

Metallurgical Analysis of Railgun Material

Khershed P. Cooper¹, Harry N. Jones¹ and Robert A. Meger²

¹Materials Science and Technology Division, ²Plasma Physics Division
Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC 20375, USA

Abstract— The effect of number of shots on multiple launch railgun barrel material performance under significantly high current conditions was studied. Metallurgical analysis was conducted on rail samples from four sets of experiments involving increasing number of shots. Cross-sections of samples from two locations in the copper rail were examined using a variety of metallographic techniques. During each shot a thin film of molten aluminum from the armature deposited on the rail surface. The deposit became thicker and multi-layered with increasing number of shots and was consistently thicker in the bottom half of the vertically oriented rails than in the top half. Preferential removal of material occurred along the rail edges, which resulted in grooving over the length of the rails. Grooves were consistently deeper near the top edge of the rails compared to the bottom edge. A proposed mechanism for grooving is dissolution of the rail material into molten aluminum flowing towards rail interior due to aerodynamic drag and over the rail edge due to surface tension effects, assisted by extremely high rail edge temperatures. Asymmetry in armature-rail gap due to magnetic interactions with the support structure may be the cause of asymmetry in deposit thickness and groove depth.

I. INTRODUCTION

The ability to achieve repeatability in an electromagnetic railgun is limited by material performance. Railgun bore materials experience extreme temperatures and stresses due to the high currents and pressures, and wear from sliding contact. These factors seriously affect bore life. Postmortem analyses of the rails give important clues into understanding railgun behavior and provide a window into determining possible deterioration mechanisms in the bore material. Metallurgical analyses look for changes in microstructure and composition and type and extent of deformation or erosion in the rails. A previous study by Meger *et al* [1] examined rails from a 20-shot experiment performed at a lower 1.0 MA current. It presented evidence for deposit build-up and rail damage in the form of grooving. The study postulated several mechanisms for grooving,

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among them, melting of liner surface due to high current and velocity skin effect, plowing of liner material, deformation of liner material due to magnetic pressure, and boiling off of copper due to arcing near the rail edges. Gee and Persad [2] proposed plastic deformation or “corrosive wear” by chemical interaction with the liquid aluminum film. Hsieh [3] performed EMAP3D calculations and showed that groove formation is due to material softening due to high local temperatures and material yielding. Stefani *et al* [4] concluded that grooving was caused by erosion of the rail material by molten aluminum, facilitated by thermal softening. Also proposed is a liquid metal pinch effect or constriction of liquid metal by magnetic pressure as a cause of groove erosion [5].

II. EXPERIMENTAL

Four multiple shot experiments in the 3, 6, 20 and 1 shot sequence were performed at Institute for Advanced Technology (IAT), University of Texas-Austin. A pulsed current peaking at 1.6 MA was driven through vertically-oriented GlidCop® Al-25 copper rails separated by G-10 insulators. The ensuing Lorentz force propelled a 7075-T6 aluminum armature at velocities in excess of 1.5 km/s. Heating at the armature-rail interface was significant enough to melt the armature surface in contact with the rails. As the armature accelerated over the length of the railgun, a molten aluminum film was left in its wake and remained as a solidified deposit on the rail surface. No attempt was made to remove this deposit and subsequent shots were made on the coated rails. IAT provided the authors with a set of rails of positive polarity (right hand rail looking from breech end to muzzle end) from the four experiments for optical and scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). From each rail, two sections were removed for analysis, one near the breech end (location 36 cm) and another downstream (location 94 cm).

