Investigations on Wire-EDT for Precision Turning of Cylindrical Mild Steel Bars Using Gear-driven Rotary Setup

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This paper highlights the aspects of circularity error 'CE', mean surface irregularity depth 'R_z', and machining erosion rate 'MER' for straight-turning cylindrical mild steel bars (CMSBs) by wire electrical discharge turning (wire-EDT). Rz reflects surface quality, MER indicates machining speed and productivity, and CE measures the deviation from the ideal circular shape. Micrograph analysis was performed on the bar turned at the optimal combination with minimum surface roughness. Nine combinations of wire-EDT variable parameters—pulse-on duration (T_{on}), pulse-off duration (T_{off}), and servo voltage (S_V)—were arranged using a Taguchi L_9 (3^3) orthogonal array, with each combination repeated twice. This resulted in eighteen experiments to evaluate the potential of wire-EDT and the influence of variable parameters on CE, R_z, and MER. The spark-on duration was found to be significant for the machining erosion rate, while both spark-on duration and spark-off duration were found to be significant for the average surface irregularity depth. A circularity error of 17.06 µm, an R_z of 8.1 µm, and a MER of 8.86 mm³/min were achieved at the optimum combinations. The results from confirmation tests closely match the optimum, showing strong agreement with a variance of less than 6% for CE, R_z, and MER. The results of this study are useful for the turning of cylindrical bars made of various materials.

Keywords: *Cylindrical Mild Steel Bar, Wire Electrical Discharge Turing, Straight Turning, Surface roughness; Machining Erosion Rate, Circularity Error, Optimization, SEM.*

1. INTRODUCTION

Mild steel is a type of carbon steel with a low carbon content, typically between 0.05% and 0.25%. Its key characteristics include moderate tensile strength, good ductility, lower hardness compared to high-carbon steels, and susceptibility to corrosion and rust. Due to its favorable balance of strength, ductility, affordability, and ease of fabrication, mild steel is widely used across industries such as construction, automotive, machinery, pipelines, consumer goods, shipbuilding, infrastructure, defense, aerospace, decorative applications, and environmental and agricultural equipment. While mild steel is not suitable for direct contact with biological tissues or high-corrosion environments, its mechanical properties and affordability make it ideal for indirect medical applications, such as diagnostic equipment, patient beds, medical packaging, hospital furniture, and tools like forceps, scissors, and surgical trays. Despite its good machinability, the machining of mild steel using conventional processes has several limitations [3-4]. These include: (i) poor surface integrity due to built-up edge (BUE), tool marks, burrs, and chatter marks caused by vibrations; (ii) difficulty in maintaining tight dimensional tolerances due to tool deflection, thermal expansion, and variations in material properties; (iii) adverse environmental impact due to generation of metal chips and coolant waste in the form of vapor; (iv) excessive tool wear due to its abrasive nature; (v) requirements for advanced tool coating to minimize tool wear; (vi) improper chip control affects surface finish, tool life, and poses safety hazards; (vii) excessive heat generation leading to dimensional inaccuracies and change in metallurgical properties; (viii) low machi–nability index; (ix) requirements for post-processing methods to meet desired quality; (x) material restric–tions, as mild steel is unsuitable for machining brittle materials; (xi) generation of mechanical and thermal stresses due to direct contact between tool and workpiece; (xii) microstructural changes caused by the high heat affected zone; and (xiii) requirement for skilled operators for effective machining.

Furthermore, surface quality directly impacts the functionality and performance of the machined part. Poor surface quality can affect dimensional accuracy, increase friction and wear, and lead to excessive corrosion in corrosive environments [5]. Irregularities on the machined surface contribute to premature wear of parts that require tight tolerances for smooth operation, resulting in reduced lifespan, increased noise, and inefficient performance. Therefore, the surface quality of turned parts is crucial to their functionality,

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durability, appearance, and manufacturing efficiency, making it a critical consideration in machining pro–cesses. Achieving the desired surface finish requires selecting the right machining techniques, tooling, cutting parameters, and post-processing methods to meet the specific requirements of the application.

