A Review On Thermal Analysis Of Electro Discharge Machining

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Abstract

The high temperature gradients generated at the gap during electrical discharge machining (EDM) result in large localized thermal stresses in a small heat-affected zone. These thermal stresses can lead to micro-cracks, decrease in strength and fatigue life and possibly catastrophic failure. In this paper basic review is presented based on different parameters and various methods used by other to estimate the temperature distribution and thermal stress analysis.

Keywords: Electrical discharge machining (EDM), FEM, Temperature distribution, Thermal stresses

1. Introduction

Electrical Discharge Machining (EDM) is undeniably a thermal process where thermal energy is generated in a discharge channel. Heat generated in the channel, causes the work material to melt and even evaporate. High temperature generated due to high-density thermal energy discharge leads to not only thermal erosion but also to formation of recast layer with micro-cracks on machined surface. The presence of multi-layered heat affected zone and brittleness of the hardened layer has been reported to reduce the fatigue strength of electro discharge machined components [1, 2]. The computation of temperature and thermal stress fields in the workpiece, therefore, are of considerable interest as far as surface Integrity is concerned.

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 complicated phenomenon, coupled with surface irregularities of electrodes, interaction between two successive discharges, and the presence of debris particles, make the process random in time as well as space and therefore, deterministically derived thermal models yield results that do not match favorably with the experimental evidence. If we see from the perspective of machining energy, each pulse during the discharge process is an output of energy and the input discharge current together with discharge duration and relatively constant voltage for given workpiece and tool electrode materials is representative of the energy per pulse expended in the spark gap region.

The total energy depends on the number of sparks each second and the amount of energy in each spark. The electrical energy supplied during this process is converted into heat energy and this energy is distributed between the various components of the system (workpiece, tool electrode and dielectric fluid) and is shared by large number of physical processes occurring during the main stages (ignition, main discharge, melting, evaporation, and expulsion) of EDM process [3,4].

Electro-discharge machining (EDM) is a thermal process where thermal energy is generated in a discharge channel, called 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 and therefore, the electro-discharge machined surface is subjected to post-EDM processes such as grinding and polishing to remove these sub-surface defects. In this context, computation of temperature and thermal stress profiles in the workpiece are of considerable interest to study the thermal stress-induced surface damage resulted in electro-discharge machining.

1.1 Important parameters of EDM

There are different parameters like spark on time, spark off time, breakdown voltage, gap current, duty cycle etc. Which are play very vital role in erosion of material are presented below.

1. Spark On-time (pulse time or Ton): 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 Toff): 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 as spark gap. Spark gap can 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 pulse 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 to per cycle. Voltage is given by in this experiment is 50 V.
7.Diameter of electrode (D): It is the electrode of Cu-tube there are two different size of diameter 4mm and 6mm in this experiment. This tool is used not only as a electrode but also for internal flushing.
8.Over cut : It is a clearance per side between the electrode and the workpiece after the marching operation.

1.2. Dielectric fluid

Material removal mainly occurs due to thermal evaporation and melting. As thermal processing is required to 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.
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 along with it.
(d) It acts as a coolant in quenching the sparks.

Table1. Design Variable

Machining parameter	Constant parameter	Design parameters
Discharge current	Duty cycle	Material Removal rate.
Pulse on time (Ton)	Flushing pressure	Tool wear rate
Diameter of U-shaped tool	Polarity	over cut (OC)

1.3. Tool Material

Tool material should be such that it would not undergo much tool wear when it is impinged by positive ions. Thus the localized temperature rise has to be less by tailoring or 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.

1.4. Work Material

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

There are different types of tool material are using the EDM method and the tool steel Contains carbon and alloy steels that are particularly well-suited to be made into tools. 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.

1.5. EDM process

The electrical discharge machine (EDM) removes work piece by an electrical spark erosion process. Common methods of evaluating machining performance in EDM operation are based on the following performance characteristic: MRR, SR, and EWR. 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 will occur [6].