III. RESULTS

The appearance of the surfaces of the 30-36 cm and 90-96 cm copper rail segments after each of the four experiments is shown in Fig. 1. In these pictures the armature is moving from left to right and the top edge of the rail is at the bottom. The solidified aluminum deposit appears as a silvery coating on the rail

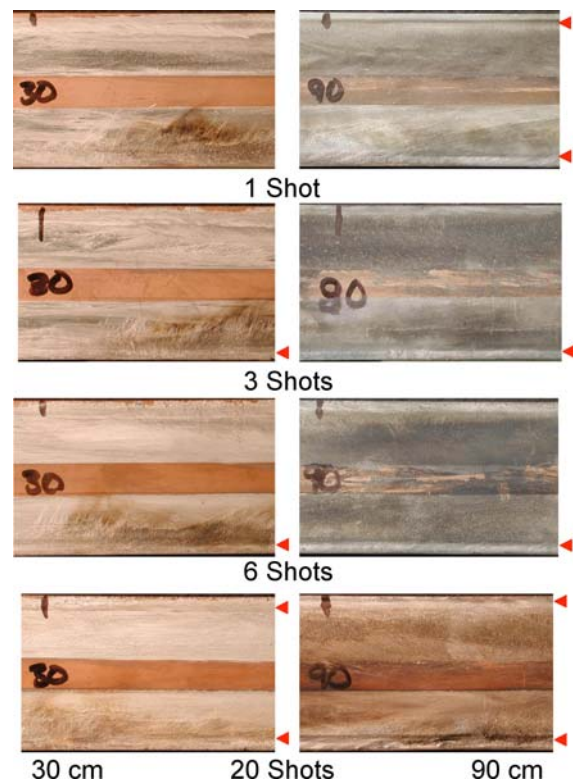


Fig. 1. Photographs of 30-36 cm and 90-96 cm copper rail sections showing appearance of rail surfaces. Arrowheads point to grooves near rail edges. (In these pictures, the armature is moving from left to right and the top edge of the rail is at the bottom.)

surface on either side for a bare central track. Flow patterns on the deposit show that the liquid film flow direction is from rail edge to rail interior. Some of the aluminum also appears to have flowed over the rail edges. In most sections, grooves (marked by arrowheads) are visible close to both rail edges. Grooving is localized removal or “erosion” of material from the rail surface and usually spans the length of the rail.

