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Simulation of the Current Distribution and the Heat Load of a Brush Projectile in a Railgun with the Finite Element Code ANSYS

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One of the main issues of electromagnetic railguns is the heating of the solid contact between the current brushes in the projectile and the rails. The heat load of the brushes must be limited in order to avoid transition of the solid contact into a plasma contact and thus to avoid the deterioration of the rails. Therefore the heating of the contact between the rail and the current brush is studied. For the determination of the current distribution and the heat distribution the finite element code ANSYS was used. This code allows the combination of an electromagnetic and a thermal analysis. The current distribution in the brushes, obtained in the electromagnetic analysis, is used in the thermal analysis to calculate the temperature distribution. These temperatures are then re-entered in the electromagnetic analysis to adapt the temperature dependent resistivity. We compared the results of the simulations with ANSYS with experimental data obtained with a non-augmented railgun at the French-German Research Institute ISL. Analysis of the muzzle voltage can be used to determine the moment of transition. The experimentally obtained currents are used in the ANSYS model in order to calculate the temperature distribution and the action integral in the brushes at the moment of transition.

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1. Introduction

One of the advantages of electromagnetic guns is their high muzzle velocity compared with conventional guns. Furthermore, there is a decrease in vulnerability due to the absence of powder. Throughout the years, many different types of electromagnetic guns and energy storage have been developed. An overview can be found in [1] and [2]. One of the main issues of electromagnetic railguns is the heating of the solid contact between the current brushes in the projectile and the rails. The heat load of the brushes must be limited in order to avoid transition of the solid contact into a plasma contact and thus prevent deterioration of the rails. A description and analysis of the velocity skin effect and current distributions can be found in [3–5]. The papers [6] and [7] of Cardelli et al. describe an integral approach for the analysis of the current and the temperature distribution in a railgun.

In this paper, a study of the heating contact between the rail and the current brush is discussed. The finite element code ANSYS, was used to simulate the current distribution and the heat distribution in the current brushes. This code allows the combination of an electromagnetic (EM) and a thermal analysis. We compared the results of the simulations from ANSYS with experimental data obtained with a non-augmented railgun at the French-German Research Institute ISL. Observation of the wear caused by contact transition allows us the determination of the position where transition took place. Contact transition also results in a ≈ 20 V rise in the voltage measured at the muzzle of the rails. Analysis of the muzzle voltage can be used to determine the moment of transition. The experimentally obtained currents are used in the ANSYS model in order to calculate the temperature distribution and the action integral in the brushes at the moment of transition.

2. Simulations

The motion of the projectile is not modelled. Therefore, the velocity skin effect was not taken into account. For the simulations of the rails and the current brushes, the physical properties of copper are used. For fibre current brushes a filling percentage of 75% was taken into account. The EM analysis allows us to calculate the current distribution and thus the action integral in the current brush. The calculated joule heat distribution is transferred to the thermal analysis at each load step (50 μs) and used to calculate the temperature distribution. This temperature distribution is then re-entered in the EM analysis.

2.1. Geometry

The non-augmented railgun has a square caliber of 15 mm × 15 mm. The rails have a square cross-section of 15 mm × 15 mm and the length of the rails is 1.5 m. The radius r of the brushes is 3.5 mm. The model in ANSYS has a length of 14 cm. The other dimensions are respected. The model was simulated in an air environment.

2.2. Electromagnetic analysis

For the EM analysis, a temperature dependent resistivity is taken into account for both the rails and the current brushes. The values for pure copper in the solid phase are used. For the current brushes, a filling percentage of 75% was taken into account to calculate the resistivity. A contact resistance between the rails and the current brushes was also modelled. Therefore, the resistivity of a 0.1 mm thick layer between the brush and the rails was adapted to obtain a contact resistance of 2.5 $\mu\Omega$ per contact [8]. Only a quarter of the railgun is modelled (Fig. 1). The transversal and longitudinal cross-section plane, the outer surface of the boundary region and the two planes perpendicular to the rails, who define the beginning and end of the simulated part of the rails, define the outer limits of the model. The magnetic boundary used for the longitudinal cross-section is flux normal, while the reminder are flux parallel.

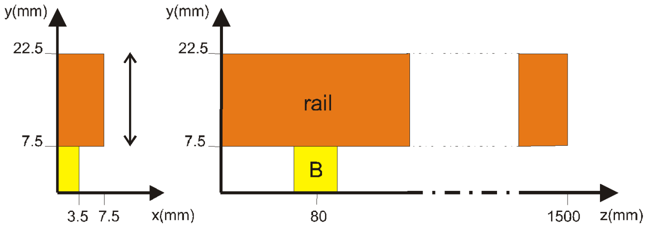

Fig. 1. Geometry of the studied railgun. (left) Transversal cross-section, (right) longitudinal cross-section.

