ELECTROTHERMAL ANALYSIS OF MICRO/NANOWIRE INITIATORS FOR ENERGY PRODUCTION APPLICATIONS

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Abstract: Micro/nanoscale initiators can enhance the pressure output and reduce the required voltage input for ignition because micro/nano wires have a large surface area and high electrical and thermal conductivities. We investigated electrothermal behavior of Cu and Au microwires with diameters in the range of 25 ~ 250 µm. Microwires with smaller diameter ignited quickly and the ignition of microwire was captured. We used Finite Element Method (FEM) to predict the electrothermal behavior of micro/nanowire initiators by combining an electric circuit model and a heat-transfer model with Joule heating as the heat source. The effect of the thermal-dependence of electrical resistivity and thermal conductivity of the wire is included. The simulation results are in good agreement with the experimental observations in terms of the burning time and voltage rise profile of microwires connected to a power source. The model is extended to nanoscale for initiation behavior predictions of nanowires. Micro/nanoscale initiators along with FEM model can be used to guide the electrical circuit design and obtain optimum operation conditions for development of initiators, fire investigation, and energy harvesting applications.

Keywords: electrothermal analysis, finite element method (FEM), micro/nanowire initiators, fine wire fusing, wire igniter, energy production

INTRODUCTION

Fusing fine wires has been studied for heat transfer [1] and pre-arching mechanism [2] using sub milimeter scaled wires with different diameters. Mechanism of firing a conducting wire has been investigated for a fire investigator in order to examine the consequence or the cause of the fire [3] and for a exploding bridge wire (EBW) and exploding foil initiator (EFI) as a electric detonator [4].

Finite element method (FEM) has been used as a useful tool in order to improve the design and system reliability of thick film initiators of crash sensors for automotive applications [5,6]. We have established a FEM to predict the electrothermal behavior of micro/nanowire initiators by combining an electric circuit and heat-transfer models with Joule heating as the heat source and the simulation results were confirmed by the experimental results in terms of the burning time and voltage rise profile of microwires connected to the power source of 12 V 12 Ah battery.

Electrothermal behavior of Cu and Au microwires with diameters in the range of 25 ~ 250 µm was investigated using Ohm's law and temperature dependence of resistivity. By adding current viewing resistor (R_{CVR}), resistance and temperature development were obtained based on the current flow.

FEM modeling of the thermoelectric behavior of microwire is extended to nanowire for initiation behavior predictions. Thermoelectric analysis of micro/nanoscale initiators can be used to design the optimum electrical circuit for development of initiators [4] and guide fire investigation [5] and energy harvesting applications [7,8].

THEORY

The electric-thermal coupled problem is given by the equation from transient heat conduction [9]

$$c_v \rho_m \frac{\partial T}{\partial t} = \sigma_e |E|^2 + \nabla \cdot (k \nabla T) \qquad (1)$$

and the equation for the electric field E

$$\frac{\partial \rho_e}{\partial t} = E \cdot \nabla \sigma_e + \sigma_e \nabla E \qquad (2)$$

with electrical conductivity as a function of temperature written as [10]

$$\sigma_e = 1/(\rho_0 (1 + \alpha (T - T_0))) \qquad (3)$$

Where the electrical conductivity σ_e, thermal conductivity k, and specific heat c_v are all functions of temperature. The diffusion of electrons in metal $\partial \rho_e / \partial t$ is set to zero.

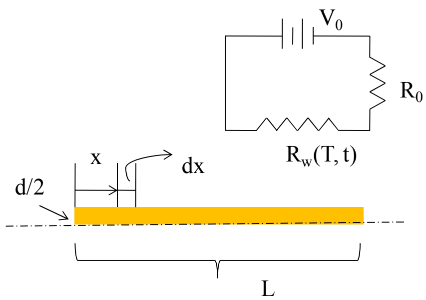

Figure 1. Schematic illustration of the electrical thermal coupled model. V_0 is a voltage source, R_w is a wire resistance, and R_0 is a sum of all other resistance in the circuit.

We have established a FEM model to predict the electrothermal behavior of micro/nanowire initiators by combining an electric circuit and heat-transfer models with Joule heating as the heat source. The heat loss from the micro/nanowire initiation is negligible due to the extremely short time of an order of milliseconds for a microwire and nanoseconds for a nanowire. The above coupled problem is solved by a commercial FEM solver COMSOL multiphysics [11]. The electrical resistivity for copper microwire [12] is

$$\rho_e = 16.78 \times [1 + 0.004041 \times (T - 293)] \ n\Omega \cdot m \quad (4)$$

and for gold microwire is

$$\rho_e = 22.14 \times [1 + 0.003715 \times (T - 293)] \ n\Omega \cdot m \quad (5)$$

The resistance of microwire is taken as the reciprocal of the resistivity and can be written as function of time and dimensions, and can be obtained through

$$R_w = \frac{1}{\frac{1}{rL}\iint \sigma_e(r,x)drdx} \frac{l}{\pi \cdot r^2} \quad (6)$$

The calculation is based on the circuit as shown in Figure 1 with a 12 V 12 Ah battery source. The temperature development through the microwire versus time is shown in Figure 2. The highest temperature occurs in the middle of the wire while the ends fixed at room temperature. The simulation result of the voltage rise through the microwires was confirmed by the experimental observations shown in the following section.

