Heat transfer analysis of the EDM process on silicon carbide

R. Mahdavinejad
Mechanical Engineering Deptartment, University of Tehran, Iran

Abstract

The Electro discharge machining (EDM) process is based on the generation of a plasma channel, its growth and the creation of a boiling crater on the workpiece surface. Material removal is mainly due to the presence of thermodynamic forces. Therefore, the process is under the influence of the heat transfer behaviour of the plasma channel and the workpiece. In the heat transfer mechanism, heat conduction is known to be the main major mode. Besides, there is another heat source within the silicon carbide body due to its electrical resistance and it results in Joule Heating. The physical properties of SiC material such as its electrical resistance and thermal conductivity are highly affected by temperature. This paper deals with the solution of the heat conduction and voltage drop equations within the workpiece in a cylindrical coordinate system on a finite cylinder regarding the circular plasma heat source. The finite difference method is used to solve these equations. Calculations show that voltage drops within the SiC body are higher than ones expended on the workpiece surface by a plasma channel. Results also show that an increase in discharge current increases the voltage drops and heat generation within the workpiece body while affecting deeper areas.
Keywords: heat transfer, electro-discharge machining, silicon carbide, plasma channel, finite difference.

1 Introduction

Silicon Carbide (SiC) is the fourth hardest material in the world only after diamond, Boron nitride and Boron carbide. It is widely used in industry due to its special specifications as described in Table 1.

Its high hardness, low conduction of electricity and heat, and also good heat shock resistance which make it suitable for use in furnace as heat-element, in atomic centres as protector and regulator of neutrons, and in machining as an abrasive material [1]. Acheson produced SiC for the first time in 1982 by an industrial method [2]. REFEL SiC that is a special kind of Silicon Carbide has a better heat conduction due to its special production process that makes it of more widely usage. The machining of SiC by conventional methods, with regards to its high hardness, is not possible [3]. Among non-traditional machining methods, EDM is the best one of SiC machining [4].

Table 1: Some characteristic of steel and ceramic materials.

Material	Density (g/cm^3)	Hardness (H.V)	Thermal Expansion 1.0E-6/ºc	Thermal con. (W/m.ºc)		Spec. Heat (J/g.ºc)	Electrical Res. (Ω.cm)
				100º	1200º		
REFEL SiC	3.10	2500	4.30	83.6	38.9	670-710	0.42 (At 25ºc) 0.016 (At 1200º)
Hot Pressed Silicon Nitride	3.20	2500-3500	3.20	17.5	14	-	-
Hot Pressed Alumina	3.90	2500	9.0	8.4	5	-	-
Reaction bonded Silicon Nitride	2.60	900-1000	3.2	15	14.2	-	-
Tungsten Carbide (6% Co)	15.0	1500	4.9	86	-	205	20
Steel	7.86	800	12.2 (At 100ºc) 13.4 (At 1000º)	51.9	29.7	418	1.0E-5

ED machining method is widely used for making tools, dies and other complex-shaped parts [5]. This process is based on the erosive effects of discharges between the electrodes that are immersed in a dielectric tank. The basic principles of the fundamental theories have suggested that the mechanism is based on a thermal conduction phenomenon governed by heat generated from arc channel and dissipated into the tool and workpiece [6]. As shown in Figure 1, tool and workpiece electrodes, are closed to each other and the space between them is filled with dielectric fluid. Between the nearest opposite peaks of electrodes, non-continues discharges take place and a small part of workpiece surface is removed in each pulse. Finally the supplementary face of tool is made on the workpiece.

In this non-traditional machining method, the behaviour of this semi-conductor material is different from conductors. Thermodynamically mechanism is the main mode in this process that is aligned with creation of melting spots and bulk boiling phenomenon. The high temperature gradients generated at the gap during electrical discharge machining result in large localized thermal stresses in a small heat-affected zone [7]. These thermal stresses can lead to micro-cracks, decrease in strength and fatigue life and possibly catastrophic failure [7]. Although an enormous amount of research effort has been put into representing the EDM process by experimental methods, a more elaborate semi-empirical model, based on thermal-mechanical and statistical approaches, has not as yet been reported [8]. The present paper attempts to overcome this shortcoming.

