EFFECT OF CIRCUIT PARAMETERS AND WIRE PROPERTIES ON ENERGY DEPOSITION OF EXPLODING AN AL WIRE IN WATER

Qing Zhou, Qiao-gen Zhang*, Lei Pang, Jun Zhang, Jun-ping Zhao, Jia-sen Chang, Hu Wang
School of Electrical Engineering, Xi'an Jiaotong University, Xi'an 710049, China
* Email: <hvzhang@mail.xjtu.edu.cn>

Abstract: The wire material passes through all the states, including solid, liquid, gas state and plasma during the progress of electrical wire explosion. The deposited energy throughout the electrical wire explosion comes from the Joule heating of current. The energy deposition has an important effect on the transition of the wire material from the condensed state to conducting plasma. In this paper, the energy deposition of underwater electrical explosion of Al wires driven by pulsed voltage of microsecond time scales was investigated. The current and voltage on the wire load was measured by a self-integrating Rogowski coil and a voltage divider, respectively. The stages of wire melting, liquid and vaporization was defined in terms of some critical points. The resistive voltage at the wire load was obtained by subtracting inductive voltage from the measured value of the voltage drop. The deposited energies in three stages mentioned above and before breakdown were calculated by integrating the product of the current and resistive voltage in corresponding stage. Results of electrically exploding Al wire underwater for the pulse in microsecond time scale showed that the effect of circuit parameters on the deposited energies in the stages of melting and liquid state was not obvious, but the effect in the stage of vaporization was the opposite. The effect of wire properties on the deposited specific energy in the stage of vaporization was more obvious than that in the stages of melting and liquid state as well. The inhomogeneity of energy deposition also had an important effect on underwater electrical explosion of an Al wire.

1 INTRODUCTION

Electrical explosion of wires is widely used in various applications, such as pulse sharpening in pulsed power technique [1], pulse ignition of rocket fuel and explosive [2], development of X-ray sources for microelectronic technologies [3], etc. Since the high energy is deposited, underwater electrical wire explosion (UEWE) has great application prospect in shock wave generation and nanopowder preparation, which attracts various scientific and technological purposes [4, 5]. The wire electrical explosion passes through the four states from the condensed state to conducting plasma, i.e. solid, liquid, vapor and plasma. The energy deposition into the wire material by Joule heating determines the process of phase transition. It is influenced by many factors, such as the material properties including species, length and diameter of the wire, the circuit parameters including circuit inductance, capacitance and applied voltage, and the characteristics of medium including species, density and pressure. Although many studies on energy deposition have been investigated in nanosecond time scale, the energy deposition with lower dI/dt in microsecond time scale UEWE is required to make further researches.

This paper describes the results of an experimental study on underwater electrical explosion of an Al wire in microsecond time scale. The resistive part of voltage and energy deposition is calculated by mathematical method. The effect of circuit parameter, including applied voltage and circuit inductance, and the Al wire properties consisting of length and diameter on the energy deposition during underwater electrical explosion of an Al wire is analyzed.

2 EXPERIMENTAL SETUP

Figure 1 is the block diagram of the experimental setup. It was an *LC* circuit containing a capacitor with capacitance *C* of 1μF. The capacitor was charged to three voltages of 7, 10 and 12 kV, resulting in stored energy up to 24.5, 50 and 72 J, respectively. The ratio of three stored energy was approximately 1:2:3. The capacitor was discharged into a wire load through a spark gap switch and circuit inductance *L*. In the experiment, the inductance *L* could be changed with two values of 2.66 and 6.90 μH. The whole circuit resistance except wire resistance is approximately 0.5 Ω. A self-integrating Rogowski coil and a voltage divider were used for the measurements of the current and voltage at the wire load, respectively. Al wires of different lengths of 1-5 cm and diameters of 40, 60 and 100 μm were used. The exploding wire was placed in a water tank. The electrical conductivity of water was approximately 200 μS/cm. A simple "dynamic model" of the inductance in Ref. 6 was used because of low inductive voltage in microsecond explosion. The inductive voltage drop was subtracted from the measured value of the voltage drop to obtain the resistive component of the voltage drop.