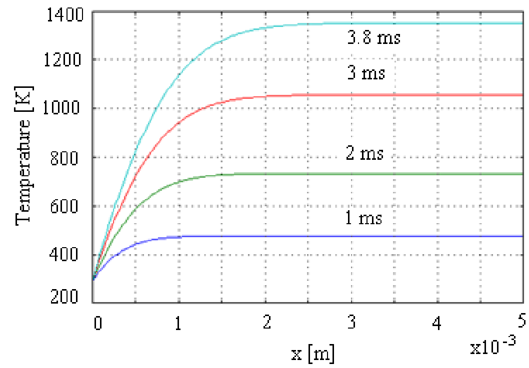

Figure 2. Temperature development through the 10 mm long Cu microwire with 100 um diameter. 5 mm is the center position of the wire.

EXPERIMENTAL

The electric voltage rise of 10 mm long Cu microwire with 100 um diameter was measured by the fast response oscilloscope using a relay which was switched by a function generator.

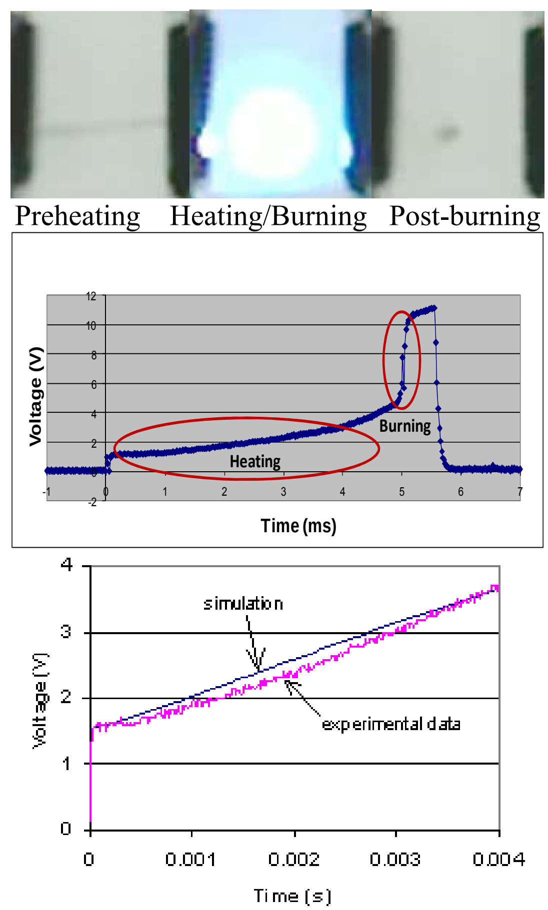

Figure 3. The captured moment of ignition of microwire-based initiator (top). Voltage development of microwire shows heating and burning process by few milliseconds of current flow (middle). The experimental result is in good agreement with a simulated result during heating (bottom).

Figure 3 shows the captured moment of fast ignition of a microwire by a video camera and the voltage development of microwires which is in good agreement with the simulated result during heating.

Electrothermal behavior of 10mm long Cu and Au microwires with diameters in the range of 50 ~ 250 µm was investigated and summarized in Table 1. A microwire with smaller diameter ignited quickly in short period of time of current flow due to finite length effect [1].

Material	Diameter (µm)	Resistance (mΩ)	Burning Time (ms)
Au	50	126	0.73
Au	100	32	3.220
Au	250	8.2	67.9
Cu	100	25	5.42
Cu	200	6.8	56.1

Table 1. Burning time vs. diameter. Burning time is getting longer as the diameter gets larger.

Additional resistance of 0.5 Ω, R_{CVR}, was added in order to get an accurate current flow through 10 mm long Cu microwire with 100 um diameter. In serial connection, the current through microwire is the same value of the current through R_{CVR}. Resistivity increase caused by temperature increase was calculated based on the Ohm's law and temperature dependence of resistivity (Eq. 4) as shown in Figure 4. Resistance of microwire increased slowly upto 191 ms and temperature of microwire also slowly increased until it was broken off.

