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Thermal Analysis of Electromagnetic Launcher Using Numerical Simulation

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Abstract

The electromagnetic launcher is a high energy device which fires the projectile at hypervelocity. It uses high intensity electrical current pulse to accelerate projectile at such high velocity. This paper describes the thermal effects on armature of the electromagnetic launcher due to frictional heat generated between armature and the rails as well as heat generation due to joule heating in the rails. Finite element model is developed to obtain the temperature distribution on armature due to friction using ANSYS commercial software. Also, a numerical code in MATLAB is developed to obtain temperature distribution in the rails due to joule heat. Based on these analyses, it is found that heat generated due to friction plays dominant role. Also, other factors like joule heating at the contact of armature and rail, arcing at contact can increase the temperature and can cause armature to be melt and deposit on rail, which may affect the launcher performance.

Keywords: Frictional Heat, Armature, Electromagnetic Launcher, Joule Heating, Rails.

1. Introduction

Electromagnetic launcher is being widely studied for future military weapon because of its performance. Normally electromagnetic launcher consists of two parallel plates. The plates are kept intact by using containment structure made of steel. The projectile is accelerated by current carrying armature. When current is passed through rails, magnetic field is generated between the rails. When current is passed through armature, the interaction between armature current and magnetic field between rails generates the Lorentz force and it accelerates the armature and in turn projectile. The purpose of using this principle for launcher is to increase the range of the weapon and velocity up to 2 km/s. For decades the railgun has been studied so far as a laboratory tool. Nowadays from the literature review it is found out that efforts on this research are moving this technology into the practical system rather than as a laboratory system.

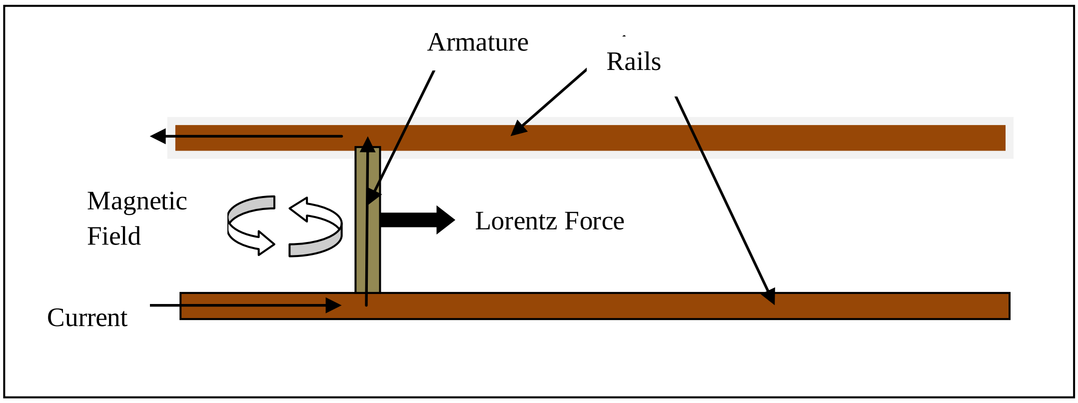

Figure1. Working principle of Electromagnetic launcher

Li et al. [2013] reported that the thermal character of the interface between rail and armature significantly affects the launch performance of electromagnetic rail gun. Numerical simulation has been done for different values of coefficient of friction and compared with experimental data. Brown et al. [2007] investigated experimentally effect on the coefficient of friction in the presence of high current density. Motes et al. [2012] studied the joule heating effects on rail for different conditions like fully diffused, transient, transient with change in material properties by numerical simulation and results are compared with the experimental results. Ranc and Sutter [2012] experimented to investigate the value of flash temperature for high sliding velocity for dry friction. Experiments are carried out by using airgun. Chen et al. [2014] studied the different transition phases of the armature to investigate the wear rate and heat. Cooper et al. [2005] studied the effects on the rails experimentally for continuous firing with same pair of rails. Cooper et al. [2005] studied effect of high power launch or railgun barrel materials. A rail used for 20 shots of medium caliber launcher. Friction and electrical heating in the surface can held to melting and material loss, changes in contact area ,gouging and transition to arc contact. Chenxue et al. [2005] studied the problem in rail launcher of melting armature on some special places. Eckenfels et al. [2003] studied the different phases in armatures while it is in motion. For the analysis 3m, 15 x 30 mm rails for 620KJ energy has been used. Experiment has been carried out to identify the mechanism behind the mass loss of armature. From the literature review it has been observed that joule heating and frictional heating plays crucial role in rail heating and performance of launcher. It causes aluminium deposition on rails, ablation and wear. It is observed that not much work has been done to explore the effects of the frictional heating on electromagnetic rail gun. The prime objective of this paper is to study and analyse the effects of frictional heating on electromagnetic rail gun using finite element based analysis with the help of commercial ANSYS software.

