook and loop connection. A schematic of the micro-sliding tester used in this study is shown in Fig. 2. The Velcro specimen is located between the upper and lower plates. The upper plate attached with the loops is stationary and the lower plate attached with the hooks moves back and forth along the longitudinal direction of the plate. The vibration frequency can be adjusted from 1 Hz to 23 Hz by a variable speed motor. The sliding amplitude is also controlled from ±10 to ±100 μm by a variable cam which cycles up to 3600, at which the electrical contact resistance approaches a steady state. The micro-sliding tester has natural frequencies of 29.75 Hz and 59.50 Hz. Due to these conditions, the natural frequency does not affect the apparatus or the experimental result in the frequency range. The electrical contact resistance is measured through the four-wire method [13] and recorded by a computer. The four-wire method uses separate pairs of probes to measure the current and voltage, respectively. This is a method which can be used to avoid the voltage drop caused by the resistance in the current lead wire.

2.3. Experimental variables; frequency of mechanical load and electrical load

We have chosen several experimental variables affecting the electrical contact resistance under the low-frequency vibration condition such as amplitude, frequency, and electrical load. In automotive vibration, the low-frequency of dynamic loads in the vertical vibrational range of 4–8 Hz and the lateral vibrational range of 2 Hz, respectively, causes passenger fatigue [26]. In addition, vibration from the roughness of the road is restricted by the suspension, but shows a frequency level of 1 Hz, and the vibration during the idle stage and running stage occurs at a frequency level of 5–25 Hz. In our experiments, the range of frequency covers a low-frequency region from 1 Hz to 23 Hz [27]. The amplitude of the vibration load at 12–80 μm may reduce the life of the electrical connector [13]. For electrical loads, the voltage drop and current cover up to 1.4 V and 3.5 A, respectively. The range of electrical loads is chosen because the cell voltage is up to 1.2 V for a secondary battery of Ni-Cd [28].

2.4. Estimation of electrical contact resistance

We have modeled a Velcro system to estimate the electrical contact resistance between Velcro plates, as shown in Fig. 3. It is assumed that the resistivities of the upper and lower plates are ρ₁ and ρ₂, respectively. The Velcro parts, including the fibers and hooks, make a sufficiently small contact area between the two parts, resulting in a contact resistance per unit length, R_c. The voltages of the upper and lower plates, V₁(x) and V₂(x), vary along the plate of length L. The voltage drop between the two plates

![Fig. 1. Conductive Velcro of (a) hook (b) loop.](image1)

![Fig. 2. Micro-sliding tester.](image2)
generates a current density per unit length of
\[ i(x) = \frac{V_1(x) - V_2(x)}{R_c}. \]  
(1)

The total current along the plate, \( I(x) \), is
\[ I(x) = \int_0^x \int_0^\xi \rho \, d\xi \, dx. \]  
(2)

In the lower plate, Ohm's law describes that
\[ \frac{\partial V_2(x)}{\partial x} = \frac{\rho_1}{A_2} \]  
(3)

where \( A_2 \) is the cross-sectional area of the lower plate. Differentiating (3) and combining with (1),
\[ \frac{\partial^2 V_2(x)}{\partial x^2} = \frac{\rho_2}{A_2} \frac{V_1(x) - V_2(x)}{R_c}. \]  
(4)

The same analysis for the upper plate can be performed, showing that
\[ \frac{\partial^2 V_1(x)}{\partial x^2} = \frac{\rho_1}{A_1} \frac{V_2(x) - V_1(x)}{R_c}. \]  
(5)

where \( A_1 \) is the cross-sectional area of the upper plate. The resulting Eqs. (4) and (5) make a system of differential equations. The boundary conditions for these equations are
\[ \frac{\partial V_1}{\partial x}(0) = 0, \quad \frac{\partial V_2}{\partial x}(0) = 0, \quad V_1(x) - V_2(x) = \Delta V. \]  
(6)

The first two boundary conditions occur because there is no conduction to the left of \( x = 0 \), thus the current at that location is equal to zero. The third condition gives the measurement of the voltage drop during the experiment. The substitution of the three boundary conditions into Eqs. (4) and (5) give a solution with one arbitrary unknown constant, but it can be determined if any constant potential is chosen as a datum, or if the third boundary condition is replaced by prescribed values of \( V_1(L) \) and \( V_2(L) \), making four boundary conditions in all. Therefore the final solutions for voltage \( V_1(x) \) and \( V_2(x) \) are
\[ V_1(x) - C = \Delta V \left( \frac{k_1}{k_1 + k_2} \right) \]  
\[ V_2(x) - C = -\Delta V \left( \frac{k_2}{k_1 + k_2} \right). \]  
(7)

where \( k_1 = \rho_1/(A_1 R_c) \), \( k_2 = \rho_2/(A_2 R_c) \), and \( C \) is an arbitrary voltage. The constants \( \rho_1/A_1 \) and \( \rho_2/A_2 \) are measured as 25.8 Ω/m and 12.6 Ω/m, respectively.

