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Aluminum surface analysis after exposed to dense electrothermal launcher plasma

Abstract

An electrothermal Plasma Gun (ETG) device is composed of a capillary discharge tube made of Teflon operated with simple RLC circuit. The maximum gun power ranged between (11.3 – 106 MW) and varies linearly with discharge voltage. The device is composed of 4 capacitors (70 μF, 10 kV, 1.3 μH) which are connected in parallel to a plasma source by means of one high power plane transmission line by means of a switch triggered by negative pulse 360/385V. The experimental of the vapor shield concept in an electrothermal launcher is reported. When the amount of vapor is enough produced under high heat flux, the vapor shield mechanism will help limit the surface erosion in electromechanical devices. From the experiments results we found that the mass loss from the capillary wall and the electrodes increase with increasing the input energy. The morphology of the particulate and surface structure which generate by the plasma ablation is investigated. Moreover, the morphology studies are described according to the visual appearance of micrograph which taken by the scanning electron microscope (SEM). The results of the (SEM) term describe whats the SEM image looks like but not necessary what is actually might be or what is the material type is.

Key Words

Electrothermal gun; Capillary discharge; Surface analysis.

INTRODUCTION

An improved capillary discharge technique[1,2] enables the production of Launcher plasma representing a radially symmetric light source. The paper describes the first results of investigations on the launcher plasma generated by a capillary discharge. Moreover, the diagnostics of the plasma source produced in the launcher plasma has been carried out. The method consisted in generating an electrical discharge between two electrodes mounted at the two ends of a capillary tube in atmospheric pressure. In details, the electrothermal capillary plasma is a device designed for producing a high temperature and high velocity plasma gun. The capillary device, typically made out of Teflon and Artelon which are closed at one end by an electrode, the other end being open, with an annular electrode. The two electrodes are connected by a wire running through the capillary and by an external circuit. This circuit includes a pre-charged storage device, usually a capacitor bank, and a switch to close the circuit. When the switch is closed the wire rapidly heats and explodes, initiating a plasma discharge in the capillary which then carries the current. The efflux of material from the open end is compensated for by material being ablated from the capillary wall.

Ablation and melting of surfaces in devices such as electromagnetic launchers and electrothermal accelerators are of fundamental concern. The plasmas in these devices can expose surfaces to heat fluxes which make erosions and mass loss of the system components. The mechanism of that is when the electric energy is inputted to the system leading to heating of initial plasma that is weakly ionized. As the plasma is heated, radiation from the plasma produces ablation of the breech-wall material. The ablated material dramatically increases the plasma density. Due to the pressure buildup the plasma is transported axially, which leads to both particle and convective energy loss of the plasma. The discharge process is essentially controlled by the ablation of the wall material in the breech.

EXPERIMNTAL SET-UP

A schematic diagram of the experimental arrangement and its principle is shown in Figure 1. The experiment consists of ET source section (plasma gun), transmission line, capacitor bank, and associated diagnostics. The capacitor is connected to the cathode of the gun via a transmission line and a spark gap switch. The anode of the gun is inserted in the center of the capillary tube. The electrical energy of the capacitor is discharged through the gun upon closure of the switch. The plasma gun is typically operated in air between 2–15 torr. A high electrical current vaporizes an aluminum wire in a small tube and generates hot plasma by joule heating. Moreover, the plasma source is generated by the rapid discharge of 3.5 *kJ* of electrical energy into a Teflon (Lexan) capillary. This energy is stored in a 70 μF capacitor charged to a maximum of 12 *kV*. The capillary is (1*mm-10 mm)* in diameter, (10 *mm - 200 mm)* long, and is open at one end only. The discharge is initiated with a thin copper and aluminum fuse wires (less than 1 *mm*), ablation and ionization of material from the capillary surface sustains the discharge.

