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Design and Launching Performance of Armature Coating with Low Melting Point Alloy

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Abstract: Hydrodynamic lubrication is an effective method to improve the sliding electrical contact performance for electromagnetic railguns. A kind of U-shaped aluminum armatures coated with low melting point alloy was designed, and the solid coating could melt and form a fluid dynamic lubrication film during initial launching process. A series launching experiments were comparatively conducted about armatures with and without coating, the current waveform, the muzzle velocity, and the contact resistance were collected. The experiments results reached three aspects. First, the variation of the sliding electrical contact resistance of the armature/rail can be divided into three stages: rapid reduction stage, stabilization stage, and oscillation and rising stage. And the coating works mainly in the first stage. Second, with the increasing number of repeated launching, the amplitude of oscillations in the last stage gradually decreases, and the muzzle velocity tends to be stable. And in the last stage, with the increase of rail depositions, contact resistance gradually tends to stability. Third, compared with common armature, the armature coating with low melting point alloy occupies a shorter launching time interval and gets a higher muzzle speed. That work has some reference significance to the sliding electrical contact of the electromagnetic railgun.

1. Introduction

Electromagnetic railgun is a new concept of kinetic energy weapon which uses electromagnetic force to accelerate macro projectile to hypervelocity. Compared with conventional weapons, electromagnetic railgun has many advantages, such as ultra high initial velocity, ultra long range, fast response and easy to control. It has broad application prospects in the military field in the future, which has attracted extensive attention and carried out in-depth research in various countries in the world[1-2]. The key technologies of electromagnetic railgun include power control technology, rail and armature structure, and sliding electrical contact technology. The researchers found that in the process of sliding electric contact, the armature/rail contact interface changes very complex, which has a great influence on the contact state of the armature/rail, the current conduction quality and launching system energy usage[3-4]. In the initial stage, in accordance with the "one gram per ampere" rule applied to the armature with pre-stressed method, will form a huge friction between solid aluminum armature and solid copper rail, caused a low launching efficiency.

In recent years, scholars have done more research work on the application of conductive coating to improve the sliding electrical contact characteristics of railgun. Engel added liquid gallium-indium-tin and water film between the armature / rail contact interface of railgun as conductive coatings, respectively. The launching experiments were carried out and the influence of the two materials on the sliding electrical contact performance of railgun was analyzed[5]. Chuantong Du et al. added graphene to the surface of the armature to study the influence of graphene on the improvement of sliding electrical contact and launching performance of railgun[6]. Although domestic and foreign scholars have carried out the research on the lubricant used in the sliding contact of electromagnetic railgun, it is still in the initial stage. Therefore, the preparation of conductive coating and the improvement of the contact resistance of the armature / rail are still to be further studied.

2. Theoretical Analysis

Since that surface of the object is not absolutely smooth but rough，electrical contact theory suggests that when two metals are in contact with each other, the contact surface is in the form of conductive spots, the actual contact area is only a small part of the nominal contact area，as shown in *Fig. 1*.

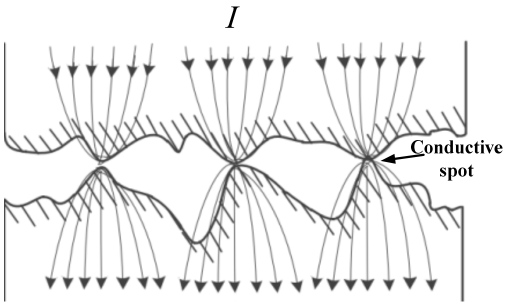


Figure 1. The structure of actual contact

The results show that the relationship between applied positive pressure, metal hardness and contact area is as follows:

$$F_c = \xi H A_a \quad (1)$$

H is a measure of the ability of a metal to withstand concentrated load deformation; ξ is the pressure factor, whose value depends on the degree of deformation of the rough surface, taking 1 in most actual contact systems.

When a current passes through the contact interface, it is contracted to pass through the a-spot, and the contact resistance due to the contraction of the current is called the contraction resistance. Holm through research, it is concluded that the contraction resistance of a single a-spot can be expressed as

$$R_s = (\rho_1 + \rho_2)/4a \quad (2)$$

ρ_1 and ρ_2 is the resistivity of the contact metal，a is the radius of the area where the metal is in contact with the metal.

