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Performance Optimization Of H13 Die Steel Machining In An Automated Hybrid Edm System With Rotating Fixture Integration

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ABSTRACT
Electrical Discharge Turning (EDT) is a novel and effective technique that combines the benefits of Electrical Discharge Machining (EDM) and traditional turning processes. It is especially advantageous for fabricating complex cylindrical components from hard-to-machine materials like H13 die tool steel. The primary objective of this research is to investigate the machinability of H13 using a rotating workpiece attachment on a die-sinker EDM machine.
A custom-built attachment was designed to enable rotational motion during the EDM process, simulating turning conditions. Taguchi's design of experiments (DOE) methodology was used for experimental planning, with parameters such as pulse on time, pulse off time, peak current and rotational speed being varied to observe their effects on material removal rate (MRR). The results revealed that peak current significantly affects both MRR and SR, followed by pulse on time.
The highest MRR of 0.328 g/min were achieved under optimized conditions. This study demonstrates the viability of EDT with rotating attachments as an advanced machining solution for producing precision cylindrical parts from high-strength materials.

INTRODUCTION
Electrical Discharge Machining (EDM) is well-established for machining hard materials and intricate geometries. Recently, nascent hybrid techniques—such as Electrical Discharge Turning (EDT)—have emerged, allowing dielectric-based electrical machining on rotating cylindrical specimens. Notably, the integration of rotating attachments with die-sinker EDM machines is a promising adaptation for cylindrical part production, yet remains underexplored.
In parallel, recent studies on EDM using powder-mixed dielectrics have demonstrated significant surface enhancements. For example, Singh et al. (2024) achieved a 159 % increase in microsurface hardness on H13 steel with graphite-dispersed dielectric, underlining the potential for performance improvement via dielectric engineering. Additionally, Nas et al. (2025) examined wear resistance and surface quality optimization of untreated AISI H13 using advanced EDM techniques. This study aims to combine the benefits of rotating workpiece EDM (EDT) with the well-documented advantages in surface engineering to machine cylindrical components from H13 die steel using Taguchi experimental design for parameter optimization.

LITERATURE REVIEW
Electrical Discharge Machining (EDM) has long been recognized as a non-traditional method for machining electrically conductive, hard-to-cut materials, especially for producing intricate shapes. While conventional EDM methods are limited to 2D profiles and fixed workpieces, the introduction of rotational mechanisms has significantly extended their capabilities. Rotating Electrical Discharge Turning (EDT) and Wire EDM Turning (WEDT) have emerged as very efficient tools of manufacturing cylindrical geometries with very high precision and surface integrity. As an illustration, it is possible, as demonstrated by Khan et al. (2023), to obtain ±5 μm tolerance on rotational workpieces with WEDT, whereas Gohil and Puri (2024) and Patel (2024) investigated

the impact of spindle speed and experimentally confirmed that it plays a very important role on dimension accuracy as well as on roundness.

In addition to mechanical advancements, numerous researches have emphasized the impact of machining conditions on improving Material Removal Rate (MRR), Surface Roughness (SR), and tool wear. Bahgat et al. (2019) examined pulse effect on time, current, and electrode material on EDM of H13 die steel and deduced that peak current produces maximum impact on MRR and tool wear. Singh et al. (2024) extended it further by using a graphite-dispersed dielectric in EDM, achieving 159% increase of the surface hardness of H13 steel and verified the performance of powder-mixed dielectric fluids. Similarly, very recently, while dealing with materials research on Cu–TiC cermet electrodes, it is evidenced that pulse current is the most dominating parameter on SR, and their findings of modeling have good agreements with experimentation.

Recent advances in EDM also encompass using external fields and nano additives. Jadidi et al. (2020) and subsequent work have suggested magnetic-field-assisted EDM enhances flushing performance, evacuation of debris, and reduces overcut. These complementary procedures augment mechanical rotation in enhancing machining performance, more notably in high-strength alloys such as H13 and EN24. Optimizing paradigms such as Taguchi Design of Experiments (DOE), Response Surface Methodology (RSM), and Grey Relational Analysis (GRA) have become familiar tools in parametric influence study. Siddiqui et al. (2024) applied the former techniques in optimizing the machining of alloy Ti6Al4V, while Sana et al. (2024) applied AI-integrated powder-mixed EDM installations in predicting multi-objective outcomes. Their studies underscore the relevance of advanced modeling techniques, which are increasingly integrated into EDM process planning.