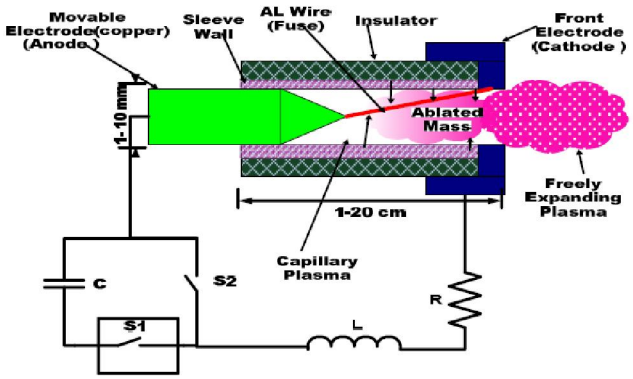

Figure 1 : A circuit diagram of an electrothermal capillary discharge system.

The peak current through the plasma is approximately 37 *kA* for a discharge energy of 0.9kJ, and the discharge duration is approximately (more or less 200 μs). The anode is made of copper and the cathode is made of aluminum. The aluminum wire is enclosed in a cylindrical tube, and has contact to two electrodes. The plasma device was designed and constructed to study the phenomena occurring during the interaction of a high-heat flux with a material surface[3]. This device works on the same principle as an electrothermal mass accelerator. The device is equipped with specialized plasma diagnostics for discharge current, voltage, mass loss measurements and material diagnostics include weight loss, scanning electron (SEM) microscopy and X-Ray Fluorescence (XRF) Spectrometer.

RESULTS AND DISCUSSION

Current and voltage measurements of the capillary

In atmospheric pressure a clear signature of the wire explosion is evident (the current sharply drops and increases again shortly afterwards)[4]. The peak in the current and voltage (resistance) is known as the "wire-burst." The wire fragmentation is accompanied by a small inflection in the current profile. Moreover, the discharge current trace shows a clear double peak structure. The first peak is due to the ignition wire explosion and the second peak represents the main discharge. The gun voltage and current for a 1.3 KJ discharge is shown in Figure 2 for charging voltage = 3.5 KV. The gun voltage is measured across the source section with a high voltage probe (BK-PR-28A). The current trace was measured using a Rogowiski coil and the signal was integrated with respect to time to get the total current in the plasma circuit during the discharge. The gun voltage increases rapidly after the initiation of the discharge, typically reaching the maximum voltage within 10 μs. The current increases much more slowly than the voltage. It takes about 22 μs from the initiation of the discharge for the current to reach its maximum. It is apparent in the figure that the gun current lags the gun voltage. This indicates that the source section has an inductive component.

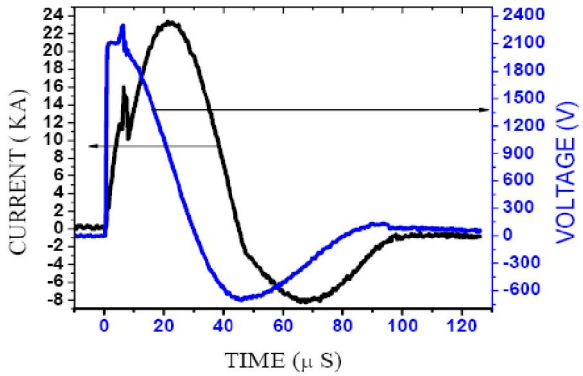

Figure 2 : Discharge current and voltage of the gun at charging voltage =3.5 KV.

Discharge current and energy versus input capacitor voltage

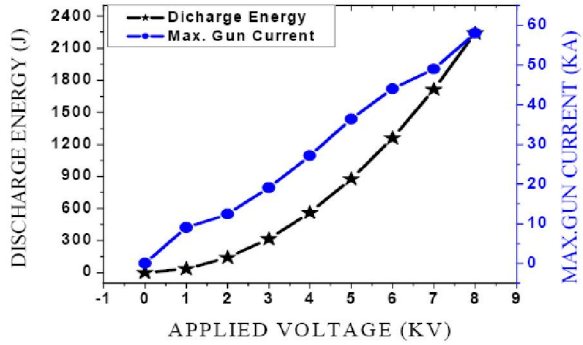

Figure 3 : Discharge energy and Max. gun current versus applied capacitor voltage.