To overcome the challenges of the conventional turning process, wire electrical discharge turning (wire-EDT) is being explored for turning cylindrical bars. Wire-EDT is a modified version of wire electrical discharge machining (wire-EDM) [6]. The term “wire-EDT” refers to a wire-EDM machine that incorporates an additional rotary setup, which securely holds and rotates cylindrical bars at a controlled speed to facilitate turning operations. Thus, Wire-EDT differs from wire-EDM primarily in the inclusion of this rotary setup. While both wire-EDM and wire-EDT are based on spark-erosion machining principles, they serve distinct purposes. Wire-EDT, also known as wire-EDM turning, is a specialized process primarily used for the precise turning of difficult-to-machine conductive materials. Wire-EDT is specifically designed for turning metallic cylindrical bars but can also be used to manufacture small-scale cylindrical and rotary parts, such as bars, pins, tools, electrodes, and probes.

Wire-EDT is a spark-erosion-based, non-conventional machining process used to cut electrically conductive materials with the aid of localized flushing of deionized water. In wire-EDT, a fine, electrically conductive wire serves as the tool electrode. Typically, a 0.25 mm diameter brass or zinc-coated brass wire is employed for this process. Straight and tapered turning can be achieved by moving the worktable along the X-axis or Y-axis, while the wire continuously moves from the upper guide to the lower guide through the rotating workpiece at a controlled speed and a certain applied tension, without making direct contact. This controlled movement and tension of wire helps prevent wire breakage and short-circuiting, thus ensuring smooth machining. A consistent gap also known as the ‘interelectrode gap (IEG)’ is maintained between the wire (tool electrode) and the workpiece to avoid short-circuiting during turning [7-9]. Erosion of the work material occurs around the outer cylindrical surface due to the generation of sparks between the IEG, which melts and vaporizes material from the workpiece [10]. This process is commonly used to turn cylindrical or contoured shapes on electrically conductive materials. It is capable of machining hardened materials while maintaining both dimensional and geometrical accuracy. Additionally, it offers high precision, achieving tight tolerances and a fine surface finish compared to conventional turning methods. Therefore, wire-EDT is widely adopted in industries such as aerospace, automotive, and biomedical, where precise turning and enhanced dimensional accuracy are required. Wire-EDT turning offers several advantages over conventional methods, including minimal tooling requirements, enhanced precision and accuracy, the ability to turn complex shapes, no direct contact cutting (which minimizes mechanical stress and distortion), a minimal heat-affected zone, excellent surface finish, material versatility, higher efficiency, and the potential for automation and unattended operation. These benefits make wire-EDT a preferred choice for manufacturing cylindrical and rotating parts made from difficult-to-machine materials [11-12]. Previous studies have explored the potential of wire-EDT for straight and tapered turning of cylindrical bars made from various challenging materials. This section reviews significant research focused specifically on the straight and taper turning of challenging materials using wire-EDT.

Nag et al. [13] performed straight turning on cylindrical titanium alloy bar ‘CTAB’ and concluded that the values of machining erosion rate (MER), ave–rage surface roughness (Ra), and wire wear rate (WWR) drop as the gap-voltage, spindle rotational speed (SRS), and spark-off duration increase. They achieved average roughness of 1.13 µm, MER of 17.33 mm3/min, and WWR of 0.0346 at optimal conditions. In another study, Vignesh and Ramanujam [14] performed straight turning of titanium grade 5 cylindrical bars and conclu–ded that MER rises with longer spark-on times, wire speeds (WS), and SRS, while Ra decreases with higher WS and SRS. Another study by Naik et al. [15] found that surface roughness reduced as spark-off duration, servo voltage, and wire feed rate increased while tur–ning an Inconel cylindrical bar by wire-EDT. Carbon-steel and titanium alloy microbars and micro taper pins were manufactured by wire-EDT in multiple steps i.e. rough, semi-finished, and finished by Sun et al. [16-17] using low-speed wire-EDT (LS-wire-EDT). Zakaria et al. [18] found that turning with low pulse concentration and gap voltage results in lower surface roughness on parts turned by wire-EDT. Roy et al. [19] performed straight, taper, and spherical turning on cylindrical titanium alloy bars by wire-EDT using a belt-driven rotary setup. They observed higher MER and lower va–lues of Ra at higher values of the SRS and wire inclination angles during multi-step taper turning by wire-EDT. In another interesting study, Cakıroglu and Günay [20] performed turning by electrical discharge machining (EDM) using a fabricated tool electrode.