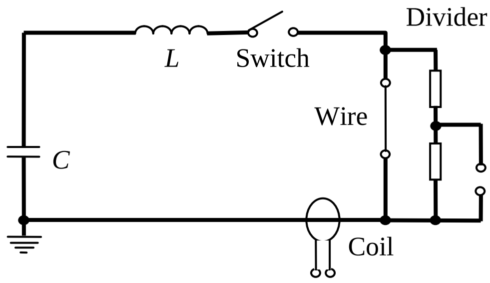

Figure 1: Experimental setup

3 EXPERIMENTAL RESULTS

Presented in Fig. 2 are typical waveforms of discharge current and voltage drop on Al wire of 100 μm in diameter and 5 cm in length with the capacitor charged to the voltage of 7 kV and the circuit inductance of 2.66 μH. In Fig. 2, two sudden jumps appear on the waveform of the voltage, i.e. from t_1 to t_2 and from t_3 to t_4. The first step from t_1 to t_2 is related to the wire melting. As the energy is deposited into the wire, the superheated liquid appears. After the point t_3, intensive expansion of the wire begins, leading to the phase explosion. The voltage collapse appears at the voltage peak point t_4, resulting in the formation of the plasma. From Fig. 2, it can be seen that the explosion discharge occurs, forming a plasma channel over a very short period, compared with the time of wire explosion. So we used point t_4 as the vaporization end to calculate the vaporization energy. The three stages, i.e., melting, liquid and vaporization, can be defined from t_1 to t_2, t_2 to t_3 and t_3 to t_4, respectively. The energy deposition before breakdown can be calculated from the beginning to t_4. From Fig.2, it should be noted that there are great changes in the voltage waveform at four points. The uncertainties in defining four points lead to the calculation errors in deposited energy in the stages of melting, liquid vaporization, and before breakdown. The time of four points was obtained by differentiating voltage waveform to reduce errors in the definition of four points. In our study, the error in deposited energy before breakdown

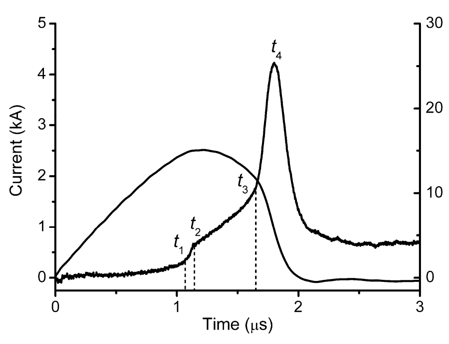

Figure 2: Typical discharge current and voltage waveforms of exploding Al wire (Ø 100 μm, l=5cm, L=2.66 μH, U_0=7 kV)

resulting from defining point t_4 was less than 3% and thus neglected. The underwater electrical explosions of an Al wire with different applied voltage, circuit inductance, the length and diameter of Al wire were studied based on the analysis of the current and voltage waveforms as well as the calculated energy deposition.

The waveforms of current and voltage as well as the evolutions of electrical power and energy deposition with exploding Al wires of 100 μm in diameter and 3 cm in length for the different applied voltages of 7, 10 and 12 kV are presented in Fig. 4. The current rise rate is approximately up to ~2.4, ~3.6 and ~4.3 kA/μs for the applied voltages of 7, 10 and 12 kV, respectively. Obviously, the time from the solid state to the liquid state for applied voltage of 12 kV is shorter than those of 7 and 10 kV. The current rise rate increases with the increase of applied voltage, leading to higher energy deposition into wire as well as acceleration of explosion process, i.e. obviously shortening the stages of solid, melting and liquid. Additionally, the pressure of magnetic field induced by current restrains the expansion of exploding wire before phase explosion, leading to superheated metal liquid and intensive expansion during phase explosion. In this condition, the resistance of exploding wire and the current change very fast, forming a high voltage drop on the load.

