Advances in Engineering Research, volume 185
2nd International Conference on Electrical and Electronic Engineering (EEE 2019)

Parameters Optimization of Passive Electromagnetic Armor Based on Orthogonal Experiment

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Keywords: Metal jet, Orthogonal experiment, Passive electromagnetic armor, Temperature characteristics.

Abstract. In order to improve the defense ability of the passive electromagnetic armor (PEA), the parameters of the armor are optimized based on the orthogonal experiment. It analyzed the working principle of the PEA and the phase change of metal jet, and then the temperature control equation of the metal jet was obtained. After that the capacitance *C*, the charge voltage *U* and the distance of armor plates *d* were optimized based on the orthogonal experiment and the numerical simulation method of temperature field. At last, a group of optimized parameters were obtained. It can draw the conclusion from the research that the temperature distribution of the metal jet is not even, and the external surface of the metal jet has the highest temperature, as the internal side has the lowest temperature. Meanwhile, the charge voltage *U* has the greatest effect on the temperature of metal jet, and the capacitance *C* has the least effect. The research results are very important to the design and the application of PEA.

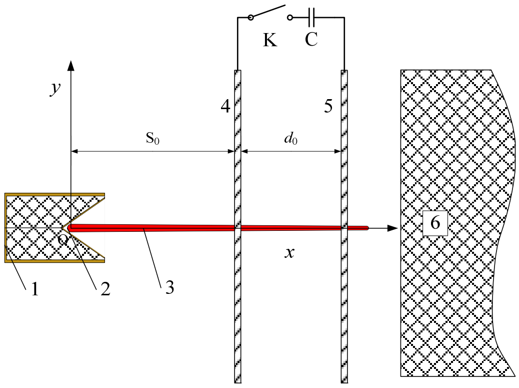
Introduction

As the development of the armament technology, the penetration ability of anti-tank weapons has been increased greatly, which brings serious challenge to the tanks and armor vehicles [1]. Then, how to improve the guard capacity of the armored vehicles is a hot spot of research for military scientists. The passive electromagnetic armor (PEA), one of the latest kind armor, can decrease the effective length of the metal jet caused by shaped charge, or even make it explode under the synthesis action of the ohmic heating effect, the electromagnetic force, and etc., which will decrease the penetration to the main armor of the tanks and armored vehicles. Then the survival probability will be improved. Thus, the technology of PEA is studied by different scientists home and abroad.

Their researches mainly focus on the establishment of the mathematical models, principle analysis and experiment verification, and etc [5-8]. However, the optimal design of the PEA still needs further study. Thus, aiming to improve the working effect of the PEA, this paper will analyze the optimal design of the PEA based on the calculation and simulation module for temperature characteristics of high-speed metal jet designed by the research group.

Principle of the PEA

The working principle of PEA is illustrated in Fig.1. The PEA is usually composed of capacitors, armor plates and etc. The armor plates are connected with the capacitors [9]. When the high speed metal jet caused by high explosive anti-tank cartridge (HEAT) passes through the armor plates, the capacitors will discharge to the metal jet and generate high pulsed current, as well as strong electromagnetic field. The metal jet which is under the working of hydro-kinetic force effect and ohmic heating effect will deflect and disperse. Finally, the metal jet will be destroyed and the damage ability will be abated [10].



1-shaped charge, 2-virtual source point, 3-metal jet, 4-front armor plate, 5-back armor plate, 6-main armor, K-trigger switch, C-pulse capacitor banks

Figure 1.working principle of PEA

Temperature Model of the High-speed Metal Jet

Current research shows that the temperature of the metal jet is between 800℃ and 1000℃. It is lower than the melting point of the copper. When the high pulsed current flows through the metal jet, the temperature of the metal jet will rise and change it into liquid. Furthermore, when the temperature is enough, the metal jet may be vaporized. To a certain extent, it may begin to explode and be changed into plasma. The physical state of the metal jet may undergo plastomer- liquid - vapor - plasma when it passes through the metal plates of the PEA. Thus, it is very significant to build the calculation model of the temperature for the metal jet, and then solve and analyze the characteristics of it.

As the meal jet can be simplified as a two-dimensional model which is divided in to micro-units along its radial direction and axial direction. Each unit is shown in Fig.2.

