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Research Article

Production of Kanthal-D Nanoparticles Using Exploding Wire Method

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Abstract

This work examines the production of nanoparticles using exploding wire method (EWM). It is applied by the sudden discharge of a high voltage energy, stored on a power source, through a thin wire. The required high voltage energy was obtained with the use a voltage multiplier circuit which was first designed in the simulation environment. Then the circuit realized by the circuit elements' parameters obtained through the simulation. Kanthal-D (FeCrAl alloy) wire was chosen as the thin metal, and all wire exploding experiments were carried out in air environment. The obtained nanoparticles were examined by SEM, and point analysis was applied to a target area on the SEM image. It is observed that the dimensions of obtained Kanthal-D nanoparticles in this study vary between 0-250 nm. In addition, EDS chemical microanalysis was performed to reveal obtained nanoparticles' composition. Fe (71-7-74-7%), Al (4.8%) and Cr (20.5-23.5%) atoms were detected in the exploded nanoparticles. With this study, it has been shown for the first time in the literature that the stored energy obtained by a voltage multiplier circuit can be used in the EWM to produce nanoparticles in appropriate sizes

Keywords: exploding wire, nanoparticles, voltage multiplier, SEM

Tel patlatma yöntemi ile Kanthal-D nanotanecik üretimi

Öz

Bu çalışmada tel patlatma yöntemi ile nanotanecik üretilmesi gerçekleştirilmiştir. Patlayan tel yöntemi, yüksek voltajda enerji depolanan bir güç kaynağının ince bir tel üzerinden aniden boşaltılmasıyla elde edilir. Bu yöntem için gerekli olan yüksek voltaj kaynağı gerilim katlayıcı devre yardımıyla yapılmıştır. Gerilim katlayıcı devre öncelikle simülasyon ortamında gerçekleştirilmiş ve elde edilen devre parametreleri ile devre elemanları seçilerek gerçek devre dizayn edilmiştir. Tel patlatma deneyleri hava ortamında gerçekleştirilmiş ve tel olarak Kantal-D teli seçilmiştir. Deney sonucunda elde edilen tanecikler SEM cihazı ile incelenmiştir. SEM görüntüsü üzerinde bir hedef bölgeye uygulanan nokta analizine göre Kantal-D nanotaneciklerin boyutlarının 0-250 nm arasında değiştiği görülmektedir. Ayrıca üretilen nanotanecik kompozisyonu ise EDS analizi ile kontrol edilmiştir. EDS analizinden Kantal-D tel nanotaneciklerin de Fe (% 71-7-74-7), Al (% 4.8), Cr (% 20.5-23.5) atomlarının tespit edildiği görülmüştür. Bu çalışma ile literatürde ilk kez gerilim katlayıcı devrede depolanan enerji tel patlatma yönteminde kullanılarak uygun boyutlarda nanotanecik üretilebileceği gösterilmiştir.

Anahtar Kelimeler: tel patlatma, nanotanecik, voltaj katlama, SEM

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1. Introduction

Nanoparticles are used in a wide and constantly growing area that includes medicine, cosmetics, aircraft/food industry, paint and armour materials. Also, construction industry, textile, energy, automotive, electronics, aviation are other areas of nanomaterial usage.

Different methods are used for nanoparticle production, of which one approach is exploding wire method (EWM)(Chang et al. 2021). For this; studies were first recorded in the 18th century using electrical discharge to vaporize a metal wire or foil. Dutch philosopher Martin van Marum (1750-1837), studied in electricity as well as medicine and geology, succeeded in heating and melting a thin wire using the discharge of leyden batteries, a simple form of a capacitor. Edward Nairne (1726-1806) was the first person try to understand the exploding wire idea (Hansen 2011)

It took great curiosity in the following 200 years and became an intense research subject in the 1950s(Hansen 2011). Systematic researches to produce particles with exploding a wire was first started in Russia in 1970s(Sedoi and Ivanov 2008). The dispersed composition and other properties of the formed nanoparticles depend on the conditions of the explosion. These conditions include electrical parameters, structure and properties of metal wire and its geometry such length and diameter, wire microstructure. Umakoshi et al. exploded aluminium and aluminium silicon using EWM and investigated the obtained particles in 1994 (Umakoshi, Yoshitomi, and Kato 1995).