Past research has shown that belt-driven rotary setups and direct current (DC) motors coupled with holding devices have been used for turning cylindrical bars made of Inconel and steel by wire-EDT. A major issue with the belt-driven setup is slipping, while the DC motor setup suffers from variations in rotational speed due to fluctuations in voltage and frequency. Although some studies have employed variable frequ–ency drive devices to address these challenges, issues persist. Additionally, limited research has focused on turning by wire-EDT, with most studies primarily examining the effects of variable parameters on average surface roughness and machining erosion rate. In this study, a low-speed gear-based rotary setup powered by a stepper motor was used to turn a cylindrical mild steel bar. While previous studies have utilized belt-driven setups for turning cylindrical bars made of Inconel and steel, limited work has explored turning with wire-EDT using a low-speed gear-based rotary setup. This study aims to investigate the feasibility and effectiveness of wire electrical discharge turning (wire-EDT) for machining mild steel bars. The overall objectives of this study are (i) to explore wire-EDT for turning cylindrical bars using a newly developed low-speed gear-driven rotary setup, (ii) to optimize the wire-EDT variable parameters, namely spark-on duration, spark-off duration and servo voltage, to maximize machining erosion rate and minimizing circularity error (CE) and mean surface irregularity depth (RZ) in turning cylindrical mild steel bars; (iii) to analyze the influence of wire-EDT parameters on machining erosion rate, mean surface irregularity depth, and circularity error in turned mild steel bar; and (iv) to investigate the microstructural analysis (e.g., recast layer, heat-affected zone) of surface and subsurface regions of mild steel bars turned by wire-EDT.

2. EXPERIMENTAL DETAILS

This section summarizes the materials, machines and methods, turning procedure, experimental procedure, and response measurements.

2.1 Materials, Machine, and Methods

The workpiece material used in this study includes AISI 1018 mild steel cylindrical bars with a diameter of 15 mm and a length of 60 mm, as shown in Fig. 1. AISI 1018 mild steel consists of the following chemical composition by weight: Carbon (C) 0.15% - 0.20%, Manganese (Mn) 0.60% - 0.90%, with a maximum of 0.04% Phosphorus (P) and 0.05% Sulfur (S). AISI 1018 is a commonly used mild steel grade known for its excellent machinability, weldability, and relatively low cost. It is often selected in applications where moderate strength and hardness are required, along with good ductility and ease of machining. Before machining, the cylindrical mild steel bars were faced and turned on a manual lathe using a single-point cutting tool made of high-carbon steel to achieve uniform flat end surfaces and a consistent diameter throughout the length of the bars. Subsequently, the cylindrical bars were thoroughly cleaned with sandpaper and visually inspected for any surface defects. The turning experiments were conducted on an Electronica Sprintcut-Win wire electrical discharge machine (Manufacturer: EMTL India), with a rotary setup attached to its worktable, as shown in Fig. 2(a). This is a non-submerged, vertically traveling wire-EDM machine equipped with CNC controls, a servo mechanism, a wire drive mechanism, and a dielectric flow system. A gear-driven rotary setup was employed, featuring a stepper motor and a three-jaw chuck. The chuck was connected to a worm gearbox via a spindle, with the gearbox linked to the stepper motor through a coupling. The stepper motor was powered by a control unit, which enabled the adjustment of rotational speed, ensured constant speed, and compensated for variations in speed caused by fluctuations in voltage and frequency during the turning process. An electrically conductive zinc-coated brass wire with a diameter of 0.25 mm and a tensile strength of 500-700 N/m² was used to turn the mild steel bar, with deionized water (i.e., dielectric fluid) flowing continuously. The continuous flow of deionized water removed eroded particles from the interelectrode gap through localized flushing, preventing wire passage blockages in the machining zone and ensuring smooth turning without short-circuiting. Wire-EDM primarily moves the wire electrode in a linear direction, while wire-EDT involves both the linear movement of the wire electrode and the rotational movement of the workpiece. Wire-EDM is used to produce intricate shapes and contours, whereas wire-EDT is employed for turning operations (e.g., straight or taper turning) to create cylindrical or contoured surfaces. Wire-EDT is particularly suited for manufacturing components where conventional turning methods may not be feasible or where high precision is critical.