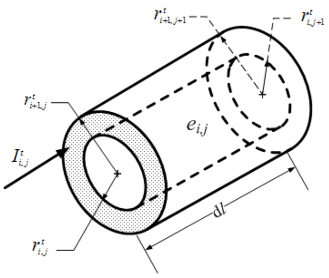


Figure 2. 2D model of the units

In the Fig.2, the $I_{i,j}^{t}$ and $\mathrm{d}l$ are the current and length of the micro-unit respectively. $r_{i,j}^{t}$ and $r_{i,j+1}^{t}$ are the inner radius of micro-unit, $r_{i+1,j}^{t}$ and $r_{i+1,j+1}^{t}$ are the external radius.

The temperature field of the units can be expressed by

$$\mathrm{d}E_{i,j}^{t} = \mathrm{d}Q_{i,j}^{t} \tag{1}$$

where, $\mathrm{d}E_{i,j}^{t} = m_{i,j}^{t} C_{\mathrm{p}} \mathrm{d}T_{i,j}^{t}$ is the increment of internal energy; $m_{i,j}^{t}$ is the mass of unit, C_{p} is the specific heat under constant pressure; $\mathrm{d}Q_{i,j}^{t}$ is the heat increment.

The resistance of micro-units is as follows:

$$R_{i,j}^{t} = \rho_T \frac{\Delta v(t_0 + t)}{\pi\left(r_{i+1,j}^{t} r_{i+1,j+1}^{t} - r_{i,j}^{t} r_{i,j+1}^{t}\right)} \tag{2}$$

The ρ_T in (2) is the resistivity of metal jet.

And then the increment of heat energy per second can be defined by:

$$\mathrm{d}Q_{i,j,t} = I_{i,j}^{t\ 2} R_{i,j}^{t} \mathrm{d}t \tag{3}$$

The equation in (1) can be written as:

$$m_{i,j}^{t} C_{\mathrm{p}} \mathrm{d}T_{i,j}^{t} = I_{i,j}^{t\ 2} R_{i,j}^{t} \mathrm{d}t \tag{4}$$

The initial conditions are :

$$T_{i,j}^{t} \mid_{t=0} = T_{0} \tag{5}$$

As the discharge circuit of the PEA can be seen as an *R-L-C* circuit, the numerical calculation method based on finite difference method is put forward. Then a simulation and calculation module for temperature distribution of high-speed metal jet is designed.

Optimal Design of PEA Module

As to the optimal design of the module for the PEA, the most important is to make the electrical parameters of the power source match with the parameters of the configuration parameters. There are many methods of optimization at present. However, the method of Orthogonal Experiment, which is commonly used in the engineering field, has many advantages, such as high efficiency, easy to use, and etc.. Thus, the parameters of the module for the PEA are optimized and analyzed based on the method of Orthogonal Experiment, which contributes to the improvement of the guard capacity of the PEA.

Analysis of the Optimization Target

The effect of the temperature to the PEA is significant from the analysis above. Thus, the temperature of the metal jet is chosen as the optimization target in this paper. Generally, if the temperature of the metal jet is higher, it means that the metal jet gasifies or becomes to explode into plasma easily. Then the damage to the main armor is abated and the defense capacity of PEA is better.

Establishment of the Factor Level Table

The changes of the physical state for the metal jet mainly depend on the temperature of the metal jet. However, the temperature of metal jet is affected by the resistance of the metal jet, the discharge current in the metal jet, and the working time of the current on the metal jet. These factors depend on the capacitance and the voltage of the capacitor banks, the distance between the back plate and the front plate of the PEA. Thus, we choose the capacitance *C*, the charge voltage *U*, and the distance *d* of the armor plates as the factors to optimize. According to the research results obtained by our research group before, each factor has 3 levels. The table of factor levels is shown in the Table I.

Establishment of the Orthogonal Experiment Table

It can be seen from Table I that it is a table with 3 factors and 3 levels. Thus, it is necessary to build an orthogonal experiment table for 3 factors and 3 levels. As there is not a suitable orthogonal experiment table to use at present, an orthogonal experiment table for 4 factors and 3 levels is chosen as a substitute. After putting the values of the levels into the table, the orthogonal experiment table is obtained as shown in Table II.