Figure 3 illustrates the input energy and max. gun current versus the applied voltage results of the electrothermal plasma gun. The applied voltage is the capacitor voltage before initiating the discharge. It can be seen from the figure that the peak of energy increases with increasing initial voltage and the peak of current increase also. The input energy in the above figure is calculated from the following relation:

$$E = \frac{1}{2}CV^2$$

Where E is the input energy, C is the capacitance, equal to 70μF of the electrothermal gun and V is the applied voltage.

Gun power and energy measurements

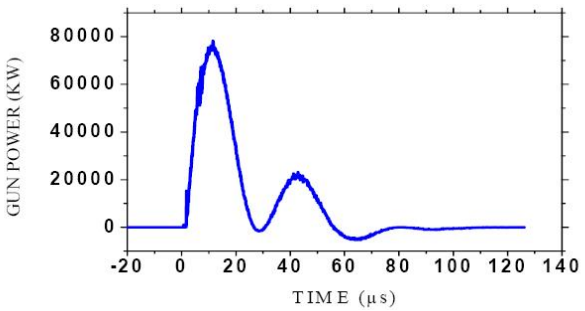

Figure 4 : Gun power for a 1.3 kJ discharges.

The gun power of the capillary device is determined from the following relation,

P (t) = V (t) x I (t)

Where V (t) is the gun discharge voltage measured with the high frequency voltage probe, and I (t) is the gun discharge current measured with the Rogowiski coil.

A typical gun power trace is shown in Figure 4. It can be seen that the gun power increases rapidly after initiation of the discharge, reaching its maximum of 78 KW in less than 15μs. The maximum gun power is shown for different input energies in Figure 5. The maximum gun power is about 11.3 MW at low energies and increases to around 106 MW at the higher discharge energies. The results show that the maximum gun power increases gradually with input energy.

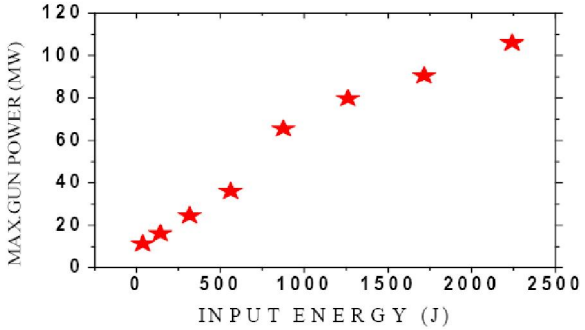

Figure 5 : Maximum gun power at different input energies.

Figures 4 and 5 show the time dependent power and energy dissipated in the arc calculated from the current and voltage Signals with the same method which we are following in Figure 2. The energy required to vaporize the aluminum trigger wire can be seen in the area under the small peak on the power in the first 15 microseconds of the signal as shown in Figure 2. The energy needed to heat the aluminum wire represents a negligible fraction of the total energy input. Once the capillary discharge is established, we assume the small quantity of aluminum plasma used to start the discharge which is rapidly swept from the capillary.

Aluminum surface analysis

Some initial results were obtained on the analysis of aluminum targets that have been exposed to the 3-kJ plasmas produced as described in the experimental system section. A Scanning Electron Microscopy (SEM) was performed in order to observe surface tomography. Energy Dissipative X-ray Analysis (EDXA) was used to investigate the compositional variations of the target superficial layers. X-ray fluorescence (XRF) technique is among other elemental analytical compositions techniques which are used to study and analyze the component of the sample. The X-ray Fluorescence (XRF) spectrometer is used to analyze the samples. Figure 6 represents the schematic diagram of the XRF system used for the study. The system consists of a low power air-cooled X-ray tube as an excitation source. Figure 7 shows examples of a clean aluminum surface and another one exposed to a 1.3-kJ plasma observed with SEM as shown in Figure 9. The surface topography of the clean surface appears as more homogeneity. By contrast, the surface exposed to the plasma shows evidence of ablated and melted material that has been redeposit after being carried by the plasma.