2. Analytical Calculation for Temperature

Frictional heating mechanism in electromagnetic launcher is different than other frictional heating mechanism because of three conditions

1) Actual action time is very short
2) Armature moves with very high velocity
3) Complexity at the interface.

According to fundamental tribological theories the heat flow density q_f can be represented as,

$$q_f = \mu w v \tag{1}$$

Where μ is coefficient of friction, ω is normal load in N, v is armature sliding velocity in m/s Block, Jaeger and Archard's theory can be used for the contact temperature calculation. Flash temperature due to friction between the two bodies can also be determined by the formula [7].

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$$\text{Flash Temperature} = \frac{0.399 * W * \mu * (U\text{a} - \text{Ub})}{k.b.} \left(\frac{k}{\rho * C * U * b}\right)^{0.5} .. \tag{2}$$

Where k is thermal conductivity, C is specific heat, ρ is the density, b is half of the width of the body, Ua and U_b relative velocity of moving bodies. The value of flash temperature obtained using above equation is 219.82 °C. This value will be verified with numerical simulation.

Joule heat due to high current density can be expressed as,

$$q = I^2 \text{R} \tag{3}$$

Where I is current density, R is the resistance.

3. Effect of Frictional Heating

The simulation model for frictional heating is developed to study the effect on armature performance. The rails and armature are modelled considering following assumptions.

1) Solid-solid contact condition is assumed on the interface of rail and armature

without considering melt film on rail surface.

2) Sliding velocity of armature and coefficient of friction is considered to be constant.

To study this phenomena simulation is carried out and results are analysed. To study this phenomena simulation is carried out and results are analysed. The analysis is carried out for 2 m length of rail. For ease of modelling, armature is considered as rectangular block having equivalent area in contact with the rail. Armature is made up of aluminium and rail is made up of copper and the respective material properties are assigned to the model (Refer to Table 1 for the details). Numerical analysis is performed using 10 node hexahedral first order element with global size of 5 mm. To maintain positive contact between the rail and armature, height of armature made 31 mm for 30 × 30 mm bore. The normal load which is required to deform armature by 1 mm is obtained by simulation in ANSYS which is 200 KN. Normal load of 200 KN is applied on the armature. The co-efficient of friction between rail and armature is 0.113 [Chen et al., 2014]. A constant velocity of 2000 m/s is applied to the armature. Initially, ambient temperature condition is applied to the rail and armature. A fix support at the bottom surface of the rail is applied. The simulation is carried out to obtain the temperature of armature. The maximum output temperature of the armature is determined. Temperature profile with armature movement is plotted..

Table 1: Mechanical properties and geometric parameters of rail and armature.

PART	MATERIAL	THERMAL CONDUCTIVITY (W/m.k)	DENSITY (kg/m^3)	SPECIFIC HEAT (J/Kg.k)	DIMENSIONS (mm)
Rail	Copper	401	8300	387	60×35×2000
Armature	Aluminium	165	2770	876	30×30×50

