Response to Reviewer 1 Comments

Point 1: Overall, the article is interesting, but it is not very clear what it is intended to demonstrate. It would be necessary to better define what the "Acetal Aerosol Environment" is and what it is used for. Also specify in what kind of specific applications this study can be useful. Sliding electric mechanisms are very varied and can vary greatly between them, driving from milliamps to hundreds of amps in applications as different as consumer electronics or electric traction. On the other hand, it is indicated that high temperatures favor the evaporation of aerosol [line 35], but in the development of the paper no reference is made to temperature again.

Response 1: Thanks for the reviewer's kind advice. Acetal aerosol environment for exposed electrical contact components is considered as environmental contaminant. The glue is better than aerosol in this paper. High sevice temperature will accelerate the evaporation of organic glue. Volatile glue absorbed on the surface of electrical contact component will affect the sliding electrical contact performance of milliamp precision aviation or military equipment. Slight change of glue concentration may cause the decrease in reliability of milliamp precision aviation or military equipment. Therefore, contant current of 100 mA was chosen in this paper. The manuscript is also modified into "However, acetal glue commonly used for the packaging of electric contact component will accelerate evaporation and stick to the surface of exposed electrical contact component at higher service temperatures. Volatile glue absorbed on the surface of electrical contact component is considered as environmental contaminant. The stability of electrical signal transmission on the Cu alloy decreases dramatically under acetal glue environment, leading to a decrease in reliability of electrical components, especially for some milliamp precision aviation or military equipment."

Point 2: In my opinion, the design of the experiment, while seeming correct and useful, should be explained in more detail. Especially as far as the geometry of the copper contact is concerned. It is imperative to give a notion of the contact surface. In addition, the vibration values are not well quantified.

Response 2: Thanks for your suggestion. The geometry of the brass alloy wire is added in Figure 1 to better show the diameter (1 mm) and bending diameter (5 mm) of brass alloy wire. Besides, the vibration value is also quantified in Figure 1. The manuscript has been revised into "The liner motor drove the pure copper block on the sliding module to achieve reciprocating sliding in the horizontal direction. An external vibration platform was mainly composed of cam and servo motor, which was installed on the sliding module to realize vertical vibration of pure copper block. The sliding electrical contact under external vibration condition was obtained between the interface of friction pairs."

