Process Simulation of Electrical Discharge Machining: A Review

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Abstract Electrical discharge machining (EDM) is a metal removal machining process that is characterized by erosion caused by a rapidly occurring discharge between the tool and the workpiece. In the modern world, EDM faces numerous challenges when it comes to machining hard materials and complex shapes of structures. The thermal stress that develops just after the end of the spark and the residual stress that continues to develop after corresponding cooling, as well as the impacts of process parameters such as pulse on time, pulse off time, peak current, and output parameters such as metal removal rate, surface roughness, tool or electrode wear ratio, have been heavily researched and investigated in the past. The focus of this research is to examine prior findings about the used a suitable optimization technique for the EDM process and its variants as well as create a path to future scientific investigation.

Keywords Electrical discharge machining (EDM) · Finite element method (FEM) · Thermal stress · Residual stress · Simulation · Modelling

1 Introduction

Machining processes have been developing long along with the development of the human race, from the formation of wheel to computerized non-conventional machining. Now today's world demands high quality, precision machining processes for obtaining the standards, economical products in minimum time to achieve the industrial goal with higher efficiency. One of the most significant emerging machining processes to achieve the required goal in the world is Electrical Discharge Machining (EDM), which is a desirable non-conventional machining process getting attention for zero force, a contact-less process which enables machining of hard materials and complex geometries, with high precision, good surface finish which is not achieved

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by conventional machining processes and its capability to regulate the process parameters to accomplish the requisite surface finish and dimensional accuracy. EDM has a wide-ranging application in industries such as die industries, aerospace, automotive, electronics industry, mould making, medical, micromechanics, etc.

Electrical Discharge Machining is a metal removing process, which removes metal by the means of electric spark thermal erosion with a constant electric field in a dielectric medium. The electrically conductive workpiece and tool are connected to the positive and negative terminal of the generator respectively, so they have a huge amount of free electrons to flow. When a potential difference is generated between tool and work-piece, the electric field will be developed, free electrons will be plucked in large numbers due to electrostatic force and get accelerated towards work-piece. Energized electrons will ionize the dielectric molecules generating more ions and electrons which will again undergo collision, leading to a huge increment in the concentration of ions and electrons between tool and workpiece, plasma channel will be established between tool and work-piece. Electrons will follow the least resistivity path, will move toward the work-piece in huge amount, hence spark will be generated and the work-piece will be impinged by electrons having high kinetic energy which will be converted into high-density thermal energy which results in localized melting workpiece causing material removal. This thermal erosion produces a recast layer on the machined surface with microcracks. Here due to localize non-uniform heating and rapid cooling of material generates a multi-layered Heat Affected Zone in the subsurface of the workpiece and consequently produces thermal stresses. If these stresses have magnitude more than the material's yield stress, they will persist in the workpiece as residual stress during subsequent cooling, which contributes to fatigue crack growth, crack closure, and fracture [1].

To study the complex process of EDM, we need to study the establishment of plasma channel between workpiece and tool, thermodynamics of the spark causing thermal erosion, microstructural and metallurgical changes of material. For this study, a heat transmission thermal problem needs to be constructed to model the EDM mechanism, where the electric spark generated in EDM is the heat input, and by solving this heat transmission thermal problem for the workpiece will give us the temperature distribution in it. And to solve this numerical model finite element method is used and the impact of various process parameters on the output parameters, temperature distribution, thermal stresses and residual stresses can be investigated.

1.1 Variants of EDM

Die-sinking EDM is a variant of EDM where the final desired shape of the workpiece is complemented by the tool shape when an electric field is set up between them and thermal erosion takes place.

Powder mixed EDM is a variant of EDM process where suitable electrically conductive abrasive powder particles are added into the dielectric fluid resulting in decreases its insulation strength as these powder particles get ionized upon setting an electrical field and show accelerated zigzag motion between electrodes, leading to an increase in the inter-electrode gap, as result of which EDM performance improves and heighten surface finish is obtained in comparison to the conventional EDM.

