Electro-Spark Nanomachining Process Simulation

Gh. Tahmasebi Pour, Y. Tahmasebi Pour, and M. Ghoreishi

***Abstract*—Electrical Discharge/Spark Machining (EDM/ESM) is an advanced machining process that has various applications in macro and micro fabrication. Advantages and intrinsic potentials of the process is promising application of this process in nanofabrication. The spark nanomachining is a precise, sensitive and costly process. Therefore, simulation of nano-hole produced by each spark in this process prevents spending extra time and cost to perform spark nanomachining process through trial and error method. In this paper nano-hole machined by the spark nanomachining process on a gold nano-film is simulated under practically experimental conditions. Radius, depth and volume of the nano-hole are evaluated versus process conditions. It is observed that radius of the nano-hole is increased exponentially with increasing spark pulse duration. Also, depth, volume of the removed material from the workpiece surface and material removal rate (MRR) are increased with increasing consumed energy by each spark.**

***Index Terms*—Electro spark / discharge machining, ESM, EDM, electro spark nanomachining, simulation**

I. INTRODUCTION

Electrical Discharge/Spark Machining (EDM/ESM) process is a thermal machining process in which thermal energy produced by the electric sparks is used for removing material from the workpiece surface. EDM has found broad and diverse applications on both macro and micro scales. Fast-paced development of nanotechnology and the necessity to benefit from the new techniques have given rise to attraction of interests to use the spark nanomachining process in nano scale.

Considering that the spark nanomachining is a precise, sensitive and costly process, simulation of nano-hole produced by each spark in this process makes it possible to predict the optimum level of the process parameters in order to achieve a nano-hole with the desired dimensions prior to conducting the real process. This issue prevents spending extra time and cost to perform the spark nanomachining process through trial and error method.

Simulation of the crater resulting from a single spark in the EDM process has been reported by the several researchers so far. Van Dijck presented a model for the calculation of the volume of molten metal in macro scale EDM process [1]. A theoretical model for crater on the anode surface in the EDM process was reported by Patel [2]. Singh reported a thermo-electric model of material removal during conventional EDM process [3]. Das developed a finite element-based simulation for calculation of deformation in the EDM process [4]. Panda presented analysis of spark eroded crater formed under growing plasma channel in electrical spark machining process [5]. Yeo proposed an analytical model based on electro-thermal theory to estimate the geometrical dimensions of micro-crater resulting from the Micro-EDM process [6]. Tan developed a model for simulation the overlapping of craters in Micro-EDM process [7]. A process simulation for the micro-EDM machining on molybdenum was presented by Allen [8]. Dimensions of the micro-craters were estimated using a thermo-numerical model for a single spark process in [8]. To author's knowledge, modeling of the nano-hole machined by the Spark nanomachining process has not been reported so far.

In this research paper, nano-hole resulting from the spark nanomachining process on a gold nano-film is simulated by using the Computational Fluid Dynamics (CFD) to predict shape, dimensions and volume of the aforementioned nano-holes. Latent heat, melting and solidification phenomenon and mushy zone are considered in accurate simulation of the spark nanomachining process by using the finite volume based CFD method.

II. SIMULATION OF SPARK NANOMACHINING PROCESS

In the spark nanomachining process, electrical field causes vaporization, decomposition, and ionization of the dielectric fluid and formation of a nanometric plasma channel between the nano-tool and workpiece. Then electrical spark occurs inside the plasma channel and the produced thermal energy lead to local melting and vaporizing of the workpiece surface. Upon the outage of electrical spark, plasma channel is disappeared and pressure of the plasma channel is removed from the molten pool surface. So contents of the molten pool will effuse into the dielectric and a nano-hole is formed on the workpiece surface. In the EDM process, pressure of the plasma channel is very high during the initial moments of channel formation [9]. Thus, since spark pulse duration in the spark nanomachining process is in the order of nano-second, a high negative pressure is exerted on the molten pool surface subsequent to outage of spark and plasma channel removal [10]. Accordingly, it is supposed that the part of the molten pool which has experienced the complete melting is effused from the molten pool into the dielectric and the mushy zone is solidified. The results of practical experiments in [10] have verified this phenomenon.

In this study Enthalpy-Porosity technique is used to simulate molten pool and nano-hole produced by the spark nanomachining process. This technique works based on energy alterations in melting and solidification process. The energy equation is written for a two dimensional model in

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Gh. Tahmasebi Pour is with the Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran (e-mail: tahmasebipour@ut.ac.ir).

Y. Tahmasebi Pour and M. Ghoreishi are with the Faculty of Mechanical Engineering, K.N. Toosi University of Technology, Tehran, Iran (e-mail: lm-tahmasebipour@araku.ac.ir, e-mail: ghoreishi@kntu.ac.ir).