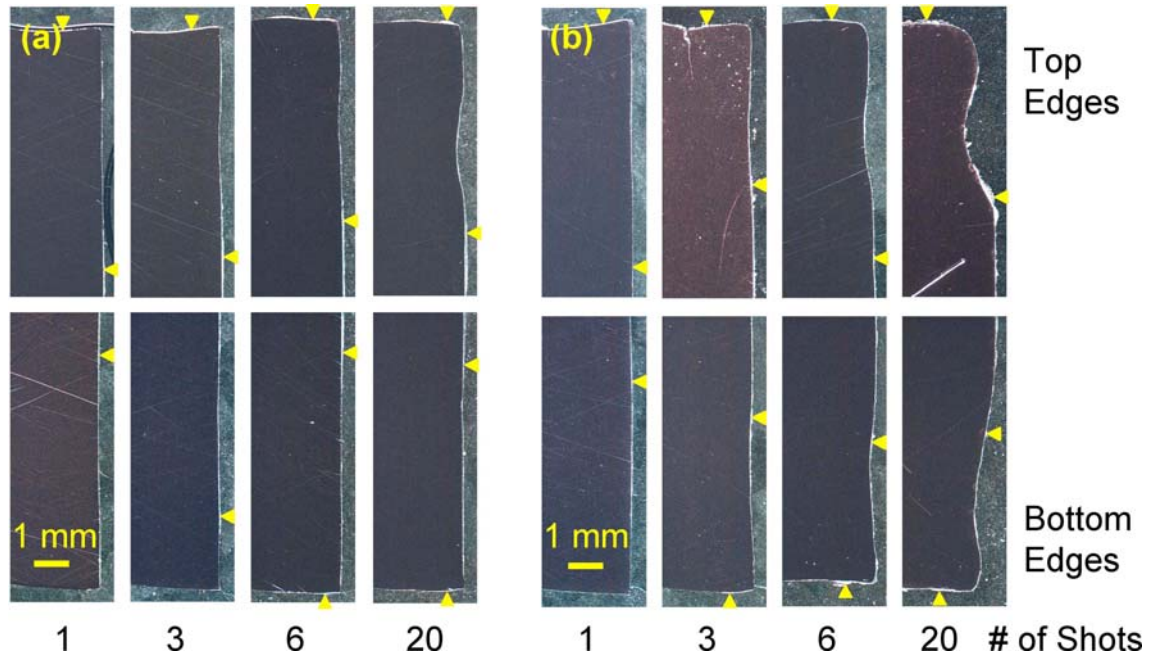


Fig. 2. Optical photomicrographs (Mag=20x) showing cross-sections near the top and bottom edges of the rails as a function of number of shots. (a) 36 cm sections. (b) 94 cm sections.

Optical photomicrographs of cross-sections near both rail edges are shown in Fig. 2. The thin silvery film (marked by arrowheads) along the edges of the cross-sections is the thin aluminum deposit. Using the relatively flat middle section of the rail surface as a reference point, groove depths were measured and the results are plotted in Fig. 3. Linear increasing trends in groove depth with increase in number of shots are evident. Grooves are 4 to 6 times deeper in the 94 cm samples than in the 36 cm samples. They are 1.5 to 2 times deeper in the top edge of both sets of samples than in the bottom edge. In the 94 cm samples, the increase in groove depth is proportional to the increase in number of shots, i.e., doubling the number of shots doubles groove depth. In the 36 cm samples, the increase in groove depth is not proportional to the increase in number of shots, i.e., doubling the number of shots increases the groove depth by less, 1.33 times. Using the deepest point in the groove, its location was measured from the rail edge and the results are

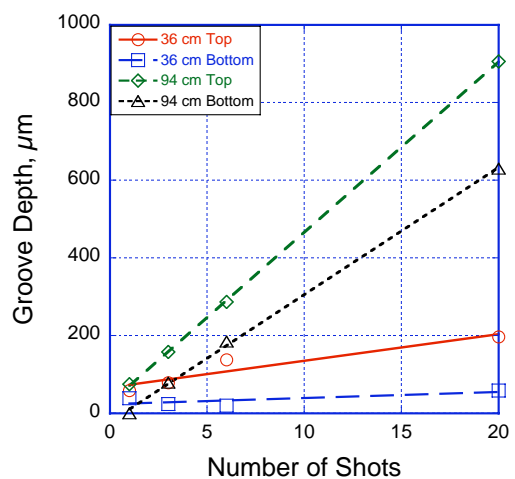


Fig. 3. Graph showing plots of groove depth as a function of number of shots.

given in Table I. There is a small variability in groove location as a function of number of shots in most cases. In the 36 cm samples there is significant variability in groove location from the top edge to the bottom edge, the averages being 3.5 and 4.9 mm, respectively. In the bottom edge there is significant variability between the 36 cm and 94 cm samples, the averages being 4.9 and 3.2 mm, respectively.

Table I. Distance in mm of groove location from rail edge.

Number of Shots	36 cm section		94 cm section	
	Top	Bottom	Top	Bottom
1	3.8	4.4	3.2	--
3	3.4	4.9	3.0	3.8
6	3.1	4.9	3.2	3.3
20	3.8	5.3	3.3	2.3
Average	3.5	4.9	3.2	3.2

