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Temperature and Thermal Stress Analysis of Electrical Discharge Machining - A Review

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Abstract

High residual thermal stresses are developed on the surfaces of Electric Discharge Machined parts because of the high temperature gradients generated at the gap during Electrical Discharge Machining (EDM) in a small heat-affected zone. These thermal stresses can lead to micro-cracks, decrease in fatigue life and strength and possibly catastrophic failure. The results of the analysis show high temperature gradient zones and the regions of large stresses where,sometimes, they exceed the material yield strength. A transient thermal analysis assuming a Gaussian distribution heat source with temperature-dependent material properties can be used to investigate the temperature distribution. In this paper basic review is presented based on different parameters and various methods applied by others to estimate the temperature distribution and thermal stress analysis.

Keywords: Electrical Discharge Machining (EDM), Finite Element Method(FEM), Material Removal Rate (MRR),Temperature distribution, Thermal stresses

1Introduction

EDM provides an effective manufacturing technique that enables the productionof parts made of hard materials with complicated geometry that are difficult to produce by conventionalmachining processes. Its ability to control the process parameters to achieve the required dimensional accuracyand surface finish has placed this machining operation in a prominent position in industrial applicationsand effectively used in a wide range of industries such as die and mould-making, aerospace, automotive, medical, micromechanics, etc.

The complex nature of the process involves simultaneous interaction of thermal, mechanical, chemical and electrical phenomena, which makes process modeling very difficult.EDM can be described as a process for eroding and removing material by transient action of electric sparks onelectrically conductive materials.The workpiece andthe electrode immersed in a dielectric liquid and separated by a small gap. The main mode of erosion is caused by the local thermal effect of an electric discharge[1].

The erosion by an electric discharge involves phenomena such as heat conduction, energy distribution, melting, evaporation, ionization, formation and collapse of gas bubbles in the discharge channel [19].

The tool is made cathode and work piece as anode. When the voltage across the gap becomes sufficiently high it discharges through the gap in the form of the spark in interval of 10 micro seconds and positive ions and electrons are accelerated, producing a discharge channel that becomes conductive. It is just at this point when the spark jumps causing collisions between ions and electrons and creating a channel of plasma. A sudden drop of the electric resistance of the previous channel allows that current density reaches very high values producing an increase of ionization and the creation of a powerful magnetic field[2,3]. The moment spark occurs sufficient pressure developed between work and tool as a result of whicha very high temperature is reached and at such high pressure and temperature that some metal is melted and eroded.

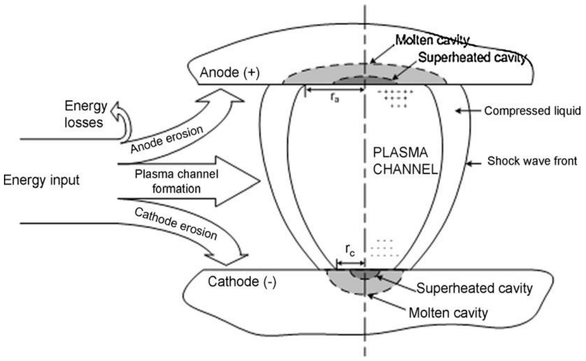

Fig.1. EDM operation

EDM is a thermal process where thermal energy is generated in plasma channel. Heat generated in the plasma channel in each spark, causes the work-material to melt. Extremely high temperature resulted due to transient heat flux, induces thermal stresses within the heat-affected zone, which is the most potential zone of initiation of network of micro-cracks[17]. Microscopic studies reveal multi-layered heat-affected zone including a hardened layer that possesses high brittleness, and reduced fatigue strength of the work-material[4].In this context, analysis of temperature and thermal stress profiles in the workpiece are of considerable interest to study.

1.1 Important parameters of EDM

There are different parameters whichwillplay a very vital role in erosion of material presented below.

1.Spark On-time (pulse time or T_{on}):

The duration of time (µs) the current is allowed to flow per cycle. Material removal is directly proportional to the amount of energy applied during this on-time. This energy is really controlled by the peak current and the length of the on-time.