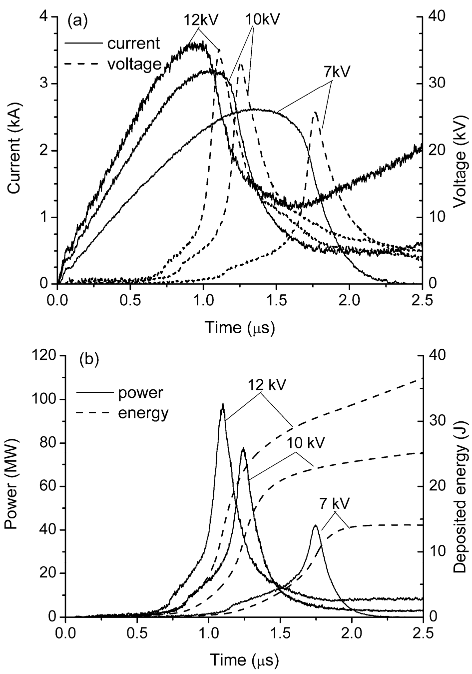

Figure 3: Waveforms of exploding Al wire with diameter of 100 μm and length of 3 cm at applied voltages of 7, 10 and 12 kV (L=2.66 μH). (a) current and voltage. (b) electrical power and deposited energy

Figure 4 shows the dependence of deposited energy during melting, liquid stage, vaporization

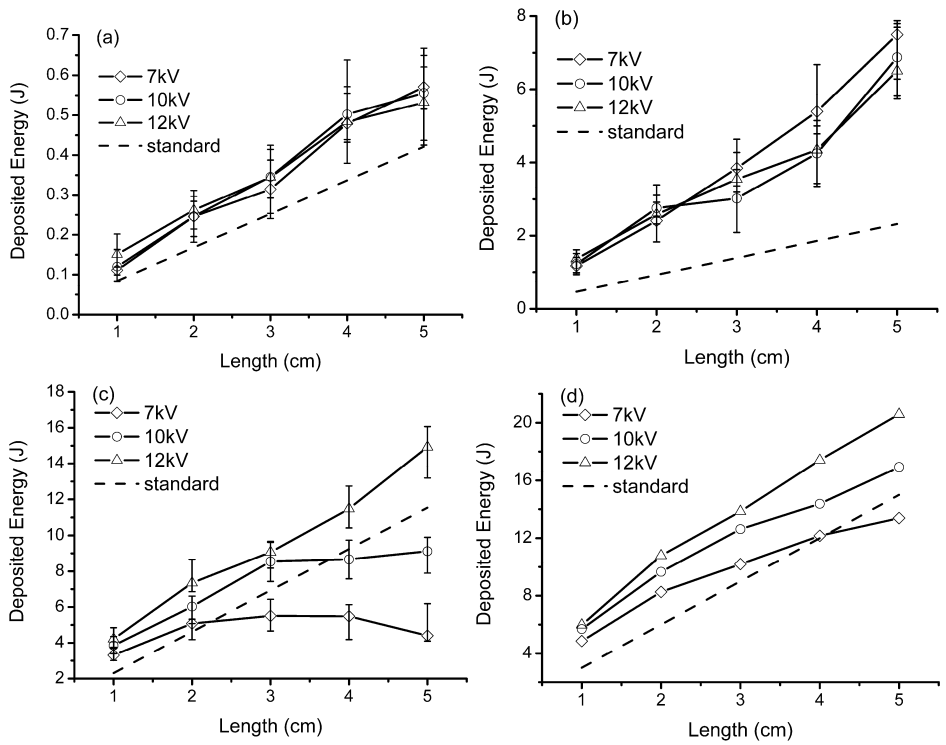

Figure 4: Wire length dependence of deposited energy in different stages with exploding Al wires of 100 μm in diameter at applied voltages of 7, 10 and 12 kV (*L*=2.66 μH). (a) Melting. (b) Liquid stage. (c) Vaporization. (d) Before breakdown