Comprehensive reviews by Pop and Titu (2023) and Kumar et al. (2024) support these findings and emphasize the dominant influence of pulse on time and discharge current across various EDM applications. These reviews also highlight sustainability, dielectric composition, and AI-based modeling as the next frontiers in EDM research.

RESEARCH GAP

Despite considerable progress in EDM research, a significant gap remains in the integration of rotating workpiece mechanisms with die-sinker EDM machines for cylindrical machining applications—particularly for H13 die tool steel, a material commonly used in high-stress tooling applications. While the majority of studies have focused on Wire EDM (WEDM) or conventional die-sinking EDM, limited attention has been given to the development and evaluation of mechanically rotating fixtures in die-sinker configurations. Moreover, enhancements such as magnetic field assistance, powder-mixed dielectrics, and specialized electrode designs have been explored individually, yet their combined effect in a rotating setup remains underreported.

Additionally, although Taguchi DOE and related statistical optimization methods are well-established in EDM parameter analysis, their application in rotational die-sinker EDM systems has not been extensively documented. Most existing research either lacks experimentation on H13 steel under rotating conditions or does not examine the interdependency of discharge parameters, rotation speed, and fixture design on machining performance. This study seeks to bridge this gap by introducing a novel rotating attachment for die-sinker EDM, systematically optimizing input parameters using Taguchi design, and developing predictive models for Material Removal Rate (MRR) — thus advancing the applicability of Electrical Discharge Turning (EDT) for high-precision cylindrical part manufacturing.

OBJECTIVES

The objective of this research is to design a rotating workpiece attachment suitable for integration with a die-sinker EDM machine. This attachment will enable cylindrical machining of hard materials like H13 die tool steel. The study also aims to develop and test the fixture within an actual EDM setup. Using the Taguchi method, the effects of various machining parameters will be analyzed. The goal is to optimize material removal rate and surface roughness through systematic experimentation. The methodology adopted, as illustrated in Fig. 1, is structured to systematically achieve these objectives.

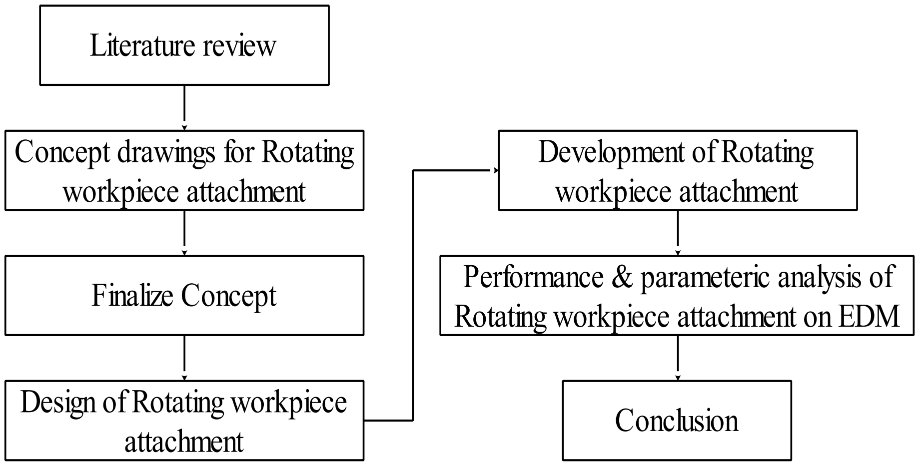

Fig.1. Methodology adopted

EXPERIMENTAL SETUP

Experiments were conducted on a TOOL CRAFT Spark Erosion EDM machine. The rotating fixture was custom-designed and attached to the work table. Control of rotation speed was achieved through a stepper motor. EDM machine specs included: 350x220 mm table size, 60L dielectric capacity, and 15–25 A current.

All the experiments will be conducted using an EDM machine made by TOOL CRAFT SPARK EROSION MACHINE. This machine's Z axis is powered by a servo motor, which is managed by the control panel. The gap voltage between the tool and the workpiece electrode is the basis for the servo control feedback.

The gap distance is determined by feeding the tool into the workpiece during machining in order to maintain the gap voltage all the time. The manual control of the X and Y axes is utilized. The EDM machine is shown in Fig. 2., which includes a dielectric system, a pulse generator system, and a servo gap control system. Table 1. displays the configurations of the EDM machine made by TOOL CRAFT SPARK GENERATOR.