Table 1. Levels of factors

Factors / Levels	*C* (μF)	*U*(V)	*d*(mm)
1	800	6000	50
2	1200	7000	100
3	1400	8000	150

Table 2. Table of orthogonal experiment

Parameters / Experiment index	C (μF)	U(V)	d(mm)	T(K)
	1	2	3	
1	800	6000	50	1357
2	800	7000	100	2136
3	800	8000	150	2575
4	1200	6000	100	1969
5	1200	7000	150	2291
6	1200	8000	50	2407
7	1400	6000	150	1852
8	1400	7000	50	2111
9	1400	8000	100	3123

It can be seen from the orthogonal experiment table that it is necessary to take 9 experiments and get the maximum temperatures at different factors and conditions.

Generally speaking, it is unnecessary to measure the temperature of the metal jet in the experiment of the PEA. Thus, the calculation module for temperature characteristics of high-speed metal jet with the high pulse electromagnetic field is used to calculate the temperature by simulation.

During the calculation, the distance S_0 in Fig.1 is 160 mm. Meanwhile, the equivalent resistance is 15 mΩ, and the inductance of the discharge circuit is 1 μH. The head velocity of the metal jet is 8km/s, and the tail velocity is about 2km/s. When the head part moves to touch the front plates, the radius of the head is 1 mm. Besides these parameters, other parameters are set according to the results in the table of factor levels. After that the high-speed metal jet is analyzed with the discharge current, and then the working time on the metal jet and the temperature characteristics of the metal jet are obtained, as well as the maximum temperature.

Taking the index 1 in Table I for instance, the discharge current of the power source is obtained by simulation, which is shown in Fig .3. After normalization to the radius of the metal jet, the maximum temperature of the units for metal jet is 1357K. The temperature distribution is shown in Fig.4. Furthermore, the distribution of the current density at different position as in Fig.5.

Meanwhile, the tail of metal jet moves away the front armor plate at the 53μs, and then the current in the metal jet is turned off.

The Fig.4 displays that the maximum temperature is 1357K, which is consistent with the melting point of the metal jet. It means that this part of metal jet has reached to its melting point and has been turned into liquid. However, the temperature of other part of the metal jet is lower than the melting point and its physical state is not changed. Thus, not all of the metal jet are liquid, which is the reason of the "platform " for the temperature in Fig.4.

The Fig.5 shows that the current density at the outer part of meta jet is higher as the effect of the skin depth. Furthermore, as the velocity of the metal jet is high, it is unnecessary to take the effect of the thermal convection in the air into consideration. Thus, the outer surface will melt at earlier time.

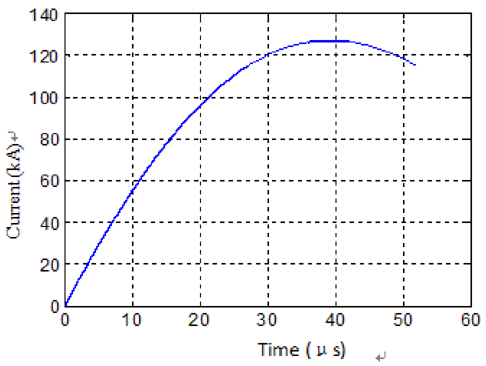


Figure 3. Curve of discharge current

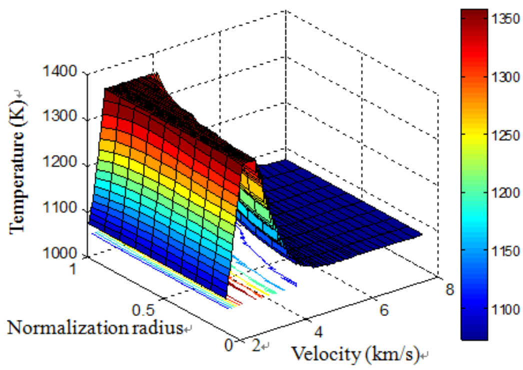


Figure 4. Temperature distribution of metal jet

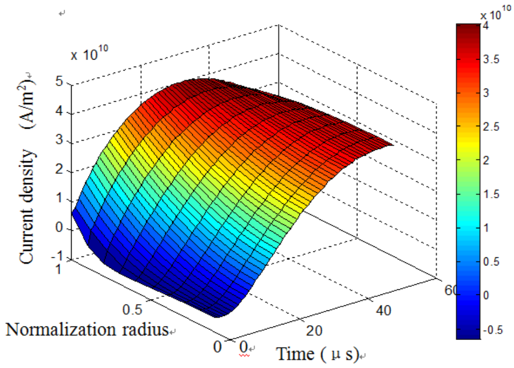


Figure 5. Current density distribution

According to the analysis above, the temperature distribution of the metal jet with different parameters is shown in Table II.