In their study, Wang et al. produced Cu-Zn particles when a very strong impulse current with a density of 107 A cm-2 was applied to a capacitor with 36 kV charge voltage using the Cu-Zn wire (Shi, Zou, and Wang 2016). Sindhu et al. produced nanoparticles up to 100 nm size using aluminum wire in nitrogen, helium and argon environments. The process was carried out by charging 3 μF capacitors to a voltage of 25 kV using a 2-layer voltage multiplier circuit and then discharging on the wire(Sindhu, Sarathi, and Chakravarthy 2008). Das et al. 2012 produced nanoparticles with an average size of 55 nm by exploding copper wire in nitrogen environment using 7.1 μF capacitor charged at 9 Kv (Das et al. 2012). Wankhede et al. worked on charging and discharging a capacitor using varying voltages such as 600 V, 700 V, 800 V and 900V to obtained nanoparticles(Wankhede, Sharma, and Jha 2013) .

Tubular nanoparticles were obtained applying a charging voltage of up to 20 kV and peak current of 10 kA to metal wires such as copper and tungsten using a GVP generator (Lebedev Physical Institute, Russian Academy of Sciences) by Romanova et al. in 2015. (Romanova et al. 2015). In 2016 Shi et al. obtained nanoparticles using tungsten wire in a laser-coated gas chamber by charging a 10nF capacitor with 60kV charging voltage (Shi et al. 2016). In their study in 2017, Jerrin et al. charged a 50nF capacitor at 70 kV-80 kV for exploding copper wires and obtained nanoparticles (James 2017)(Ateş and Bahçeci 2015). Recently exploding wire studies also performed by (Peng et al. 2016) and (Ranjan et al. 2019)

2. Material and Methods

Exploding Wire Method (EWM):

The method of producing nanoparticles from a thin metal wire using high current density for a very short time and in a very high

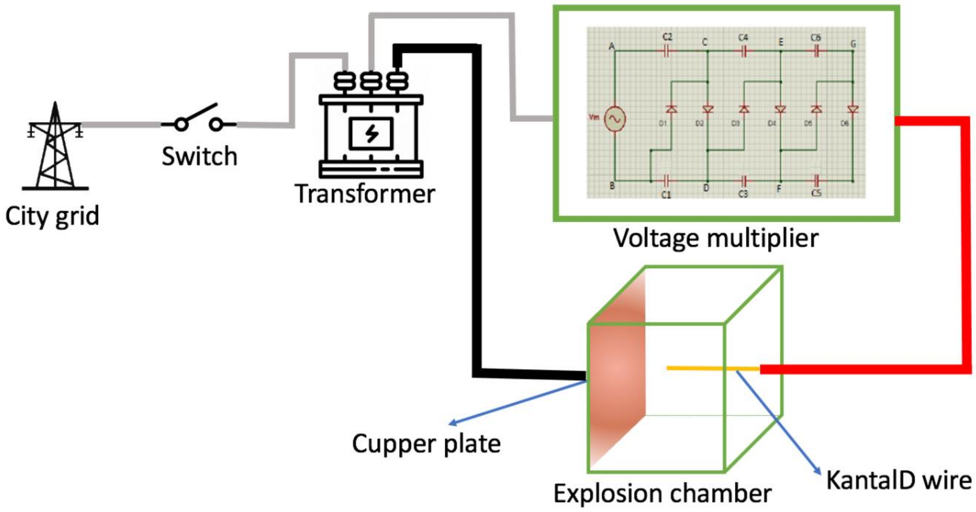

Figure 1. The proposed exploding wire block diagram

temperature and inert/reactive gas environment is called exploding wire method (EWM). The wire to be exploded is generally chosen as gold, iron, aluminum or platinum materials and is generally less than 0.5 mm in diameter(Rae and Dickson 2019). In this method, the wire first turns into plasma and then gets compressed over time with the effect of the high current. The overheated metal plasma at some point, rapidly expands creating a shock wave in the ionized gas environment around it. The detonation speed of the wire can reach 106-108 m/s range with the effect of this shock wave (James 2017). The experimental setup used in the study basically composed of three main components and is shown schematically in Figure 1. These are a transformer followed by a voltage multiplier circuit that rises the transformer output voltage to a high voltage value required for the wire to explode, and an insulated glass medium in which the explosion takes place

Experimental Setup for EWM

The experimental setup used in the study basically composed of three main components and is shown schematically in Figure 1. These are a transformer followed by a voltage multiplier circuit that rises the transformer output voltage to a high voltage value required for the wire to explode, and an insulated glass medium in which the explosion takes place. These components in the experimental setup were produced using the electrical component values and design parameters given in Table 1.