2.Spark Off-time (pause time or T_{off}):

The duration of time (µs) between the sparks (that is to say, on-time). This time allows the molten material to solidify and to be wash out of the arc gap. This parameter is to affect the speed and the stability of the cut. Thus, if the off-time is too short, it will cause sparks to be unstable.

3.Arc gap (or gap):

The Arc gap is distance between the electrode and workpiece during the process of EDM. It may be called asspark gap. Spark gapcan be maintained by servo system.

4. Discharge current (current Ip):

Current is measured in amp Allowed to per cycle. Discharge current is directly proportional to the Material removal rate.

5.Duty cycle (τ):

It is a percentage of the on-time relative to the total cycle time. This parameter is calculated by dividing the on-time by the total cycle time (on-time plus off time).

6.Voltage (V):

It is a potential that can be measure by volt it is also effect to the material removal rate and allowed per cycle. Voltage is given by in this experiment is 50 V.

7.Over cut :

It is a clearance per side between the electrode and the workpiece after the marching operation.

1.2 Tool Material

Tool material should be selected such that it shouldnot undergo more wear due to impingement of positive ions. Itshould have high electrical and thermal conductivity. There would be less volume removal or tool wear and thus less dimensional loss or inaccuracyfor the same heat load and same tool wear by weight.

The localized temperature rise should be less by properly choosing its properties or even when temperature increases, there would be less melting. Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM.

1.3Work Material

EDMiscapable of machining geometrically complex or hard material components, that are precise and difficult-to-machine such as tool steels, composites, super alloys, ceramics, carbides, heat resistant steels etc.

There are different types of tool material made using the EDM method and the tool steel contains carbon and alloy steels that are particularly well-suited to be made into tools.At the present time, EDM is widespread technique used in industry for high precisionmachining of all types of conductive materials such as: metals, metallic alloys, graphite, or even some ceramic materials, of whatsoever hardness. Their suitability comes from their distinctive hardness, resistance to abrasion, their ability to hold a cutting edge, and/or their resistance to deformation at elevated temperatures (red-hardness). Tool steel is generally used in a heat-treated state. Tool steels are made to a number of grades for different applications. In general, the edge temperature under expected use is an important determinant of both composition and required heat treatment. The higher carbon grades are typically used for such applications as stamping dies, metal cutting tools, etc.

1.4Dielectric fluid

Material removal mainly occurs due to thermal evaporation and melting. As thermal processing requiredto be carried out in absence of oxygen so that the process can be controlled and oxidation avoided. Oxidation often leads to poor surface conductivity (electrical) of the work piece hindering further machining. Hence, dielectric fluid should provide an oxygen free machining environment. Further it should have enough strong dielectric resistance so that it does not breakdown electrically too easily but at the same time ionize when electrons collide with its molecule. Dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material.

The dielectric fluid has the following functions:

(a) It helps in initiating discharge by serving as a conducting medium when ionised, and conveys the spark. It concentrates the energy to a very narrow region.

(b) It helps in quenching the spark, cooling the work, tool electrode and enables arcing to be prevented.

(c) It carries away the eroded metal and acts as a coolant in quenching the sparks.

1.5Electro Discharge Machining process

In this process the metal is removed from the workpiece due to erosion case by rapidly recurring spark discharge taking place between the tool and work piece. Common methods of evaluating machining performance in EDM operation is based on the performance characteristic like: MRR, SR, and EWR[16].Basically, this characteristics' are correlated with the machining parameters such as work piece polarity, pulse on time, duty factor, and open discharge voltage, discharges current and dielectric fluid. Proper selection of the machining parameters can obtain higher material removal rate, better surface roughness, and lower electrode wear ratio [5]. Machining takes place by the discharge pulse from the cathode to the anode. Usually, the polarity is set, so that the work piece acts as the anode and the tool electrode acts as the cathode, in order to obtain a higher material removal rate. The discharge pulse gap is relatively small, thus the accuracy of components or parts manufactured by EDM is very high. EDM is a thermo electrical material removal process, in which the tool electrode shape is reproduced mirror wise into a work material, with the shape of the electrode defining the area in which the spark erosion takes place