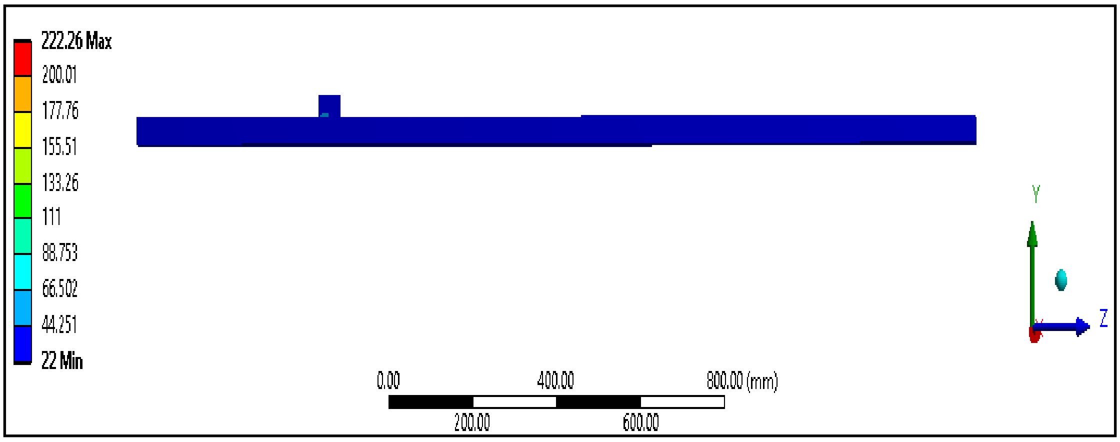

Figure 2(a) Armature after 0.25ms on the rail

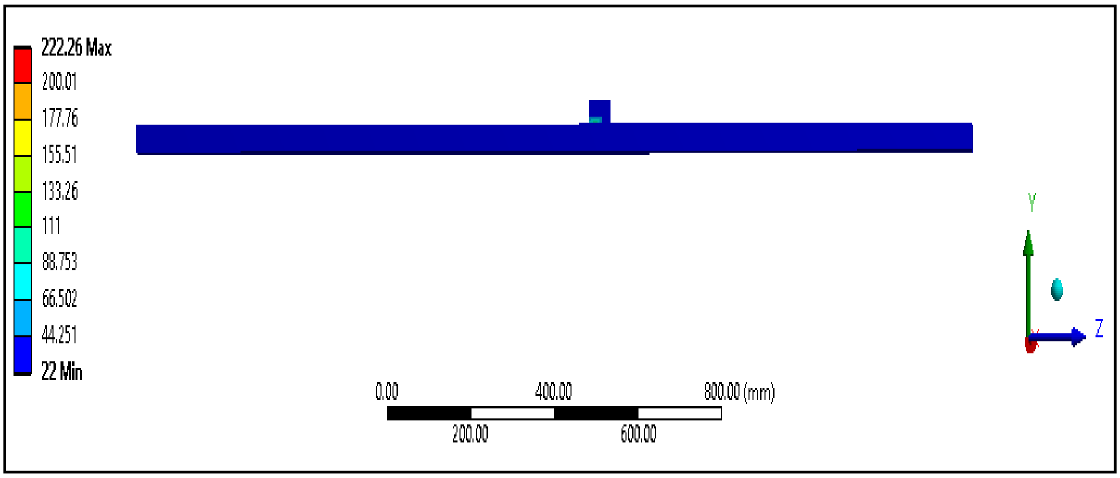

Figure 2(b) Armature after 0.5ms on the rail

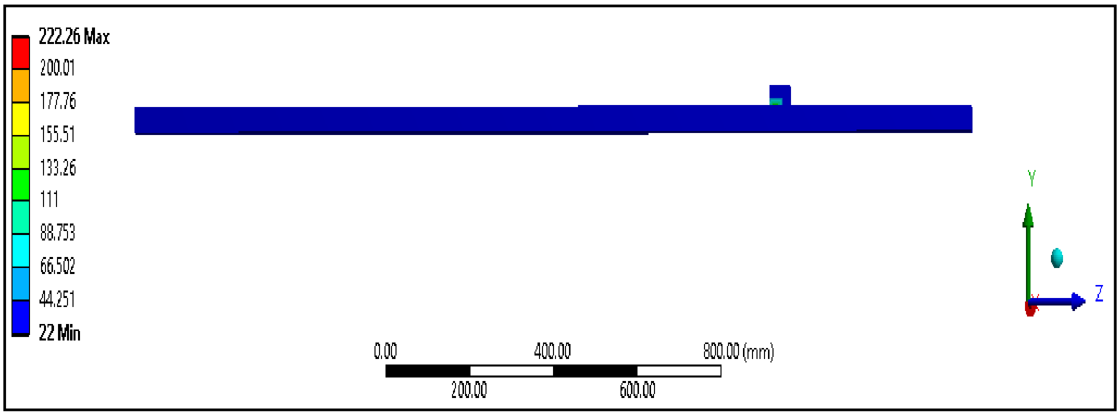

Figure 2(c) Armature after 0.75ms on the rail

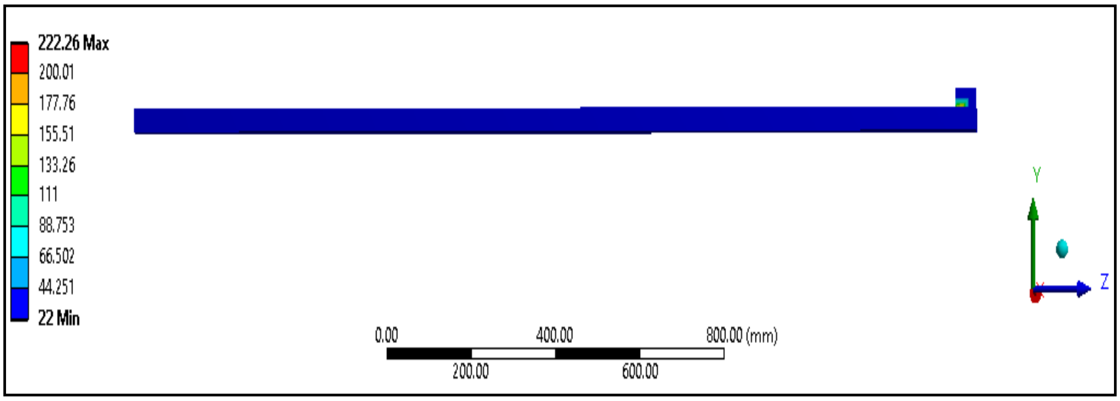

Figure 2(d) Armature at the muzzle end

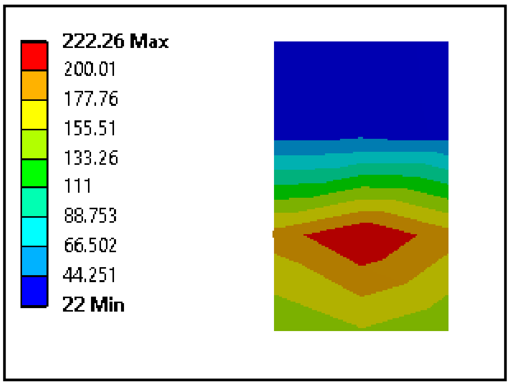

Figure 2(e) Temperature at the bottom surface of armature after 1ms

Figures 2 (a)-(e) shows the different positions of the armature on the rail along with the temperature distribution. In Figure 2(a), it is observed that the temperature of armature goes around 88° C after 0.25 ms. In Figure 2(b), the temperature of armature goes up to 111°C after 0.50 ms. After 0.75 ms as shown in Figure 2(c), the temperature of armature is 140 °C and at end of the movement temperature is observed as 222 °C. Figure 2(e) shows the bottom surface of the armature, where the maximum temperature is