Table 1. Parameters of circuit element used in the proposed method

Parameters	Values
The material of wire	Kanthal-D
Diameter of the wire	2mm
Media	Air
Maximum Charging voltage	6 Kv
Capacitor Capacity	$40\ \mu F - 1250V$
Diode	$30\ A - 2200\ V$
Trafo	$220V$: $300{,}350{,}400$, $100VA$

Adjusting the input voltage:

Transformer, the first main component of the experimental setup, increases its 220V input

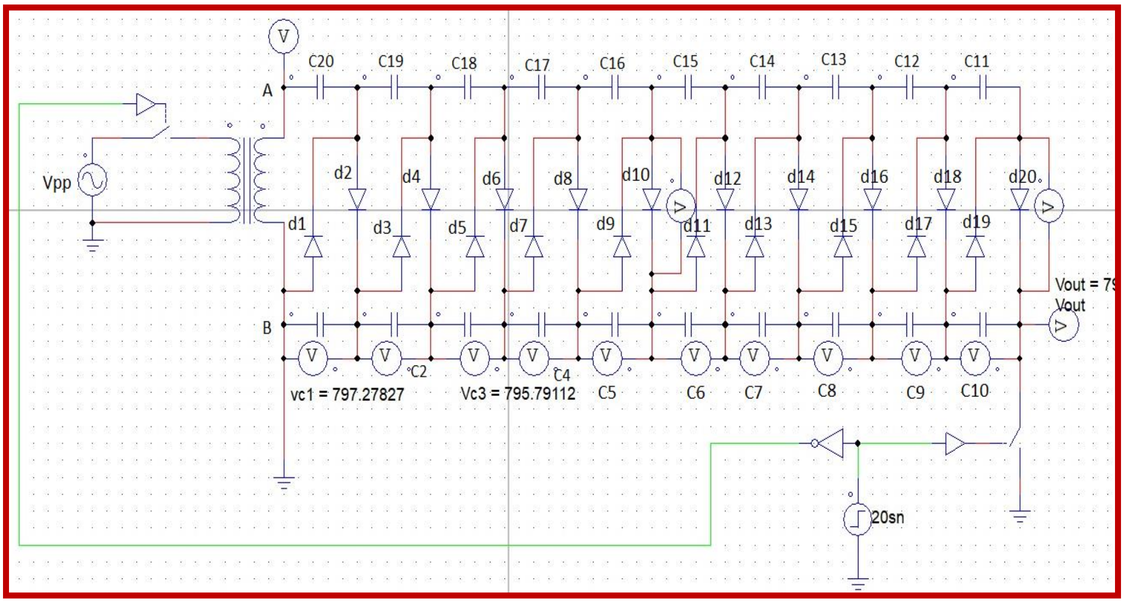

Figure 2. 20-layer voltage multiplier circuit for the simulation study

voltage to four different values as 300V, 350V, 400V, 450V and applies that voltage to the voltage multiplier circuit. Thus, the output of the voltage multiplier circuit can also be adjusted to four different values depending on the multiplication factor of the multiplier circuit. This output voltage, in this study, can be adjusted in 6000-9000V range.

Voltage Multiplier Circuit:

A voltage multiplier circuit is an electrical circuit which is composed of cascaded capacitors and diodes. Diodes, in this circuit, are switched between cut-off and conduction, enabling the capacitors to be filled and discharged. The voltage value at any node is equal to the input voltage folded by the number of capacitors between input and this specific node. These circuits are generally used in applications that require high voltage with small current supply. In the study, this particular component is used to produce high voltage required for the wire exploding process. The required voltage value for wire exploding is determined as 8000V. The input voltage, on the other hand, is 400V, at most. Hence, the voltage multiplier is designed to have a folding ratio of 20.

