Research Progress on Interface Lubricating of Sliding Electrical Contact with low velocity in Electromagnetic Railgun

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Abstract. As a kind of new concept kinetic weapons with hypervelocity, the electromagnetic railgun has a control technology on the sliding electrical contact between armature/rails. The initial sliding electrical contact belongs to the solid-solid dry friction state, which has a serious impact on the system launch efficiency and the rail life. This paper analyzes the research progress of liquid lubricated and solid lubricated technologies commonly used in the sliding contact of electromagnetic railgun in the initial launch stage. The application of hydrodynamic lubrication technique to electromagnetic railgun was discussed from the aspects of theory basis, preparation process, electro-thermal characteristics, mechanical properties and chemical properties. Finally, the application of low melting point alloy coating to improve the initial sliding contact of electromagnetic railgun was put forward. This article has important significance to the research of electromagnetic railgun technology.

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 (Fig.1). 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].

The simple electromagnetic railgun can be regarded as a single turn coil linear motor. It consists of two parallel rails, a metal armature and projectile, a pulsed power supply system and a control switch [2] (Fig.2). When the pulsed power supply is switched on, the metal armature clamped between the two rails moves along the rail under the action of the electromagnetic force and accelerates the projectile. In the acceleration process, the impulse current flows through the armature from one rail to the other one forming a loop. The armature and the rail cooperate with each other to maintain a good sliding electrical contact, so as to realize the continuous conduction of the current loop.
2. Problems in the development of electromagnetic railgun

The key technologies of electromagnetic railgun include power control technology, rail and armature structure, and sliding electrical contact technology. Among them, the sliding contact between the armature/rail has the greatest influence on the launch efficiency and the rail life of the electromagnetic railgun, which is the key technology of the electromagnetic railgun. 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]. The railgun composed of aluminum armature and copper rail as an example, 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 the later stage of the launching, the armature moves rapidly along the rails, and the armature/rail contact interface is subjected to the double action of Joule heat and friction heat. The melting layer and even the gasification layer of aluminum are formed on the contact surface of the rails. Although the molten layer has a certain lubrication effect on the electric contact between the armature/rail, the loss of the armature material will lead to the separation of the contact surface, leading to the serious transition to arc discharge. In addition, the formation of eutectic alloy in the high temperature electromagnetic environment of the armature/rail metal particles will lead to the increase of the contact resistance of the armature/rail interface, leading to deterioration of the electrical conductivity.

In order to solve the problems of sliding electrical contact in initial process of electromagnetic railgun, the experts in various countries conducted research work in the generation mechanism, causes
and solutions, and other aspects. Most scholars are mainly engaged in the electro-thermal characteristics and thermal effects of sliding electrical contact interface, the characteristics of sliding electrical contact resistance, and the formation mechanism of rail liquefaction layer. With the development of the research on the mechanism of metal liquefaction layer during high-speed sliding electrical contact between armature/rail, the researchers found that the mechanism of the armature/rail contact interface of the electromagnetic railgun has some commonalities with the hydrodynamic lubricating mechanism of the bearing. They are generated by friction between the liquefied layers if lubricating film pressure balance outside the load to achieve lubrication. Therefore, it is a new research direction to improve the sliding electrical contact performance of armature/rail interface by adding lubricant [4]. 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 current research progress and achievements are concluded and summarized, which has important reference value for the application of lubricants in the study of sliding electrical contact of electromagnetic railgun.

3. Research of lubricant applied to sliding electrical contact of electromagnetic railgun

3.1. Application and Research of liquid lubricant

The advantage of liquid lubricant is that it can increase the real contact area. The liquid lubricants used for sliding contact of electromagnetic railgun mainly include liquid metal and water film.

Drobyshhevski studied theoretically the characteristics of the liquid lubricant applied to the sliding contact of the electromagnetic railgun [5]. It is considered that the indium as the external lubricant during the sliding contact process of the armature/rail contact interface can significantly reduce the Joule heat and friction heat, but there are not experiments verified. Compared the electromagnetic railgun with and without lubricant, Ghassenmi and Barsi also found that the liquid indium lubricant can delayed the melting of the armature [6]. The experimental study of liquid indium and water film as the interface lubricant between the copper armature and the copper rail sliding electric contact has been carried out by Engel [7]. It is proved that liquid indium is more suitable as the lubricant of the electric contact interface between the copper armature and the copper rail (Fig3, Fig4).