observed at the trailing end of the armature. The Maximum temperature obtained from Equation(2) is 219.82°c and by the simulation is 222.26°c. Maximum temperature is below melting point temperature of armature which is 710°. Hence for 2 m length of the rail and 3 MJ of input the friction between rail and armature will not affect the performance of the electromagnetic launcher.

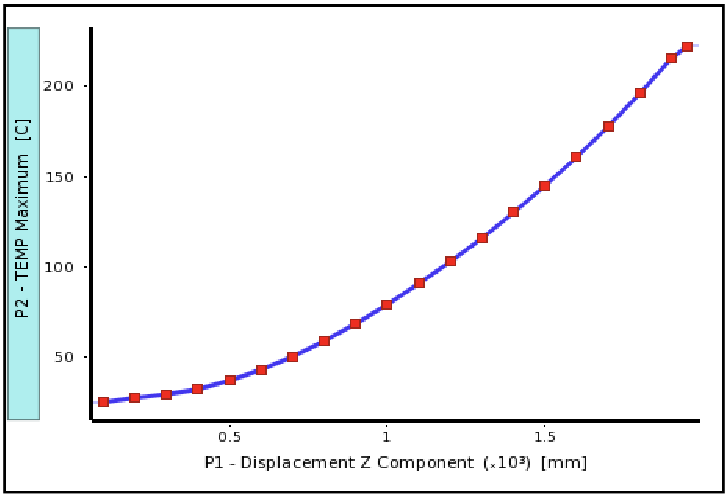

Figure 3 Temperature Vs Displacement of Armature

4. Effect of Joule Heating

Another important factor in the smooth working of launcher is heat generated due to resistance offered to current flowing through the conductors (rails). Since intensity of current passing through is high, heat generated due to this is mainly concern with the rail. The current profile with time is generated by doing numerical simulation in Ansoft Maxwell Software. To simulate this Inductance is used as a input. The current profile with time for 3MJ of energy as shown in Fig.4.