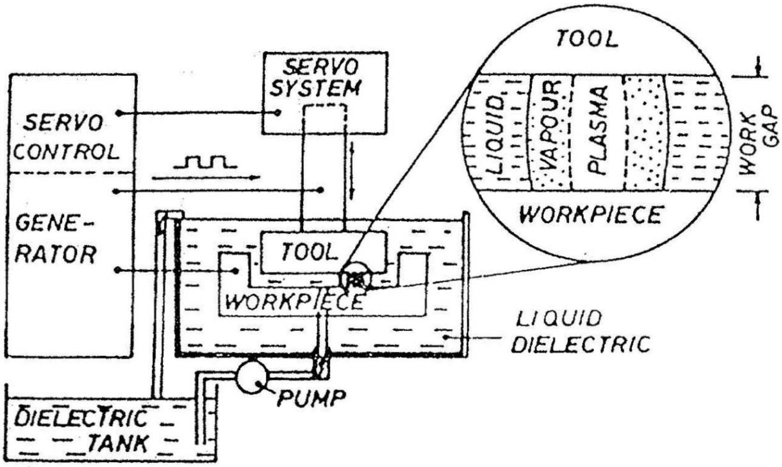

Figure 1: Electro discharge schematic machining process.

2 Principles of heat conduction in EDM

Heat transfer in EDM is mostly a part of plasma-channel heat conduction that reaches to the workpiece and almost all of this is distributed in the workpiece body by heat conduction process [9]. The other heat transfer mechanisms are neglected, since their effects are very small in comparison with heat conduction into the workpiece [10]. The common differential equation of heat conduction in the workpiece is as follow:

$$\nabla .(k\nabla T) + q\circ = \rho c \frac{\partial T}{\partial r} \tag{1}$$

Where k represents heat-conduction coefficient (W/m °C), $q°$ is the rate of internal heat generation (W/m^3), ρ refers to density (Kg/m^3), and c stands for specific heat (J/kg °C). So far various models have been used to solve this conduction equation that almost all of them are for conductive materials in which, the internal Joule heat term, are very small and neglected. To solve the heat-conduction equation in EDM about six models [9] have been suggested that the point source with time dependant radius on a semi-infinite cylinder model is used in this paper.

3 Equations in point heat source model with time dependent radius on a finite cylinder in cylindrical coordinate

In this model, the area of heat source is increased with pulse durations and as the heating flux is constant, its density is decreased (See Figure 2). The differential equation of heat conduction in this model is as follows:

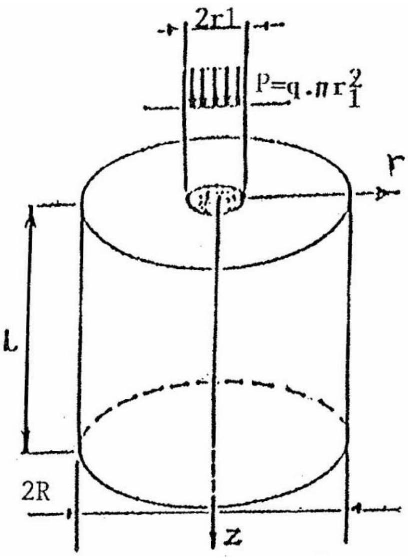

Figure 2: Point sourse model with time dependent radius on a limit cylinder.

$$\frac{1}{r}\frac{\partial}{\partial r}(k.r\frac{\partial T}{\partial r})+\frac{\partial}{\partial z}(k\frac{\partial T}{\partial z})+q\circ(r,z,t)=\rho.c\frac{\partial T}{\partial t} \tag{2}$$

The boundary conditions of this equation are:

$$T(R, z, t) = T_o \tag{3}$$

$$T(r, L, t) = T_o \tag{4}$$

$$K\frac{\partial T(r,o,t)}{\partial z}=0 \qquad r > r_1(t) \tag{5}$$

$$K\frac{\partial T(r,o,t)}{\partial z}=q \qquad r \le r_1(t) \tag{6}$$

And initial conditions are:

$$T(r, z, o) = T_o \tag{7}$$

Where R is the cylinder's radius of solution field (m), L is the length of cylinder on solution field (m), T_o is the ambient température ($^{\circ}$C), $r_1(t)$ represents the heat source radius (m), and q stands for the heat flow density (W/m^2).In this model it is assumed that the melting and evaporation processes do not take place. In eqn(2), $\overset{o}{q}$ is the rate of Joule heating per unit volume, and its value depends upon the pulse current and the electrical coefficient resistance of the workpiece at any point. The above equation is solved by numerical method in a body graded to small elements. In numerical solution of this equation, although the specifications in each element are assumed to be constant, but the variation of the specifications in different elements are considered.