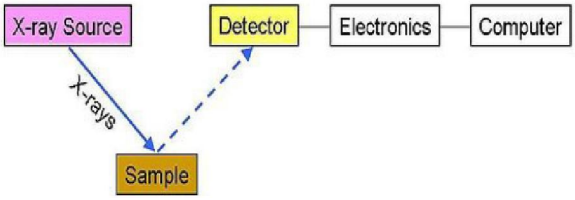

Figure 6 : Schematic diagram of the XRF system.

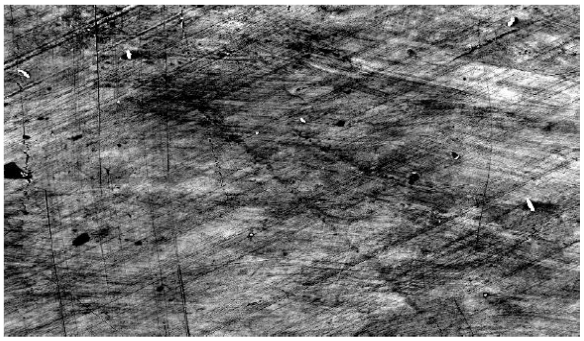

Figure 7 : SEM photographs of a clean aluminum sample.

The deposited films were investigated by several analytical techniques but presently only a scanning electron microscopy (SEM) result has been shown here. Figure 8 shows the XRF results of the pure aluminum sample before exposed to the plasma and the major elements concentrations is the aluminum with intensity of (99.9790%). Other elements such as S, Fe, and Rh were observed with minor concentrations less than (1 %).

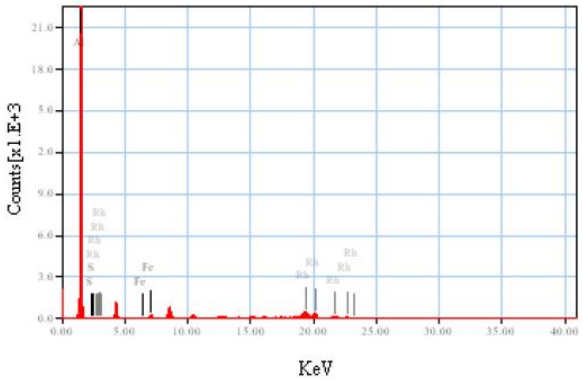

Figure 8 : Typical energy dispersive XRF spectrum of a pure aluminum sample.

Films which have been deposited with plasma gun include S, Fe, and Rh according to the graph but the intensity of these elements is very low. In general, especially in the case of thin film deposition, the structure and morphology as well as the stoichiometry of the film depend strongly on the energetic conditions at the surface[5]. Here we present the study of the Aluminum Sample as a thin film deposition by means of atmospheric pressure of electrothermal launcher Plasma. We use a capillary tube as a source of plasma with a maximum power 106 MW. The main purpose of these coatings is to provide materials with added resistance to wear, corrosion, and oxidation and may also have applications in electrical and electronic fields[6].

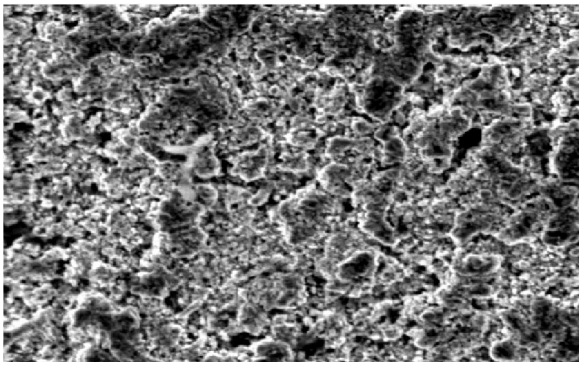

Figure 9 : SEM photographs of an aluminum sample exposed to a 1.3 KJ plasma.