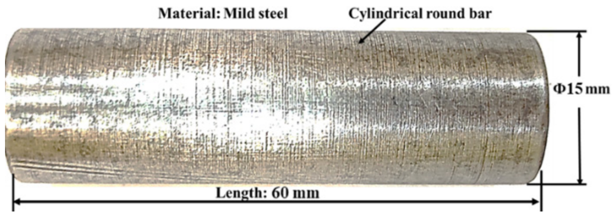


Figure 1. 3D view of cylindrical mild steel bar with detailed specifications.

2.2 Procedure for straight turning by wire-EDT

This section provides a detailed explanation of the procedure for turning a mild steel bar using wire-EDT. The process of straight turning is completed in four stages: (i) part-programming, (ii) preparation, (iii) machining, and (iv) measurement. The sequence of these stages and their specific activities is depicted in Fig. 2 and further elaborated upon in the following sections.

Part-programming stage

- *This is the initial phase involves making a part-program for straight turning by ELCAM software.*

Preparation Stage

- Installation of micro-controller-based gear-driven rotary setup on the worktable of wire-EDT, then firmly hold the mild steel bar on the 3-jaw chuck of the rotary setup.
- Ensure their proper alignment using a dial indicator to facilitate accurate machining.
- Set up the wire electrode and adjust any necessary parameters on the wire-EDT for the turning.

Machining/Turning Stage

- Start the wire-EDT machine and ensure all parameters are set correctly before turning.
- Monitoring the machining process closely to maintain consistent parameters throughout including continuous rotation of cylindrical bar at the predetermined speed while the wire performs straight turning.

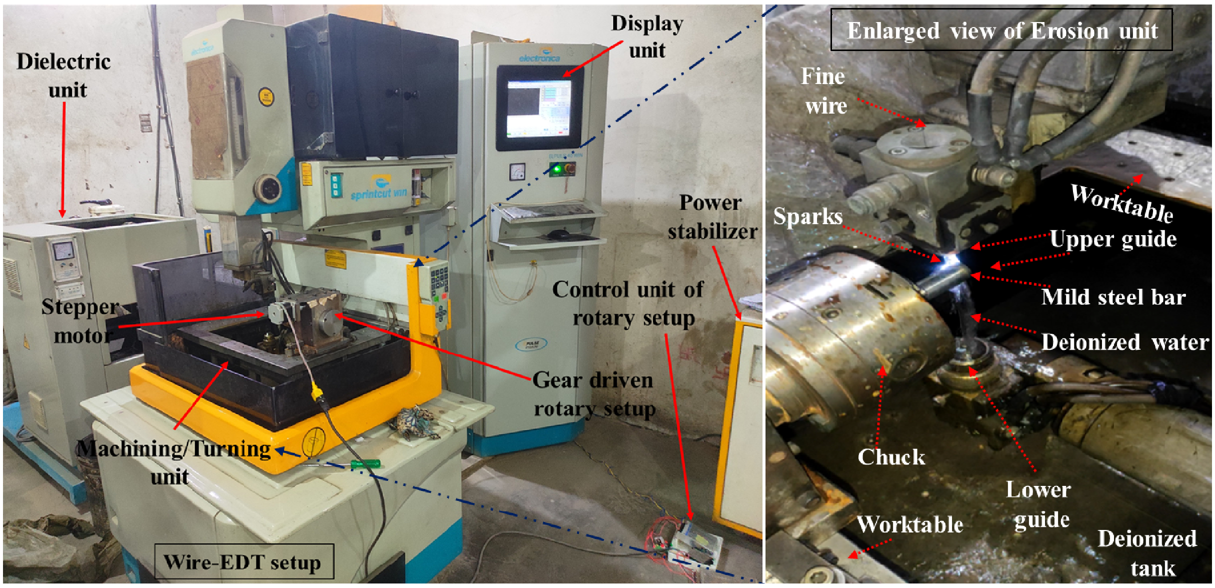
Measurement and Analysis Stage

- Record in-setu responses such as variations in cutting speed and turning time displayed on the machine screen.
- *Post-machining measurements such as s*urface roughness, erosion rate, and circularity error.
- Analyze the collected data using statistical methods to evaluate the effectiveness of the wire-EDT in achieving desired turning outcomes.