and before breakdown on the wire length for exploding Al wires with diameter of 100 μm in the case of different applied voltages. The dashed line is the energy required in corresponding stage in standard condition[7]. The error results from that one in defining the critical points mentioned above. The effects of applied voltage on the deposited energy in the stages of melting and liquid are not that obvious. But the deposited energy in liquid stage for applied voltage of 7 kV is slightly higher than that for 10 and 12 kV, while their difference becomes more obvious with the increase of the wire length. It may result from a growth of energy loss caused by heat transmission in the stage for applied voltage of 7 kV. The deposited energy during vaporization and before breakdown has an obvious increase with the increase of applied voltage. The longer the wire is, the more obvious their difference between different applied voltages becomes. Furthermore, the deposited energy during vaporization for both 7 and 10 kV shows a saturation trend for Al wire longer than 2 cm, which may the result of the insufficiency of initial energy, especially for the applied voltage of 7 kV. For applied voltage of 7 kV, the deposited energy before breakdown with exploding Al wire of 100 μm in diameter and 5 cm in length is lower than the atomization enthalpy. It is indicates that the wire material is not completely vaporized before breakdown and the material exists in the form of vapor and drop mixture, or wire material absorbs energy from the reaction between Al and water.

Figure 5 shows the waveforms of current and voltage as well as the electrical power and energy deposition with exploding Al wire of 100 μm in diameter and 3 cm in length for circuit inductance of 2.66 and 6.90 μH. The current rise rate increases with the decrease of circuit inductance, namely, ~3.6 kA/μs for *L*=2.66 μH and ~1.4 kA/μs for *L*=6.90 μH. The process of exploding Al wire for

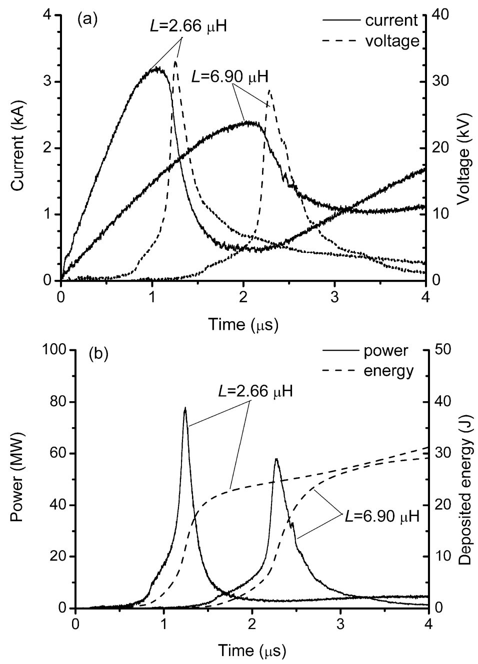

Figure 5: Waveforms of exploding Al wire of 100 μm in diameter and 3 cm in length using circuit inductance of 2.66 and 6.90 μH (U_0=10 kV). (a) current and voltage. (b) electrical power and deposited energy