Another manifestation of the contact resistance is the resistance of the oxide film on the metal surface, which has little effect on the total contact resistance in most applications, so it is neglected in this analysis and calculation process.

Assume that the total number of contact spots is n，the total contact resistance obtained from equations (1) and (2) is

$$R = \frac{\rho_1 + \rho_2}{4n} \cdot \sqrt{\frac{\xi H \pi}{F_c}} \quad (3)$$

The total resistance of the contact interface is R_c , resistivity of contact interface is ρ , resistivity of coating is ρ_D , thickness is h . Since the thickness of the plating layer is on the order of microns，the joule heat generated by the contact resistance is assumed to be approximately the heat absorbed by the plating layer.

The contact resistance heat $j^2 \rho \delta t$ is equal to that heat absorb by the coating $VSH \cdot \rho_D \cdot h \cdot \delta T$, So that the rate of change in temperature can be obtain as follows

$$\delta T / \delta t = \rho / (VSH \cdot \rho_D \cdot h) \quad (4)$$

VSH is the specific heat of the coating material， δT is the temperature rise. The temperature rise expression for a given time is as follows：

$$\delta T = \rho / (VSH \cdot \rho_D \cdot h) \cdot \int_{t_1}^{t_2} j^2 dt \qquad (5)$$

Formula (5) can be concluded that when the coating melting, the minimum temperature rise. δT should not be less than the melting point value of the material. Since that coat melts at the instant of current flow, it is defined herein as the flash-melting-point of the coating material and serve as a basis for selecting the melting point of the coating material.

A schematic view of the armature / rail interface is shown in *fig. 2*, with a rectangular coordinate system fixed to the armature, the rail moving to the left at velocity u and acceleration a, and a liquefied layer filled in the gap between the armature and rail interface with a thickness h as a function of position.

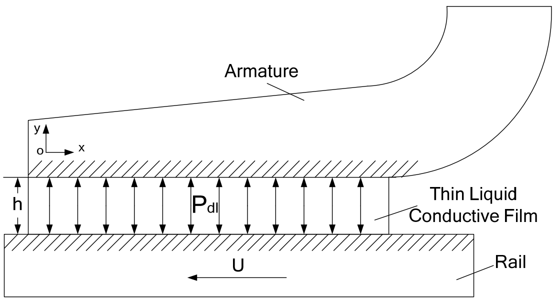


Figure 2. The Schematic of Hydrodynamic analysis

In general, the hydrodynamic lubrication model should be established based on Reynolds equation, Navier-Stokes equation representing conservation of momentum and continuity equation representing conservation of mass on the basis of some simplified assumptions. Since Reynolds equation is universal for hydrodynamic lubrication, it can be used to describe hydrodynamic lubrication between armature / rail interfaces. When the armature is accelerated, the molten metal layer between the contact interface of the armature /rail is subjected to inertia force, so the inertia force component of the liquefied layer should be considered in the momentum equation. Thus, the Navier - stokes equation for the metal liquefaction layer at the armature / rail interface is:

$$\rho_d \left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial P_{dl}}{\partial x} + \eta \frac{\partial^2 u}{\partial y^2} + \rho_d a \qquad (6)$$

ρ_d is the density of the liquefied layer， u , v are velocity components of the liquefied layer in the x and y directions, respectively. P_{dl} is hydraulic pressure， η is viscosity coefficient of the fluid， a is acceleration of fluid.