3. Results and discussion

3.1. Measurement of the electrical contact resistance according to a variable frequency and load amplitude

The electrical contact resistance by frequency for different load amplitudes is shown in Fig. 4 when an electrical current of 0.1 V is prescribed. We have measured the electrical contact resistance after 3600 loading cycles.

The responses of the electrical contact resistance for load amplitudes of ±10 μm and ±25 μm vary significantly, and reach their maximum values at a frequency of 7–10 Hz, compared with the case of higher amplitudes of ±50 μm and ±100 μm. From these results, we find that there are two factors causing higher electrical contact resistance in a conductive Velcro system under a vibrating load: a certain range of frequencies and a low load amplitude.

In terms of frequency, as most dynamic systems experience large deformations at the resonance frequency, it is postulated that the fibers of a loop plate deform significantly and can make the contact area smaller, leading to an increase in the electrical contact resistance. Since conductive Velcro is much more flexible, it may not explain the behavior of electrical contact resistance according to a dynamic load based on the theory of conventional electrical connectors. To properly estimate the effect of a certain frequency on electrical contact resistance, we perform an experiment to find the vibration characteristics of Velcro using an LMS tester with an accelerometer. As shown in Fig. 5, the acceleration amplitude according to frequency is obtained, indicating that the vibration amplitude of the Velcro joint is significantly large near a frequency of 10 Hz. The fiber structure of the loop and hook has an intrinsically large damping effect, thus the acceleration amplitude around 10 Hz is finite and has a gentle slope. Compared with the results in Fig. 4, this acceleration amplitude response with frequency parallels the behavior of electrical contact resistance with frequency. This similar tendency indicates that the characteristics of Velcro vibration affect, in some measure, the behavior of the electrical contact resistance according to frequency.
certain frequency and load amplitude, the fibers of the loops in the Velcro structure endure greater movement, resulting in considerable change and decrease in contact area, and corresponding increases in the electrical contact resistance. After the experiment, if there is no dynamic load, the electrical contact resistance returns to static values. Although it is difficult to estimate the natural frequency for a dynamic system with a high damping coefficient, it is suggestive that the dynamic effect at a certain frequency is a factor for having high electrical contact resistance in a conductive Velcro system.

The second factor for increasing the electrical contact resistance of a conductive Velcro system under dynamic loading is low load amplitude. The reason is that the system experiences resonance, which with prescribed amplitude implies that the forces transmitted through the Velcro joint are lower than they would be away from resonance. And this result ties in to some extent with the observation that lower amplitudes cause more resistance. In other words, larger forces reduce resistance, as in regular electrical contact resistance experiments. It is generally accepted that the electrical connector wears severely under low load amplitude, in addition to high-frequency [23,29–31]. One of previous experimental model has a flat plate and the counter part is 1.5 mm radius hemispherical rider. Both of them were made of brass and coated with small thickness of tin. The resulting wear debris, such as oxide particles, accumulates and causes an increase in the electrical contact resistance. However, the wear evolves quickly under a high vibration speed above a certain threshold, accelerating the removal process of the oxide layer and leading instead to a decrease in the electrical contact resistance [24]. Furthermore, as the load amplitude increases, the electrical contact resistance of the electrical connector becomes smaller because the oxide particles are pushed out of the contact region, and thus the accumulation height of the oxidation particles is reduced [25]. A similar tendency may be captured in this conductive Velcro analysis. Thus, we believe that the low load amplitude, a conventional reason to increase the electrical contact resistance in an electrical connector, could be a source of increasing electrical contact resistance.
3.2. Wear behavior of conductive Velcro

From the previous section, two factors were found to cause higher electrical contact resistance in a conductive Velcro system under a vibrating load: resonant frequency and low load amplitude. The wear process could be an outcome due to the increase in the electrical contact resistance. Since the electrical conduction in the Velcro system occurs in the microscopic contact spots between the fiber-like loops and hooks, large electrical contact resistance is established, which can generate heat. The increase of temperature due to heat can damage the contact surfaces of the coating layer in the loop and hook, which accelerates the wear process. To confirm the wear behavior in conductive Velcro, the load amplitude of ± 25 μm with frequencies of 5, 10, and 15 Hz are induced for 100,000 cycles to check the surfaces of a hook and loop using SEM. The silver coating surfaces of the hook and loop are analyzed through EDX mapping, checking the distribution of silver coating and confirming how much silver coating may exist. If the distribution of the silver coating is small relative to initial conditions, we assume that the coating is removed by wear.