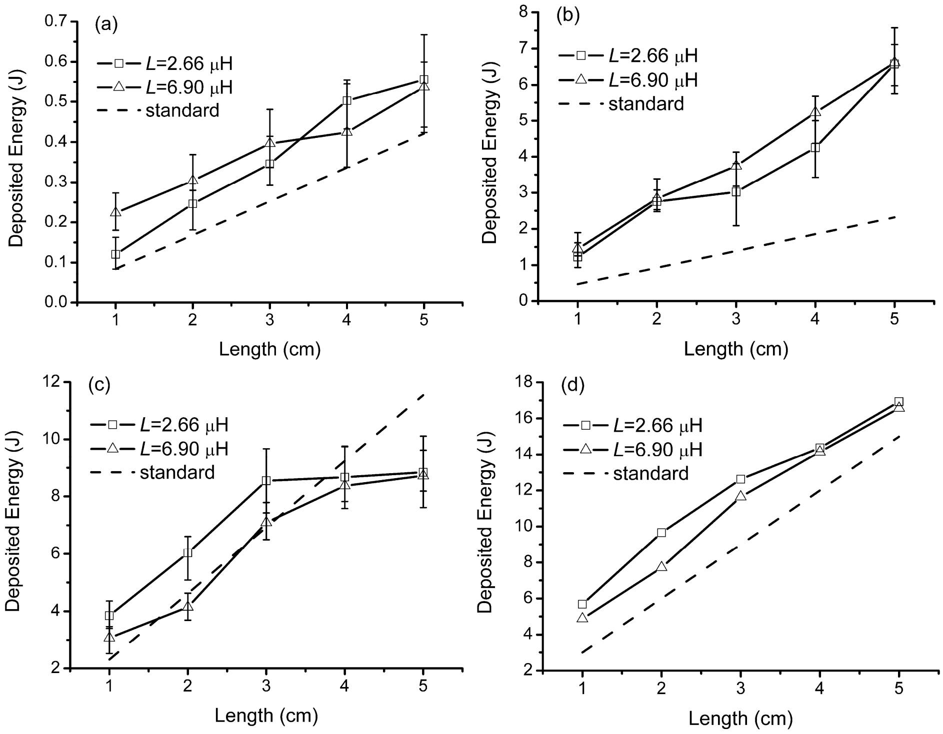

Figure 6: Wire length dependence of deposited energy in different stages by exploding Al wires of 100 μm in diameter with circuit inductance of L = 2.66 and L = 6.90 μH (U_0 = 10 kV). (a) Melting. (b) Liquid stage. (c) Vaporization. (d) Before breakdown.

L=6.90 μH，especially the stages of solid, melting and liquid, is obviously delayed compared with that of L=2.66 μH. The effect of decreasing circuit inductance on explosion is the same as that of increasing applied voltage. The processes of wire explosion and energy deposition are accelerated by increasing current rise rate.

Figure 6 shows the dependence of the energy deposition into exploding Al wires of 100 μm in diameter during melting, liquid stage, vaporization and before breakdown on the wire length in the case of different circuit inductance. The effects of circuit inductance on deposited energy in both stages of melting and liquid are not obvious as well, as with those of applied voltage. However, the result is the opposite in vaporization stages. The deposited energy in liquid stage with circuit inductance of L= 2.66 μH is slightly lower than that with L= 6.90 μH, which is contrary to the deposited energy during vaporization. The process in liquid stage is prolonged with the increase of circuit inductance, leading to more energy loss. The pressure of magnetic field induced by current restrains the expansion of exploding wire in vaporization stage, leading to high peak voltage and more energy deposition in the stage. From Fig. 6(c), it is indicated that it is easy for the deposited energy in vaporization stage to reach its maximum value with shorter wire length when circuit inductance is larger. Since the energy loss has a growth trend with the increase of explosion time in L= 6.90 μH, the difference between deposited energy before breakdown with circuit inductances of 2.66 and 6.90 μH is reduced with the increase of the wire length.