Wire EDM is another variant of EDM where discharge occurs between metallic thin wire and workpiece, the metallic thin wire is used to cut shapes. Main cuts and trim cuts are performed on the work material using WEDM, the main cut is preferred when material removal rate (MRR) or cutting speed is a primary need and when high surface finish is more desired than the trim cut of performed at lower power setting after the main cut. [2]

2 Technique Used for the Study

2.1 **Finite element method (FEM)** is a computational technique for solving differential equations developed for mathematical modelling to investigate engineering problems in the fields of heat transfer, structural analysis, fluid dynamics, and also coupled problems like thermo-structural, electromagnetic, thermochemical, etc. In FEM the domain of the problem is discretized into small elements with the help of nodes and the differential equation is solved within the boundary of the element and by combining these discrete solutions, a global solution is obtained [3]. The chances of having error in the solution are minimized by increasing the number of elements hence reducing the element size.

2.2 **X-Ray Diffraction (XRD)** method is governed by the Bragg's law, when a specific wavelength (λ) beam of X-ray falls on the workpiece's surface, the scattered radiation undergoes interference. Bragg's law is stated by the below equation:

$$n\lambda = 2d \sin\theta$$

where,

n Order of diffraction
θ Diffraction angle
d Distance between crystallographic planes

Firstly, the strain generating the shift in crystallographic planes is evaluated assuming linear elastic distortion of the crystal lattice and then the value of stress is evaluated using Hooke's law [4]

2.3 **Taguchi Method** is a statistical methodology to enhance the quality of the product to be manufactured, by the optimization of process parameters. The main intention is to improve the quality of a product and design robust systems that are more reliable under uncontrollable conditions [5].

2.4 **Scanning electron microscopy** is a technique used for the visualization and investigation of surfaces**,** where a fine electron beam is scanned through the fracture surface to produce a picture and the rate at which the image is scanned tells the issues. The pictures can later be advanced employing frame integration and averaging [6]. An electrically conductive workpiece is required for this method, at least the surface should be conductive, and, the workpiece should be electrically grounded to avoid the accumulation of an electrostatic charge at the surface.

2.5 **Focussed Ion Beam (FIB) milling—Digital Image Correlation (DIC)**. FIB is used to mill standard geometries and the relaxation causing the surface displacements is captured by the scanning electron microscope (SEM), than images are created using DIC software, these are then used with finite element modelling for calculation of the residual stresses in the workpiece [7].

3 Previous Works

Mohanty et al. [8] uses Field Emission SEM for two cases WS_2 combined with de-ionized water and MoS_2 powders mixed in deionized water and discovered that WS_2 coated samples have a heighten density of surface crack and residual stresses develop on the recast surface than that of MoS_2 powder coated samples. Yue et al. [9] performed experimental analysis using SEM, the influencing effect of thermal stress on material removal during EDM of the C_f_SiC composite and the stress distribution on the C_f_SiC composite's discharge surface was investigated. Thermal stress was generated that exceeded the tensile strengths. Srinivasa Rao et al. [10] investigated the impact of wire EDM parameters upon the residual stresses in aluminium 2014 T6 alloy with a L8 orthogonal array Taguchi method confirms that increasing the pulse on time and peak current, increases surface roughness and cutting speed. The spark gap voltage, pulse on time, peak current, and cutting speed all had a substantial impact on residual stresses.

Some researchers have conducted an experimental analysis employing the X-Ray Diffraction method and also performed computation analysis using FEM for the validation of results. Aghdeab et al. [11] using the X-ray diffraction method and FEM the residual stress arises during EDM was determined, and discovered that the residual stress boosted with raising the current, pulse on time, and pulse off time. Sundriyal et al. [12] investigated the powder mixed near-dry (PMND-EDM) process, and it was discovered that raising the concentration of metallic powder in the dielectric was assisting in broadening the plasma channel owing to an enhanced conduction all through machining and increasing the inter-electrode gap. Das and Joshi [4] used FEM model, calculated the wire safety index. The stresses arised on the wire were found to be greater than the molybdenum's yield stress. Tlili and Ghanem [13] developed a thermomechanical model based on hydrodynamic Gruneisen-type conduct for the hydrostatic component of the stress, paired with Johnson–Cook plasticity model which reports for strain-rate-dependent stress in the scope of a shockwave condition and observed traction type residual stresses on the surface which is balanced by sublayer's compressive stresses. Saxena [14] estimate the thermal stresses and discovered that the initial compressive stresses encircling the formed crater, after heating change its nature to tensile, and as the crater reaches greater depth, the stresses transits into compressive residual stresses which bring the system into equilibrium. Zhanga et al. [15] Examined the thermal deformation of a thin-walled sample and concluded that the force at the bottom must equate the residual stress at the top of the thin-walled sheet. Where Salvati and Korsunsky [2] assesses micro- to nano-scale residual stress, used FIB-DIC method for modeling, which was validated by FEM analysis, and discovered that peak current and pulse on time, are critical for the intensity of induced residual stresses and crack emergence.

