

Development of Transient Damage Behaviors of Copper Alloys under High Velocity Sliding Electrical Contact

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Abstract The transient damage problems of copper alloys are the central topic for improving the accuracy and lifetime of electromagnetic launcher. The research works on transient damage behaviors of copper alloys under high-speed sliding electrical contact during the past two decades were summarized in this paper and some suggestions for future research were presented. Firstly the three damage forms of copper alloys under high-velocity sliding electrical contact were introduced, respectively. Then the main technical methods that can solve the damage problems of copper alloys were presented. Finally some proposals for further study on transient damage behavior of copper alloys under sliding electrical contact were put forward.

Introduction

Surface transient damage problems of copper alloys under high-velocity sliding electrical contact, especially in electromagnetic launching, lead to deterioration of the lifetime and accuracy of the launcher. During electromagnetic launching, the friction types of sliding electrical contact change with the increment of armature velocity, transferring from arc erosion to mechanical wear, melt wear and impact. Meanwhile, the damage forms of copper alloys change with the increment of armature velocity, transferring from arc erosion to edge grooving and hypervelocity gouging. Up to now, some important progress has been made on transient damage problems of copper alloys.

Most studies on damage of copper alloys tried to establish the coupling effect of electromagnetic, stress and temperature fields between armature and rails during electromagnetic launching using simulation analysis methods. Then the coupled physical fields were used to understand the damage characteristics of copper alloys, such as damage types, spatial distribution and evolution process. Surface coating hardening treatment was extensively studied to enhance the erosion resistance ability of copper alloys. Based on the multi-shot tests, the surface profile, micro structural characteristics and hardness of grooving of copper alloys had been determined and analyzed to reveal how material properties and launching conditions affect the grooving forming. Material properties and surface defects on the threshold velocity of gouging were also investigated to reduce the impact of gouging on copper alloys. In this paper, the research works and technical solutions on transient damage problems of copper alloys under high-velocity sliding electrical contact during the past two decades were summarized and some suggestions for future research were presented.

The Surface Transient Damage of Copper Alloys during Electromagnetic Launching

The Grooving of Copper Alloys during Electromagnetic Launching

Grooving on copper alloys was reported for the first time by Geeet *al.*[1] in multiple electromagnetic launching. Grooves initiated approximately 35 mm from the starting position, and were sharp groove shape and 62.8 μm deep. Poor thermal and electrical conductivities may be responsible for severer

damage of Be-Cu alloy relative to other tested alloys. Watt *et al.* [2] discovered that there were two kinds of grooving damage types: the well-defined grooves and the less defined grooves. The less defined grooves are about 5mm wide and 0.5mm deep. Megeret *al.* [3] found that the grooving damage on copper alloys often occurs in the first half of rails. The energy dispersive spectrum results of the deposited layer of one-shot show that the top layer is carbon-rich and silicon-rich; the middle layer is Al-rich cellular-dendrites and inter-cellular Al_2Cu ; the layer closest to the copper alloys is Cu-rich dendrites. In 20-shots, the microstructure of the deposited layer is varying scale of cellular-dendritic microstructures.

Materials surface softening and the erosion of molten aluminum are the two main physical mechanisms responsible for grooving forming. In 2007, Watt *et al.* [2] observed the less defined grooves at 30 centimeter from the starting position. Watt concluded the dissolution of copper alloys by molten aluminum facilitated by resistive heating, was responsible for grooving forming. Cooper *et al.* [4] discovered that the maximum grooving depth located at the edge of insulation materials, spreading towards the center and edge of rails. Cooper concluded that grooving forming originated from the dissolution of copper alloys because of the flow of high velocity and high temperature molten aluminum as a result of velocity skin effect. After conducting 20 times launches, Megeret *al.* [3] concluded that the grooving depth linearly increased with the increment of the number of shots.

The Gouging of Copper Alloys during Electromagnetic Launching

Gouging is a surface damage phenomenon that usually occurs in high velocity sliding contacts. Gouging craters are typically teardrop shaped and about 1-3cm in length and 1-2cm in depth. The typical morphology of a typical gouging crater is shown in Fig. 1. It is noticed that significant hump of the rail is observed in front of the gouging crater, indicating the rail undergoing severe plastic deformation. In 2012, Zhu *et al.* [5] performed composition analysis and metallographic observation on gouging craters. It was found that the main chemical compositions of gouging craters include carbon, oxygen, aluminum, copper and zinc. The internal morphology of gouging craters were tearing edge, recrystallization morphology and scratch, which indicated the interface between armature and rails underwent severe plastic deformation and temperature rising.