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cylindrical coordinate system with axial symmetry as:

$$\frac{\partial}{\partial t}(\rho H)+\nabla.(\rho\vec{\mathbf{v}}H)=\nabla.(\mathrm{k}\nabla T)+S \tag{1}$$

where, ρ: average of workpiece density, H: enthalpy, $\vec{v}$: fluid velocity, k: average thermal conductivity, T: temperature, S: source term. Specific enthalpy is computed through (2).

$$H = h_s + fL + C(T - T_m) \tag{2}$$

where, h_s: saturation enthalpy of solid state, f: liquid mass fraction, L: latent heat, C: specific heat capacity, and T_m: Melting point. If h_s and T_m are respectively considered as reference enthalpy and temperature, then specific enthalpy is calculated through (3).

$$H = fL + CT \tag{3}$$

The liquid mass fraction can be expressed as (4):

$$f=\begin{cases}0 & H\prec 0\\ \dfrac{H}{L} & 0\prec H\prec L\\ 1 & H\succ L\end{cases} \tag{4}$$

A. Assumptions

The following assumptions have been considered in order to simulate nano-hole resulted from the spark nanomachining process:

a) Consumed energy by a single spark and its effects has been studied.

b) The average of physical properties of the material has been used.

c) The difference between density of solid and liquid states has been underestimated.

d) It is supposed that a constant percentage of spark energy is taken in by the workpiece.

e) The workpiece material is considered isotropic.

TABLE I: GOLD AND SILICON PROPERTIES.

Material	Au	Si
Density (kg/m3)	19320	2330
Thermal conductivity coefficient (w/m.k)	297	83
Melting heat (kj/kg)	67	1658
Specific heat capacity (j/kg.k)	129	750
Melting point (k)	1338	1696

According to practical experiments of the spark nanomachining process which have been tested by [3], it is assumed that the workpiece is a gold nano-film which is prepared by sputter coating on a silicon substrate. Table I indicates gold and silicon properties.

B. Boundary Conditions

Fig. 1 shows schematic form of nano-hole resulted from conduction of the spark nanomachining process on a gold nano-film, heat flux due to electrical spark and hypothetical boundary of the problem. Plasma channel of the spark nanomachining process is the source of heat generation and transmission to the workpiece surface. Hence, the radius of existing heat source on the nano-film surface has been considered equal to the radius of the plasma channel. Considering nanometric scale of the plasma channel radius and nanosecond scale of spark pulse duration in the spark nanomachining process [10], heat flux distribution has been assumed uniform.

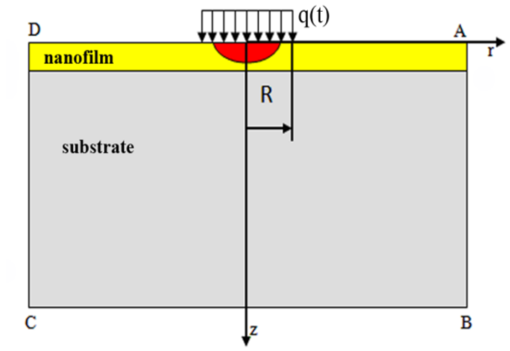

Fig. 1. Schematic diagram of the spark nanomachining process.

Temperature in AB, BC and CD boundaries are taken equal to the environment temperature (300 k). Conditions of DA boundary during pulse on-time are as follows:

$$z=0,\ k\frac{\partial T}{\partial z}=\begin{cases}q(t) & 0\prec r\prec R\\ 0 & R\prec r\prec 2.5R\end{cases} \tag{5}$$

In $r > 2.5\ R$ range, temperature has been considered constant and equal to environment temperature due to its long distant from the heat source and also its contact with a large volume of liquid dielectric. $q(t)$ is heat flux distribution function which is calculated through (6).

$$q(t)=\frac{\mathrm{FVI}}{\pi R^2(t)} \tag{6}$$

where, F is the percentage (18 %) of the total power which is transmitted into the work piece [11], V is the average of spark voltage (v), I is the average electric current of spark (A), $R(t)$ is radius of heat source located on the workpiece surface (equal to the plasma channel radius) (m). Plasma channel radius of the spark nanomachining process depends on time and is computed via (7) [10].

$$R(t) = 0.89356\ t^{0.84848} \tag{7}$$

In this study, through solving the governing equations on the spark nanomachining process (1-4) using finite volume based CFD method by the Fluent 6.3 software, the nano-holes resulted from the process have been simulated. For this purpose, workpieces are meshed with 10 nm × 10 nm elements. In order to investigate the effects of spark nanomachining process parameters on shape, dimensions and volume of the nano-holes, conditions of the experiments shown in Table II which have been tested by [10] are used.

III. RESULTS AND DISCUSSION

Table II shows the spark nanomachining process conditions that were practically used by [10] and the results of the nano-hole simulation. Results of the simulation of nano-hole in the spark nanomachining process for a gold nanofilm (with 100 nm thickness) as workpiece and a silicon wafer as substrate are shown in Table II and Fig. 2.