Electrothermal behavior of 10mm long Cu and Au microwires with diameters in the range of 25 ~ 100 µm was investigated and summarized in Table 2. Cu micowire with a 200 µm diameter and Au micowire with a 250 µm diameter did not burn with R_{CVR}.

Material	Diameter (µm)	Resistance (mΩ)	Burning Time (ms)
Au	25	620	1.47
Au	50	158	6.19
Au	100	44	75.0
Cu	100	32	191

Table 2. Burning time vs. diameter with the current viewing resistance (R_{CVR}) of 0.5 Ω. Burning time is getting longer as the diameter gets larger.

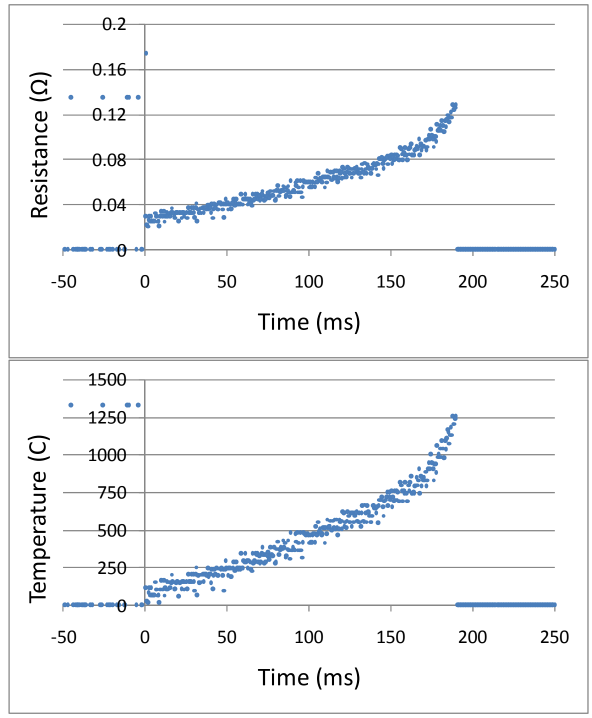

Figure 4. Resistance increases during heating until the wire burns and breaks (top). Temperature increase calculated based on temperature dependence of resistivity (bottom).

Charging and discharging circuit were made in order to apply high voltage within very short period of time. The electrical circuit consists of charging and discharging two parts as shown in Figure 5. The function generator is used to open and close the relay 1 to make square wave from the power source battery. This square wave is input to the transformer. The capacitor C is starting to be charged after the bridge rectifier from the output of the transformer. The voltmeter gives the progress of the charging. The voltage of capacitor can reach up to 300V in 3 minutes. Once the desired voltage is reached, the function generator is turned off and the switch 1 is closed. A very small resistor, R_{CVR}, is added to the discharging circuit to monitor the current changing. High speed oscilloscope is used to record the real-time voltages of R_{CVR} and initiator during the ignition process.

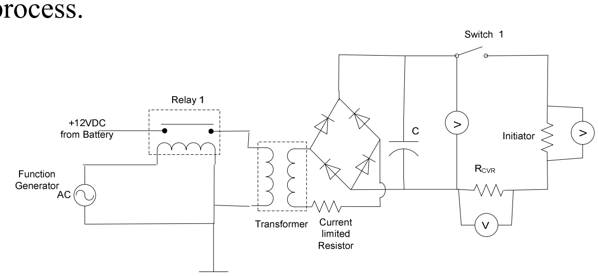

Figure 5. Schematic of the electrical circuit

Six of 1 μF capacitor were connected in parallel in the circuit and charged upto 450V in order to provide more current. The discharged current was then applied to a microwire by switching the relay and the function generator. Only Au micowire with 12.5 and 25 μm diameter was burned and the burning time was as quick as 100 μs or less.

We did initiation experiments using very thin Au microwires with a diameter of 12.5 and 25 μm and the voltage development was as quick as sub 100 μs and a little noisy. More measurement with a different diameter can be done in order to establish the relationship between wire diameter and burning time. Burning time is much faster for a charging circuit with high capacitor such as 68 μF.

CONCLUSION

We have investigated electrothermal behavior of 10 mm long Cu and Au microwires with diameters in the range of 25 ~ 250 μm for micro/nanowire initiators. Based on our FEM modeling, we have simulated the electrothermal behavior of micro/nanowire initiators by combining an electric circuit and heat-transfer models with Joule heating as the heat source. Simulated results were confirmed by the experimental data in terms of the burning time and voltage rise profile of microwires connected to a 12 V 12 Ah battery power source. This method can be used to predict the thermoelectric behavior of nanowire initiators. Resistivity increase caused by temperature increase was calculated based on the Ohm's law and temperature dependence of resistivity by using current viewing resistance. Six of 1 μF capacitor were connected in parallel in the circuit and charged upto 450V in order to provide more current.

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