![Fig 3. The copper railgun and armature](image1)

![Fig 4. The rail and armature coated with indium](image2)

Both liquid metal and water film can be used as lubricants in the sliding process of electromagnetic railgun. The former has good electrical conductivity and the latter has a small friction coefficient, but both have some limitations. Although the effect of liquid lubricant on the sliding electrical contact interface of electromagnetic railgun has been fully demonstrated in theory and experiment, but there are still some obstacles in practice. The main difficulty lies in the lubricant injection design and system integration and compatibility.
3.2. Research of solid lubricant
In order to overcome the shortcomings of liquid lubricants, scholars began to try to apply solid lubricants to improve the sliding electro contact of the armature/rail of electromagnetic railgun. The main researching objects are PTFE and graphene. Singer [8] found that PTFE can effectively reduce the wear of the armature contact surface and improve the launching performance of the armature by lubrication of the contact surface between the copper rail and the aluminum armature. Although contact resistance properties are not mentioned in the experiment, it is clear that PTFE is a kind of insulator. Slade [9] has conducted experimental studies on ferrous metals in sliding contact and other compound lubricants containing chlorine and sulfur to reduce friction. He believes that such materials have corrosive or other side effects on metal interfaces and are not suitable for use in armature/rail interfaces in electromagnetic launch. The mechanism of graphene improving friction performance of armature/rail was studied by chuan-tong Du [10]. It is considered that the addition of graphene to the armature surface can effectively reduce the friction between the armature/rail. Although the experimental contact resistance slightly increased, the muzzle speed of the armature has been increased.

The solid lubricant in the sliding contact interface of electromagnetic railgun has two aspects of advantages: it can be prepared in the form of a coating on the armature or rail surface in advance and, the friction coefficient can be reduced. The disadvantage is that the contact resistance of armature/rail increased.

3.3. Research of Low Melting Alloy Lubricant
The low melting point alloy is solid at normal temperature and liquid state in a certain high temperature, which can be used as a lubricant in the sliding contact of electromagnetic railgun. The main researching objects are tin, bismuth and indium. Hsieh try to use tin, bismuth, indium and other low melting point metal as a solid lubricant to control the wear surface melting of the armature material on the aluminum armature surface by boundary lubrication [11]. Some experimental results have been obtained. In fact, in the later stage of the launch of the electromagnetic railgun, the aluminum armature melted into a liquid metal film which can also play a good lubricating effect.

4. Low melting point alloy for armature coating of electromagnetic railgun
Due to the inherent characteristics and the advantages of liquid lubrication, low melting point alloy is one of the ideal lubricants for the sliding electrical contact interface of electromagnetic railguns. From a practical point of view, the preparation of the low melting point alloy coating on the surface of the armature is feasible. This article will analyze the theoretical basis, preparation technology, electric-thermal characteristics, mechanical properties, and chemical properties.

4.1. Theoretical basis
The pre-stress between armature/rail in the initial stage of electromagnetic railgun launching is the largest, and its contact interface is in solid-solid dry friction state. After the electromagnetic railgun is energized, Lorentz force gradually increases from zero. When it exceeds the static friction, the aluminum armature starts to move and gradually accelerate. The low melting point alloy in the armature/rail contact interface can melt into a liquid state by the Ohmic heating of the initial current. At this time, the static friction of the armature/rail contact interface is replaced by the viscous force of the liquid layer to change from solid-solid dry friction state to solid-liquid-solid wet friction state between the armature/rail. In the case of the same current density, the smaller the static friction force is, the greater the acceleration force gets, the greater the muzzle velocity reaches; the Lorentz force overcomes the static friction to make the less works, the system energy utilization rate will be higher.