TABLE II: SPARK NANOMACHINING PROCESS CONDITIONS AND SIMULATION RESULTS FOR THE AU NANOFILM WORKPIECE AND SI WAFER SUBSTRATE

Expt. No.	Average Power (w)	Pulse Duration (ns)	Nano-hole Radius (nm)		Nano-hole Depth (nm)	
			Au	Si	Au	Si
1	0.15	4	55	0	45	0
2	0.5	12	180	30	100	10
3	0.7	40	510	240	100	105
4	1	80	850	455	100	160

In Fig. 2, simulated form of the nano-holes (a_1, a_2, a_3, and a_4) produced by the spark nanomachining process on the workpiece surface have been shown for experiments 1 to 4, respectively.

Fig. 2(a_1) represents simulation results of experiment 1. In this simulation, radius and depth of the nano-hole resulted from the spark nanomachining process are equal to 55 nm and 45 nm respectively and thickness of mushy zone is about 8 to 10 nm. Considering that the thickness of gold nano-film is 100 nm, therefore the material has been removed only from the gold nano-film.

Fig. 2(a_2) indicates simulation results of experiment 2. It is observed that radius and depth of simulated nano-hole are 180 and 110 nm respectively and thickness of mushy zone is about 12 to 15 nm. This experiment shows that besides gold nano-film, a small portion of silicon substrate (10 nm in depth) has been melted and removed as well.

Simulation results of experiment 3 are shown in Fig. 2(a_3). It is observed that radius and depth of the simulated nano-hole are 510 nm and 205 nm respectively and thickness of the mushy zone is about 20 to 25 nm. In addition, a crater with 240 nm radius and 105 nm depth has been created on the substrate surface too.

Fig. 2(a_4) represents simulation results of experiment 4. In this experiment, radius and depth of the produced nano-hole are respectively 850 nm and 260 nm and thickness of the mushy zone is about 45 to 50 nm. It is observed that besides gold nano-film, a crater with radius of 455 nm and depth of 160 nm has been created on the silicon substrate surface.

Fig. 3 indicates radius of the simulated nano-hole toward spark pulse duration. It can be clearly observed that radius of the nano-hole is increased exponentially along with increasing spark pulse duration. Extension of pulse duration gives rise to increase in radius of heat source on the workpiece surface. It may increase the heat affected zone and hence radius of the nano-hole is increased as well.

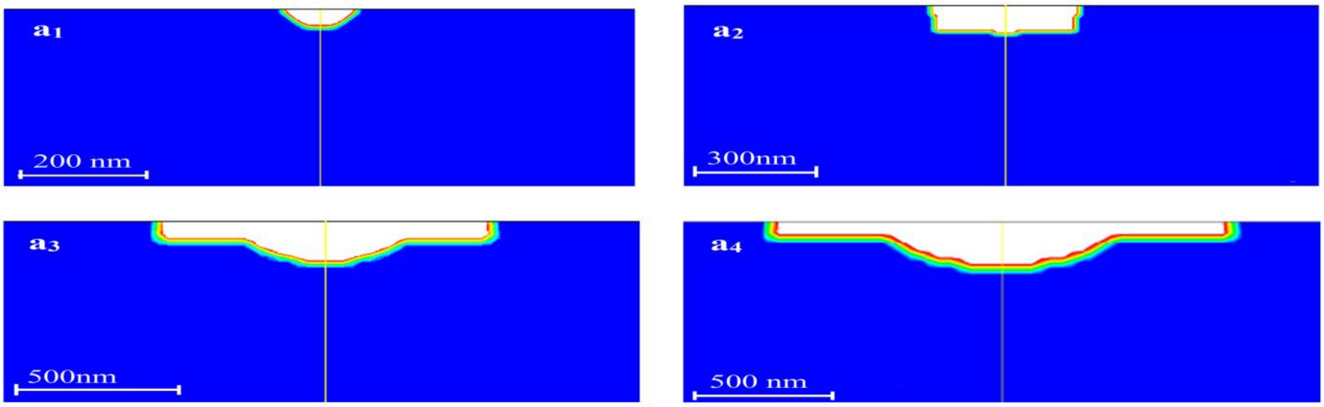

Fig. 2. Nano-holes simulated under experiments 1 to 4 conditions for a gold nanofilm with 100 nm thickness as workpiece and a silicon wafer as substrate, respectively.