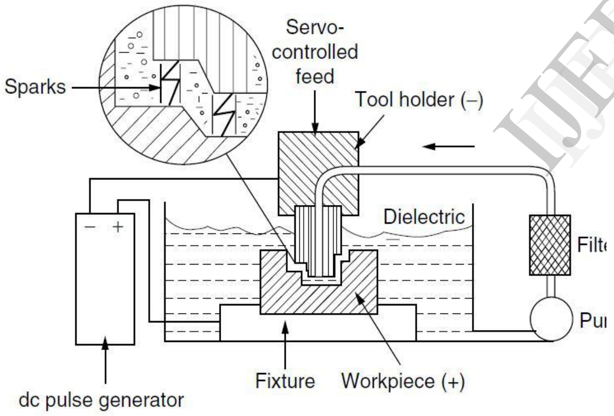

Fig.2. EDM process[5]

2. MRR and Tool wear

Kunieda et al. [7] has revealed a new method toimprove EDM efficiency by supplying oxygen gas into gap.They found that the stock removal rate is increased due tothe enlarged volume of discharged crater and morefrequent occurrence of discharge. He discovered that a 3D shape can be machined veryprecisely using a special NC tool path which can supply auniform high-velocity air flow over the working gap andMRR is improved.

The mechanism for minute tool electrode wear in dry EDM was studied by Yoshida and Kunieda [8]. The toolelectrode wear is almost negligible for any pulse durationbecause the attached molten work piece material protectsthe tool electrode surface against wear. From observationof the cross-section of the tool electrode surface, it wasfound that the tool electrode wore by the depth of only2 mm during the early stage of successive pulse dischargessince the initial surface of the tool electrode was notCovered with the steel layer.

ZhanBo et al. [9] studied the feasibility of 3D surfacemachining by dry EDM to investigate the influence ofdepth of cut and gas pressure, pulse duration and pulseinterval and the rotational speed of the tool electrode. Theresult shows that optimum combination between depth ofcut and gas pressure and when pulse duration 25 mm it isleads to maximum MRR and minimum tool wear. As the rotational speed increases the tool wear increasesmoderately.

Jeswani [10] revealed that the addition of about 4 grams/litres of fine graphite powder in kerosene increases MRR by 60% and tool wear by 15%. Yan and Chen [11] describes the effect of dielectric mixed with electrically conductive powder such as Aluminium powder on the gap distance, surface roughness, material removal rate, relative electrode wear ratio, and voltage waveform. It is shown that the dielectric with suspended electrically conductive powder can enlarge the gap distance and can improve the energy dispersion, surface roughness, and material removal rate.

Vinod Yadav et al. [12] had developed the finite elements modelto estimate the temperature field and thermal stresses due to Gaussian distributed heat flux of a spark during EDM. First, he had developed code to calculate the temperature in the workpiece and then the thermal stress field is estimated using this temperature field. The effects of various process variables (current and duty cycle) on temperature distribution and thermal stress distribution had reported.

He had developed mathematical model for single spark and assumed to be axisymmetric, governed by the following thermal diffusion differential equation:

$$\rho C\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(k\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$

Where, T is temperature, t is time, ρ is density, k is thermalconductivity, C is specific heat capacity of workpiecematerial in solid state and r and z are coordinateaxes.

By using Galerkin finite element formulation he had obtain temperature distribution and thermal stresses within cylindrical domain due to heat flux of single spark.

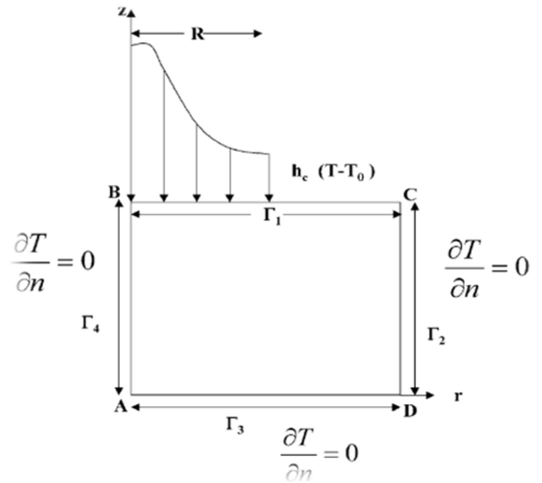

Fig. 3. Thermal model of EDM[12]