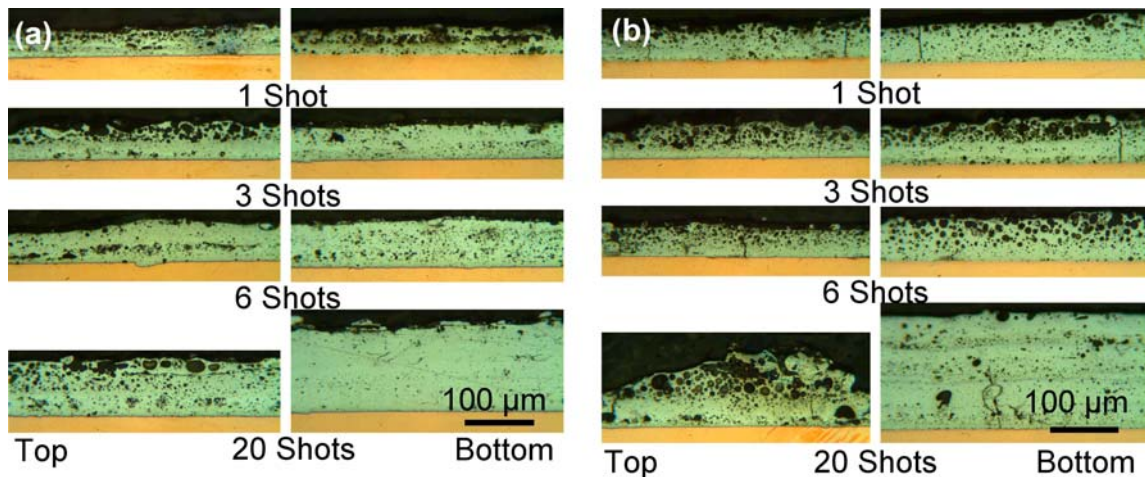


Fig. 4. Optical micrographs showing cross-sectional view of aluminum deposit in top and bottom halves of the copper rails as a function of number of shots. (a) 36 cm sections. (b) 94 cm sections.

Optical micrographs showing aluminum deposit thickness and multi-layering are given in Fig. 4. Multi-layers are defined by distinct interfaces. Micrographs are from the thickest portion in the deposit, which was typically halfway between the rail edge and rail axis. The thickness of the deposit and number of layers increase with increase in number of shots. However, the number of observed layers are much less than the number of shots. The deposit is thicker in the bottom half of the rails than in the top half. The average thickness of the deposit was measured and results are plotted in Fig. 5(a). Linear increasing trends between deposit thickness and number of shots are observed. However, the increase in thickness is not proportional to number of shots, i.e., doubling the number of shots increases thickness by 1.25 to 1.60 times. Also, thickness increases at a greater rate in the bottom half compared to the top half of both sets of

samples. The thickness of the residual deposit in the groove was also measured and the results are plotted in Fig. 5(b). The groove deposit is thin, varying from 2 and 17 μm . Except for the linear trend in the 36 cm top sections, the rest of the data shows random scatter and a lack of any trend in the groove deposit thickness with number of shots.

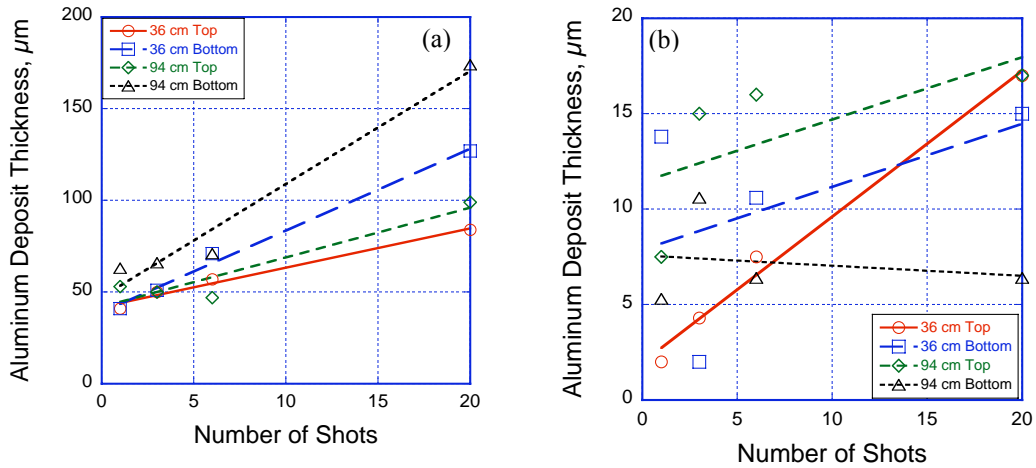


Fig. 5. Graphs showing plots of aluminum deposit thickness as a function of number of shots. (a) Thickest portion of deposit. (b) Deposit in groove.

