Measurement Method of Deformation of Liquid Metal by Pulsed Electromagnetic Field

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Abstract. In order to verify that the non-uniform diameter of the metal jet can be deformed to a smaller diameter difference after the action of the electromagnetic field, a convenient and feasible test method is proposed. Mercury liquid metal was used as the test medium and a thermometer was used as the test equipment. A high-speed camera was used to record the deformation of the liquid metal, and the deformation of the liquid metal by the electromagnetic field was visually shown. The test results show that the liquid metal mercury is rapidly deformed by the electromagnetic field. The greater the magnetic induction intensity is, the stronger the deformation is. The greater the pulse discharge current is, the more obvious the mercury deformation is. The deformation measurement result conforms to the basic theory of the electromagnetic field. This method can be used to measure the electromagnetic field. The rapid deformation and flow under the effect provide a reference for the study of the deformation measurement of the electromagnetic enhanced armor technology and the electromagnetic constrained forming technology.

1. Introduction

The penetration force of the armor-piercing projectile is proportional to the effective length of the metal jet, but there is a huge velocity gradient during the flight of the metal jet, which causes the metal jet to break and has a large loss of the armor strength. Fedorov [1], Littlefield [2] and other studies have found that the application of a pulsed electromagnetic field during flight can cause deformation of the metal jet. The higher the flight stability, the greater its effective length and the stronger the penetration force. Hirsch [3] established a theoretical model for the particle scattering angle of metal jets, and discussed the mechanism of particle scattering. Ma Bin [4] and Meng Xueping [5] established a theoretical model of pulsed magnetic field metal jets and studied timing control and discharge parameters. The influence of the metal jet on the restraint effect, the test results show that the impact of the metal jet penetration enhanced by the electromagnetic field. Due to the extremely short flight time of metal jets, it is difficult to observe and measure the deformation of the metal jet after the electromagnetic field is applied. The experimental verification is less, and there is no direct research literature on the effect of pulsed magnetic field on metal jets.

In the process of analyzing the interaction between the jet and the target plate, the intensity effects of the jet and the target plate can be ignored. The metal jet is similar to the fluid material, so the liquid metal mercury is selected as the test medium, and the thermometer is used as an experimental instrument to facilitate observation and measurement of the electromagnetic field. Deformation effect.
By setting different initial conditions, the effects of different charging voltages and different positions on the effect of electromagnetic force were analyzed, which provided a reference for the subsequent measurement of the deformation of liquid metal by the pulsed magnetic field.

2. Principle of test, device and system settings

2.1. Principle of test
In order to eliminate the influence of coil heat generation on the change of the thermometer, and then measure the deformation of the liquid metal by the electromagnetic field, the kerosene thermometer and the mercury thermometer were selected as the test objects, and the temperature-sensitive bubbles of the kerosene thermometer and the mercury thermometer were placed inside the coil. The number of changes in the display of the two thermometers was taken simultaneously with a video camera. The test principle is shown in Figure 1. When the exciting coil is pulsed, a changing magnetic field is rapidly formed inside the coil. Mercury placed in the thermometer inside the coil induces an induced current. The induced current interacts with the induced magnetic field to generate electromagnetic force. It is inferred that the liquid metal mercury is greatly increased. The electromagnetic force changes abruptly, and then the temperature-sensitive bubble is energized by the coil to generate heat, and the indication continues to rise slowly. In the kerosene thermometer, there is no induced current and is not affected by the electromagnetic force. Only the ohmic heat generated by the coil is energized. As a result, it is assumed that the number of kerosene thermometers will rise slowly without abrupt changes.

![Figure 1. Electromagnetic field acting on two thermometers](image)

Under the premise of eliminating the variation of the current generated by the coil heat generation on the thermometer, the effect of the electromagnetic field on the temperature-sensitive bubble at the same position and at different voltages was measured. When the frequency of the axial pulsed magnetic field reaches a certain value, due to the skin effect, the electromagnetic force of the mercury receptor is mainly concentrated in the surface layer, the internal electromagnetic force is very small, and the diameter of the mercury temperature sensing bubble is larger than the diameter of the capillary, so the mercury feeling. The induced bubble current density and magnetic induction intensity are greater than the corresponding values at the capillary, resulting in a larger electromagnetic pressure difference, under the action of the electromagnetic field, mercury flow deformation occurs, the thermometer shows a sudden change, according to the thermometer's mutation size comparison Mercury is deformed by the electromagnetic force and qualitatively analyzes the effect of the electromagnetic field on the deformation of liquid metal. The measurement principle is shown in Figure 2.
2.2. System configuration and test setup
The test system is mainly composed of a charging module, a capacitor bank, a control switch, a three-electrode switch, a high-speed camera system, an excitation coil, a thermometer, and a current and voltage measuring device. The high-speed camera system includes a high-speed camera, a light source, and a computer. The number of test shooting frames is 5,900 fps. The excitation coil is a densely wound straight solenoid coil with a length of 50 mm and a rectangular cross-section of mm. The mercury thermometer and kerosene are used for comparison tests. The specifications of the thermometer are national standard 0-100°C, and the division value is 1°C. When measuring the deformation of mercury at different voltages, a mercury thermometer with a measuring range of 0-100°C and an indexing value of 0.5°C is used; the total capacitance of the capacitor bank is used. 5000V, 6000V, 7000V and 8000V are selected as the test voltage. When the charging module is charged to the set voltage, after manually triggering the high-speed camera and the control switch, the trigger signal turns on the three-electrode switch, the capacitor bank is discharged through the excitation coil, and the camera records the change condition of the thermometer. After each test, the remaining thermometer is returned to room temperature, and the charging voltage of the capacitor bank is adjusted to conduct the next test.