Table No. 1. Material properties and process parameters used in the this paper

Material: HSS			
C (J/kg K)	419	*To* (K)	298
E (GN/m^2)	208	*U*b (V)	40
*h*c (W/m^2 K)	10,000	αt (/K)	11.7 ×10^{-6}
I (A)	8	N	0.3
K (W/mK)	40.2	ρ (kg/m^3)	8691
R (μm)	125	*T*m (K)	1965
*R*w	0.08		

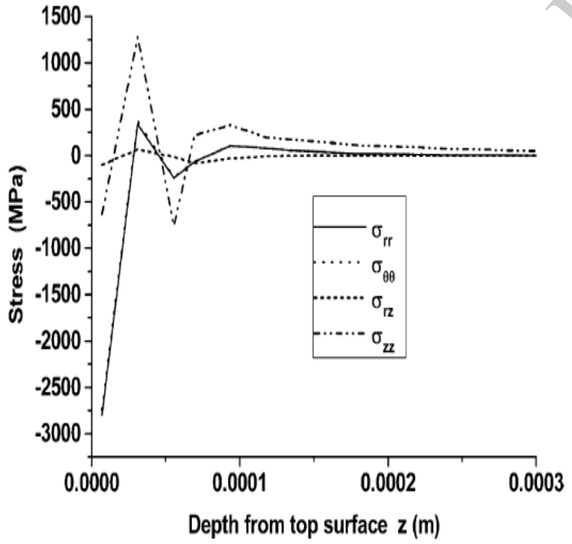

Fig.4. Variation of stress components in HSS workpiece for Ub=40 V, I=8 A, Rw=0.08, R=125 µm, ton=100 µs, duty cycle=50%. Results after 100µs (a) along the radial distance at 7 µm below from the top surface (b) along depth at r=7 µm.[12]

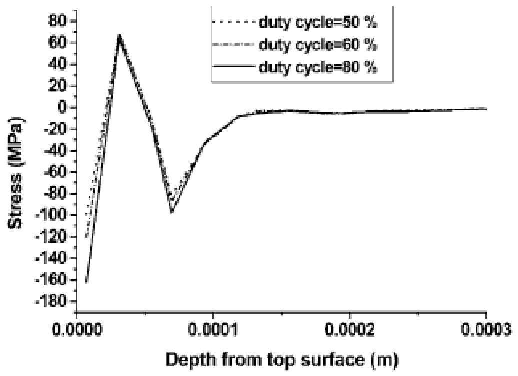

Fig.5. Variation of stress components with duty cycle along depth in HSS workpiece at 7 µm below from the top surface for *U*b=40 V ,*I*=8 A, *R*w=0.08, *R*=125 µm, t_{off}=100 µs. Results after one spark on-time.[12]

M K Pradhan [20]has shown that if T_{on} is higher, the spark radius R will also be larger and the heat will be distributed to a larger area, (as the plasma channel becomes wider with increase of T_{on}, the heat flux distribution becomes less steep), which may not produce the higher peak temperature, but will remove morematerial.

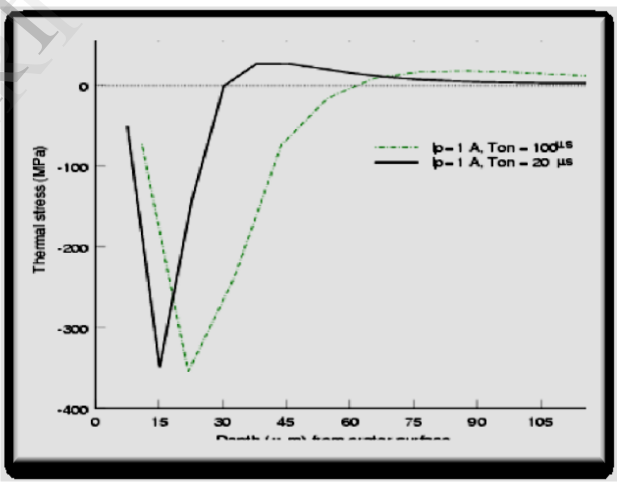

Fig.6Effect of pulse duration on thermal stress for pulse current = 1A[20]

In the figure presented, it can be clearly seen that the profile of T_{on} =100 µs, though more heat is produced, but the peak temperature approaches 4000K. However, the profile of T_{on}=20 µs with lower heat supplied to a radius of 75 µm for a very short time, thus produces a peak temperature of slightly higher than 4000K. This may be attributed to, though less amount of heat is produced and the heat is concentrated to smaller area, produce slightly higher peak temperature, than that for larger T_{on}.