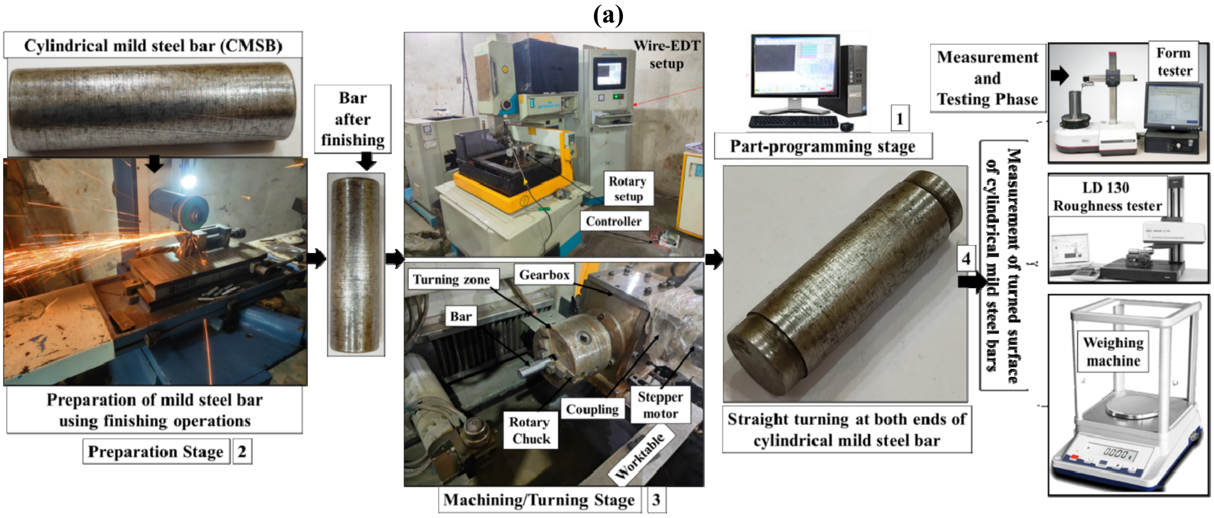
2.3 Experimentation

Spark-erosion-based processes are generally considered slower machining methods compared to conventional techniques like milling, turning, or drilling. The selection of appropriate machining parameters is critical in wire-EDT, requiring careful consideration and optimization to achieve the best results in terms of productivity, quality, and cost-effectiveness. Adjusting wire-EDT parameters based on material properties and process conditions en–sures efficient material erosion while maintaining high standards of precision and surface finish. A 'one factor at a time' approach was used to design and conduct eight preliminary trials, with the objective of performing turning without wire breakage at the maximum cutting speed. Based on preliminary trials and machine limitations, the constant and variable parameters, along with their corres–ponding values and levels, were selected for this study. Nine experimental runs were conducted using the Taguchi L_9 (3^3) orthogonal array, by varying three wire-EDT para–meters. Each parameter had three levels. To minimize uncontrolled variations and enhance statistical accuracy, each run was replicated twice. As a result, a total of eigh–teen straight-turning operations were performed on both ends of nine cylindrical titanium bars using wire EDM. In total, nine cylindrical bars were used for the eighteen experimental runs, with identical experimental conditions applied at both ends of each bar, as shown in Fig. 3.

Fig. 3 depicts a 3D view of a cylindrical mild steel bar after turning, along with its detailed specifications. The aim of these experiments was to identify the influence of three variable wire-EDT parameters on the responses (i.e. performance indicators). Table 1 provides comprehensive details on the cylindrical bars, the wire-EDT parameters, their levels, and the constant parameters used in the experiments. The experimental design utilizes a Taguchi L_9 (3^3) orthogonal array, which facilitates efficient testing of multiple process parameters with a reduced number of experiments. This approach strikes a balance between the number of experimental runs and the ability to identify both the main effects and interactions of the parameters. By employing this design, we can identify the most inf–luential process parameters for optimization and develop a more robust process. The experiments were conducted by performing a 10 mm straight turning along the bar's axis, with the worktable moving along the negative X-axis, passing through the zinc-coated brass wire.



(a)



(b)

Figure 2. Wire-EDT machine setup used for straight turning and the procedure of turning cylindrical mild steel bars: (a) wire-EDT setup; and (b) turning procedure by wire-EDT.