Fig.2. EDM Machine

Table 1. EDM Machine

Work Table	
Table Size	350X220 mm
Table Travel Longitudinal	220mm(X-axis),130mm(Y-axis)
Work Tank	
Tank Size	600X370X290 mm
Dielectric Fluid Level Over Table	200 mm
Work Piece	
Maximum Height	150 mm
Maximum Weight	100 kg
Servo Head	
Quill Stroke	200 mm
Electrode Pattern Size LXB	100X100 mm
Max Electrode Weight	20 kg
DIELECTRIC System	
Reservoir Capacity	60 litres
Filtration Level	10 microns
Pulse Generator	
Working Current	15 or 25 amps

MATERIAL SELECTION

The selection of workpiece material is a critical aspect of this experiment, as machining characteristics and EDM performance vary significantly across materials. In Electrical Discharge Machining (EDM), the choice of material greatly influences the efficiency, surface finish, and overall quality of the process. For this study, AISI H13 die steel was selected due to its exceptional properties and widespread application in tool and die industries. Classified under the AISI H-series as a chromium-based hot work tool steel, H13 is engineered to withstand extreme thermal and mechanical stresses during metal-shaping, shearing, and punching operations. Its air-hardening capability and balanced alloy composition minimize distortion during heat treatment, making it ideal for high-precision applications. H13 offers excellent toughness, resistance to fatigue, and heat transfer with an ideal balance, making it highly popular for hot and cold work die tools. Common applications include ejector pins, inserts, core pins, casting die cavities, forging and extrusion dies, plastic mold cavities, shot sleeves, and trimming dies. Owing to good high-temperature capability and fast cooling ability, H13 is widely used in thermoplastic as well as compression mold tooling, typically with 50–52 HRC hardness.

AISI H13 die steel, selected for the current study, is a chromium alloy-containing hot work tool steel renowned for higher thermal resistance, toughness, with good dimensional stability. Its chemical composition comprises principal alloying elements such as chromium (4.75–5.50%), molybdenum (1.10–1.75%), and vanadium (0.30–0.60%), responsible for providing it with higher strength and wear resistance. Its physical properties encompass 7.80 g/cm³ density and 1427°C melting point. Its mechanical properties include high tensile strength of 1200–1590 MPa and high modulus of elasticity of 215 GPa, suitable for high-stress applications in tools. Its thermal properties encompass good conductivity of 28.6 W/mK and stable thermal expansion, enhancing high-temperature machining performance. The workpieces chosen were appropriately dimensioned, as specified in Fig.3, for matching the rotating EDM setup for cylindrical machining tests.

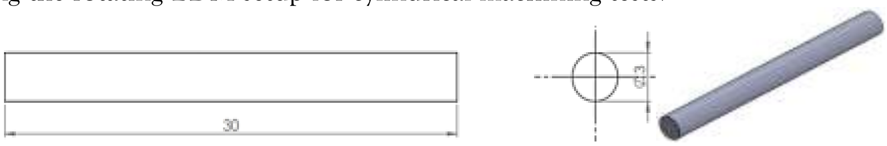

Fig.3. Workpiece specimens

DESIGN OF EXPERIMENT

Design of Experiment (DOE) is an ordered protocol used for exploring, assessing, and optimizing research and manufacturing processes. It facilitates the assessment of interactions between numerous process variables and their effects on desirable results in a methodical manner. In the current study, DOE is employed as method of measuring the effect of varying EDM parameters on performance metrics such as Material Removal Rate (MRR). Of the numerous DOE methods available—Factorial, Response Surface, and Taguchi—the Taguchi method is employed due to user-friendliness, economy, and robustness. Thought of by Dr. Genichi Taguchi in Japan, it utilizes orthogonal arrays (OAs) as well as signal-to-noise (S/N) ratios with the intention of reducing variance of experiments as much as possible and defining optimum conditions. It reduces experimental trial numbers while maximizing result reliability. The Taguchi method is also employed as method of determining the contribution as well as interaction of each procedural parameter with guidance on procedural control and optimization. The eight-step protocol—the problem identification and factor level selection through array design, experimentation, and performance prediction—the repeatable and extensive methodology ensures complete results.