Since the launch system is a quasi-static model of motion, the variation of the velocity of the liquefied layer with time is ignored, so the formula（6） is simplified as follows

$$\frac{\partial P_{dl}}{\partial x} - \rho_d a = \eta \frac{\partial^2 u}{\partial y^2} \qquad (7)$$

According to the non-slip boundary conditions, the velocity boundary conditions corresponding to the above equation are as follows:

$$\begin{aligned} y &= 0, u = 0 \\ y &= h, u = U \end{aligned} \qquad (8)$$

Two integrations of u with respect to the y coordinate are available:

$$u = \frac{1}{2\eta}\left(\frac{\partial P_{dl}}{\partial x} - \rho_d a\right)(y^2 - yh) + \frac{U}{h} y \qquad (9)$$

The continuity equation of the liquefied layer fluid is as follows

$$\frac{\partial \rho_d u}{\partial x}+\frac{\partial \rho_d v}{\partial y}=0 \qquad (10)$$

By integrating equation (10) in the range [0, h] in the thickness direction of the liquefied layer and substituting equation (9), one-dimensional Reynolds equation can be obtained as follows:

$$\frac{\partial}{\partial x}\left(\frac{\rho_d h^3}{\eta}\frac{\partial P_{dl}}{\partial x}\right)=\left(6U\rho_d+\frac{3\rho_d^2 a h^2}{\eta}\right)\frac{\partial h}{\partial x}+12\rho_d Vm \qquad (11)$$

Vm is the rate at which the armature solid coating melts when heated.

3. Preparation process

The common U-shape armatures use in this paper, weighing 17g and designated 6061 aluminum alloy, which has good tensile strength. In order to make it fit with the rail well and achieve a certain initial contact pre-stress, the radial dimension of the tail end of the armature contact arm is designed to be 21.4 mm, and the theoretical contact area of the armature / rail is 20 mm x 25 mm , as shown in *Fig. 3*.

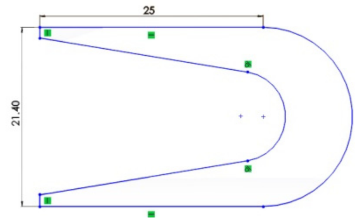


Figure 3. Diagram of Armature

Preparing a coating for an armature means adding a low-melting-point metal to the surface of the armature by a specific process. The purpose is to make the coating melt when the railgun is launched, reduced the friction between the armature / rail, and improved the contact performance of the armature / rail.

Brush plating is a rapid plating method at room temperature without plating bath. It relies on a brush in contact with the anode to provide the electrolyte needed for electroplating and deposit the metal ions in the electrolyte on the surface of the substrate under the action of external current to prepare a film layer. The bonding strength between coating and substrate is generally higher than 70 MPa.

4. Experiment

Test platform is 20 mm x 20 mm square diameter railgun, the maximum launch route is 1000 mm. The upper shell and the lower shell are glass fiber epoxy, positioning and pre-tightening the rail by using an up-and-down pressing mode.

To ensure that the experiments were comparable, the two groups of experiments were carried out on new copper rails, the starting position of the armature is 90 cm away from the muzzle.

Parameters such as discharge current and armature speed are measured in experiments. The discharge current is obtained by synchronously collecting and synthesizing the current measured by the independent Rogowski coil in each power supply module. The average armature speed is calculated by using the B-dot magnetic probe to sense the magnetic field change and the induced voltage signal generated by the current flowing through the armature. The B-dot m-probe is mount directly above that railgun, in the same plane as the center point of the armature, and at the same distance from the two rail. B-dot magnetic probe from the muzzle is 10cm, 20cm and 30 cm, its position as shown in *Fig. 4*.

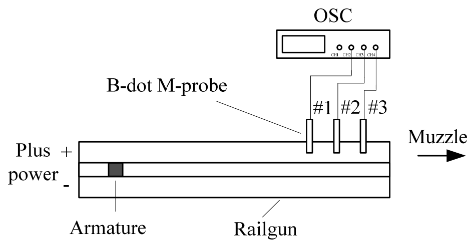
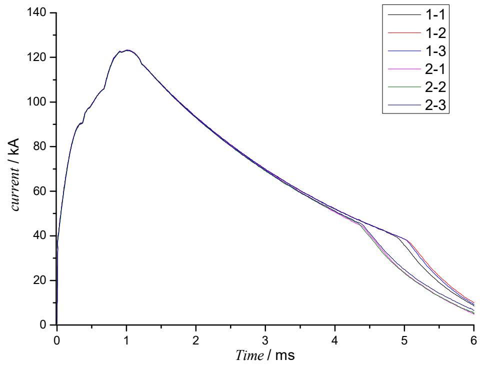


Figure 4. Schematic diagram of installation position of B-dot M-probe

5. Results

According to the test results, the discharge current waveform in the launched process of each group of armatures is shown in *Fig. 5*.