Analysis of the Experiment Results

After the orthogonal experiment, the method of range analysis is used to analyze the experiment results in Table II. Then, the results are shown in Table III, in which the K_i is the sum of the all results whose factor index is i, k_i is its average. The calculation method is as follows:

$$K_i = \sum_{l=1}^{3} T_{ij} \tag{6}$$

$$k_i = \frac{K_i}{3} \quad (i=1, 2. 3; l=1, 2, 3) \tag{7}$$

where T_{ij} is the temperature of the metal jet in the Tale II whose level index and experiment index are i and j, respectively.

For instance, as to the first level 800μF of the factor C, the K_1 can be calculated as follows:

$$K_1 = 1357 + 2136 + 2575 = 6068$$

In the Table III, the symbol R is the range value of the orthogonal experiment. It can be obtained by the equation as follows:

$$R = \max(k_i) - \min(k_i) \tag{8}$$

According the orthogonal design-direct analysis, the corresponding level to the largest K_i is just the value which can make the metal jet get highest temperature. Thus, all the corresponding levels for the largest K_i are the optimal parameters group for the metal jet. For instance, as to the factor C, the largest K_i is 7086, the corresponding level of which is 1400μF. According to the analysis method, the optimal parameters group is as follows: C=1400μF、U=8000V、d=100mm.

Furthermore, according to the theory of range analysis, the factor who has the largest R will has the greatest effect to the optimal target. Thus, the effect to the temperature of metal jet from large to small is as follows: charge voltage U, distance between the armor plates d, and the capacitance C.

Verification of the Optimal Results

It can be seen from the optimal results that when the capacitance, charge voltage, and the distance between two armor plates are 1400μF, 8000V, 100mm, respectively, the metal jet can reach to the maximum temperature 3123K. The temperature characteristics is shown in Fig .6.

Furthermore, From the Table II we can find that the temperature of metal jet with the parameters of optimal group is higher than the temperature with other parameters. It means that the optimal parameter group obtained by the orthogonal experiment is correct, which verifies the valid of the method.

Meanwhile, it can make the discharge current and its working time match with the speed of metal jet by the optimization of the electrical and configuration parameters for the PEA, which is beneficial to the improvement of the guard capacity for the tanks and armor vehicles.

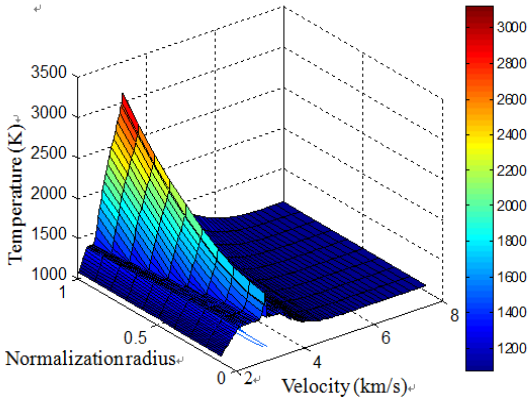


Figure. 6. Temperature distribution of metal jet

Table 3. Range analysis of experiment results

Factors analysis \ Factors	C	U	d
K_1	6068	5178	5875
K_2	6667	6538	7228
K_3	7086	8105	6718
$k_1(K_1/3)$	2022.67	1726	1958.33
$k_2(K_2/3)$	2222.33	2179.33	2409.33
$k_3(K_3/3)$	2362	2701.67	2239.33
R	339.33	975.67	451

Summary

The parameters for the module of PEA are optimized based on the orthogonal experiment method. Furthermore, the optimal results are verified. The conclusions based on analysis above are as follows:

(1) When the parameters for the module of the PEA are C=1400μF, U=8000V, and d=100mm, respectively, the metal jet can reach the maximum temperature, which contributes to improvement of the guard capacity of the PEA.

(2) Among the parameters of C, U and d, the charge voltage U has the maximum effect to the temperature of metal jet. On the contrary, the capacitance has the minimum effect to the temperature.

(3) The temperature distribution of the metal jet on its section surface is not even. From the center of the metal jet to the outer surface, the temperature will increase gradually. Thus, the outer surface of the metal jet will melt, gasify or even explode in to plasma at first, which will decrease the penetration ability of the metal jet.

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