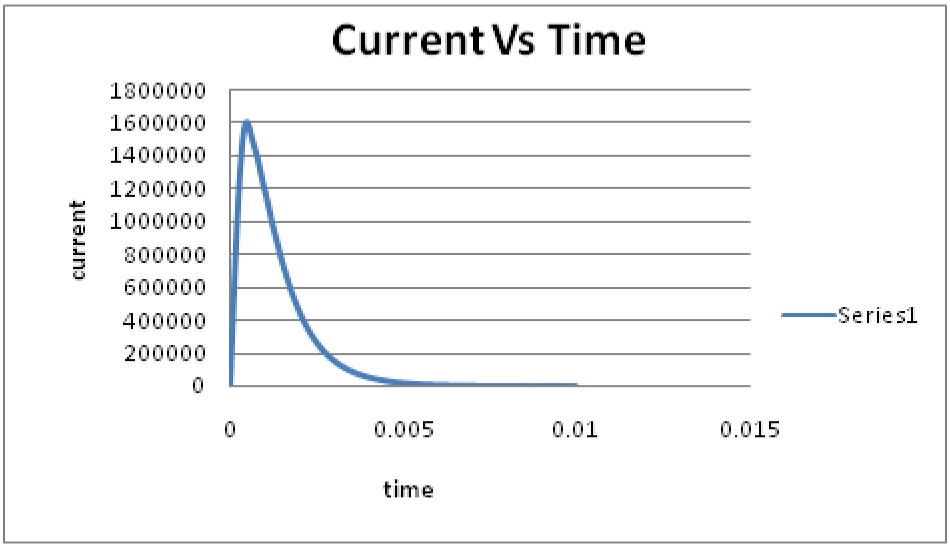

Figure 4.Current profile for 3 MJ of energy

To study the effect of joule heat on the rail fully diffused condition is assumed. For this assumption, temperature profile can be estimated by knowing current time profile in Figure 4.

The temperature profile with time can be estimated by using

$$\rho_{mass} \times c_p \times \Delta T = \rho_{ele} \int I^2 \, dt \qquad (4)$$

Where ρ is mass density, Cp is specific heat, ρ_{elec} is electrical resistivity, I is current density. A numerical code in MATLAB is developed to solve the above equation to obtain the temperature profile with time. The results obtained from the code are plotted in fig. 5.

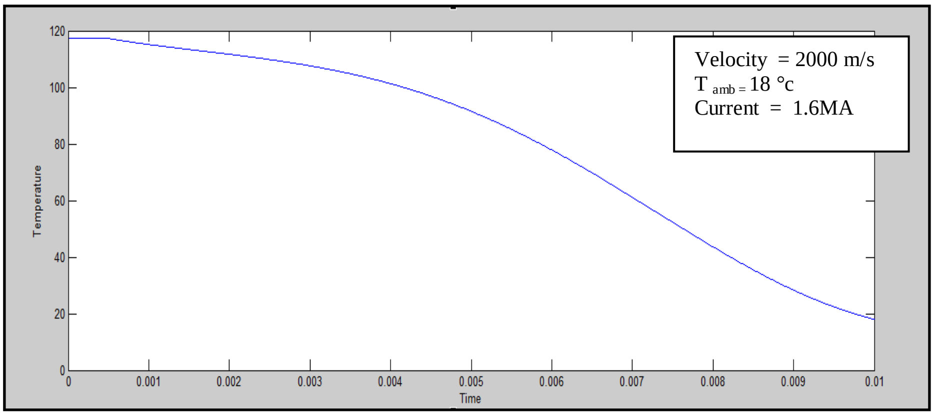

Figure 5 Result of temperature Vs time for rail

From Figure 5, it can be seen that maximum temperature is observed at the breech end of the rail. The maximum temperature of the rail is 120 °C. Since intensity of current is maximum at the breech end, the maximum temperature is observed at breech end of the rail. Since the results are obtained for 3 MJ of energy, it is found that if intensity of current is further increased to significant level, then joule heat can play important role in the working of launcher.

5. Conclusion

The thermal analysis of electromagnetic launcher is carried out using numerical simulation. The effect on the performance of launcher is studied for the case of Joule heating and frictional heating. The present study reveals that there is significant rise in temperature of armature due to frictional heating. Joule heating increases the temperature of rail for single shot and 3 MJ of energy. The maximum temperature is observed at the end of the armature. It is observed from the present study that Joule heating of the rail can affect the life of the rails with increase in intensity of current.

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