Table 1. Details of experimentations and turning variables combination of experimental runs for straight turning.

Wire-EDT variable parameter				Taguchi Experimental runs			
Parameter, symbol' and (unit)	Levels Actual (Coded)			Ex. Runs	T_{on}	T_{off}	S_V
	Low (-1)	Medium (0)	High (1)		μs	μs	V
Spark-on duration 'T_{on}'(μs)	0.8 (-1)	1.0 (0)	1.2 (1)	01	0.8	59	15
Spark-off duration 'T_{off}'(μs)	59 (-1)	61 (0)	63 (1)	02	0.8	61	20
Servo voltage 'S_V'(V)	15 (-1)	20 (0)	25 (1)	03	0.8	63	25
Performance outcome indicators	Circularity error '*CE*'. Machining erosion rate '*MES*'. Mean surface irregularity depth 'R_Z' In-situ responses Turning time			04	1.0	59	20
				05	1.0	61	25
				06	1.0	63	15
				07	1.2	59	25
				08	1.2	61	15
				09	1.2	63	20
Constant wire-EDT parameters	*Peak current 'I_P': 12 A; Wire speed 'W_S': 3 m/min; Wire tension 'W_T': 1140 g; Flushing pressure 'W_P': 15 kg/cm^2; Cutting speed 'C_S': 100 %; Spindle rotational speed: 50 Rpm*						
Specifications — *Bar*	*Bar type: Cylindrical, Bar material: Mild steel; Bar diameter: 15 mm; Total length of bar: 60 mm; and Turning length: 10 mm; Depth of cut: 0.5 mm*						
Wire	*Wire material:* Zinc coated brass wire; *Wire diameter:* 0.25 mm; *Wire tensile strength:* 800 N/mm^2						
Dielectric	*Machining Medium*: Deionized water; Dielectric conductivity: 20						

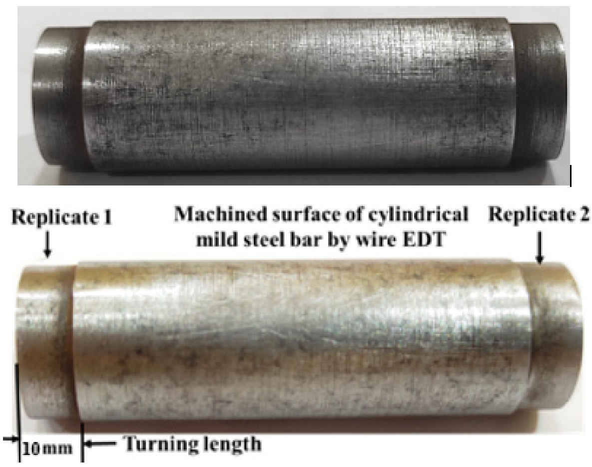


Figure 3. 3D view with detailed specifications of a cylindrical mild steel bar after precision straight turning on both ends by wire-EDT.

2.4 Measurements of responses

This study evaluates three key performance indica–tors—machining erosion rate (MER), mean surface irregularity depth (Rz), and circularity error (CE)—to assess the capability of wire-EDT in turning cylindrical mild steel bars. Machining erosion rate (MER) is a crucial performance indicator in spark-erosion-based machining processes, representing the volume of material eroded from a workpiece per unit of time. MER, expressed in mm³/min, indicates the amount of material eroded from the workpiece per minute and serves as an indicator of the productivity of wire-EDT. Therefore, MER is essential for evaluating the process's efficiency, productivity, and cost-effec–tiveness. Optimizing MER is vital for improving pro–ductivity, reducing costs, and achieving desired mac–hining outcomes in spark-erosion-based processes. By carefully selecting and controlling the variable para–meters, the productivity of wire-EDT can be maxi–mized while maintaining quality and efficiency, par–ticularly in small-batch production or precision work. MER can vary depending on the type of materials, geometry, variable parameters, and type of spark-erosion-based processes i.e. wire-EDM, and wire-EDT. MER can be calculated by measuring the diameter and length of the turned parts before and after turning, then computing the volume of eroded material. Machining time is displayed on the screen and recorded after each experiment. MER can also be calculated based on the width and length of the cut, along with the wire feed rate, as expressed in Equation 1.