Pulse on time, or pon, controls spark length, corresponding exactly with the amount of energy transferred and thus with material removal rate. Pulse off time, or toff, is the time between pulses and corresponds with debris ejection and spark effectiveness. Gap voltage determines the spark gap and influences the discharge intensity, while servo feed controls the inter-electrode distance in real-time. Peak current, expressed in amperes, dictates the maximum power applied during each discharge. The primary response variables analyzed include surface roughness—resulting from residual molten material and discharge craters; material removal rate—calculated by the weight difference before and after machining divided by time; and electrode wear rate—defined by the volume loss of the tool relative to the workpiece. These variables serve as key indicators of process efficiency and quality in EDM machining.

The Taguchi method was adopted using an L9 orthogonal array. Four parameters were studied:

- Pulse on time (100, 200, 500 µs)

- Pulse off time (10, 20, 50 µs)
- Peak current (10.93, 17.18, 23.43 A)
- RPM (0.5, 0.75, 1)

Response variables:

- Material Removal Rate (MRR)

DOE by Taguchi method shows in Table 2.

Table 2. DOE by Taguchi method

Sr no	Pulse on time(µs)	Pulse off time(µs)	Current(A)	RPM
1	100	10	10.93	0.5
2	200	20	23.43	0.5
3	500	50	17.18	0.5
4	100	20	17.18	0.75
5	200	50	10.93	0.75
6	500	10	23.43	0.75
7	100	50	23.43	1
8	200	10	17.18	1
9	500	20	10.93	1

By using a precision weight instrument, we assessed the material removal rate both before and after machining.
Response parameter

- Material Removal Rate

Evaluation of MRR
The material MRR is the ratio of the weight changes of the workpiece prior to and thereafter machining to the machining time.

$$MRR = \frac{Wjb - Wja}{t} \quad (1)$$

Whereas, Wjb = Workpiece weight prior to machining, Wja = Weight of workpiece after machining, t = Machining time = 4 min

RESULTS AND DISCUSSION

Response table
Table 3 show the response tables for MRR and SR along with the input parameters.

Table 3 Response table for MRR

STD	RUN	Pon (µs)	Poff (µs)	IP (A)	RPM	Initial Weight (gram)	After Machining Weight (gram)	Difference (gram)	**MRR (g/min)**
1	9	100	10	10.93	0.5	3.020	2.640	0.380	**0.095**
5	1	200	20	23.43	0.5	3.030	2.190	0.840	**0.210**
9	7	500	50	17.18	0.5	3.040	2.110	0.930	**0.233**
2	8	100	20	17.18	0.75	3.020	2.060	0.960	**0.240**
6	3	200	50	10.93	0.75	2.990	2.330	0.660	**0.165**
7	5	500	10	23.43	0.75	3.040	1.790	1.250	**0.313**
3	6	100	50	23.43	1	3.010	1.700	1.310	**0.328**
4	4	200	10	17.18	1	2.900	1.890	1.010	**0.253**
8	2	500	20	10.93	1	2.950	2.300	0.650	**0.163**

Analysis of variance
The term "analysis of variance," or "ANOVA," refers to a series of statistical models that have been utilised to examine mean differences and the corresponding estimate techniques (such "variation" within and between

groups). Ronald Fisher, a statistician, invented the ANOVA. The law of total variance, which divides the observed variance of a given variable into components attributed to various causes of variation, is the foundation of ANOVA. An ANOVA expands the use of the t-test beyond two means by offering a statistical test to determine if two or more population means are equal. Stated differently, when comparing two or more means, the ANOVA is employed.

Elements of ANOVA Table

- SOURCE: The ANOVA table is divided into variation sources that represent all treatments/factors and the Error(residual) and total variation.
- DF: Degrees of freedom of variation source
- SS: Sum of Squares for the source
- MS: Mean Squares for source
- F: F-Statistic associated with source (assess significance)
- p: p-value associated with F-statistic (assess significance)

Analysis of variance for Material removal rate

Table 4 displays the factors' analysis of variances. factors A-Pon, B-Poff, C-IP, and D- RPM show significant effects on the outcome, as their individual F values are non-zero with corresponding p-values indicating significance. This unequivocally shows that Pon, Poff, IP, and RPM are the most important parameters impacting the rate of material removal. It also shows that Pon x Poff, Pon x IP, and Poff x Ip are significant whereas other factors are not. These interactions Pon x rpm, Poff x rpm, Ip x rpm have no sum of squares and zero degree of freedom suggesting that they are not influencing material removal rate.