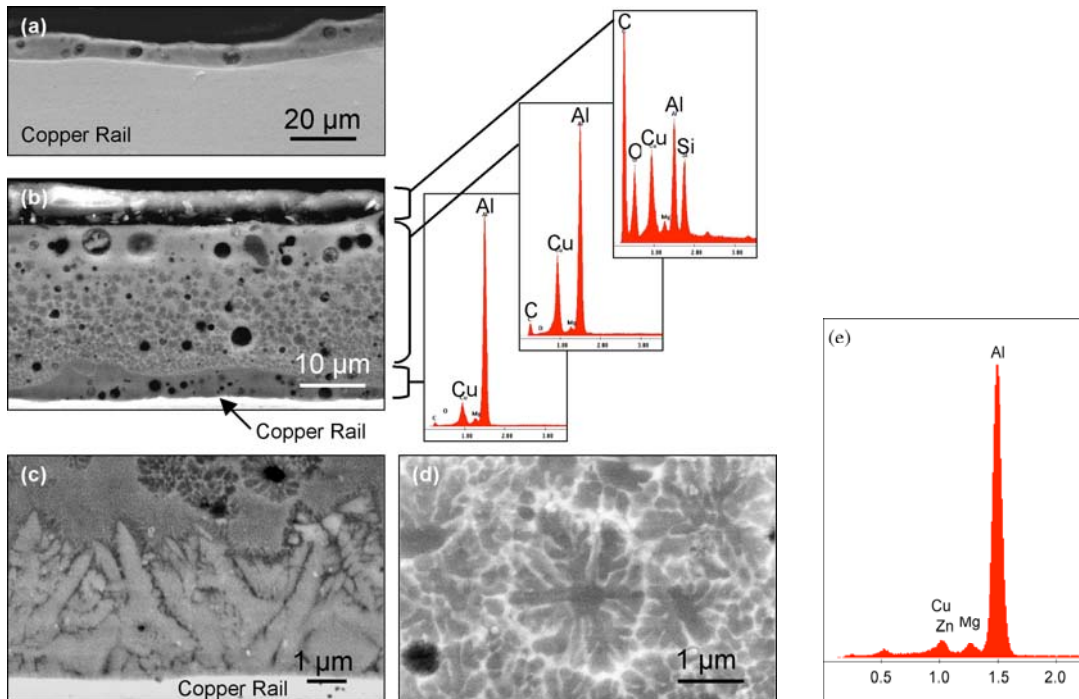


Fig. 6. SEM micrographs of deposit in the top half of 1-shot 36 cm rail sample. (a) Deposit in groove. (b) Multi-layer deposit in thick portion with EDS spectra of each layer. (c) Rail-deposit interface showing Cu-rich dendrites. (d) Cellular-dendritic microstructure in deposit. (e) EDS spectrum of 7075 aluminum armature reproduced for comparison.

SEM micrographs of the deposit in the groove and thick portions in the top half of the 1-shot and 20-shot 36 cm rail samples are given in Figs. 6 and 7, respectively. The groove deposits, shown in Figs. 6(a) and 7(a), are porous and single layer. The deposits in the thick portion, shown in Figs. 6(b) and 7(b), are also porous, but multi-layer. EDS spectra of the deposit in Fig. 6(b) show that in the multi-layer deposit, the layer closest to the rail has less copper than the layer above it. For comparison, the EDS spectrum of the 7075-Al armature is shown in Fig. 6(e), which shows very little copper. Hence, the copper reflections in the deposit spectra can only be due to alloying of the deposit with copper from the rail. The topmost layer in Fig. 6(b) is carbon-rich, which may be condensation of burnt organic byproducts. In the 1-shot sample, the rail-deposit interface, Fig. 6(c), shows copper-rich dendrites growing into the deposit. A high magnification view, Fig. 6(d), of the middle layer in Fig. 6(b) shows a microstructure of Al-rich cellular-dendrites and inter-cellular Al_2Cu . In the 20-shot sample, all three layers in the deposit, Fig. 7(b), have cellular-dendritic microstructures, but of varying scale. With large pores and fine microstructure, the topmost layer is very similar in appearance to the deposit in the groove.