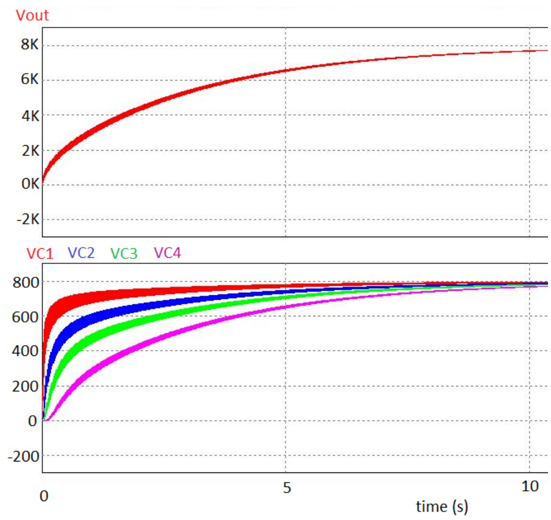

Figure 3. (a) Output voltage in the output layer (b) Capacitor voltages in intermediate layers

20-Layer Voltage Multiplier Circuit Simulation:

The voltage multiplier circuit was first designed in a simulation environment using

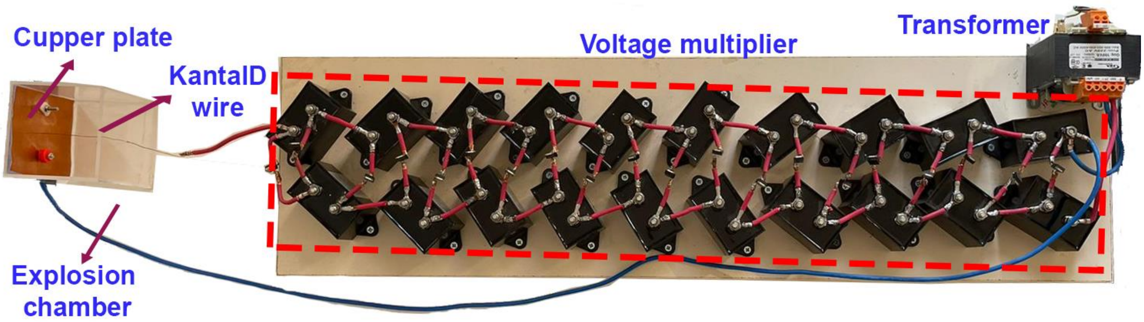

Figure 4. The designed exploding wire test setup

Powersim (PSIM) software and then implemented. The 20-layer voltage multipler circuit designed for this purpose is shown in Figure 2, and the simulation results are shown in Figure 3. Capacitors that are located at the top row and bottom row of the design (namely C20 and C1, respectively, for the first layer) are charged separately in different alternans of the applied input. The voltage drop on each capacitor is accumulated through all capacitors and transmitted to the output as folded input. Thus, the 283V (400V rms) AC applied to the input is elevated to approximately 797.3V at the first layer and 7969.0V at the last layer. The voltage ratio between the final layer and input is very close to the design multiplication parameter of 20. The voltage values of various nodes of the design were observed with attached voltmeters to these locations. The voltage values of different layers in the design and V_{out} output voltage measurements, all obtained accordingly, are shown in Figure 3. Based on these results, the simulated design stabilizes with in approximately 10 seconds. As a result of the simulation studies, it has been observed that capacitors (except the first capacitor) have a voltage value of approximately 2 times the input voltage, and a reverse voltage value of approximately 2 times the input voltage for diodes. Considering all these, it has been determined that the following circuit elements will be appropriate to use in the real circuit; Capacitors with a capacity of C = 40 μF and a voltage value of 1250V, diodes with a current value of 30A and a voltage of 2200V, and finally, the input voltage value that should be given to the input of the multiplier should be 400V.

20-Layer Voltage Multiplier Circuit:

The realized voltage multiplier circuit following the simulation, used in the experiments, is shown in Figure 4. In this figure, the voltage multiplier circuit is shown with the transformer located at its input.

The insulated glass environment, the last component of the setup used in experimental studies, is a cell produced from plexiglass material in order to completely isolate the explosion process from the external environment. Thus, it is aimed to prevent adverse effects of high pressure, high temperature and scattering of particles that occur at the time of explosion. The