All four parameters are significant effects on the outcome and most effected parameter is RPM (23.366%) and IP (59.87%). As shown in table 8.3 effect in percentage on Pon and Poff time (0.035%) and (7.242%) respectively. Which indicates Poff is also most effected parameter. Interaction parameters like Pon x Poff (4.125%), Pon x IP (2.028%), Poff x Ip (1.592%) in which Pon x Poff show significant effects on the outcome.

Table 4 ANOVA for MRR

Source	Sum of Squares	Df	Mean Square	Percentage (%)
Model	0.04175608	8	0.005491	-
A-Pon	0.00001448	1	0.00001448	**0.035**
B-Poff	0.003024	1	0.003024	**7.242**
C-IP	0.025	1	0.025	**59.872**
D-RPM	0.009339	1	0.009339	**22.366**
AB	0.001760	1	0.001760	**4.125**
AC	0.0008468	1	0.0008468	**2.028**
AD	0.000	0	0	**0.000**
BC	0.0006648	1	0.0006648	**1.592**
BD	0.000	0	0	**0.000**
CD	0.000	0	0	**0.000**
A^2	0.001107	1	0.001107	**2.651**
Pure Error	0.000	0		
Cor Total	0.04175608	8		**100**

Final Equation in Terms of Coded Factors:

$$MRR = +0.19 + 2.129E-003 * A + 0.025 * B + 0.080 * C + 0.065 * D + 0.031 * A * B + 0.022 * A * C - 0.026 * B * C + 0.053 * A^2 \quad (1)$$

With Pon, MRR also increases with Pon in the 340–500 μs region. Typically, MRR rises with Pon until it reaches a maximum value, at which point it begins to fall. This is because the plasma that forms between the workpiece and tool electrode gap (actually impedes energy transfer at higher tones, which lowers MRR. The pulse durations

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in this experiment are 100, 200, and 500 µs. Thus, the pulse duration vs. MRR plotted graph indicates that the MRR value decreases between 100 and 340 µs.

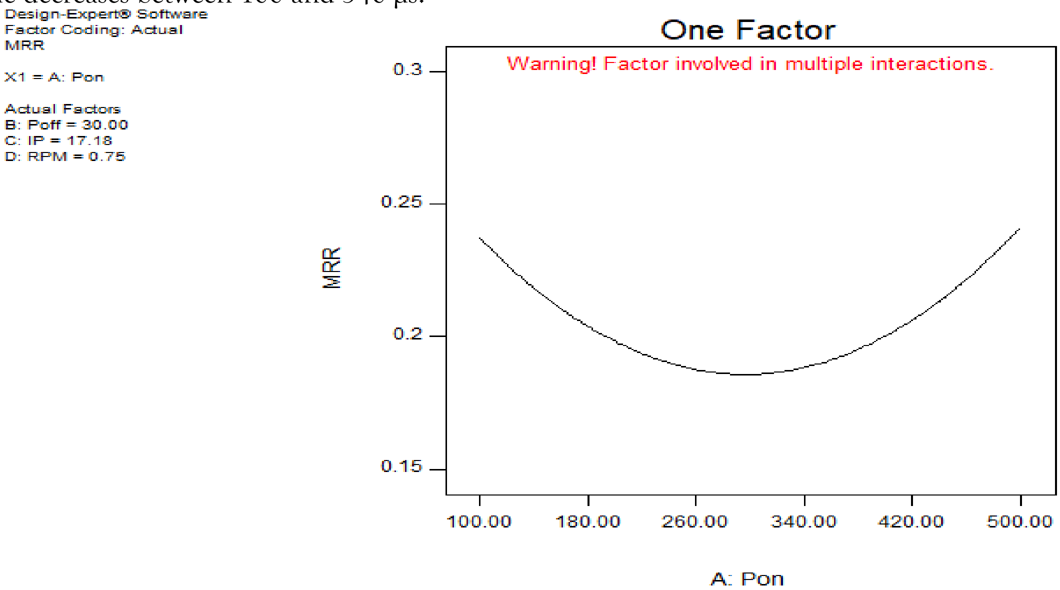

Fig. 3 Pon vs MRR

As shown in Fig. 4 MRR increased with increased pulse off time, while Pon time 300 µs, current 17.18 and RPM-0.75 where time is fixed at 4 min.