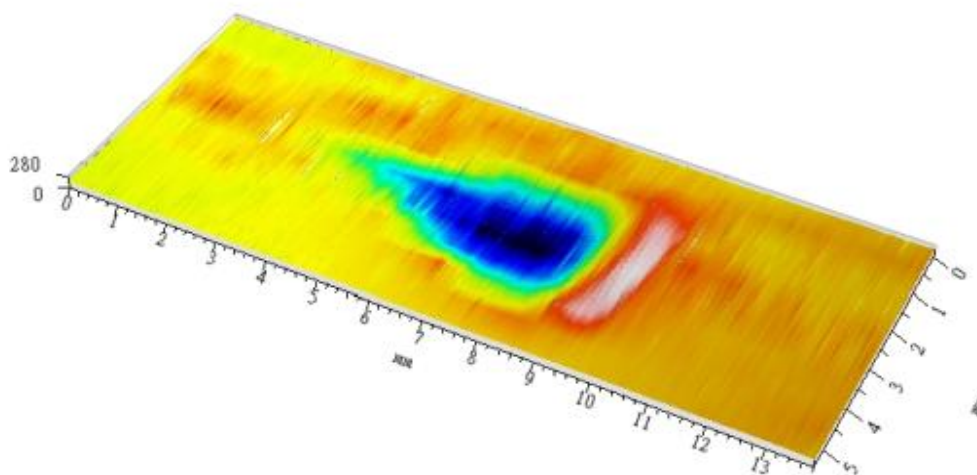


Fig. 1 Optical profilometry image of a typical gouge crater

The gouging forming mechanism and the affecting factors of gouging threshold velocity were extensively studied on gouging damage of rails. In general, the gouging threshold velocity is affected by friction pairs and material properties of armature and rails. In 1999, Stefani and Parker [6] conducted tests on C1100 rails with different armature materials. It was found that the gouging threshold velocity increased with the increment of hardness of armatures, meanwhile, the hardness

of the harder materials H and the normal shock pressure P showed a linear correlation: $P=0.073H+9.343$. Tarcza *et al.* [7] found that harder of rail materials can result in higher gouging threshold velocity with the same armature materials. AFIT found that the ratio of yield strength and density can be fitted with linear correlation with gouging threshold velocity. Gouging can be prevented by using armature materials with higher yield strength and low density. In 2014, Watt [8] *et al.* conducted electromagnetic launching on flat and indented copper rails and examined the effect of surface indentations on gouging onset velocity and morphology. It was found that surface indentations had little effect on gouging onset velocity. However, the gouging craters morphology could be obviously changed.

The first model of gouging was proposed by Baber [9], which described gouging as a process of surface asperities interacting with armatures at high velocity. From calculated results, the gouging threshold velocity was determined by density, yield strength, the angle of attack and bulk wave velocity. Higher yield strength and lower angle of attack can weaken the damage from gouging. Based on simulation analysis, Li [10] *et al.* found that higher yield strength rail material and rational hook angle can reduce the impact of gouging. Tachau [11] *et al.* proposed a gouging model, which described gouging as a process of small angle shocking at high velocity. Calculation showed that the gouging initiation not only needed the existence of asperities, but also needed space between armature and rails. Jin [12] *et al.* found that gouging size was determined by the armature velocity, the armature length and the initial temperature, while interface load had little effect on gouging size. Higher armature velocity, longer armature length and higher initial temperature would lead to bigger gouging size. Laird [13] *et al.* studied the effect of rail temperature on gouging and found that higher rail temperature would result in deeper gouging crater, while the depth of gouging crater decreased above 2000K. Laird attributed gouging to combined effect of plastic deformation of rails, thermal softening of rails and the normal velocity of armature.

The Arc Erosion of Copper Alloys during Electromagnetic Launching

Arc erosion is one of the principal technical challenges that degrade the lifetime, accuracy of the launcher. Arc erosion occurring in the initial stage, is due to local melting affiliating by resistive heating owing to velocity skin effect. Designing reasonable armature and rail structure is one way that can effectively lower the damage of arc erosion. Tao [14] *et al.* found that designing multilayer rail can reduce arc erosion based on simulation analysis results. Qin [15] *et al.* discovered that the arc erosion can be reduced by applying an external magnetic field. Chen [16] *et al.* found that increasing the resistivity of rails and reducing the height of rails can reduce the arc erosion.