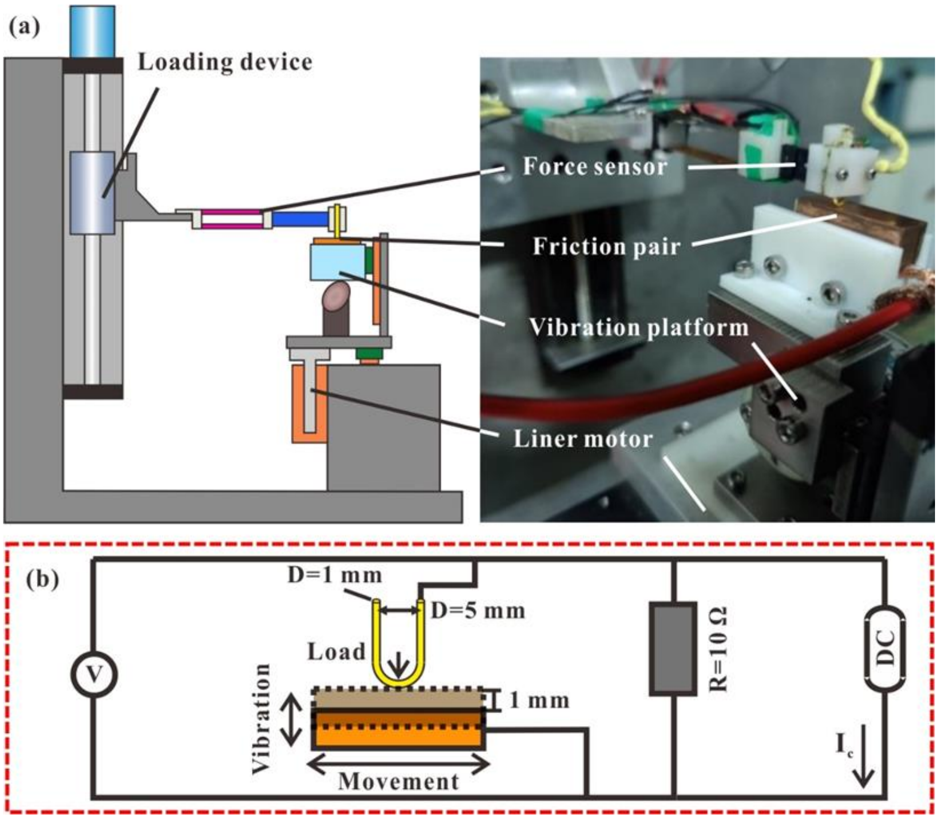


Figure 1. Schematic diagram of equipment: (a) Test device; (b) Contact resistance measurement system.

Point 3: [32] - Plenty of point after reference.

Response 3: Thanks for your advice. The points have been deleted.

Point 4: [34 - 35] - Reference to temperature.

Response 4: Thanks for your suggestion. As reported by Ref. [1], the volatility of glue increases as the drying temperature is increased to 120 °C. Therefore, the manuscript has been modified into "However, acetal glue commonly used for the packaging of electric contact component will accelerate evaporation and stick to the surface of exposed electrical contact component at higher service temperatures [1]."

[1] Yu, M.; Song, M.; Kim, M.; Kim, D. Experimental study on the formability of aluminum pouch for lithium polymer battery by manufacturing processes. J. Mech. Sci. Technol. 2019, 33, 4353–4359.

Point 5: [47] - ominal by nominal.

Response 5: Thanks for your suggestion. The spelling error has been corrected.

Point 6: [59] – batter, I don't understand.

Response 6: Thanks for your advice. The batter is revised as the battery.

Point 7: [79] - On the improved method of measuring four-wire resistance. Explain in detail how the method is applied. Equipment used. Voltmeter and current generator. Models. Choice of values. Is 100 mA used in any case? Length of the measuring threads? Comparison of the measure with a pattern?

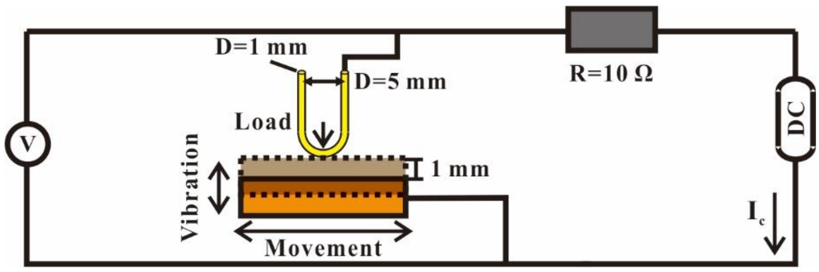
Response 7: Thanks for your advice. In this paper, the used equipment in the improved method is the same as the traditional four-line method, which includes a voltmeter, a current generator, a constant resistance, and some wires. Two models are shown in Figure 2. When constant resistance is connected in series, as shown in Figure 1a, the measured voltage (V) is calculated as follow:

$$V = I_c * (R + R_m)$$

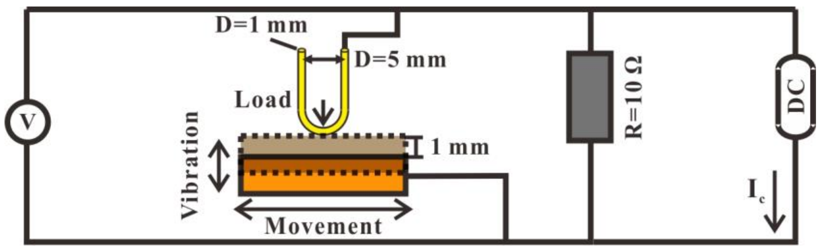
Where I_c is output current; R is constant resistance; R_m is contact resistance between the interface of friction pairs. Thick aerosol or large vibration might cause high contact resistance at the interface of friction pairs. At this time, as the R_m is greater than a certain value, the measured voltage may be out of range of voltmeter, leading to damage to voltmeter. However, when constant resistance is in parallel, as shown in Figure 2b, the measured voltage is calculated as follow:

$$V = I_c * \left(\frac{1}{\frac{1}{R_m} + \frac{1}{R}}\right)$$

The measured voltage decreases as the R_m increases, which can protect the voltmeter from damage. Therefore, we modifies the traditional four-line method. The contact resistance of 10 Ω is commonly used in circuits. As mentioned in Response 1, the constant current of 100 mA was chosen for its application in milliamp precision aviation or military equipment. Of course, The constant current of 100 mA is not unique in electrical contact study.