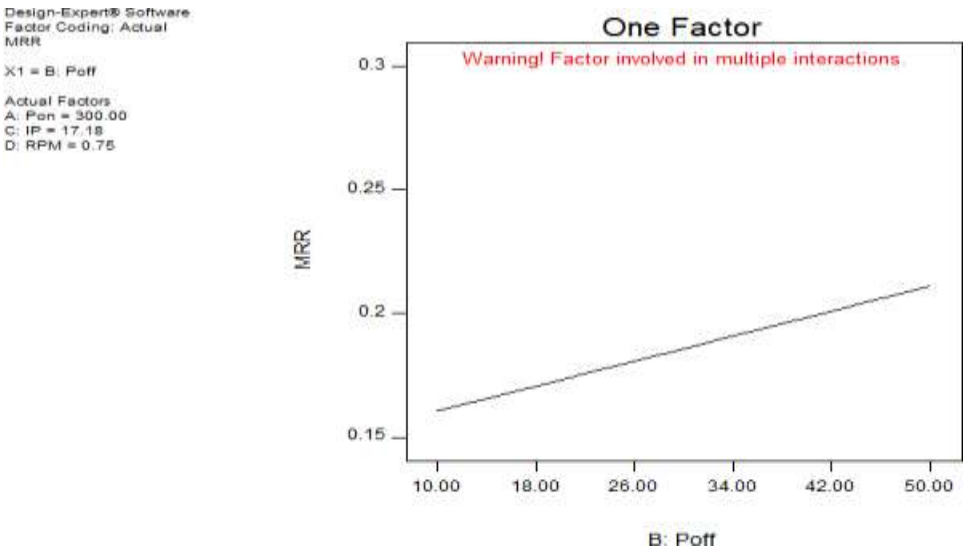

Fig. 4 Poff vs MRR

The main effect plot for IP vs. MRR in Fig. 5 illustrates how several machining parameters, such as Ip, Ton, and tool diameter, have a substantial impact on MRR when it comes to electrical discharge machining. In the range of 10.93 to 23.43A, the discharge current (Ip) is linearly corresponding to MRR. This is to be expected since a larger pulse current results in a stronger spark, which raises the temperature and melts more material away from the workpiece. Furthermore, it is abundantly obvious that the other component has less of an impact than IP.