A comparison between the XRF analyses of the clean aluminum sample and the plasma-exposed surface clearly showed the appearance of pure aluminum for the sample without any treatments but for the sample exposed to the 1.3 KJ plasma we found by analysis some other elements appear like copper, zinc, and aluminum peaks appears on the surface as shown in Figure 10. The operating voltage and the current of the X-ray tube were 30 kV and 0.6 mA, respectively. The measurement time for the determination of the main components of the sample inside the XRF system was 300 seconds. The sample exposed to the plasma for a 10 shots. The appearance of copper, zinc, and aluminum peaks can be explained as the exploding of the aluminum and copper wire due to the energy supply. The zinc peak results from the deposition of these materials due to the copper wire are not very pure.

In general, the results of mass loss measurements are made on metallic samples, as well as erosion of gun components (the plasma gun electrode, and the capillary sleeve.) Experiments were conducted at discharge energies between 0.35 and 1.7 kJ. In these experiments, the mass loss of the samples was measured to determine the net sample erosion, results from aluminum (Al), discussed in section E and F. Figures 9 and 11 show SEM images of the treated aluminum sample after exposed to plasma with energy 1.3 KJ. To facilitate comparison, and to utilize the uniformly treated region of the sample, SEM images were obtained at the same condition for both the treated and untreated sample. The sample in Figure 9 exposed to the plasma for a 10 shots by using Al and copper wire. The Cu wire is used in the first and second shot only, after that we use Al wire for 8 shots. Hence, the concentrations of Al and Cu on the sample after exposed to the plasma are shown as follow:-

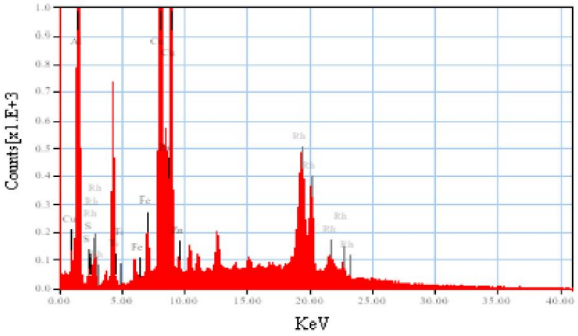

Figure 10 : Energy dispersive XRF spectrum of an aluminum sample exposed to a 1.3 KJ plasma with Al and Cu wire.

The XRF results of the aluminum sample after exposed to the plasma show that the major elements concentrations is the aluminum and copper which are (96.0155 %),(3.6934%) respectively. Other elements such as S, Ti, Fe, Zn and Rh were observed with low concentrations which are (0.1252%), (0.1257%),(0.0199%) and (0.0203%) respectively as shown in Figure 10.

In order to investigate the change in the surface homogeneity before and after exposed to the plasma we make a comparison of the surface morphology which illustrate a marked change in the surface properties of the aluminum sample before and after exposed to the plasma. Moreover, Surface roughening and agglomeration of in-

ternal morphology appear to change gradually from Figure 9, these effects ultimately result in the appearance of a thin film deposition of the surface. This observation appears to be in good agreement with the XRF results. The morphology was uniform but with different degrees of roughness. The increase in the degree of roughness with increased plasma exposed to the sample and copper wire exploded that change the concentration and indicates formation of the new phase in the host matrix which agrees with XRF measurements. The vapor shield is effective in the case of aluminum as has been observed from SEM system that shows ablation (vaporization and no melting) features of the aluminum surface.