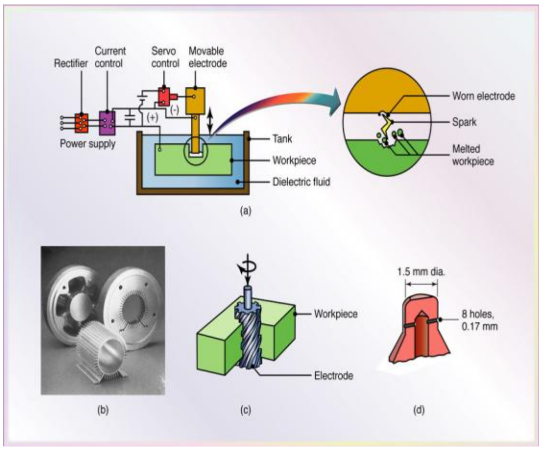

Fig.1. EDM process [6]

2. MRR and tool wear

In 1991 Kunieda et al. [7] has revealed a new method to improve EDM efficiency by supplying oxygen gas into gap. They found that the stock removal rate is increased due to the enlarged volume of discharged crater and more frequent occurrence of discharge. Then in 1997 Kunieda et al. [30] discovered a 3D shape can be machined very precisely using a special NC tool path which can supply a uniform high-velocity air flow over the working gap and MRR is improved as the concentration of oxygen in air is increased.

The mechanism for minute tool electrode wear in dry EDM was studied by Yoshida and Kunieda [8]. The tool electrode wear is almost negligible for any pulse duration because the attached molten work piece material protects the tool electrode surface against wear. From observation of the cross-section of the tool electrode surface, it was found that the tool electrode wore by the depth of only 2 mm during the early stage of successive pulse discharges since the initial surface of the tool electrode was not Covered with the steel layer.

ZhanBo et al. [9] studied the feasibility of 3D surface machining by dry EDM to investigate the influence of depth of cut and gas pressure, pulse duration and pulse interval and the rotational speed of the tool electrode. The result shows that optimum combination between depth of cut and gas pressure and when pulse duration 25 mm it is leads to maximum MRR and minimum tool wear. As the rotational speed increases the tool wear increases moderately.

Jeswani [10] revealed that the addition of about 4 g/l 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 Al 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.

In 2001 Vinod Yadav et al. [12] in 2002 had developed the finite elements model to 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, r is density, k is thermal conductivity, C is specific heat capacity of workpiece material in solid state and r and z are coordinate axes.

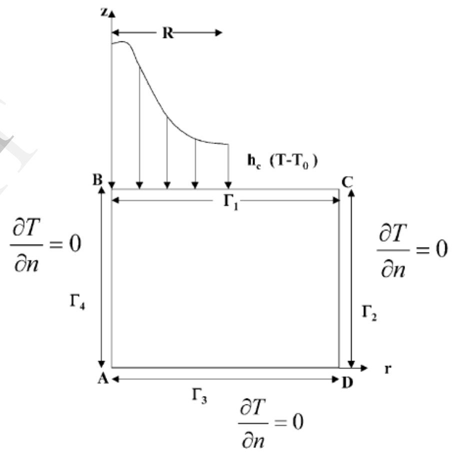

Fig. 2. Thermal model of EDM

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

Table No. 2. Material properties and process parameters used in the this paper [13]

Material: HSS			
C (J/kg K)	419	*To* (K)	298
E (GN/m^2)	208	*Ub* (V)	40
hc (W/m^2 K)	10,000	αt (/K)	11.7 $\times 10^{-6}$
I (A)	8	ν	0.3
K (W/mK)	40.2	ρ (kg/m^3)	8691
R (μm)	125	*Tm* (K)	1965
Rw	0.08		

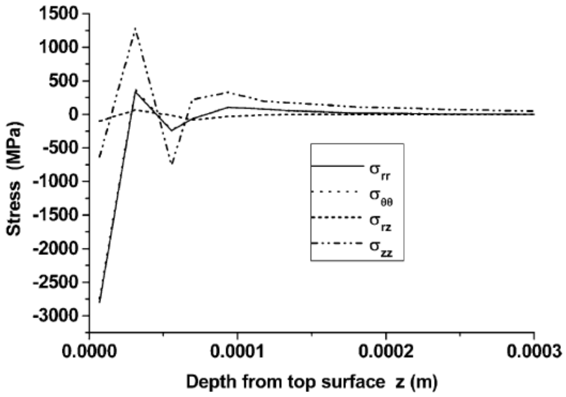

Fig.3. Variation of stress components in HSS workpiece for Ub=40 V, I=8 A, Rw=0.08, R=125 µm, ton=100 µs, duty cycle=50%. Results after 100µs (a) along the radial distance at 7 µm below from the top surface (b) along depth at r=7 µm.