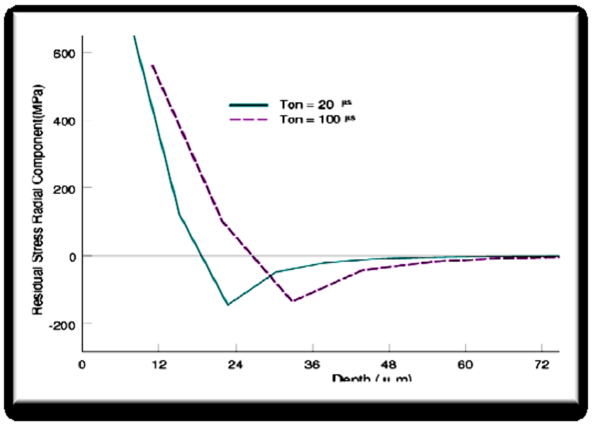

Fig.7Effect of pulse duration on thermal stress for pulse current = 9A[20]

The distinctive stress distributions in EDM process, enumerated at the end of heating cycle are presented. Here, Gaussian heat flux distribution with energy partition (Pf) value of 0.08 is used for the calculation of temperature distribution. Later on, by varying the two parameters i.e. pulse duration and current, a parametric study of thermal stresses are presented. The maximum compressive stresses are located on the surface of the newly created crater and decreases away from the crater radially as well as axially.

Bu¨ lent Ekmekci[14] showed Procedures and results of experimental work to measure residual stresses and hardness depth in electric discharge machined surfaces. Layer removal method is used to express theresidual stress profile as a function of depth caused by a die sinking type EDM. Thin stressed layersare removed from machined samples by electrochemical machining. Corresponding deformationsdue to stress relaxation are recorded for each removal to determine the stress profile from elasticitytheory. The relational dependence of the machining parameters with residual stresses is obtainedand a semi-empirical model is proposed for plastic mold steel for de-ionized water as dielectricliquid. These stresses are found to be increasing rapidly with respect to depth, attaining to itsmaximum value, around the yield strength, and then fall rapidly to compressive residual stressesin the core of the material since the stresses within plastically deformed layers are equilibrated withelastic stresses.

B.Izquierdo et al. [15] had given new contribution to the simulation and modeling of the EDM process. Temperature fields within the workpiece generated by the superposition of multiple discharges, as it happens during an actual EDM operation, are numerically calculated using a finite difference schema.

A result shows that a unit amplitudeshape function can be proposed to represent the change incurvature with respect to depth on electric dischargemachined surfaces[18].

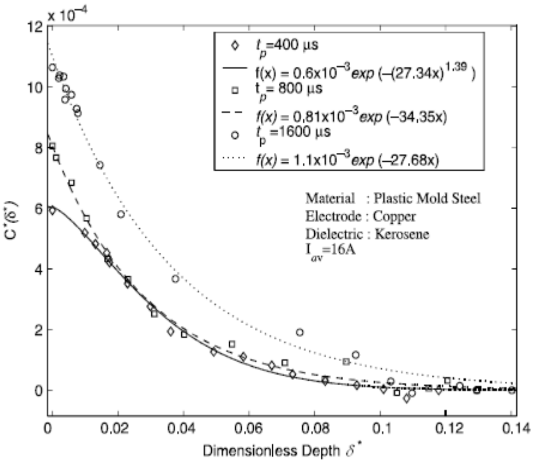

Fig.8. Change in curvature on cracked samples.[18]

High tensile residual stresses are generated by EDM. They increase from the surface and reaches to their maximum value. This maximum value is around the ultimate tensile strength of the material. Then residual stress falls rapidly to relatively low values of compressive. Compressive stresses are related to sample thickness since residual stresses within plastically deformed layers are balanced with elastic stresses in the core of the material.