Coating refractory metal, such as W, Mo on the surface of copper alloy launchers is another way that can reduce the impact of arc erosion. After 70 shots in plasma armature launchers operating at the 500 kA/cm liner rail current densities, weight loss per shot of the Mo coating rails was only one fiftieth of that of bare Cu rails [17]. Some microcracks were found on the surface of Mo coating rails, while porous structure of molten layer was found on surface of bare Cu rails. So Mo coating can improve the resistance ability against arc erosion, but the plasticity should be solved.

Technical Methods to Solve the Surface Transient Damage of Copper Alloys

From above discussion, it can be concluded that the solutions of the surface transient damage of copper alloys are very complicated and rather challenging. High arc erosion resistance, high strength and high conductivity are simultaneous required. It is known that increasing arc erosion resistance or strength often cause the deterioration of conductivity. For grooving and gouging at accelerating and uniform stages, enhancing the strength and conductivity of copper alloys is more important. For arc erosion at the startup stage, improving the arc erosion resistance of copper alloys is the critical topic.

Designing New High Strength and High Conductivity Copper Alloys

Other than some methods increasing the strength at the expense of conductivity, precipitation hardening can improve the strength of copper alloys while retain high conductivity. Precipitation

hardening and coherent twin grain refinement can improve the tensile strength while maintain a high electrical conductivity. A Cu-0.8Cr-0.08Zr alloy with 200nm ultrafine structure was produced by combining equal-channel angular pressing and aging [18]. A tensile strength of 688MPa and an electrical conductivity of 71%IACS was achieved in this copper alloy. Vinogradov[19] *et al.* prepared CuCrZr alloy with a tensile strength of 700MPa and an electrical conductivity of 71%IACS by equal-channel angular pressing and aging. The nanostructured CuCrZr alloy with a tensile strength of 700MPa and an electrical conductivity of 78.5%IACS was prepared by L.X. Sun *et al.* [20] using dynamic plastic deformation at low temperature. Cu-2.5Ti-0.625C alloy with a tensile strength of 645MPa and an electrical conductivity of 82%IACS was achieved by F. L. Wang *et al.* [21] using two-step milling, spark plasma sintering and hot pressing process.

Designing Composite Structure and Applying Surface Hardening Treatment to Copper Alloys

Designing composite structure with an electrically conductive matrix and a durable surface layer can maximize the magnetic energy and durability of rails, but the adhesion between coating and matrix as well as the plasticity of coatings should be paid more attention to overcome. Based on tradeoff of magnetic energy and durability of 505 materials, M. J. Siopis *et al.* [22] concluded that the refractory metals of tungsten, chromium, nickel, tantalum and molybdenum were the top candidates as coating materials. Among these refractory metals as shown in Table 1, Molybdenum has the lower electrical resistivity and good grooving resistance, but rather low gouge and fracture resistance.

Table 1 Material rankings based on each individual form of damage [22]

damage mechanism	metric	ranking(high to low)
Gouging	σ_{uts}/ρ	W, Co, Cr, Ni, Steel, Mo, Nb, Ta
Grooving	$\rho C_p T_{\text{melt}}$	W, Mo, Ta, Cr, Ni, Co, Steel, Nb
Fracture	ε_f	Ni, Cr, Steel, Ta, Nb, Co, W, Mo

M. A. Bourhamet *et al.* [23] conducted erosion tests of pure metals and coatings at heat fluxes $33\text{GW}/\text{m}^2$ over $100\mu\text{s}$. Arc cast molybdenum shows better thermal resistance than sintered molybdenum. Sharp deep cracks were observed on sintered molybdenum, while smoother cracks formed on the surface of arc cast molybdenum. The erosion depth of Mo coating on copper matrix was $0.5784\mu\text{m}/\text{GW}\cdot\text{m}^2$, while the erosion depth of pure copper was $1.9717\mu\text{m}/\text{GW}\cdot\text{m}^2$. The erosion depth of Mo coating was only 29% of that of pure copper, and microcracks were found on the surface of Mo coating.

Conclusions

With the development of high velocity electrical contacts, the transient damage problems of sliding electrical contact in electromagnetic launching were paid more and more attention. The transient of damage process, coupling effect of multiphysical fields and complexity of damage types make the damage study of copper alloys full of challenge. For studying the mechanism of transient damage and relevant factors to inhibit the damage, some important topics are proposed as followed:

- (1) Studying the physical mechanism of transient damage by combining simulation method with experiment technique.
- (2) Developing new electromagnetic launching simulation installation, data collecting instrument and damage analyzing technique.
- (3) Designing composite structure and performing surface hardening treatment to synthesize copper rails with high strength, high conductivity and erosion resistance.

Acknowledgments

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