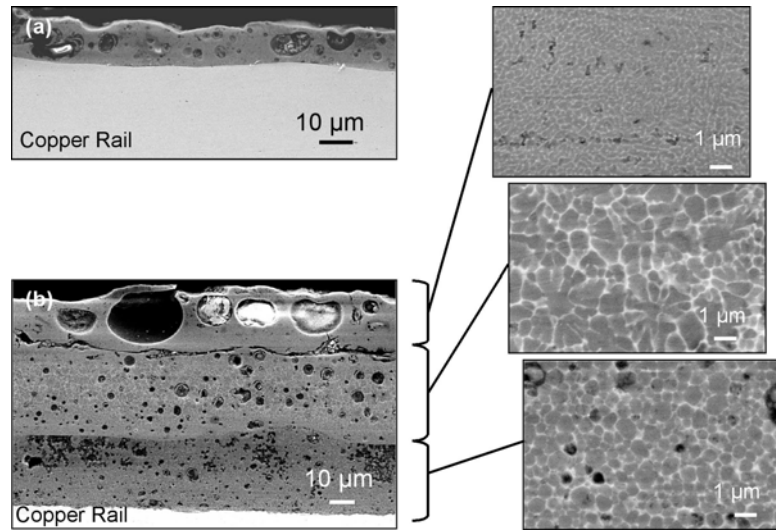


Fig. 7. SEM micrographs of deposit in the top half of 20-shot 36 cm rail sample. (a) Deposit in groove. (b) Multi-layer deposit in thick portion with microstructural detail in each layer.

IV. DISCUSSION

It is important to understand the aluminum deposition process and its implications. In its molten form the deposit may serve as a lubricant, reducing friction and wear, but in its solid form it would have deleterious effect on armature sliding and electrical contact behavior. Scanning electron microscopy has shown that the deposit is rough, porous, contain oxide particles and is prone to cracking. All of these factors will adversely affect contact conductance. Groove formation in the rails is also a cause for concern since it denotes serious deterioration of the rail, which may lead to premature railgun failure. Both, aluminum deposition and grooving in the rail material were observed in a previous experiment involving 20-shots and lower current [1]. The difference is that in these variable-shot experiments, the structural changes are much more severe due to higher current. Another observation is the asymmetry in deposit thickness and groove depth from top half of the rail to the bottom half. For these important rail material performance issues, the formation mechanisms for deposit build-up and grooving need further understanding.

The presence of distinct interfaces and changes in the scale of the microstructure and porosity within the aluminum deposit are indicators of multi-layering. However, the number of layers is much less than the number of shots. With each shot, some fraction of the previous layer is re-melted and a portion of which is swept away by the leading edge of the moving armature even as a fresh layer is added to the deposit by the trailing edge of the armature. The net effect is that less new material is added with each subsequent shot. Hence, the observed increase in deposit thickness is not cumulative. Re-melting can remove traces of previous interfaces so the number of layers always appears less than the number of shots. Re-melting also reduces porosity, resulting in a finer pore size and a denser deposit.