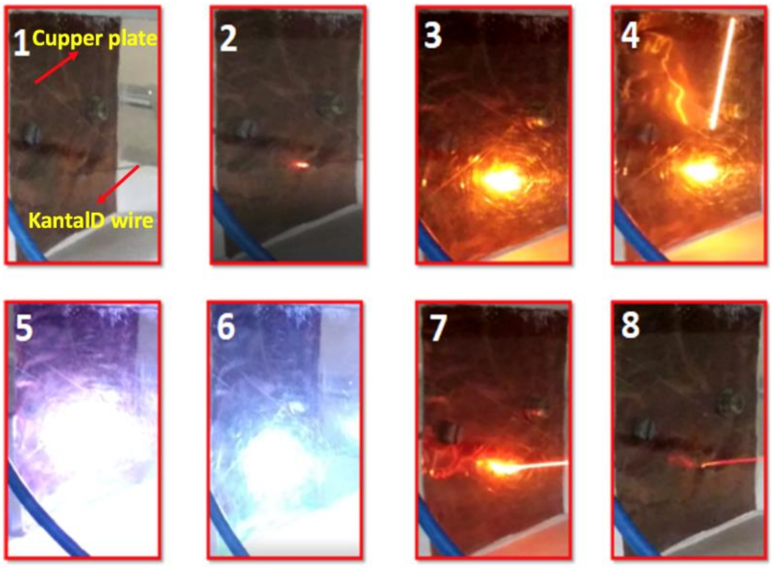

Figure 5. Wire exploding stages

experimental setup composed of three main components is shown in Figure 4.

3. Research Findings

Sudden voltage discharge on the wire causes an arc between the wire and copper plate. With the effect of this formed arc, the wire heats up rapidly and undergoes sublimation. This creates a plasma environment between the Kanthal-D wire and the copper plate, and this procedure is called as exploding. The images of the different steps of the exploding, numbered 1 through 8, is given in Figure 5.

In the exploding wire experiment, some deformations were observed on the surface of the copper plate. Hence, it was examined with a Scanning Electron Microscope (SEM), and Energy Dispersion Spectroscopy (EDS) analysis was performed to define the elemental composition of these deformations caused by explosions. The corresponding SEM images are shown in Figure 10. SEM images were also analyzed using a demo version of SPIP software to define particle size concentration. A sample image and corresponding particle size percent concentrations chart is given in Figure 11-12.

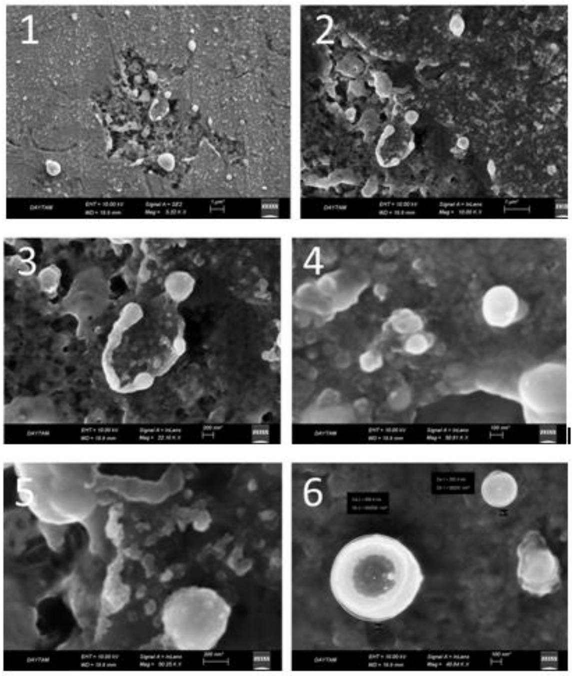

Figure 10. SEM images of the copper plate surface

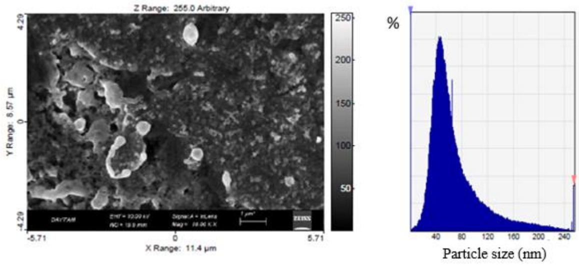

Figure 11. Particle size distributions from SEM image

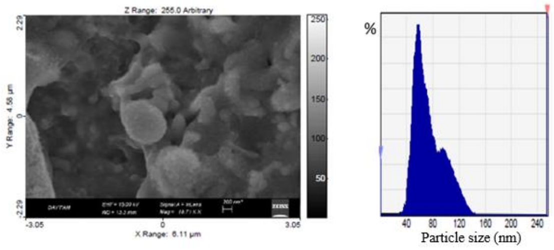

Figure12. Particle size distributions from SEM image

As a result of the performed analysis, it is observed that the size of the obtained particles after the explosion vary between ~ 0-250 nm. The reason for this dimension difference may be explained by the use of an alloy for the explosion, which may be composed of various components with different harmony energy

In order to investigate the elements among the obtained particles, EDS analysis was also performed at specific points determined in SEM image as shown in Figure 13, and the obtained results are shown in Figure 14. As a result of the analysis, Al, Cr, Fe particles detached from the exploded Kanthal-D wire and Cu particles detached from the copper plate were detected.