(a) Traditional four-line method



(b) Improved four-line method

Figure 1. Contact resistance measurement system.

Point 8: [81] - Utility of including a load resistor of 10 Ω in parallel.

Response 8: Thanks for your advice. As mentioned in Response 7, load resistor of 10 Ω in parallel can protect the voltmeter from damage when measuring the constant resistance accurately.

Point 9: [82] - High voltage transients occur by introducing a constant current at times when the contact resistance is very high. Why keep the current constant? Is it necessary to maintain the current of 100 mA during the mechanical test? Have the authors considered measuring the contact resistance after mechanical cycles?

Response 9: Thanks for your suggestion. As reported in Ref. [2–4], the current is constant and the voltage is measured to calculate the contact resistance between the interface of friction pairs. It is necessary to maintain the current of 100 mA during the mechanical test. At this time, the real-time resistance values are measured according to the method in Response 7, as shown in Figure 5. Plenty of data points of resistance will be missing if measuring the contact resistance after mechanical cycles. Therefore, it is better to measure contact resistance during the mechanical test.

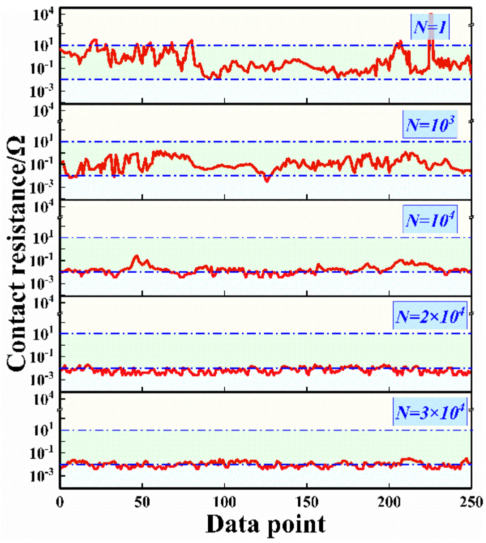


Figure 5. Entire data point of resistance at various cycles under non-vibration and 10% concentration.

[2] Grandin, M.; Wiklund, U. Wear phenomena and tribofilm formation of copper/copper-graphite sliding electrical contact materials. Wear, 2018, 398, 227–235.

[3] Poljanec, D.; Kalin, M.; Kumar, L. Influence of contact parameters on the tribological behaviour of various graphite/graphite sliding electrical contacts. Wear, 2018, 406, 75–83.

[4] Banthia, S.; Amid, M.; Sengupta, S.; Das, S.; Das, K. Reciprocating sliding wear of Cu, Cu-SiC functionally graded coating on electrical contact. J. Mater. Eng. Perform. 2020, 29, 3930–3940.

Point 10: [91] - On the values of charge and vibration. Why did the authors choose 200 mN of charge? What does a vibration frequency of 5 Hz at an amplitude of 0 mm mean? Vibration should be expressed in terms of acceleration.

Response 10: Thanks for your suggestion. The focus of our study is the combined action of vibration and concentration of glue on sliding electrical contact performance. Therefore, the constant normal load of 200 mN is selected to realize vertical loading. It is not appropriate to display a vibration frequency of 5 Hz at an amplitude of 0 mm. The manuscript in table 1 is modified as follow. The definition of vibration should be expressed in terms of vibration amplitude, which means the distance traveled in the vertical direction. Therefore, vibration amplitude is a better expression.

Table 1. Detailed parameters of the experiment.

Normal load	Displacement amplitude	Sliding frequency	Current	Vibration amplitude (frequency)	Concentration of aerosol
200 mN	6 mm	4 Hz	100 mA	0 mm (0 Hz)	0%
					10%
					30%
					50%
				1 mm (5 Hz)	0%
					10%
					30%
					50%

Point 11: [109] - What can be the origin of these impurities?

Response 11: It is good advice. The origin of these impurities is ascribed as agglomeration of glue as its concentration reaches 50%. The manuscript has been revised as "Extra agglomeration occurred on the surface of sample in the high concentration of glue addition [26]. Apparent agglomeration was observed when the glue concentration reached 50%."