The deposit in the top half of the rail appears more porous and less thick than that in the bottom half. Concurrently, the grooves near the top edge are deeper than those near the bottom edge. For excessively porous deposit and deeper grooves, the temperatures near the top edge of the rail must be higher than those near the bottom edge. This asymmetric behavior in temperature may be due to asymmetry in gap between the armature and the rail. In multi-layer deposits, the layer farthest from the rail surface has coarse porosity and is similar in appearance to the single layer deposit found in the groove. This means that the single layer deposit in the groove is the same as the topmost layer in the deposit in the rest of the rail and must be the last layer to be deposited. Porosity is a bi-product of decomposition of organic materials entrapped in molten aluminum. The groove deposit thickness is by and large independent of number of shots. For the groove to deepen, the armature sliding motion must remove both the previous aluminum deposit in the groove and additional copper from the groove. However, in the armature's wake, a thin fresh molten layer of aluminum will, due to temperature-dependent surface tension gradients, spread and cover the freshly eroded grooves, which is what is observed.

Multiple shots in the 20-shot 36 cm sample result in multi-layering in the deposit. The differences in microstructural scale between layers are due to differences in solidification rates. The topmost layer has the finest microstructure and must have quenched most rapidly, the middle layer may have coarsened due to reheating. The observed two aluminum-rich layers in the 1-shot 36 cm sample are obviously not due to multiple shots. From the wavy nature of the layer closest to the rail surface and the fact that the two layers have different copper contents, it is likely that overlapping fluid flow patterns in the wake of the single shot may have occurred and resulted in the two apparent layers. The second layer is richer in copper and may have been dragged in from the groove region. The observations point to a rather complex fluid flow mechanism in railgun operation involving partial melting of the armature. The exact nature of film flow due to aerodynamic drag and surface tension effects in railguns needs to be determined and better understood.

Dissolution of the copper into molten aluminum takes place as evidenced by alloying of the aluminum deposit with copper. While there is some dissolution of copper from portions of the rail adjacent to the grooves as evidenced by copper-rich dendrites at the rail-deposit interface, the most severe dissolution occurs near the rail edges where the grooves form. If one considers the measured location of the grooves and armature dimensions, most of the groove is outside the "footprint" of the armature as shown in Fig. 8. Hence, there is very little metal-to-metal contact in the groove

region, especially once the armature edges have started to erode away downstream. Plus, there is a liquid metal film, which acts as a lubricant and minimizes friction and wear. Thus the grooving cannot be related to mechanical or erosive wear from friction between the armature and rail. There may be localized scouring of the copper rail due to the presence of hard particles such as oxides in the liquid metal film, but no gross wear features of the magnitude of the grooves were observed anywhere else on the rail surface, especially where the armature was in contact with the rail.

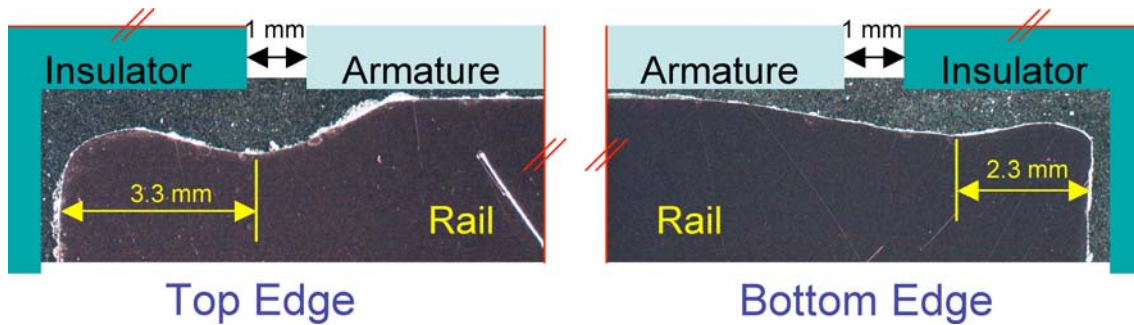


Fig. 8. Positions of armature and insulator with respect to rail edges in 20-shot, 94 cm copper rail.