S.N. Joshi, S.S. Pande[21] havedeveloped of a thermo-physical model for die-sinking EDM process using FEM. Numerical analysis of the single sparkoperation of EDM process has been carried out considering the two-dimensional axi-symmetric processcontinuum. The analysis is based on more realistic assumptions such as Gaussian distribution of heat flux,spark radius equation based on discharge current and discharge duration, latent heat of melting, etc.,to predict the shape of crater cavity and the material removal rate (MRR). Using the developed model,parametric studies were carried out to study the effect of EDM process parameters such as dischargecurrent, discharge duration, discharge voltage and duty cycle on the process performance.

Sasmeeta Tripathy[22] has generated a thermal-electrical model for sparks generated by electrical discharge in a liquid media and to determine the temperature distribution of tool and work piece. For a single discharge test, copper and En-19 was used as specimens. The amount of heat dissipated varies with the thermal-physical properties of the conductor. The model is developed by using ANSYS software. ANSYS uses the finite-element method to solve the underlying governing equations and the associated problem-specific boundary conditions. Material Removal Rate, Surface Roughness and the maximum temperature reached in the discharge channel is determined.

Table 2 Material Properties for FEA

Material Property	Copper (cathode)	En-19 (anode)
ρ (g/mm^3)	8920×10^{-6}	7700×10^{-6}
k (W/mmK)	400×10^{-3}	222×10^{-12}
α_t (Ω-mm)	1.7×10^{-11}	22.2×10^{-11}
c(J/gK)	385×10^{-3}	473×10^{-3}

A graph showing the material removal rates with varying current conditions and different T_{on}values is presented in Fig.8 It indicates that for T_{on} =100, with increase in current the material removal rate increases. The volume of material removed is increasing as the current is increasing and hence the Material Removal Rate is also increasing for T_{on}= 150 and 200.

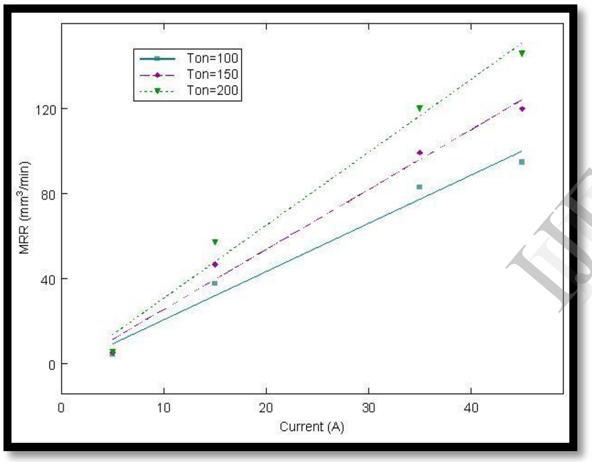

Fig.9Material removal rates with varying current conditions and different T_{on}values[22]

The material removal rate increases with $T_{on}$for same current which is obvious. As spark time increases with T_{on}, more energy is being released in the discharge channel and consequently more is the material removal rate.

3. Conclusion

From the above review we can say that thermal stresses exceed the yield strength of the workpiece mostly in an extremely thin zone near the spark. . These thermal stresses can lead to micro-cracks, decrease in fatigue life andstrength and possibly catastrophic failure. For the material of plastic mold steel high tensile residual stresses are increase from the surface and reaches to theirmaximum value. This maximum value is around theultimate tensile strength of the material.The pattern of residual stress distributionat different pulsedurations and currents is always sameunless cracking network is developed. The location oftensile peak stress is directly related to the spark energy.However, theintensity of peak stress remains unchanged.

The energytransferred to the workpiece shows downward trend for pulse duration as for the higher pulse duration there isexpansion of plasma channel and additional energy supplied is lostin maintaining the plasma channel, so energy transferred tothe workpiece is reduced.

4. REFERENCES

[1] M. Field and J.F. Khales, Review of surface integrity of machined component, Annals of CIRP 25 (1976) 569–573.

[2] Ali Ahsan, "Role of heat transfer on process characteristics during electrical discharge machining", Developments in Heat Transfer (2009) 417–435.