3. Results of test and analysis

3.1. Deformation measurement of different temperature-sensitive liquids
Two cameras take two thermometers to show the change of the number, and the measurement results are shown in Figure 3. From the measurement results under different voltages, it can be seen that the Mercury retention thermometer under a certain charging voltage, in a very short period of time, shows a sudden change in the number, and the temperature curve continues to rise after a period of time, and the kerosene thermometer is discharged after For a period of time (approximately 2s), the number is unchanged, after which the number begins to rise smoothly. This is because the mercury in the thermometer undergoes sudden changes due to
The electromagnetic force. The larger the electromagnetic force is, the more obvious is the sudden change in the number. After that, the heat generated by the coil is transmitted to the temperature-sensitive bubble and the number of mercury thermometers continues to increase. The temperature-sensitive liquid kerosene in the thermometer is non-metal, and it is not affected by the electromagnetic force during the electrification process. The number does not change abruptly. The heat generated by the energization of the coil needs a certain time to pass through the air. Therefore, the change in the number of kerosene thermometers lags behind that of mercury. Thermometer; The sudden change of the temperature indication number increases as the charging voltage increases, because the higher the charging voltage of the capacitor is, the more energy is discharged, and the greater the electromagnetic energy generated in the solenoid coil, the more sensitive the mercury bubble is. The larger the deformation after electromagnetic field action. Comparing the final temperature rise after discharge, it was found that the change in the final display of the mercury retention thermometer and the kerosene thermometer tends to be consistent and increases with the increase of the charging voltage because the Joule heat is generated when the coil passes current, and the heat conduction to the temperature After the bubble, the temperature reading is changed, and the temperature rise caused by Joule heat is greater than the temperature rise caused by the electromagnetic force. The Joule heat generated by the energization of the coil determines the final temperature rise of the two thermometers.

From the measurement results, it can be seen that when the electromagnetic field acts on different temperature-sensing liquids at the same time, only the thermometer whose temperature-sensitive liquid
is liquid metal mercury shows abrupt changes. The magnitude of the mutation is related to the action of the electromagnetic field, so the thermometer is displayed after the coil is discharged. The mutation can measure the deformation of the liquid metal by the electromagnetic field.

3.2. Deformation measurement of liquid metal at different voltages

Based on the above experiments, high-speed cameras are used to more accurately capture the abrupt changes of the thermometer under different voltages. When the mercury is affected by the pulsed electromagnetic field, the induced current inside the mercury is small, and the heating effect of the induced current is negligible. Therefore, the sudden change of mercury thermometer number is proportional to the electromagnetic pressure difference. FIG. 4 shows the mercury temperature sensing bubble placed in the position shown in the schematic of FIG. 2, where the temperature

![Figure 4. Change in the number of thermometers under different charging voltages](image)

Sensing bubble is located to the left of the coil axis. It can be seen from Figure 8 that as the capacitor charging voltage is higher, the temperature change per unit time is greater, and the longer the thermometer shows a sudden change, the temperature change tends to be faster then slower, and the thermometer shows a sudden change in the number.

Big, to further verify the above conclusions. By comparing the temperature change results of the temperature-sensitive bubble on the left side (Fig. 1) and the right side (Fig. 2) of the coil axis, it can be seen that the two-position mutation results are basically the same, because the two positions are related to the solenoid coil. Aisymmetric, the magnetic induction intensity, induced current density, etc. are also symmetrical in the two position regions. The electromagnetic force of the temperature-sensing bubble is equal in both positions, so the thermometer shows a nearly identical mutation. Through the test results, it can be found that the electromagnetic field has a deformation effect on the non-uniform diameter of the liquid metal, where the larger diameter is subjected to a larger electromagnetic force, and the smaller diameter part receives a smaller electromagnetic force. Due to the effect of the electromagnetic pressure difference, the liquid metal has a large diameter. At the small diameter, the diameters tend to be the same. The measurement results can prove that the diameter of the liquid metal with static non-uniform diameter will be consistent after being acted by the electromagnetic field. Likewise, the diameter of the high-flying metal jet is consistent with the effect of the electromagnetic field. Increased length increases the strength of its armor. The measurement method can effectively measure the deformation after the electromagnetic field acts on the liquid metal, and qualitatively verifies that the electromagnetic field
acts on the metal jet to make its diameter uniform, which provides powerful evidence for the application of the electromagnetic field to enhance the power of the armor-piercing projectile. Its promotion is applied to deformation measurement of metals after electromagnetic constrained forming.

4. Conclusion

(1) Using a high-speed camera to measure the change in the number of different temperature-sensing liquid thermometers, it is possible to distinguish the heat generated by energization of the coil and the deformation of the electromagnetic field. The heat conduction from the coil is slower, and the electromagnetic force has a shorter time and the thermometer indicates the number of mutations can be used to qualitatively measure the difference in electromagnetic pressure at the maximum diameter and the minimum diameter.

(2) When the mercury temperature-sensitive bubble is located at two symmetrical positions inside the coil, the number of mutations is basically the same, and the symmetry of the magnetic field within the coil is verified. The magnetic induction intensity distributions of the two symmetrical regions are the same and the electromagnetic forces are equal.

(3) The above measurement principle can be used to qualitatively verify the confinement effect of the electromagnetic field on the metal jet, and it can also be used as a measurement method for measuring the rapid deformation of a liquid metal, slab or tube subjected to the action of a pulsed electromagnetic field.

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