[5] Xie, C.; Wang, K. Synergistic modification of the tribological properties of polytetrafluoroethylene with polyimide and boron nitride. Friction, 2021, 9, 1474–1491.

Point 12: [118] - cu by Cu.

Response 12: Thanks for your advice. The spelling error has been corrected.

Point 13: [131] - Include the two spaces in scientific notation. 1.5× 10^4 by 1.5 × 10^4.

Response 13: Thanks for your advice. The formatting errors have been corrected in revised manuscript.

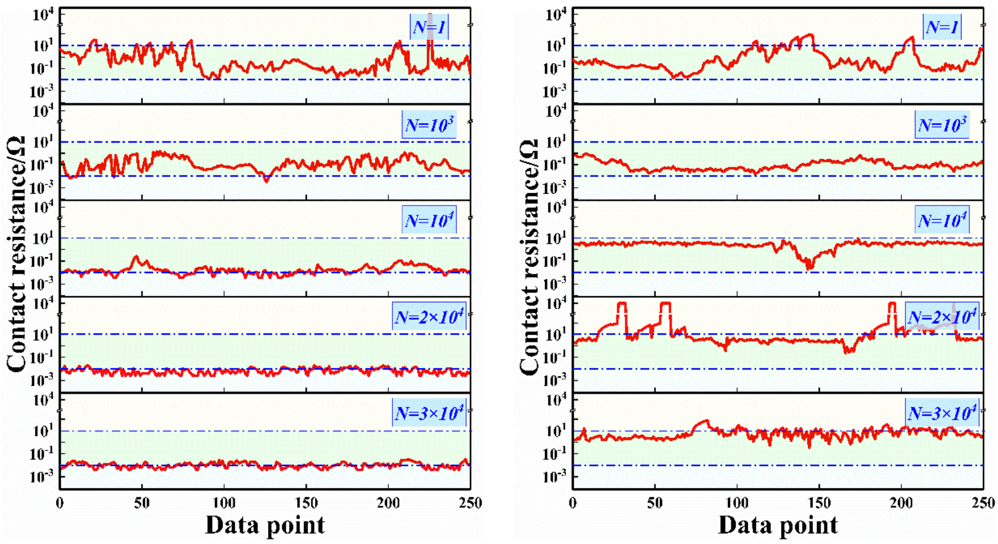
Point 14: [133] - I think authors should delve deeper into the COF. Definition, implications, trend...

Response 14: Thanks for your suggestion. COF can reflect the contact status of fricition pairs. Vibration and glue concentration will affect the removal of glue, resulting in various contact statuses between friction pairs. In the revised manuscript, the evolution of COF with cycles has been added. And final COF is also presented to show the contact status. There are two contact statuses including direct metal contact and glue residue. The COF of about 0.3 at 3×10^4 cycles indicates direct metal contact. The COF less than 0.2 indicates glue residue because of lubracation effect of glue. Therefore, the manuscript has been modified into "Figure 3 shows the COF at various glue concentrations with and without vibration. When no glue is added, the evolution of COF with cycles under non-vibration and vibration conditions has two stages including quickly ascending and stable stage. The COF at stable stage is about 0.3 for two vibration conditions. However, the COF under non-vibration condition enters stable stage after 1×10^4 cycles, while the COF under vibration condition enters stable stage after 5×10^3 cycles. As glue concentration reaches 10%, the COF under non-vibration condition shows a similar trend as no glue addition. However, COF at 10% concentration remains about 0.1 before 1.5×10^4 cycles and then reaches 0.3. The increase in the COF after 1.5×10^4 cycles may be ascribed as complete removal of glue and direct contact of metals. The COF under vibration condition is always lower than 0.2 at 10% glue concentration. This situation implies limited glue removal capacity under vibration condition. Residual glue on sample surface still acts as lubrication.

When the glue concentration is further increased to 30% and 50%, the COF remains essentially constant throughout the cycle. At this time, the COF at 3×10^4 cycles with and without vibration is lower than 0.2, which further demonstrates the residue of glue and its lubrication effect. The COF in the firstly 2×10^3 cycles increases with the increase of glue concentration from 10% to 50%, which may be due to the positive correlation between viscosity and concentration of glue. Vibration and glue concentration will affect the removal of glue, resulting in various contact statuses between friction pairs."