[3] "Simulation of thermal effects for Electrical Discharge Machining " Hans-peter schulze el.al. Nonconventional Technologies Review – No. 1 / 2007

[4] L.C. Lee, L.C. Lim, V. Narayanan and V.V. Venkatesh, "Quantification of surface damage of tool steels after EDM", Int. J. Mach. Tools Manufacture. 28 (4) (1988) 359–372.

[5]Manabhanjan sahoo1, Rudra n. Pramanik2 &Dipti r. sahoo3."Experimental investigation of machining of ungstencarbide by EDM and its mathematical expression "International Journal of Mechanical and Production Engineering (IJMPE) ISSN No.: 2315-4489, Vol-2, Iss-1, 2013

[6]http://vertex.berkeley.edu/Me221/mas2/html/processes/edm/index.html

[7] M. Kunieda, S. Furuoya and N. Taniguchi, "Improvement of EDM efficiency by supplying oxygen gas into gap", CIRP Annals Manufacturing Technology 40 (1991) 215–218.

[8] M. Yoshida and M. Kunieda, "Study on mechanism for minute tool electrode wear in dry EDM", Seimitsu KogakuKaishi/Journal of the Japan Society for Precision Engineering 65 (1999) 689–693.

[9] Y. Zhanbo, J. Takahashi, N. Nakajima, S. Sano, K. Karato, and M.Kunieda, "Feasibility of 3-D surface machining by dry EDM" (/http://www.sodic.co.jptechimgarticle_s02.pdf> Downloaded on Feb.25 2013).

[10] M.L. Jeswani,"Effect of the addition of graphite powder to kerosene used as the dielectric fluid in electrical discharge machining", Wear 70 (1981) 133–139.

[11] B.-H. Yan and S.-L. Chen, "Effects of dielectric with suspended aluminum powder on EDM", Journal of the Chinese Society of Mechanical Engineers, Transactions of the Chinese Institute of Engineers, Series C/Chung-Kuo Chi Hsueh Kung Ch'eng Hsuebo Pao 14 (1993) 307–312.

[12] Vinod Yadav, Vijay K. Jain and Prakash M. Dixit, "Thermal stresses due to electrical discharge machining", International Journal of Machine Tools & Manufacture 42 (2002) 877–888.

[13] P. Shankar,"Analysis of spark discharge in EDM process", M.Tech. thesis, Indian Institute of Technology, Kanpur, 1996.

[14] Bu¨lentEkmekcia, A. ErmanTekkaya and AbdulkadirErden, "A semi-empirical approach for residual stresses in electric discharge machining (EDM)",International Journal of Machine Tools & Manufacture 46 (2006) 858–868

[15] B.Izquierdo J.A.Sa´ nchez, S.Plaza, I.Pombo, and N.Ortega,"A numerical model of the EDM process considering the effect of multiple discharges", International Journal of Machine Tools & Manufacture 49(2009)220–229.

[16] Harminder Singh, "Experimental study of distribution of energy during EDM process for utilization in thermal models",International Journal of Heat and Mass Transfer 55 (2012) 5053–5064.

[17] S.M. Pandit and K.P. Rajurkar, "A stochastic approach to thermal modeling applied to electro-discharge machining", Trans. ASME, Journal of Heat Transfer 105 (1983) 555–562.

[18].J.P. Kruth and Ps. Bleys, "Measuring residual stress caused by wire EDM of tool steel", International Journal of Electrical Machining 5 (1) (2000) 23–28.

[19].W. Natsu, M. Shimoyamadaand M. Kunieda," Study on expansion process of EDM arc plasma", JSME International Journal, Series C 49 (2) (2006) 600–605.

[20].M.K. Pradhan, "Process simulation, modeling and estimation of Temperature and residual Stresses Electrical Discharge Machining of AISI D2 steel", ISCI (2012) 1–9

[21] S.N. Joshi, S.S. Pande "Thermo-physical modeling of die-sinking EDM process"Journal of Manufacturing Processes 12 (2010) 45_56

[22] Sasmeeta Tripathy "Thermal-electrical modeling of electrical discharge machining process. ", M.Tech. thesis, Indian Institute of Technology, Rourkela,2007