Bhattacharya et al. [16] applied FEM to simulate generated residual stresses during WEDM cutting and the volumetric strain change caused by phase transformation with the temperature introducing a user-defined subroutine. Thermal expansion is considered in the FEM analysis to account for metallurgical phase changes. Kumara and Jilte [17], discovered that the equivalent stress appears in the tool's and workpiece's core spark zone. The current density has a significant impact on the response output parameters. Mohapatra et al. [18] simulated for the wire using ANSYS Fluent and estimated the temperature and equivalent stress. The temperature of the wire was observed to vary up to 5500 K. At the centre of the wire length, equivalent stress was observed with a maximum effective stress of 397 MPa. Assarzadeh and Ghoreishi [19] performed an electrothermal simulation and discovered that progressive increases in discharge current create steadily deeper crater voids, implying the creation of more re-solidified materials atop the crater. Liu and Guo [20] accounted for massive random discharges to examine the residual stress arises in die-sinking EDM and investigated characteristics of sub surface's local and average residual stress. Singh and Kumar [21] calculated the radial, tangential and axial stresses in the electrode in the static structure module and observed that the magnitude of stress hikes with hike in current values. Pradhan [1], Biswas and Pradhan [22], Pradhan [23], Pradhan and Biswas [24] investigated the correlation between parameters and the highest temperature acquired at the end of the heating cycle and the residual stress arising, by FEA modelling, and it was discovered that compressive thermal stresses formed underneath the crater and tensile stresses existed farther from the axis of symmetry and observed that by intensifying the pulse energy the thermal stresses get affected to a greater depth. Kansal et al. [25] build the FEM model for powder mixed EDM and calculated the distribution of temperature and MRR from the temperature profiles and observed that along the radius and depth of the workpiece many different process parameters affect the temperature distributions. Allen and Chen [26] simulated for micro-EDM, analysed the residual stress and investigated the effects of vital EDM parameters on tool wear ratio and the dimension of the formed crater. Yadava et al. [27] presented for EDDG, a model has been created using FEM to assess thermal stresses. The developed algorithm first determines the temperature, and then using this temperature field, estimates the thermal stress field. Computations were performed in-plane strain conditions for various grinding wheel down feeds.

Das et al. [28] simulated with DEFORM to study the transient temperature and crater portrayal, the heat-affected zone and residual stresses in the workpiece.

Only that research is highlighted in Table 1, which used a suitable optimization technique such as the Finite Element Method (FEM), X-Ray diffraction method, FIB-DIC, SEM, and others for the EDM process and its variants such as WEDM, micro-EDM, powder-mixed EDM, powder-mixed near dry EDM, etc.

Along with the time, researchers are considering various aspects of the simulation, such as using a gaseous dielectric medium, evaluating different tool electrodes, analysing surface wettability, and micro-hardness, developing a customised mixing chamber for creating a heterogeneous dielectric mixture, and imposing the model with an infinite-element boundary to dodge shockwave reflection on the free surface, to ensures convergence towards the equilibrium condition. For the wire-EDM procedure, the wire safety index is analysed, microcracks on the wire surface are being analysed, and the authors are attempting to describe the shape and dimension of the spark.

4 Conclusion

In this review paper, a remark on various research works carried out in the field of EDM is presented.

The observed points are follows:

- It has been observed that thermal modelling of EDM mechanism followed by simulation is the key to investigate and predict the output parameters, temperature distribution and stresses, and these results have been validated by conducting experimental work.
- Experimental analysis carried out by researchers used X-ray diffraction method, Taguchi method, Scanning electron microscopy method, Focussed Ion Beam (FIB) milling—Digital Image Correlation (DIC) method.
- The experimental research shows that with increment in current pulse off time and pulse on time, increment in residual stress was observed.
- With the increment in current and voltage level, there is an increment in the maximum temperature and the maximum residual stresses.
- The depth at which the peak value of residual stresses will attain, increases proportionally with the pulse energy.
- The residual stresses comes very close or exceeds to the value of yield strength of the material at vicinity of spark location.