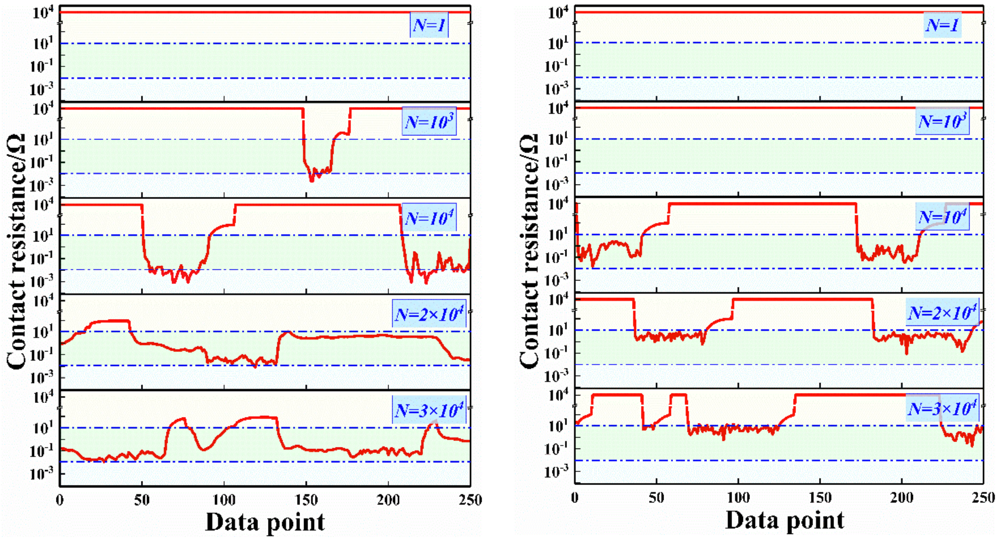
Point 15: [145] - Have you measured resistances of 10 kΩ with the method described?

Response 15: Thanks for your suggestion. The contact resistance of 10 kΩ is measured with improved four-line method. The results are shown in Figure 5. At this time, the contact resistance is up to the voltmeter range. Therefore, contact resistance of 10^4 Ω is considered to have reached insulation. The manuscript has been revised as "contact resistance of 10^4 Ω is considered to have reached insulation, which is up to the voltmeter range."



(a) Non-vibration, 10% concentration

(b) Vibration, 10% concentration

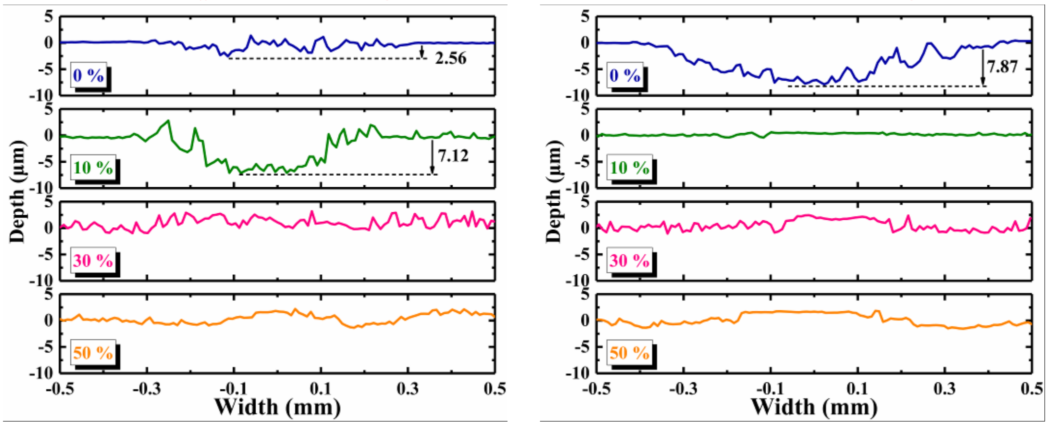


(c) Non-vibration, 50% concentration (d) Vibration, 50% concentration

Figure 5. Entire data point of resistance at various cycles under typical aerosol concentrations and vibration conditions.

Point 16: [267] - Figure 12. The ordinate axis is not consistent with what is shown. It certainly gives a sample of the created profile, but it should include a zero and a measure of endpoints for each profile.