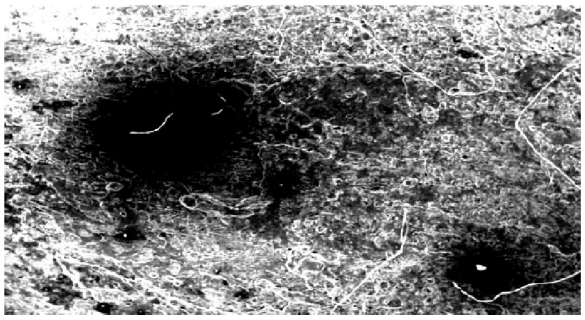

Figure 11 : SEM photographs of an aluminum sample exposed to a 1.3 KJ plasma.

The morphology description of the surface structure deformation is introducing a new concept which gives a scientific explaining of the morphology term of the particulate and surface generated by the ablation process is demonstrated and discussed. Figure 11 Shows an aluminum sample exposed to 10 shots with a copper wire only so that the intensity of the copper line are very high but the aluminum line are very low, approximately disappear, that means the sample surface are completely covered with copper. The analysis of the sample in XRF is recorded in Figure 12 which shows the copper line intensity is very high. Note, the sample is placed at a 4 cm from the open end of the capillary. But when the sample placed at 3 cm from the open end of the capillary, the sample was damage. The dark area of the above picture is a cavity caused by the very high pressure produced inside the capillary.

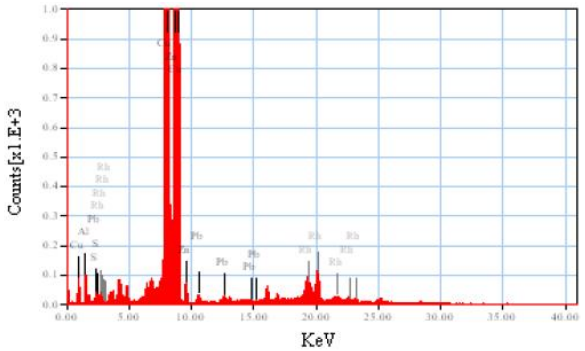

Figure 12 : Energy dispersive XRF spectrum of an aluminum sample exposed to a 1.3 KJ plasma with Cu wire.

The XRF results of the aluminum sample after exposed to the plasma shows that the major elements concentrations is the copper and aluminum which are (90.5489 %), (6.0321%) respectively. Other elements such as S, Zn and Pb were observed with low concentrations which are (0.2655%), (2.7685%) and (0.3851%) respectively as shown in Figure 12.

The capillary discharge makes it possible to obtain metal vapor plasma with the plasma components originating from the elements mixed within the wall of the capillary. In general, in a capillary discharge, the ablated sleeve material is the main source of material for the formation of the high density plasma. This process leads to the heating of the weakly ionized plasma. The radiation from the heated plasma ablates the inner surface of the capillary tube, which then increases the plasma density. The pressure buildup leads to the plasma traveling out of the source and barrel section into the air[7].

Mass ablation measurements

In Order to investigate the plasma in a capillary tube, the plasma has been generated between two electrodes (cathode and anode); the two electrodes were connected to a high voltage capacitor discharge circuit.

The plasma inside the capillary tube was heated resistively by the electric current flowing between the electrodes. The interaction of the discharge plasma with the tube wall has induced ablation of the capillary material, which, in turn, was added to the plasma. As a result, a high pressure was developed inside the capillary, causing a mass flow outward through the open side of the capillary.

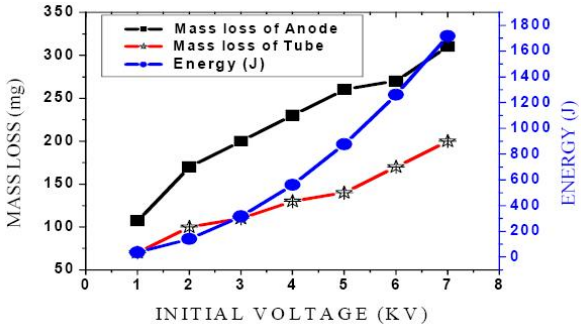

Figure 13 : Ablated mass verses initial capacitor voltage and input energy storage.