Table 1 Chronological ordered list of research work published related to simulation of Electric Discharge Machining from 2003 onwards

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2021	Aghdeab, et al. [11]	To Investigate the residual stress developed in the workpiece during EDM process	EDM	3-D	Tool steel AISI L2	X-ray diffraction and FEM	• The experimental research shows that with increment in current pulse off time and pulse on time, increment in residual stress was observed
2021	Mohanty, et al. [8]	Analysis of the micro-hardness, indentation depths, wettability, residual stress, surface crack density and surface roughness	μEDM	3-D	Ti6Al4V sample with tungsten disulfide and molybdenum disulfide coatings	Field Emission Scanning Electron Microscope(FESEM)	• Comparison of residual stress was made here for two specimens • Residual stresses for the case of WS_2 coated samples were found to be more than MoS_2 coated samples • More number of cracks were seen on the surface coated with WS_2

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2020	Salvati and Korsunsky [2]	Determination of micro- to nano-scale residual stress with in white layer, in two specimens having Main cut and Trim cut followed by main cut	EDM	2-D	AA6082-T6 Al alloy	FIB-DIC method and FEM	• Consistency was found in compressive residual stress along with the thickness of the white layer for both specimens • The compressive layer was thinner for the trim cut specimen than for that of the main cut specimen
2020	Sundriyal, et al. [12]	To investigate the impact of pulse-on time and concentration level of powder on MRR and residual stress respectively	Powder mixed near-dry EDM	3-D	EN-31 steel	X-ray diffraction and FEM	• Gaseous dielectric is used • An increment in MRR was observed with a decrease in pulse-on time • MRR increase slightly and then reduces upon increasing in powder concentration level

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2020	Das and Joshi [4]	To determine the wire safety index	WEDM cutting	3-D	Molybdenum wire	X-ray diffraction (XRD) and FEM	• The wire safety index is a ratio of the maximum residual stress developed and the yield stress of the wire • With the increment in current and voltage level, there is an increment in the maximum temperature and the maximum residual stresses • With the increment in pulse on-time, thermally affected region increases and peak temperature decreases
2020	Yue et al. [9]	To analyse the stress distribution on the Carbon-fiber-reinforced silicon carbide (Cf_SiC) composite during EDM	EDM	2-D	Cf_SiC composite with SiC coating	Scanning Electron Microscopy(SEM)	• Experimental and simulation comparison is done here • Higher cutting speed leads to the generation of thermal stress

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2019	Bhattacharya et al. [16]	Thermal analysis of the temperature profile and residual stress	WEDM cutting	2-D	P91 steel	FEM	• The Residual stresses were observed to be of tensile nature • When cutting is done at higher energy, higher the value of residual stresses were observed
2019	Zhanga et al. [15]	Investigate the surface integrity of thin-walled components during the WEDM process due to complex thermal deformation behaviour	WEDM cutting	2-D	Inconel 718	FEM	• With an increase in discharge energy, thermal and residual stresses increases, but a after particular increase in pulse-on time the discharge energy becomes sufficient to vaporize the metal, which leads to low residual stresses

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2018	Kumara and Jilte [17]	Investigation of the impact of input parameters on equivalent stress	EDM	3-D	XW-42 steel	FEM	• An increment in current and pulse on time value, increases the stress values • Stresses are higher for a higher fraction of the total heat input that is absorbed by the workpiece • Material flushing efficiency is supposed to be 100%
2018	Mohapatra et al. [18]	Investigation of temperature and equivalent stress for tool electrode	WEDM cutting	2-D	AISI 304 stainless steel	FEM	• Equivalent stress was found with maximum effective stress of 397 MPa at the middle of the wire
2018	Tlili and Ghanem [13]	To investigate the mechanical behaviour of the workpiece layer during an electrical discharge and numerical prediction of the residual stresses and work hardening	EDM	2-D	AISI 316L	X-ray diffraction (XRD) and FEM	• At the initial stage of solid–liquid boundary, in the sublayer, residual stresses are at their peak value

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2017	Assarzadeh and Ghoreishi [19]	Comparisons between experimental and simulated results of influence of input parameters on MRR	EDM	2-D	AISI 304 stainless steel	FEM	• With the increase in discharge time the temperature of workpiece decreases and the volume of vaporized material increases
2016	Srinivasa Rao et al. [10]	An analysis of influence of wire EDM parameters on residual stresses	WEDM	3-D	Aluminium 2014 T6 alloy	Taguchi method	• Tensile residual stresses were observed • As cutting speed increases, surface roughness and residual stresses also increases • The interaction of pulse on time, peak current and spark gap voltage, spark gap voltage, the interaction between pulse-on time and peak current, pulse-on time and peak current is the increasing order of parameters and their interactions' effect on residual stresses