2.3. Thermal analysis

The thermal analysis calculates the temperature distribution in the current brush and the rails. The air is not simulated in this analysis and again only a quarter of the model is simulated. Adiabatic boundaries are applied to all the outer surfaces of the model. The specific heat used for the rails and the current brush is 387 J kg^{-1} K^{-1}. The density is 8960 kg m^{-3} for the rails and 6720 kg m^{-3} for the current brush. The temperature dependent thermal conductivity of pure copper is used for the rails [9]. The thermal conductivity in a fibre current brush is anisotropic. Therefore, the calculations are made twice for an upper and a lower limit. Once with a thermal conductivity for the current brush that is the same as for the rails k_1, which serves as upper limit. The second is set with a thermal conductivity of 10^{-12} W m^{-1} K^{-1}, k_2 (ANSYS does not allow $k = 0$ W m^{-1} K^{-1}), which is the lower limit.

3. Results and discussion

The experimentally obtained results, received from a non-augmented railgun [10], are listed in Table. The inner circuit was connected to two capacitor banks charged to 7 kV each. The discharge time of the first bank corresponds with $t = 0$ ms. The discharge time, t_c, of the second bank, the measured velocity, v_b ($\Delta v/v < 5\%$), the muzzle time, t_b, and the experimentally obtained plasma time t_P, are also listed in Table. The action integral IA_P, at the plasma point and the action integral IA_b, at the muzzle are decreasing with increasing time between the discharges.

TABLE

Calculation results for different shots in a non-augmented railgun.

t_C [mm]	t_P [mm]	IA_P [C^2 s^{-1}]	t_b [mm]	IA_b [C^2 s^{-1}]	v_b [m s^{-1}]	T_P [°C] k_1	T_P [°C] k_2
0.21	1.71	52.6	2.95	59.5	694	648	1585
1.00	2.98	51.2	3.96	54	580	501	1500
1.50	3.26	45.3	4.41	48.3	539	447	1326
1.75	3.64	44.5	4.62	46.8	520	416	1303
2.00	–	–	5.38	40.4	391	268	1175

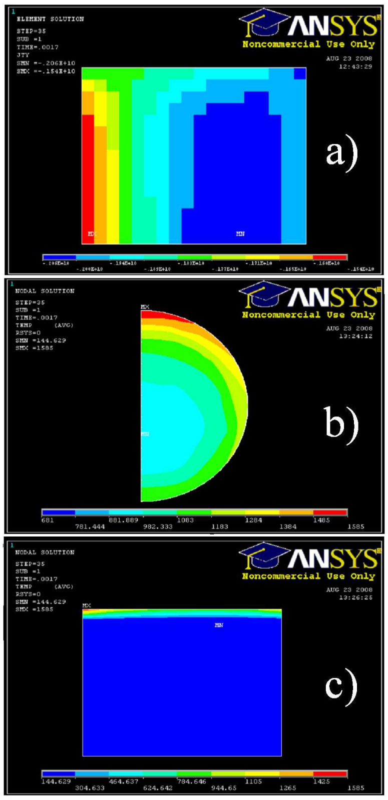

Fig. 2. Distributions in the current brush calculated for the shot with $t_c = 0.21$ ms at t_P: (a) current density at the longitudinal cross-section, (b) temperature distribution at the contact surface, (c) temperature distribution at the longitudinal cross-section.

When we compare the $T_{\max}$ at the contact surface at t_{P} for both methods (k_1 and k_2), we can conclude that the T_{P} calculated with the thermal conductivity of copper k_1 is only 23 to 41% of the T_{P} calculated with k_2. Thus, although a shot lasts only a few milliseconds, the influence of the k is not negligible. Figure 2 represents the current distribution (a) and the temperature distributions (b) and (c). The left side of (a) and (c) and the top of (b) correspond with the side towards the breech. The heating of the current brush takes place mainly at the contact surface and towards the breech. However, the highest current density at that time is found towards the muzzle. We keep in mind that the velocity skin effect is not taken into account and neither is the heat caused by the friction. These phenomena would lead to an increase in the $T_{\max}$. On the other hand, in the simulation the heating of the rails is simulated, while in the experiments the projectile is moving and continually sees a new part of the rails. The melting temperature of copper is 1083°C. In Fig. 2b it is shown (calculations for $k_2 = 10^{-12}$ W m^{-1} K^{-1}) that for the first shot with $t_{\mathrm{c}} = 0.21$ ms almost 40% of the contact surface has reached the melting temperature at t_{P}.

4. Conclusions

Neither the action integral, the maximum temperature at the contact surface, nor the percentage of the contact surface that has a temperature above the melting temperature have a clear limit at which plasma occurs. The anisotropic thermal conductivity should be taken into account for a better simulation of the heat load at the contact surface.

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