4 Numerical solution method

To solve the differential equations of heat transfer and electrical potential, the numerical method of finite difference with central difference and explicit method is used. For this purpose, the cylindrical coordinate model has been meshed in radial, vertical and tangential directions. As these two differential equations in environmental direction are symmetric, the equations are only solved for one of the planes passing the vertical axis and cylindrical radius. The meshing is of monotonous kind and the distances between grids are equal. The form of finite difference of electrical potential is as follows:

$$\frac{1}{(\Delta r)^2}[(1-\frac{1}{2i})U_{i,k}+(1+\frac{1}{2i})U_{i+1,k}]+\frac{1}{(\Delta z)^2}(U_{i,k-1}-2U_{i,k}+U_{i,k+1})=0 \tag{8}$$

Also the form of finite difference of Joule heating term is as follows:

$$J_R=\frac{[U_{i-1,k}-U_{i+1,k}]}{2\rho_e.\Delta r}\ , \qquad J_z=\frac{[U_{i,k-1}-U_{i,k+1}]}{2\rho_c.\Delta z} \tag{9}$$

where U, J_R and J_Z are electrical potential (V) and current densities (A/m^2) in r and Z directions respectively.

By calculation of Joule heating in bulk unit and substituting it in differential equations, we can obtain the explicit form of heat conduction differential equation. In this equation, which is solved for an element, the physical properties of the material are to be constant, therefore:

$$\begin{aligned}T_{i,k}^{n+1}&=\frac{\alpha.\Delta t}{(\Delta r)^2}[(1-\frac{1}{2i})T_{i-1,k}^{n}+(1+\frac{1}{2i})T_{i+1,k}^{n}]+\frac{\alpha.\Delta t}{(\Delta z)^2}[T_{i,k-1}^{n}+T_{i,k+1}^{n}]+\\&[1-\frac{2\alpha.\Delta t}{(\Delta r)^2}-\frac{2\alpha.\Delta t}{(\Delta z)^2}]T_{i,k}^{n}+\frac{\rho_e J^2\alpha.\Delta t}{k}\end{aligned} \tag{10}$$

$$T_{0,k}^{n+1} = \frac{4\alpha.\Delta t}{(\Delta r)^2} T_{1,k}^n + \frac{\alpha.\Delta t}{(\Delta z)^2} (T_{0,k-1}^n + T_{0,k+1}^n) + (1 - \frac{4\alpha.\Delta t}{(\Delta r)^2} - \frac{2\alpha.\Delta t}{(\Delta z)^2}) T_{0,k}^n + \frac{\rho_e J^2 \alpha.\Delta t}{k} \tag{11}$$

$$\alpha = \frac{k}{\rho.c} \tag{12}$$

where α is thermal diffusivity (m^2/s) and n is time index.

Table 2: Some input and output machining parameters.

No. Of Tr.	Material	O.p.c.voltage (v)		$V_{dis}+V_{sic}$ (v)	Req(Ω)		V_{dis} (v)	V_{sic} (v)	I_{dis} (A)	η
		High	Low		Low	High				
4	Si C	216	70	57	2.69	41.67	31.4	25.6	7.90	163
	Steel	216	70	32	2.69	41.67	32	-	18.5	-
6	Si C	216	70	60	1.52	41.67	31.8	28.2	9	177
	Steel	216	70	32	1.52	41.67	32	-	29.4	-
8	Si C	216	70	62	1.06	41.67	33-5	28.5	9.36	170
	Steel	216	70	32	1.06	41.67	32	-	40.3	-

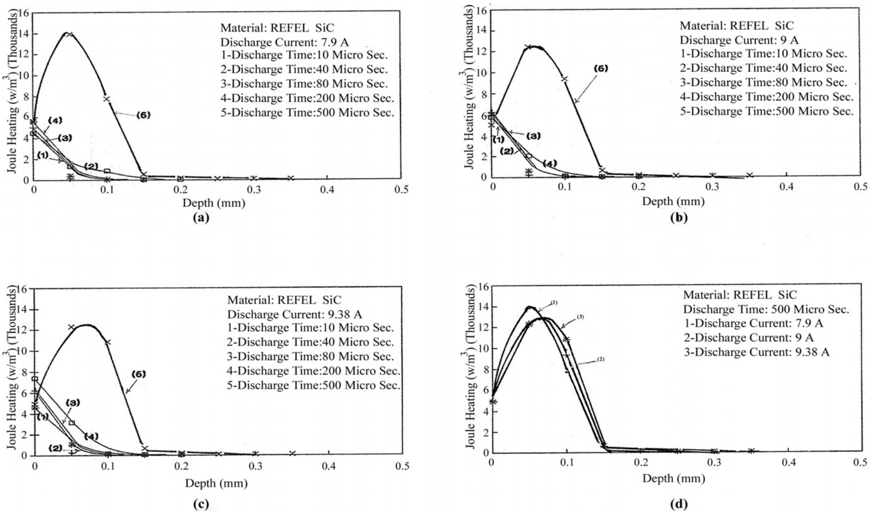

Figure 3: Variations of Joule heating rate per unit Volume with depth under various pulse durations and currents.