The mass loss from the capillary wall is measured using a digital balance and the individual masses of the tubes, anode, cathode, and ignition components (when present) are all weighed separately and then weighed again after assembly, the weighted done after every 10 shots at the same parameters. The mass loss for a single pulse as a function of the initial capacitor voltage is shown in Figure 13, after a set of 10 fires, all the components are weighed again (both together and separately). The mass of the an-

ode before discharge is 12200 mg and the mass after 70 shots at maximum 7 Kv applied voltage is 11980 mg. The mass of the capillary tube before discharge is 28500 mg and the mass after 70 shots at maximum 7 Kv applied voltage is 28300 mg. By weighing the components together and separately it is possible to determine the mass loss of the electrode as well as the material ablated form the capillary wall. As can be seen from the results, the mass loss due to electrode erosion was significantly higher than, the mass loss from the tube itself.

Measurements of mass removed from capillary wall

The experimental results show that one of the most critical parameters in the evaporation process is the discharge current. The mass of metal ablated from the electrodes increases with increasing of the current density[8]. The capillaries mass loss due to their ablation during the discharge as well as their diameters at the capillary exit is quite different after exposed to the plasma than before. Moreover, the study of the capillary and anode mass losses is important as it may allow to compare some plasma parameters results at various electrical energies and to understand the procedures to the gun performance as well as erosion of the gun component (the plasma gun electrode and the capillary sleeve).

A series of measurements were made to study the ablation process of the system components for different stored energies. The amount of ablation was determined by measuring the weight difference of the system components before and after the plasma exposure. In general, the explosion of the copper and aluminum wires provides a conducting vapor, and subsequent ablation and ionization of dielectric material from the capillary walls maintains the plasma within the capillary as the plasma jet discharges into the atmosphere. The increase of the capillary exit diameter due to the erosion of the capillary bore is shown in Figure 14.

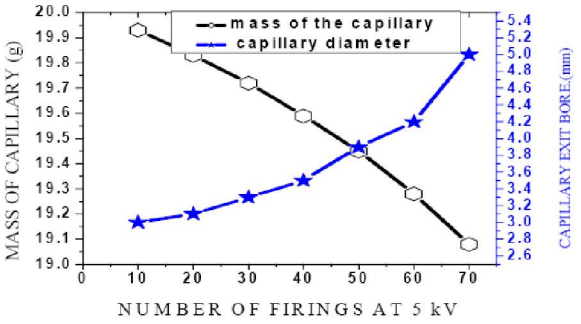

Figure 14 : Changes of the capillary exit diameter and mass with respect to number of firings.

Note that the diameter was measured only at the bore exit, but it is known that the capillary does not erode uniformly. The changes in the capillary bore exit diameter according to the number of firing are measured by using Vernier calipers. Figure 14 show that the mass of the capillary decreases gradually with the number of shots.

CONCLUSION

The analysis of the aluminum surface of treated and untreated sample with and without plasma are recorded and discussed. The results show a quit different of the surface morphology after exposed to the plasma. The maximum gun current ranged between 9 and 56 kA, and was shown to vary gradually with stored energy. The maximum gun power ranged between 11.3 and 106 MW, and was also shown to vary gradually with discharge energy. Typical discharge duration was on the order of 125 μs. The capillary device components are measured before and after the plasma created inside the capillary tube and the results show a difference of the components weight due to the mass loss. It was found experimentally that the mass loss of the inner side of the capillary tube increases with increasing of input energy and that is because of the increase in the capillary plasma pressure. The morphology of the particulate and surface structure which generate by the plasma ablation is investigated and the results show a quite different of surface before and after exposed to the plasma.

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