Meanwhile, the phase change latent heat generated by the solid lubricant melted into the liquid lubricant during heating will restrain the temperature rise of the rail to some extent, which is favorable for the continuous launching of the electromagnetic railgun.
4.2. Preparation technology.
The armature coating was proved to provide cost-effective electrical conductivity and satisfactory lubricity. As the different material formulation, thickness and preparation process are adopted, the low melting point alloy can be prepared for the specific performance of the electrical contact coating. Preparation process of the coating on armature includes: electroplating, spraying, brush plating and chemical deposition, etc. The coating performance varies with the different prepare process. In order to meet the requirements of sliding electrical contact characteristics of electromagnetic railgun, a reasonable process method is adopted to prepare the armature surface coating. Brush plating is one of the ideal processes.

4.3. Electric-thermal characteristics.
The electro-thermal characteristics of sliding electrical contact interface of electromagnetic railgun mainly include the rail surface state and the interface energy load, the two can be quantified as the interface sliding electrical contact resistance characteristic and the Joule heating power characteristic. As a result of the roughness of the contact surfaces, current flows across the contact not over the entire nominal contact zone but in so-called alpha spots, where the two surfaces approach each other at distances comparable to the inter-atomic distance and electric current lines become concentrated. Therefore, the interface contact resistance is an important indicator of sliding electrical contact performance. Chenyun et. al compared the sliding electrical contact characteristics between aluminum armatures and different material of rails in experiments [12]. The results show that the increase of contact resistance will cause transition to arc discharge; and the smaller the contact resistance is, the better the surface condition of the rail after launching is. When the low-melting alloy coating exists in the form of a liquid lubricant at the sliding electrical contact interface, the contact area greatly increases as compared with the bump contact (Fig.5). The low-melting alloy reduces the contact resistance at the armature/rail interface, slows the generation of interface heat, improves the current conduction quality, and has a positive effect on system performance.

4.4. Mechanical properties
When a low melting point alloy coating is prepared on the armature surface of the electromagnet railgun, it is firmly combined with the armature body in the form of ions. When the coating melts into a liquid layer, the lubrication film pressure is generated due to viscous fluid dynamics under the relative motion of the armature/rail contact interface, which can keep balance with the normal load on the armature/rail contact surface. The friction between the armature/rail depends on the viscous and shear forces of the liquid layer, which is much smaller than the dry friction before to achieve lubrication and improve the contact performance at the armature / rail interface.

![Fig 5. Schematic diagram of a bulk electrical interface and ideal electrical interface](image-url)
4.5. Chemical properties

During the sliding contact of the electromagnetic railgun, the molten metal particles of the armature/rail form an eutectic alloy under high temperature and electromagnetic environment, which degrades the sliding electrical contact performance at the armature/rail contact interface. Due to the relatively stable chemical properties of the low melting point alloy, the coating on the armature surface prevents the formation of a eutectic alloy between the armature/rail, and can improve the contact environment at the armature/rail interface.

5. Summary

It is still in the initial stage to improve the armature/rail sliding electrical contact performance of electromagnetic railgun by using additional lubricant. The use of liquid lubricant can increase the actual contact area of the armature/rail, but it is difficult to inject into the armature/rail contact interface and play a continuous and stable role in the sliding electrical contact process; the use of solid lubricants can reduce the coefficient of friction and the problem is how to avoid the contact resistance increase of lubricated material between armature/rail. The use of low-melting alloy as armature/rail contact interface lubricant can play a good lubricating effect, reduce the contact resistance, and improve the launching efficiency.

Overall, the low-melting alloy coating has unique advantages over the liquid lubricant and the solid lubricant, and provides a new idea to improve the sliding electrical contact performance of the electromagnetic railgun. The next step in the sliding electrical contact interface application of low melting point alloy coating should pay attention in three aspects:

1. Verifying that the low melting point alloy coating has a positive effect on the launching performance of the electromagnetic railgun and is still effective for subsequent launching;
2. Preparation of low melting point alloy coating on the armature surface, the coating process and coating thickness should be scientifically analyzed and calculated;
3. Reasonable choice of low melting point alloy coating material to prevent the deposited heterogeneous metal lubricant to form a metallurgical compound with the rail surface and avoid to degrade rail performance.

Acknowledgments

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