5 Discussion

The loss of energy in workpiece as Joule heating is more than 160 percent of plasma energy on the workpiece (See Figure3 and Table 2). This amount is produced mostly near the plasma source and the more discharge current and pulse duration, the more the Joule heating production. The curves of Figure3 also show that in short pulse durations, the maximum rate of Joule heating produced on the workpiece surface, but when the pulse duration increases, this maximum amount is transferred below the surface layer.

It can be seen from Figure 4 that the most temperature changes are on the surface of the workpiece and at a distance of less than 0.2 mm in steel and 0.4 mm in SiC from the centre of melting zone. The curves of Figure 4 also show that the longer the pulse duration, the higher the maximum temperature changes and the more the radius of high temperature zone.

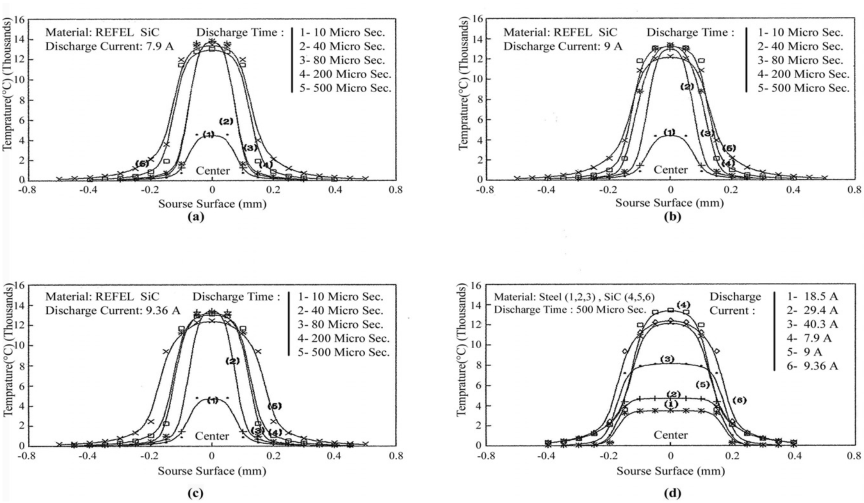

Figure 4: Variations of workpiece surface temperature with depth under various pulse durations and currents.

6 Conclusions

In electro-discharge machining of SiC, the voltage drop in workpiece is very high and the same as discharge voltage. For this high voltage reduction an important part of energy in the workpiece body is wasted as Joule Heating. This energy loss reaches its maximum on the workpiece surface for short pulse durations, and near the surface in depth for long pulse durations. The temperature of workpiece is highest in the centre of melting zone on the workpiece surface and in all directions, it reduces rapidly. In steel, the maximum temperature is lower and its reduction in depth and surface occurs in shorter distance. An increase in the discharge currents causes more voltage dropped in

SiC and a little increase in Joule heating. In comparison with SiC, the heating zone in steel is larger and with increasing in the discharge currents, this area increases extremely.

References

[1] Brook, R.J., Concise Encyclopaedia of Advanced Ceramic Materials, Max-plank-Institut für Metallforschung Stuttgart, Germany, 1991.
[2] Kennedy, p. & Shenan, J.V., Engineering Applications of REFEL Silicon-Carbide, Proc. of 3rd Conf. on Silicon-Carbide; Miami, USA, 1973.
[3] Reid, D.S. & Shaw, J.W., The machining of SiC Reactor Fuel Element Laboratories, UKEKA, Springfield, Preston, April 1969.
[4] Humphrey, P.D., An investigation into the electrical discharge machining of SiC, Reactor Fuel Element Laboratories, UKAEA, Springfield, Preston, 1976.
[5] Forrest, C.W., Kennedy, p. & Shenan, J.V. , The fabrication and properties of Self-Bonded SiC bodies, Special Ceramics, British Ceramic Research Association, June 1972.
[6] Tsai, K. M. & Wang, P. J., Semi-empirical model of surface finish on electrical discharge machining, International Journal of Machine Tools & Manufacture, Vol.4, No.10, pp. 1171-1179, August 2001.
[7] Yadav, V., Jain, V.K. & Dixit, P.M., Thermal stresses due to electrical discharge machining, International Journal of Machine Tools & Manufacture, Vol.42, No.8, pp. 877-888, June 2002.
[8] Kulkarni, A., Sharan, R. & Lal, G.K., An experimental study of discharge mechanism in electrochemical discharge machining, International Journal of Machine Tools & Manufacture, Vol.42, No.10, pp. 1121-1127, August 2002.
[9] Van Dijck, F., Physico-Mathematical Analysis of the Electro Discharge Machining Process, PhD Thesis, Catholic-University of Leuven, 1973 (English translation).
[10] Van Dijk, F., Crookall, J.R., Heuvelman, C.J., & Snoeys, R., Some Results of Physical Research in EDM, Proc. of the 5th Int. Symposium for Electro machining, pp. 68-85, 1977.