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2016	Liu and Guo [20]	Investigation of the effect of massive random discharges on the residual stress	EDM	3-D	ASP 23 tool steel	FEM	• Instead of the workpiece's top surface, the maximum average residual stress was located in the subsurface • High surface roughness was the result of low residual stress on the workpiece surface • For low residual stress, low discharge energy is favourable
2016	Saxena [14]	To investigation of residual stresses and comparing it with experimental results	EDM	2-D	AISI 4340	X-ray diffraction (XRD) and FEM	• Compressive residual thermal stresses were present
2015	Singh and Kumar [21]	To investigate the thermal stresses occurring in electrode during EDM machining	EDM	3-D	Copper and graphite electrode	FEM	• The stress increases with increment in the pulse-on time and current • The temperature of the graphite electrode was found to be more than that of the copper electrode for the identical input parameters

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Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2014	Choudhary and Pradhan [29]	To investigate the effect of parameters leading to development of residual stresses beneath the crater	EDM	2-D	Molybdenum	FEM	• The residual stresses were developed near the crater periphery in all the direction • Residual stresses were found to be tensile as well as compressive in nature • Point of failure due to residual stresses was also predicted
2012	Pradhan [1]	To Investigate the temperature distribution, thermal stresses and residual stresses	EDM	2-D	AISI D2 steel	FEM	• The intensity of the peak stresses was unaffected by the magnitude of the spark energy produced • No influence of pulse energy was found on the magnitudes of the maximum tensile and compressive residual stresses • Increment in the depth where the residual stresses develop was observed with increase in the pulse energy

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2012	Biswas and Pradhan [22]	Investigation of the impact of machining parameters on the residual stresses	EDM	2-D	AISI D2 tool steel	FEM	• For all combination of machining parameters, all component of the residual stresses gets dominated by radial component
2010	Pradhan [23]	To predict the nature of thermal stresses developed during EDM process	EDM	2-D	AISI D2 steel	FEM	• The thermal tensile stresses were observed far from the axis of symmetry and the compressive thermal stresses were observed underneath the crater • Thermal stresses develop to a greater depth when pulse energy increases

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2008	Pradhan and Biswas [24]	To investigation of residual stresses and thermal stresses due to non-uniform temperature fields	EDM	2-D	AISI 4140 steel	FEM	• The values of residual stresses are high close to the surface and decreases sharply radially and axially away from the crater • The largest value of Residual stress in the radial direction is 34 MPa in compression and 300 MPa in tension. Whereas in axial direction 16 MPa in compression and 63 MPa in tension
2008	Kansal et al. [25]	To investigate the thermal behaviour and the mechanism of material removal	PMEDM	2-D	AISID2 die steel	FEM	• Both theoretical and experimental observation says that the MRR for PMEDM is higher than for the conventional EDM • Radially elongation is more than that for depth for the craters formed in PMEDM

(continued)

Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2007	Allen and Chen [26]	To analyse the residual stress on molybdenum	Micro-EDM	2-D	Molybdenum	FEM	• After a single heat-flux numerically small residual stresses tensile in nature were remaining in the workpiece • Surface damage may cause over many spark cycles due to residual stresses build-up
2004	Yadava et al. [27]	To investigate the thermal stresses when the current is switched-off during Electrical discharge diamond grinding(EDDG)	EDDG	2-D	HSS	FEM	• Initially during grinding, at the vicinity of the top surface higher thermal stresses were found but afterwards, it shifts towards the bottom • The value of thermal stresses did not overcome the yield strength value

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Table 1 (continued)

Year	Author(s)	Objective	Process version		Workpiece material	Technique used	Remarks
2003	Das et al. [28]	To analyse the impact of multi-sparks discharge on transient temperature distribution, material alteration and developed residual stresses in the specimen due to single-pulse discharge	EDM	2-D	Copper and graphite	FEM	• There was a significant increase in the residual stress at the vicinity of the surface but with increment in the depth, the stress vanishes rapidly • At the vicinity of spark location, the value of residual stress gets close to the material's tensile strength

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