4. Results

This work examines production of nanoparticles from Kanthal-D wire, a FeCrAl alloy based on exploding wire method.

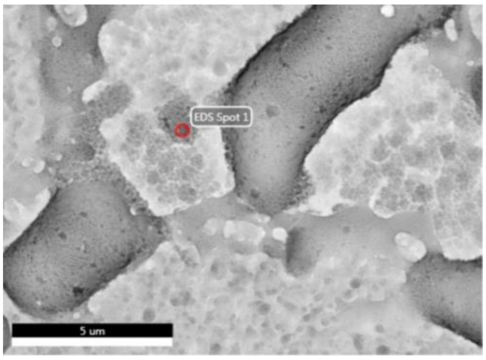

Figure 13. SEM image of explosion for 3mm distance between the plate and wire. The red circle represents the EDS analysis point.

This method requires high voltage source device and, in this work, it is handled using the voltage multiplier circuit. This circuit, first of all, simulation studies using Powersim software were carried out and the characteristics of the circuit elements that could reach the desired high voltage value were determined. Later, the real circuit was designed using these elements. During the experiment, strong enough electrical current is applied through a thin Kanthal-D wire. Resistive heating evaporates Kanthal-D wire, and an electric arc through this vapor creates an explosive shock wave and thin wire turn into solid nanoparticles. Obtained particles, adhered to the copper plate during the explosion, were visually analyzed with a SEM device. According to the point analysis, applied to a target region on the SEM image, it is observed that dimension of Kanthal-D nanoparticles varies between 0-250 nm but highly accumulated at 50nm size. Moreover, EDS analysis was also performed on the obtained sample. It is observed from the EDS analysis that Fe (71-7-74-7%), Al (4.8%), Cr (20.5-23.5%) atoms were detected in the Kanthal-D wire alloy.

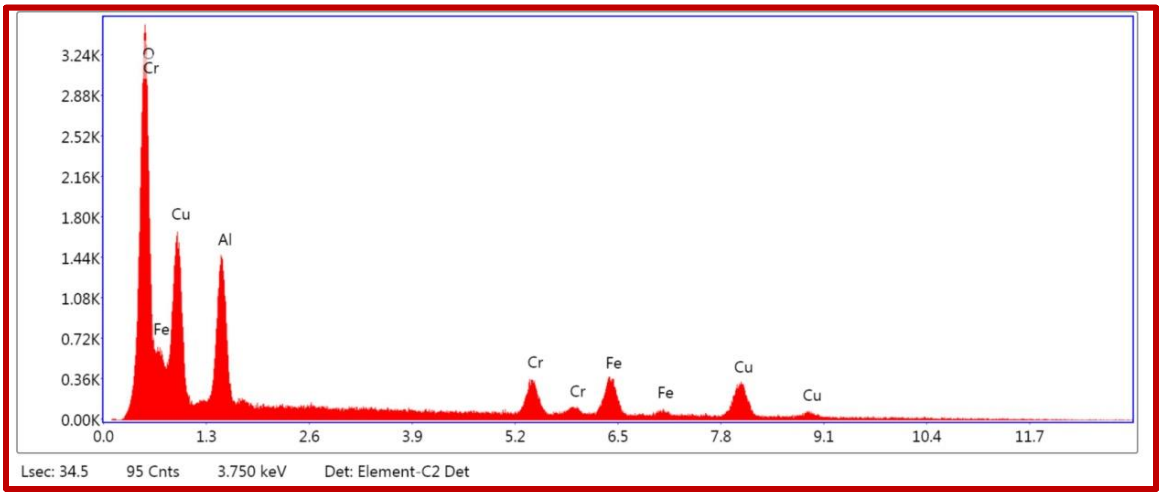

Figure 14. EDS result for the marked region in Fig. 13.

It is observed that higher the applied energy and heating on the wire, smaller the obtained particles in EWM. Hence, it has been concluded that it is possible to produce nanoparticles in desired size as a function of voltage multiplier gain to control the applied voltage and adjusting other parameters.

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