From the flow patterns on the deposit surface, it appears that the direction of the molten film flow is towards the axis of the rail. This suggests that a large portion of the aluminum film is swept from near rail edge to rail interior, which, probably also accounts for greater pickup of copper in the deposit in the rail interior. For excessive dissolution near the rail edges to occur, the temperatures have to be significantly higher in these regions. Calculations of the current distribution in moving armatures by Hsieh [3] has shown that the current densities are much higher on the sides of the armature and in the edges of the rail. The ensuing Ohmic heating would result in the high temperature conditions near the rail edges, which would accelerate the grooving process. One mechanism could be superheated molten aluminum flows over the rail edges, which is also observed, causing excessive dissolution of the copper and resulting in rounding of the rail edges such as those observed in the 20-shot 94 cm rail (see Fig. 8). Thermal fields and gradients in the rail need to be modeled by direct or inverse methods to predict the temperature distributions that result in the observed groove geometry.

Grooving could also be attributed to arcing between the sides of the armature and edges of the rail. The grooving phenomenon seen in the rails appears very similar to “undercutting” phenomenon observed in arc welding [6]. Undercutting occurs when welding is performed at high speeds, high voltages, excessive currents and with large electrodes, conditions that necessarily exist in railguns. Under these severe welding conditions the base metal adjacent to the welding electrode is melted away to form an undercut or groove. In the railgun, the armature is the electrode. With high current concentrations near the rail edges and armature sides and with the presence of armature-rail gap of varying dimensions, arcing appears quite likely.

The grooves are deeper in the 94 cm sections than in the 36 cm sections. Based on data provided by IAT, the applied current remains at peak value of about 1.6 MA and does not change appreciably between these two locations in the copper rail. Hence,

deepening of the grooves cannot be attributed to current and the ensuing Ohmic heating since they are the same. The armature velocity doubles from about 0.7 km/s to about 1.4 km/s. However, it is unlikely that speed would play a role in deepening of the grooves since dwell time would be shorter which should decrease the copper dissolution time. One possible explanation for the significant increase in groove depth from 36 cm to 94 cm could be more severe arcing due to changes in armature-rail gap dimensions. Deepening of the groove downstream needs further understanding.

Measurements show that doubling the number of shots doubles groove depth in the 94 cm samples, which is a strong cumulative effect. The same is not true for the 36 cm samples probably due to the transient nature of the grooving process early in the shot. There is variability in the groove position relative to rail edge from top to bottom of the rails and from the 36 cm section to the 94 cm section. This may be due to variability in armature starting positions, uneven armature deterioration or asymmetry in contact. The observed asymmetry in deposit thickness and groove depth across the rails is most likely a result of uneven gap formation between the armature and rail. It is well known that due to magnetic interactions with the steel support structure, there is an imbalance in forces and the armature tends to ride higher or closer to the top edge of the rail. This is confirmed by measurements of groove positions at 36 cm, which show that the top groove is closer to the edge and the bottom groove is farther from the edge.

V. CONCLUSIONS

Metallurgical studies of high current, multi-shot rails have determined that several physical processes occur in the electromagnetic railgun. Melting and deposition of armature material, dissolution of rail material and grooving are some of the physical phenomena. There is asymmetry in these physical processes across the rail width. Thicker, denser deposit forms in the bottom half of the rail, indicating a larger armature-rail gap. Less thick, more porous deposit forms in the top half, indicating a smaller armature-rail gap. The uneven gap formation between the armature and rail is probably caused by uneven magnetic forces on the armature, pushing it upwards. Grooves form as a result of severe dissolution of copper accentuated by flow of superheated aluminum over the rail edge and towards the rail interior. High temperatures, caused by resistive heating and/or arcing, most likely are facilitating the dissolution process. Deeper grooves form near the top edge, less deep grooves near the bottom edge. This difference in groove size may be due to differences in current density and temperature from edge to edge, probably a result of uneven armature-rail gap. Mechanical wear processes do not appear to be a reason for groove formation since most of the groove geometry is outside the armature width.

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