Response 16: Thanks for your suggestion. The wear scar profile has changed below which includes similar ordinate axis and independent zero calibration. Considering that there is no obvious wear scar profile change when glue concentration is above 30%, the measure of endpoints is only performed on the profiles at 10% glue concentration with non-vibration or no glue addition.



(**a**) Non-vibration (**b**) Vibration

Figure 11. Cross-sectional profile of wear scar.

Point 17: [276] - Figure 13. The measurement of the volume of displaced material is very interesting. How was it obtained? Is it the excess material at the edges of the groove or the defect of the groove itself? Is it possible that this material also comes from the sliding element? Can the material adhere to the sliding element? Again, the geometry of the contact is relevant. This is referred to in line 300, but it would be interesting to go a little deeper into this matter.

Response 17: It is good advice. The wear volume is obtained via white light interferometer and Vision software. As shown in Figure 10, when we use Vision software to calculate the volume of wear scars, we define the volume of the valley as the wear volume. The specific steps are as follows：

1. First, the acquired 3D model is imported to the software.
2. Then, the software will automatically calculate the volume represented by the valley according to the base level.
3. Finally, we use this unified standard to calculate the wear volume of other wear scars.

Material transfer from the brass alloy wire and adheres on the surface is possible. And the wear volume is also related to the geometry of the contact. In this paper, material transfer is only found when no glue addition or non-vibration condition at 10% aerosol. material transfer indicates mateiral removal on the brass alloy. At this time, the wear volume is larger under these conditions. This situation is ascribed as similar hardness between friction pairs. The manuscript has been revised as "There are two contact statuses between friction pairs including direct metal contact and glue residue. The difference in wear mechanism with and without residual glue is shown in Figures 13d–e. Glue can be completely removed at 10% concentrations under no vibration condition. At this time, the contact state changes to direct metal contact similar to no glue addition. The dominant wear mechanism is adhesive wear when metal material directly contacts. Wear debris accumulates on the surface of wear scar, accompanied by material transfer, as shown in Figure 13d. The contact resistance decreases, and COF increases. Residual glue between the friction pairs plays the roles of lubrication, anti-wear, and insulation. At this time, the wear volume of pure copper block is 2 to 3 orders of magnitude lower than that in direct metal contact, as shown in Figure 12. The brass alloy wire and pure copper block have similar hardness, indicating obvious material removal on brass alloy wire in direct metal contact. Part of material from brass alloy wire adheres on the surface of pure copper block. Therefore, Zn element is detected on the wear scar of pure copper block in direct metal contact, as shown in Figures 7–8."

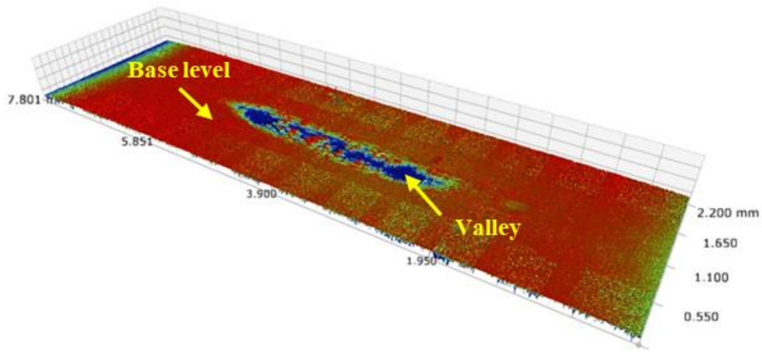


Figure 10. 3D model of wear scar.

Point 18: [276] - If they are not referenced, error bars should be removed.

Response 18: Thanks for your suggestion. Three tests are performed under each conditions. So three values of wear volume is obtained and error bars exist.

Point 19: [303] - Figure 14 - d. Wear dbris by Wear debris.

Response 19: Thanks for your advice. The spelling error has been corrected.

Point 20: [303] - Why are current lines marked between contact and substrate? The reduction of contact surface will certainly increase the current density and with it the resistance. This may justify the dynamic measurement of resistance, but the drag and friction mechanisms are so brief that they should be studied carefully and at different loads and oscillations.