$$MER = Width\ of\ cut\ length\ of\ cut\ x\ wire\ feed\ rate \quad (1)$$

In spark-erosion-based turning, MER is defined as the amount of volumetric eroded material from the workpiece to the total time taken for turning in each experimental run, as expressed by equation (2). Equation 3 represents the total amount of erosion of the turned workpiece. A DS 852G weighing machine from Essay Group Company (India) was used for weight measurements, with a precision of 0.01 g and a capa–city of up to 5000 g. The total turning time was recorded from the display of the wire-EDT machine.

$$MER\left(wire\,EDT\right) = \frac{Weight\ of\ bar - weight\ of\ turned\ bar}{Bar\ density\left(\rho\right) \times Total\ turning\ time\left(t\right)} \quad (2)$$

$$MER = \frac{Weight\ of\ eroded\ material\ in\ turning}{Bar\ density\left(\rho\right) \times Total\ turning\ time\left(t\right)} \quad (3)$$

Surface roughness is critical for functionality, dimensional accuracy, performance, and cost. Precise control and measurement are essential to ensure part quality and compliance with industry standards. Mean surface irregularity depth (R_z) is a parameter of surface roughness used to quantify the roughness of a surface. It represents the average vertical distance between the highest peak and the lowest valley within a sampling length on the surface profile. Monitoring and measuring R_z ensures that machine parts adhere to designated surface finish standards and functional requirements, thereby enhancing overall product quality and perfor–mance. Mean surface irregularity depth 'R_z' was measured using a contact type 3D roughness profilo–meter (Model: LD 130; Made: Mahr Metrology; Coun–try: Germany) with a 2 µm diameter probe and reso–lution of 0.01 µm. Gaussian filter, 4 mm evaluation length, and 0.8 mm cut-off length were used for the roughness measurements. Measurements were taken at five random locations on each specimen using a scan–ning speed of 0.5 mm/s. Scanning electron microscope (SEM) is a technique used to examine the surface morp–hology and microstructure of materials at high magni–fication and resolution. SEM of turned parts provides crucial insights into surface morphology, microstructural features, and elemental composition, supporting both quality control and research efforts aimed at enhancing product performance and manufacturing efficiency. A scanning electron microscope (SEM) SUPRA 55 from Carl Zeiss, Germany, was used to analyze the turned surface and profile of the bar with the best finish.

3. RESULTS AND DISCUSSIONS

The experiments were conducted using wire-assisted electrical discharge turning (wire-EDT) set up on mild steel bars. The Taguchi L_9 (3^3) orthogonal array was employed to vary the following parameters: spark-on duration 'T_{on}' (in µs); spark-off duration 'T_{off}' (in µs); and servo voltage 'S_V' (in V). Table 1 summarizes the experimental matrix and the corresponding results for circularity error '*CE*' (in µm), mean surface irre–gularity depth 'R_z' (µm), and machining erosion rate '*MER*' (in mm^3/min). ANOVA results for experimental data obtained from turning mild steel by wire-EDT involve analyzing the significance of wire-EDT vari–able parameters for considered responses namely circularity error, mean surface irregularity depth, and machining erosion rate.

3.1 Statistical analysis of experimental results

3.1.1 Residuals, ANOVA, and regression analyses

The experimental results were analyzed using a trial version of Minitab software to perform the residuals, analysis of variance (ANOVA), and regression analy–ses. Residual analysis was used as the primary diag–nostic tool. Normal probability plots of residuals were created for *CE*, R_z, and *MER*, as illustrated in Fig. 4**.** These plots demonstrate that most residuals are normally distributed and align closely with a straight line. Regression analysis was utilized to create models for *CE*, R_z, and *MER*. To evaluate the significance of these regression models and identify the significant wire-EDT variable parameters, an analysis of variance (ANOVA) with a 95% confidence level was perfor–med. ANOVA results enable researchers to pinpoint the most influential factors and their optimal levels for achieving the desired machining outcomes. This infor–mation is crucial for optimizing processes in industrial applications. The results of the regression analysis and ANOVA are detailed in Table 2. It is concluded that (i) spark-on duration and spark-off duration significantly impact the mean surface irregularity depth 'R_z, with spark-on duration also being significant for the mac–hining erosion rate, and (ii) the developed regression models are statistically significant at a 95% confidence level.