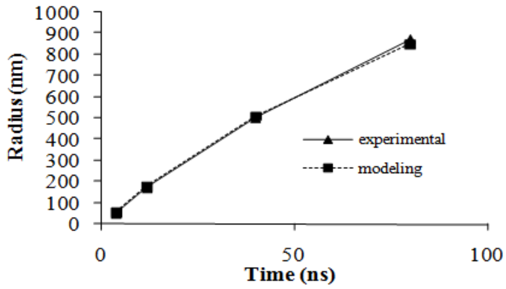

Fig. 3. Radius of the nano-hole versus spark pulse duration for both simulation and experimental results according to the experiments 1-4.

Fig. 3 indicates simulated nano-crater radius versus spark pulse duration as well as the results of practical experiments of the Nano-EDM process done by the [3]. It can be seen that the simulation results are highly consistent with the experimental results. In conclusion, it shows accuracy of the presented simulation for the spark nanomachining process. Using the Fig. 3 allows us to predict radius of the nano-hole resulted from the spark nanomachining process for pulse durations 4 ns to 120 ns.

Depth and volume of the removed material from the sample (nano-film and its substrate) surface versus consumed energy by each spark are represented in Figs. of 4 and 5, respectively. As can be seen, depth and volume of the removed material is increased with consumed energy. Increase in the consumed energy enhances applied heat flux on the workpiece surface. Therefore, more depth and volume of the sample is affected by the heat. Hence depth and volume of the molten pool and also depth and volume of the removed material is increased.

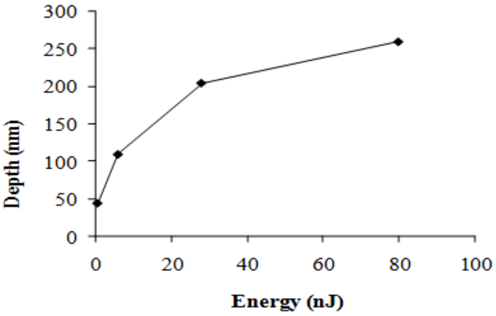

Fig. 4. Nano-hole depth versus the consumption energy according to the experiments 1-4.

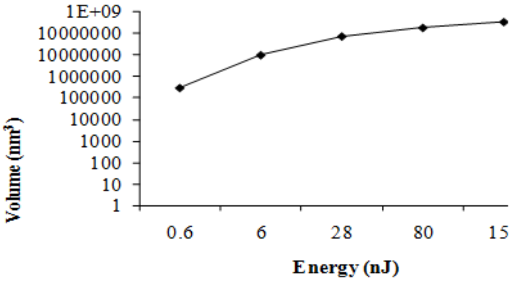

Fig. 5. Nano-hole volume versus the consumption energy according to the experiments 1-4.

IV. CONCLUSION

In this study, nano-holes resulting from the spark nanomachining process on a gold nano-film were simulated by using the Computational Fluid Dynamics (CFD). Radius, depth and volume of the nano-holes were evaluated versus process conditions. It was observed that:

1) Radius of the nano-hole is increased exponentially along with increasing spark pulse duration.
2) Depth and volume of the removed material from sample surface and material removal rate (MRR) are increased with increasing consumed energy by each spark.

Using this simulation, the optimum levels of the process parameters can be predicted in order to achieve a nano-hole with the desired dimensions. This issue prevents spending extra time and cost to perform the spark nanomachining process through trial and error method.

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Gh. Tahmasebi Pour was born in Iran in 1974. He received the bachelor of science degree in mechanical engineering from the University of Tabriz, Tabriz, Iran, 1998, a master of science degree in mechanical engineering from the Amirkabir University of Technology, Tehran, Iran, 2001, and a Ph.D. degree in mechanical engineering from the Tarbiat Modares University, Tehran, Iran, 2009.

He is an assistant professor in the Faculty of New Sciences and Technologies at the University of Tehran in Tehran, Iran. His research interests include nano science and technology, micro/nano-scale manufacturing technologies, MEMS/NEMS, nano-mechanics, synthesis and application of nano-materials, industrial nanostructures, composites and nanocomposites, multi-scale modeling and simulation, new manufacturing science and technologies, industrial automation, and mechatronics.

Dr. Tahmasebi Pour is a recipient of the TWAS prize to young scientists in 2011, 24th Khwarizmi International Award from Iranian Research Organization for Science and Technology (IROST) in 2011, certificate and gold medal from Economic Cooperation Organization (ECO) cultural institute in 2011. He ranked 2nd in the Tarbiat Modares University entrance exam for the Ph.D. degree in Iran, 2003, and ranked 3rd in the nationwide university entrance exam for the M.Sc. degree in Iran, 1998.

Majid Ghoreishi received the B.Sc. and M.Sc. degrees in mechanical engineering from the Sharif University of Technology, Tehran, Iran and Ph.D. degree in the area of nontraditional machining in 2001 from University of Manchester Institute of Science and Technology (UMIST), Manchester, England. His research interests are non-traditional machining, laser machining and welding electro; discharge machining (EDM); black box modeling; statistical modeling and analysis; neural networks; process optimization.