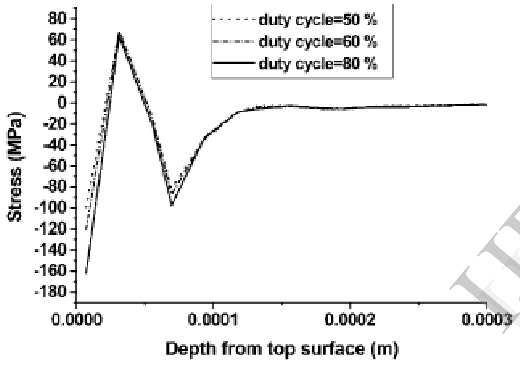

Fig.4. Variation of stress components with duty cycle along depth in HSS workpiece at 7 µm below from the top surface for *U*b=40 V , *I*=8 A, *R*w=0.08, *R*=125 µm, *t*off=100 µs. Results after one spark on-time.

The results obtained serve to illuminate the damaging nature of the thermal stresses as they develop during EDM. It is observed that, after one spark, substantial compressive and tensile stresses develop in a thin layer around the spark location. It is also found that the thermal stresses exceed the yield strength of the workpiece mostly in an extremely thin zone near the spark.

In 2006 Bu¨lent Ekmekci et al. [14] had used layer removal method to measure the residual stress profile as a function of depth beneath the surface caused by die sinking type EDM. Cracking and its consequences on residual stresses are also studied on samples machined at long pulse durations. A modified empirical equation is developed for scaling residual stresses in machined surfaces with respect to operating conditions. In this model, a unit amplitude shape function representing change in curvature with respect to removal depth is proposed. The proposed form is found to be a special form of a Gauss Distribution. It is the sum of two Gaussian peaks, with the same amplitude and pulse width but opposite center location. The form can be represented by three constant coefficients. These coefficients depend on the released energy by a power function.

He had considered following parameters for machining operation:

Dielectric	Electrode	Polarity	Pulse time (µs)	Current (A)
Kerosene	Graphite, Copper	+	8,25,50,100, 200,400,800,1600	16,8

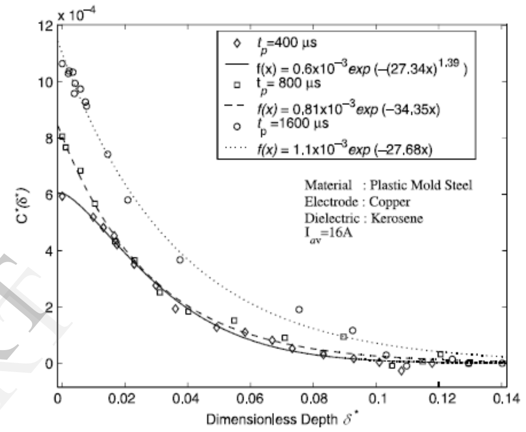

Fig.5. Change in curvature on cracked samples.

A result shows that a unit amplitude shape function can be proposed to represent the change in curvature with respect to depth on electric discharge machined surfaces [18].

The residual stresses are found as tensile in nature for all cases. They start to increase from the surface and reach their maximum value. Intensity of the peak stress is found pattern, only magnitudes of the shape and power function coefficients changes. It should be also noted that at high pulse duration and low energy levels, residual stress measurement method has failed.

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.

In 2009 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. The characteristics of the discharge for a given operation, namely energy transferred onto the workpiece, diameter of the discharge channel and material removal efficiency can be estimated using inverse identification from the results of the numerical model.

It has been shown that superposition of multiple discharges must be considered, since the amount of material removed per discharge increases (as much as 50%) as the operation progresses. This effect is related both to the stochastic nature of the process (discharge type and location) and the development of temperature fields on irregular surfaces.