Since the initial resistance of wire compared with the circuit resistance is much smaller, the current rise rates of wires with different diameters and lengths are almost same. In figure 7, the peak voltage of Al wire with diameter of 100 μm increases with the increase of wire length, but the same effect of wire length on peak voltage doesn't appear with Al wires of 40 and 60 μm in diameter. The reason may be that the inhomogeneity of energy deposition，which is intensified with the increase of wire length and has greater influence on thinner wire, leads to the premature breakdown. As a result, there are critical values in curves of peak voltage with exploding 2 and 4 cm long Al wire for 40 and 60 μm in diameter, respectively. Especially, the voltage amplitude for exploding Al wire with diameter of 40 μm has an obvious decline when the length is 5 cm. It is indicated that

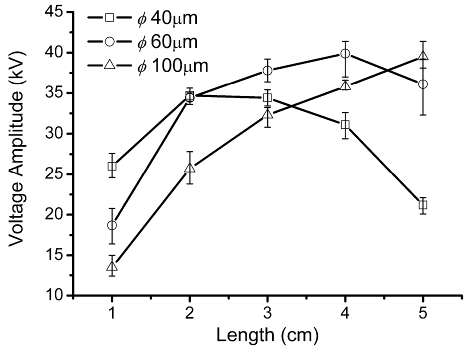

Figure 7: Dependence of voltage amplitude on wire length with exploding Al wires of different diameters (U_0=10kV, L=2.66 μH)

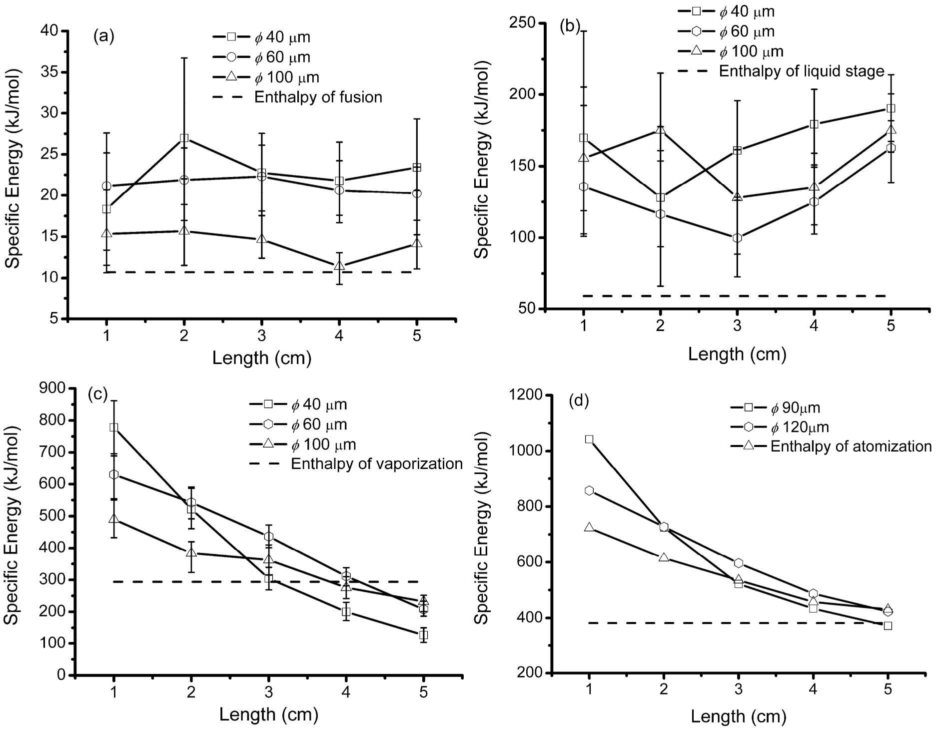

Figure 8: Length dependence of specific energy during different stages for different wire lengths (L = 2.66 μH, U_0 = 10 kV). (a) Melting. (b) Liquid stage. (c) Vaporization. (d) Before breakdown

the inhomogeneity has a greater influence on explosion when wire diameter is smaller.