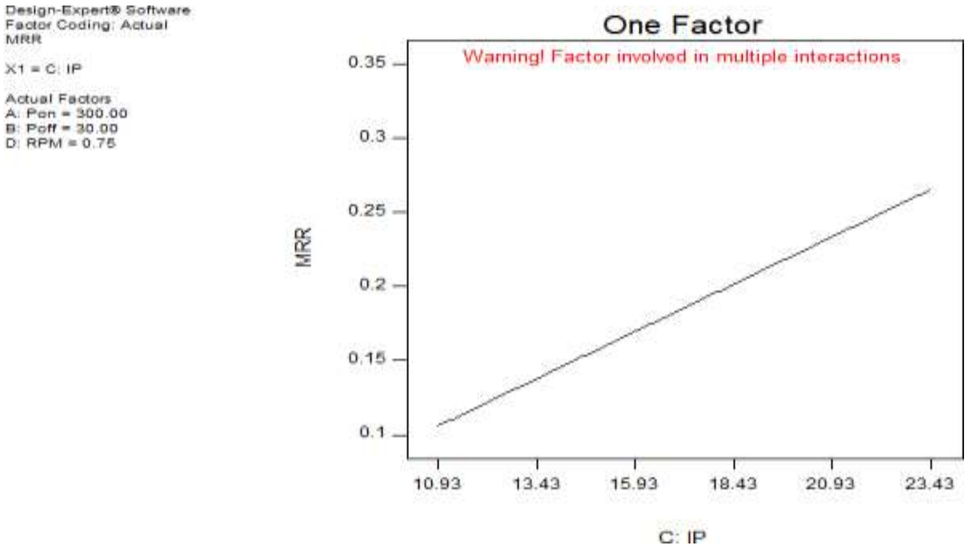

Fig.5 IP vs MRR

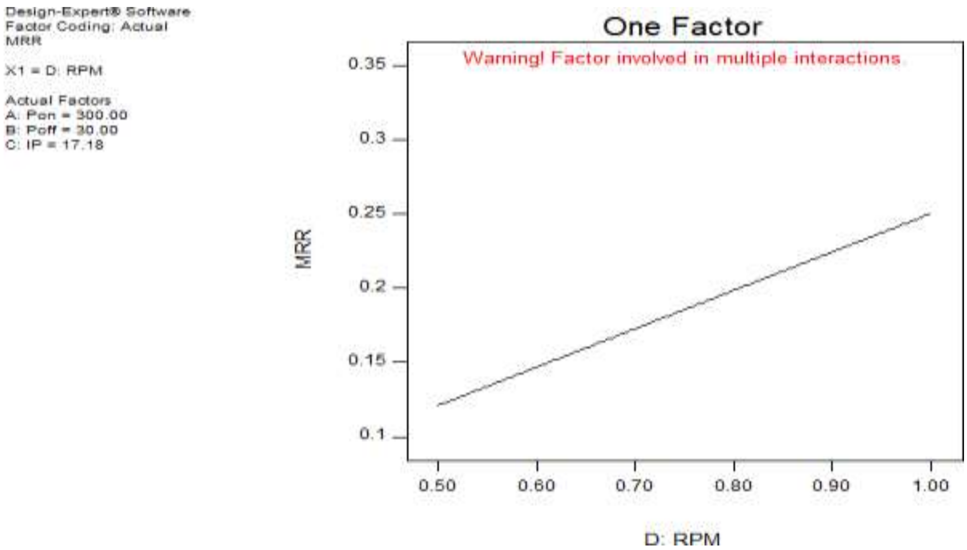

Fig. 6. RPM vs MRR

As shown in Fig. 6. MRR increased with increased RPM, while Pon time 300 µs, Poff time 30 µs current 17.18 where time is fixed at 4 min.

DIE-SINKER EDM TEST

The purpose of this test is to find difference between Die Sinker EDM machining outcomes to Die Sinker EDM machining with rotating workpiece attachment. In Die Sinker EDM test we took value as trivial value, mean value and maximum value from experiment conducted on rotating workpiece attachment to compare and find difference of MRR value and Surface Roughness value.

Table 5. MRR Value of Die Sinker EDM test experiment

PON (µs)	Poff (µs)	IP (A)	Initial Weight (gram)	After Machining Weight(gram)	Difference (gram)	**MRR (g/min)**
100	10	10.93	3.035	2.595	0.440	**0.110**
500	50	17.18	3.026	1.95	1.076	**0.269**
100	50	23.43	3.040	1.61	1.43	**0.3575**

COMPARISON OF THE TEST RESULTS

The comparison of the test results between the Die Sinker EDM and Die Sinker EDM with rotating workpiece attachment to evaluate difference outcomes value of MRR and Surface roughness. The difference margin (%) between Die Sinker EDM and Die Sinker EDM with rotating workpiece attachment calculated using equation below:

$$\text{Differencemargin}(\%) = \frac{\text{DiesinkerEDMresult} - \text{DieSinkerattachmentresult}}{\text{DiesinkerEDMresult}} \quad (2)$$

A table 6 shows the difference between Die Sinker EDM test and Die Sinker attachment test for MRR.

Table 6. Comparison test results for material removal rate

No.	Die Sinker test	Die Sinker with attachment test	Difference (%)
1	0.110	0.095	13.636
2	0.269	0.233	13.382
3	0.3575	0.328	8.251

This result shows that Die Sinker EDM machining gives better MRR, but Die Sinker EDM machining with rotating workpiece attachment can perform turning operation on Die Sinker EDM to machine hard materials like H-13 die steel by which cylindrical part can be produced.

CONCLUSION

This experimental investigation successfully demonstrated the feasibility and advantages of using a rotating workpiece attachment with die-sinker EDM to perform Electrical Discharge Turning (EDT) on H13 die tool steel. Key findings include:

- The custom-designed rotating attachment effectively transformed the die-sinker EDM into a turning system capable of machining cylindrical geometries in hard materials.
- The application of Taguchi's method enabled efficient optimization of process parameters—pulse on time, pulse off time, peak current, and RPM—resulting in significantly enhanced machinability.
- Peak current emerged as the most influential parameter, contributing over 59% to the MRR and 35% to surface roughness according to ANOVA analysis.
- The optimal combination of parameters yielded a maximum MRR of 0.328 g/min, demonstrating excellent machining performance.
- Mathematical models were developed for MRR as functions of input parameters, providing predictive capabilities for future studies.

The study concludes that the integration of EDT with a rotating fixture is a promising solution for precision machining of cylindrical components in high-strength tool steels. Future work could focus on exploring additional optimization techniques like RSM or ANN and expanding the scope to include electrode wear rate and dimensional accuracy.

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