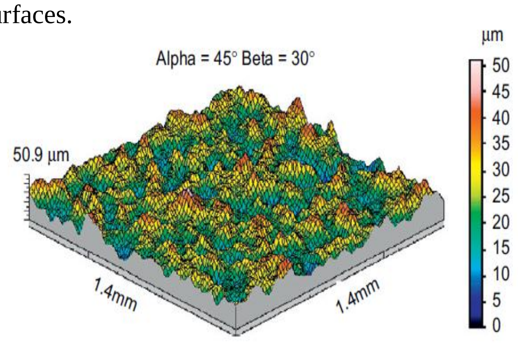

Fig.6. Comparison between simulated (left) surfaces.

In 2012 Harminder Singh [16] had evaluated effectiveness of the EDM process in terms of the material removal rate, relative wear ratio and the surface roughness of the work piece. The input discharge energy during that process is distributed to various components of the process, which further influences the material removal rate and other machining characteristics like surface roughness. Since during that process the electrical energy is converted into heat energy, hence the theoretical modeling of this process is based upon the heat transfer equations and in all existing thermal models the fraction of the energy transferred to the workpiece, is one of the important parameters [20]. The accurate prediction of the fraction of energy effectively transferred to the workpiece will help to reduce the errors of the thermal models. In this study experiments have been performed to study the percentage fraction of energy transferred to the workpiece utilizing heat transfer equations, at different EDM parameters. This study also relates the optimum parameters with the optimum utilization of input discharge energy and hence will help to improve the technological performance of this process.

He had used following governing equation with suitable boundary condition:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial Z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

Where T is the temperature (K), r is the radial axis (m), z is the vertical axis (m), t is time (s), and α is thermal diffusivity of the material (m^2/s).

It is clearly shown that F_{cw} varies with variation of either pulse duration or current. These results prove that fixed value of F_{cw} for all currents and pulse duration used by many thermal models is one of the reasons of errors in the prediction accuracy of the models.

When performing simulations employing the optimum input values the error in the prediction of surface finish is under 6% and the error in the prediction of material removal rate is lower than 3%.

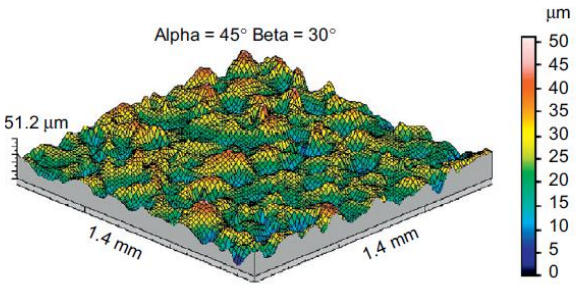

Fig.7. Comparison between simulated measured (right) surfaces.

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. For the material of plastic mold steel high tensile residual stresses are 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. The pattern of residual stress distribution at different pulse durations and currents is always same unless cracking network is developed. The location of tensile peak stress is directly related to the spark energy. However, the peak stress intensity remains unchanged.

The energy transferred to the workpiece shows downward trend for pulse duration more than because at higher pulse duration there is expansion of plasma channel and additional energy supplied is lost in maintaining the plasma channel, and hence energy transferred to the workpiece is reduced.

4. REFERENCES

[1] J.P. Kruth, L. Stevens, L. Frogen, and B. Laywers, “Study of the white layer of a surface machined by die-sinking electro-discharge machining”, Annals of CIRP 44 (1) (1995) 169–172.

[2] M. Field and J.F. Khales, Review of surface integrity of machined component, Annals of CIRP 25 (2) (1976) 569–573.
[3] Ali Ahsan, "Role of heat transfer on process characteristics during electrical discharge machining", Developments in Heat Transfer (2009) 417–435.
[4] B. Izquierdo, J.A. Sanchez, 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.
[5] 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] J.L Lin and C.L. Lin, "The use of orthogonal array with grey relational analysis to optimize the EDM process with multiple performance characteristics", international journal of machine tools &manufacture 42(2002) 237-244, received 19 nov 2000, accepted 12 July 2001.
[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 Kogaku Kaishi/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¨lent Ekmekcia, A. Erman Tekkaya and Abdulkadir Erden, "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. Shimoyamada and 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, modelling and estimation of Temperature and residual Stresses Electrical Discharge Machining of AISI D2 steel", ISCI (2012) 1–9.