Figure 8 shows the contrast between specific energy with different wire properties in four stages and enthalpy (the dashed line) in standard condition. The specific energy of melting has a growth trend with the decrease of the wire diameter except for Al wire with diameter of 40 μm and length of 1 cm but is slightly influenced by the wire length. The influence of the wire diameter on the specific energy in liquid stage shows no distinct pattern, while the influence of wire length on it is hardly noticeable. The increase of the wire diameter intensifies inhomogeneity of energy deposition on wire cross section by skin effect. So the specific energy of vaporization decreases with the increase of the wire diameter except for Al wire of 40 μm diameter in Fig. 8(c). The premature breakdown results in the rapider decline of specific energy in vaporization stage for Al wire of 40 μm in diameter than those in other diameters. The specific energy of vaporization is less than the enthalpy of vaporization with different reasons. The reason for Al wire of 100 μm in diameter may lie in the insufficient initial energy of 10 kV discharge voltage and incomplete vaporization, while it for 40 and 60 μm is the premature breakdown. The specific energy before breakdown decreases with the increase of the wire length. Moreover, it for Al wire of 40 μm in diameter decreases more quickly as well as the specific energy in vaporization stage. The specific energy before breakdown is higher than atomization enthalpy except for Al wire of 40 μm in diameter and 5 cm in length. It of Al wire of 40 μm in diameter and 5 cm in length under atomization enthalpy may result from the inhomogeneity of energy deposition, which results in premature breakdown and the lower energy deposition, and energy absorption from the reaction between Al and water.

4 CONCLUSION

Presented in this paper are the experimental results of underwater electrical explosion of an Al wire in microsecond time scale. The current rise rate has an important influence on explosion. Increased by increasing applied voltage and decreasing circuit inductance, it can accelerate the explosion process and improve the energy deposition before breakdown, peak voltage and power. Although there is no significant improvement in the current rise rate by varying the wire parameters, the process of explosion is extended and the specific energy before breakdown decreases with increasing the material amount of Al wire. Additionally, the inhomogeneity of energy deposition, which leads to the premature breakdown and lower energy deposition, has greater influence when the wire is thinner and longer.

5 REFERENCES

[1] V. A. Demidov, A. S. Boriskin, N. V. Stepanov, I. V. Konovalov, S. A. Kazakov, K. V. Shibalko, Y. V. Vlasov, V. A. Yanenko, I. V. Rozhnov, S. N. Golosov, E. V. Shapovalov, and A. S. Shuvalov: "Magneto-Cumulative Generator with Electric-Exploded Current Opening Switch

to Power High-Impedance Load," in Proc. IEEE Pulsed Power Conf., 2005, pp. 553–556.

[2] W. Chase: "Exploding wires," Usp. Fiz. Nauk, vol. 85, No. 2, 381-386, 1965

[3] V. A. Boiko, S. M. Zaharov, A. A. Kolomensky, S. A. Pikuz, A. I. Samochin, A. Ya. Faenov, and S. Ya. Hahalin: "Use of exploding wires for X-ray lithography," Pis'ma v Zhurnal Tekhnicheskoi Fizika, vol.8, no.3-4, pp. 129-133, Feb. 1982.

[4] Y. E. Krasik, A. Grinenko, A. Sayapin, and V. Tz. Gurovich: "Generation of sub-Mbar pressure by converging shock waves produced by the underwater electrical explosion of a wire array," Physical Review E, vol. 73, pp. 057301, May 2006.

[5] C. H. Cho, S. H. Park, Y. W. Choi, and B. G. Kim: "Production of nanopowders by wire explosion in liquid media," Surf. Coat. Technol., vol. 201, no. 9-11 pp. 4847-4849, Feb. 26, 2007.

[6] G. S. Sarkisov, S. E. Rosenthal, K. R. Cochrane, K.W. Struve, C. Deeney, and D. H. McDaniel: "Nanosecond electrical explosion of thin aluminum wires in a vacuum: Experimental and computational investigations," Phys. Rev. E, vol. 71, no. 4, pp. 046404, Apr. 2005.

[7] M. W. Chase: “NIST-JANAF Thermochemical Tables”, in J. Phys. Chem. Ref. Data Monogr. 9., 4th ed. Gaithersburg, MD: NIST, 1998.