Typical results for SEM and EDX analysis for each hook and loop are explained to verify the silver coating area, as shown in Figs. 6 and 7, respectively. For the hook surface, the SEM image of Fig. 6 shows dark colored (A) and bright colored (B) regions that represent the silver coating removal region and the silver coating region, respectively. This is confirmed by the results of EDX analysis. For the dark colored region (A), several chemical components are detected as C: 80.63 wt%, O: 18.81 wt%, and Ag: 0.56 wt%, which shows that the weight percent of silver is smaller than that of carbon. For the bright colored region (B), a larger amount of silver components is detected, showing that C: 8.08 wt%, O: 4.18 wt%, and Ag: 87.74 wt%. For the worn loop surface, a similar

![Fig. 8. SEM images of the hook (first column) and EDX mapping for silver on the loop (second column) for (a) 5 Hz; (b) 10 Hz; (c) 15 Hz.](image-url)
explanation of the SEM and EDX results of the hook can be applied. The dark and bright colored regions (C) and (D) represent the removal region of silver coating and the silver coating, respectively, based on the EDX spectrum results, as shown in Fig. 7.

Now, the surfaces of the individual hook and loop obtained from the conditions of varying frequencies of 5, 10, and 15 Hz are compared as shown in Fig. 8. For comparison, the hook and loop surfaces are investigated by SEM images and EDX mapping, respectively, because each figure may represent the best outcome for identifying the worn surface or the removal of silver coating. The SEM image at 10 Hz shows a larger area of worn surface and the EDX mapping at 10 Hz shows a smaller distribution of a violet colored area, compared with the case of other frequencies, meaning that the Velcro surfaces are damaged more at 10 Hz. Note that the EDX mapping detects silver as violet in color.

3.3. Measurement of the electrical contact resistance according to changing electrical load

When vibrational load frequencies of 5, 10, and 15 Hz are applied, the variation of currents in relation to change in voltage drop is measured, as shown in Fig. 9. The distinctive features of the compared results are as follows: Firstly, the fluctuation of current at a specific voltage drop above 1.1 V becomes large, especially at 10 Hz; second, the slope of the curve at low voltage drop for 10 Hz is smaller than the slope of the other two frequencies. Note that the slope of the current figure \( I = \frac{1}{R} \frac{dV}{dt} \) represents the conductance. Thirdly, the slope of the \( I-V \) plot for 10 Hz in the low voltage drop region is smaller than the slope in the high voltage drop region. This feature has already been reported in the wear experiment of the electrical connector [32,33]. When a high voltage drop is induced, compared with a low voltage drop, the high electrical potential breaks down more of the oxide layer at the contact interface, resulting in a relatively smaller electrical resistance. The effect of the oxide layer on the electrical contact resistance could be changed according to the oxidation characteristics of the materials. Ren et al. [32] has reported results similar to the present analysis for the electrical connector with gold coating. However, Park et al. [33] showed that for a tin-coated electrical connector, increasing the current accelerates the rate of oxidation of tin and the growth of oxides through Joule heating, leading to an increase in the electrical contact resistance. Since the silver coating material has similar oxidation characteristics as gold coating, it is reasonable to obtain a large electrical contact resistance at low voltage drop. Furthermore, the high current induces large electrical heating and enlarges the contact area due to the softening of the material, which could be another reason to decrease the electrical contact resistance. Electrical heating could also affect the fluctuation of current at high voltage drop.

3.4. Measurement of the electrical contact resistance by vibration direction

The effect of the direction of the vibration on the electrical contact resistance is investigated. Specifically, if the lengthwise dimension of the specimen is parallel or perpendicular to the vibration direction, the electrical contact resistance varies differently. The loop and hook sides of the specimens have the same contact area and the length of the loop part varies from 20 mm to 70 mm. The load amplitude of \( \pm 25 \mu \text{m} \) with a frequency of 10 Hz and a current of 0.1 A is applied to the system for 3600 cycles. Fig. 10 shows the variation of electrical contact resistance according to the length of the top part for two different directions of vibration, which represent “I” and “II” as parallel and perpendicular to the vibration direction, respectively. The vibration loading with “I” direction can increase the electrical contact resistance almost twice for the length of the specimen ranging from 50 mm to 70 mm, compared with the case of 20–40 mm, while there is no significant variation in the electrical contact resistance for vibration direction “II”. This suggests that the lengthwise vibration direction of the top part can significantly influence the electrical contact resistance. Similar experimental results for this phenomenon can be obtained in the ultrasonic welding reported in [34]. The results show that the lengthwise dimension of the part parallel to the vibration direction has an influence on the weld strength, while the length does not influence the weld strength for the vibration direction perpendicular to the lengthwise direction of the top part.

4. Conclusion

An experimental analysis is performed to investigate the electrical contact resistance at the interface of the conductive Velcro junction under a low-frequency vibration condition. A simple model for contact resistance in the Velcro system is also introduced. The results show that a certain range of frequency at a low load amplitude causes higher electrical contact resistance in a conductive Velcro system under vibrating load. The wear behavior after a long exposure to dynamic loading under a specific frequency at a low load amplitude is investigated to confirm its effect of the factor on a high electrical contact resistance. According to the \( I-V \) curve at a specific frequency, the electrical resistance at a low voltage drop is larger than that at a high voltage drop, and a
significant fluctuation of current at a larger voltage drop is noticed. The effect of the vibration direction on the electrical contact resistance is also investigated, showing that the lengthwise dimension of the part parallel to the vibration direction has an influence on the electrical contact resistance.

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