Response 20: Thanks for the reviewer's kind advice. The current lines between pure copper block and brass alloy wire are to express the change of actual contact area. As you said, the reduction of contact surface will certainly increase the current density and with it the contact resistance. The actual contact area is high under no vibration condition. At this time, the current line is plentiful, as shown in Figure 13c. However, the momentary separation of friction pair will reduce the number of asperity in contact status. The cross (×) on the current line indicates that the current is not turned on. Therefore, part of contact resistance reaches a large value under vibration condition. The manuscript has been revised as "art of contact resistance reaches a large value under vibration condition, which can be ascribed to the momentary separation of friction pairs. The contact state without glue addition under no vibration and vibration condition is shown in Figure 13b–c. The number of asperity in contact state decreases because of separation of friction pair, eventually leading to reduction in actual contact area [36–37]. At this time, the current density and contact resistance increase under vibration condition. The average contact resistance under vibration condition is higher than that under non-vibration condition. The momentary separation of friction pair also reduces the wear between friction pairs." The friction mechanism is interesting that residual glue will reduce electrical contact performance although it can play a role of of lubrication and anti-wear.Both loads and oscillations certainly affect the status of glue and electrical contact performance. The influence of loads and oscillations on electrical contact performance will be the focus of our next work.

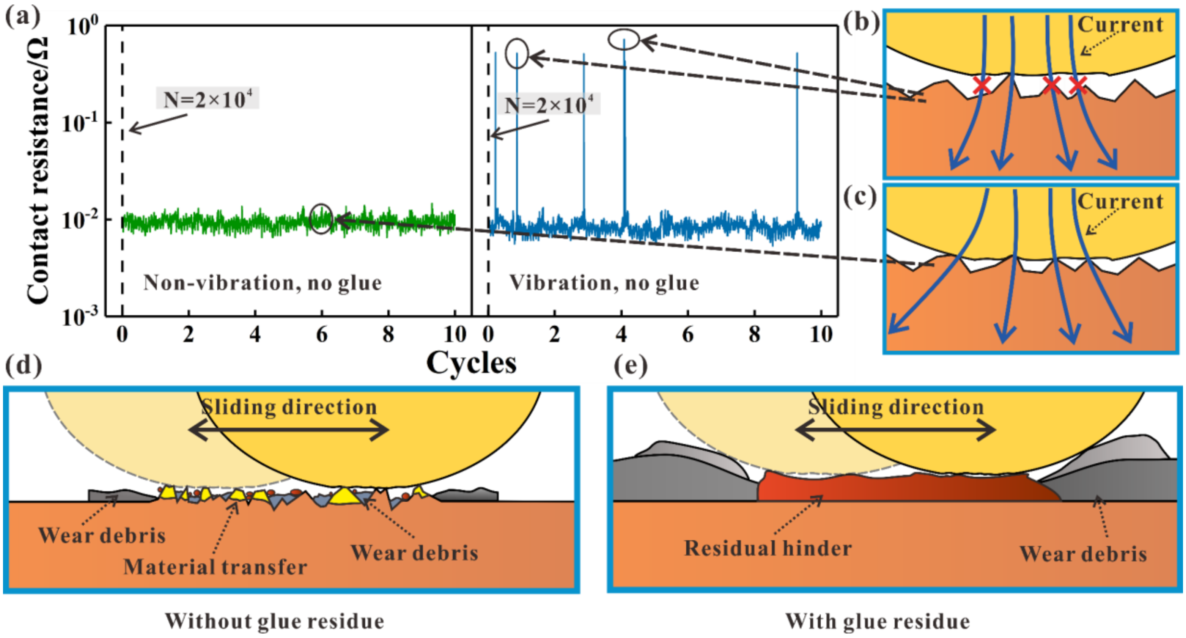


Figure 13. Combination of aerosol and external vibration on contact resistance during sliding wear: (a) Collected contact resistance; (b–e) Wear mechanism at various conditions.

Point 21: [308] - Does high-frequency refer to vibration or contact design?

Response 21: Thanks for your suggestion. High-frequency is not appropriate to express vertical vibration (5 Hz) or horizontal sliding (4 Hz). Therefore, the manuscript has been modified as "The influence of aerosol and external vibration on electrical contact performance was investigated using a self-developed micro-load reciprocating electric contact device."

Point 22: [331] - Add space between China and (U1730131).

Response 22: Thanks for your advice. The space has been added between China and (U1730131).