1-Common armature；2-coated armature

Figure 5. Comparison of discharge current waveform

The contact interface between the armature and the rail will produce arc discharge at the moment when the armature comes out of the bore, which makes the impedance load between the rails abrupt and leads to a significant turning point in the discharge current waveform, namely the armature comes out of the bore. As can be seen from *Fig. 5* , the rise edges of the two armature discharge current waveform are basically the same, and the time difference at the turning point of the falling edge is large, where in the tapping time of the common u - shaped armature is on average 5 ms, the tap time of the tin-plated u - shaped armature is about 4.5 ms, and the lat is shortened by 0.5 ms compared with the former. It can be seen that, on that premise of equal launch distance, the u - shaped armature with tin coat has shorter movement time and higher speed in the bore of the railgun.

The average velocity between adjacent B-dot M-probes was used to represent the in-bore velocity, and the average velocity at a distance of 10 cm from the muzzle was used to approximate the muzzle velocity.

Table 1 The muzzle velocity of different armature

Line current density /kA•mm^{-1}	v_M /m•s^{-1} N-Armature	v_M /m•s^{-1} C-Armature	Δv_a
5	285.7	317.1	12.90%
	279.1	321.3	
	289.3	325.9	
10	570.8	625.6	8.40%
	575.2	620.3	
	573.5	618.5	

It can be seen from the *Table 1* that the average speed of the coated armature is higher than that of the common armature in the continuous launching test under different line current densities, which is about 8.4 % - 12.9 %. When the line current density increases from 5 kA•mm-1 to 10kA•mm-1, the average speed difference between the two decreases. This is because when the driving current increases, the acting time of the coating becomes shorter. Further analysis shows that the coating plays a limited role in the whole launch process, only at the initial stage of launch.

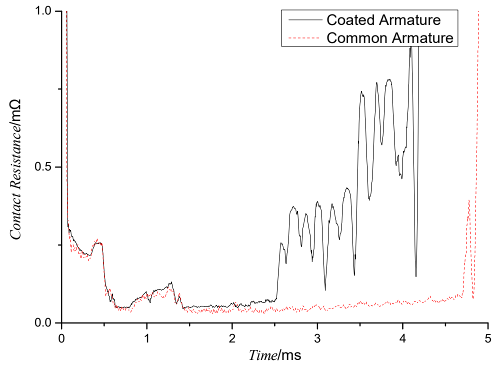


Figure 6. Variety of contact resistance

Judging from the change trend of the contact resistance between the armature and rail interface shown in the *Fig. 6*, it can be divided into three stages: first, the contact resistance rapidly decreases to about 0.1mΩ, from 0 ms to 0.7 ms; The second is the stable change phase, starting from 0.7 ms, the contact resistance is stable around 0.1 mΩ after experiencing a fluctuation. The third is the stage of oscillation and rise, which is caused by the armature producing a liquefied layer, making the contact unstable. As can be seen from the *Fig. 6*, the contact resistance between the coated armature and the rail changes greatly in the third stage, which shows that the contact situation of the coated armature is relatively complicated.

6. Conclusions

1) Under the same condition, the coated armature can achieve higher muzzle speed than the common armature, which is about 8.4 % - 12.9 %. It can be seen that after melting into liquid, the tin coating has obvious effect on reducing the friction between the armature and rail and improving the launched efficiency of the railgun.

2) The change law of sliding electrical contact resistance between the armature and rail interface can be divided into three stages: first, the stage of rapid decrease; The second is the stabilization phase; The third is the stage of shock and rise. The change of contact resistance between plated armature and rail interface is more complicated than that of common armature.

3) As the number of repeated launches increases, the amplitude of oscillation in the third stage gradually decreases and the armature muzzle speed gradually stabilizes. This shows that the contact resistance tends to stabilize gradually with the increase of rail deposits. The study has certain reference significance for sliding electrical contact of railgun.

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