Table 2. Results of regression analysis and ANOVA for all responses considered in this study.

Regression Analysis: MER versus T_{on}, T_{off}, and S_V (ANOVA)						
Source	DF	Adj SS	Adj MS	F-Value	P-Value	Remarks
Regression	3	12.4248	4.1416	4.76	0.063	
Spark-on duration	1	9.7028	9.7028	11.14	0.021	
Spark-off duration	1	1.9154	1.9154	2.20	0.198	
Servo voltage	1	0.8067	0.8067	0.93	0.380	
Error	5	4.3538	0.8708			
Total	8	16.7786				
S: 0.933144, R-sq: 74.05%; R-sq(adj): 58.48%: R-sq(pred): 0.00%						
Regression Analysis: R_z versus T_{on}, T_{off}, and S_V						
Regression	3	61.190	20.397	11.96	0.010	
Spark-on duration	1	37.300	37.300	21.87	0.005	
Spark-off duration	1	16.934	16.934	9.93	0.025	
Servo voltage	1	6.955	6.955	4.08	0.099	
Error	5	8.526	1.705			
Total	8	69.716				
S: 1.30585, R-sq: 87.77%; R-sq(adj): 80.43%: R-sq(pred): 64.99%						
Regression Analysis: CE versus T_{on}, T_{off}, and S_V						
Regression	3	68.43	22.81	1.76	0.270	
Spark-on duration	1	12.64	12.64	0.98	0.368	
Spark-off duration	1	35.77	35.77	2.77	0.157	
Servo voltage	1	20.02	20.02	1.55	0.269	
Error	5	64.67	12.93			
Total	8	133.10				
S: 3.59626, R-sq: 51.42%; R-sq(adj): 22.27%: R-sq(pred): 0.00%						
DF: Degree of freedom; Adj SS: Adjusted sum of square; Adj MS: Adjusted mean square; P: Probability; S; Standard error; R-sq: R square; R-sq(adj): Adjusted R-Square; R-sq(pred): Predicted R-Square						

The regression equations developed to predict the values of CE, Rz, and MER are as follows:

$$CE = 95.8 + 7.26T_{on} - 1.221T_{off} - 0.365S_V \quad (1)$$

$$R_z = -47.6 + 12.47T_{on} + 0.840T_{off} - 0.215S_V \quad (2)$$

$$MER = 18.6 + 6.36T_{on} - 0.282T_{off} - 0.0733S_V \quad (3)$$

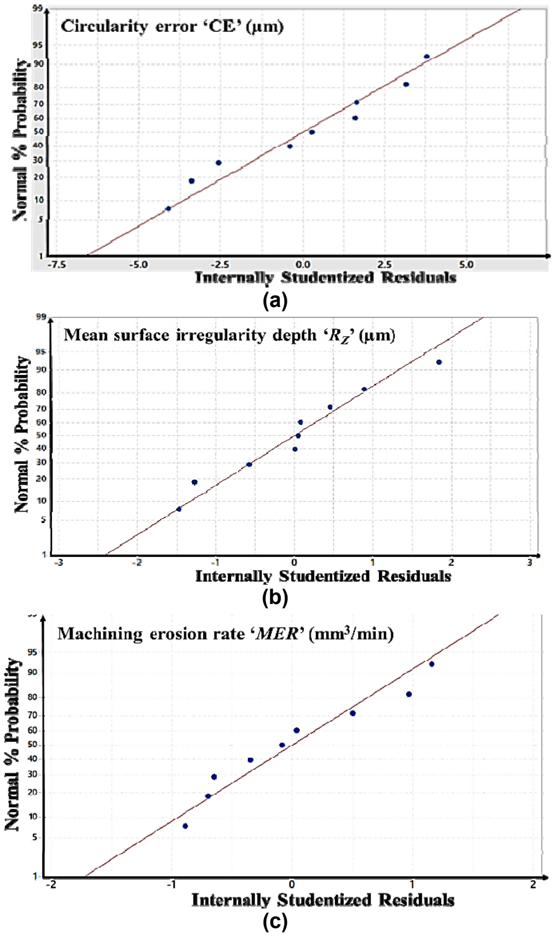


Figure 4. Normal probability graphs of selected respon– ses: (a) circularity error; (b) mean surface irregularity depth; and (c) machining erosion rate.

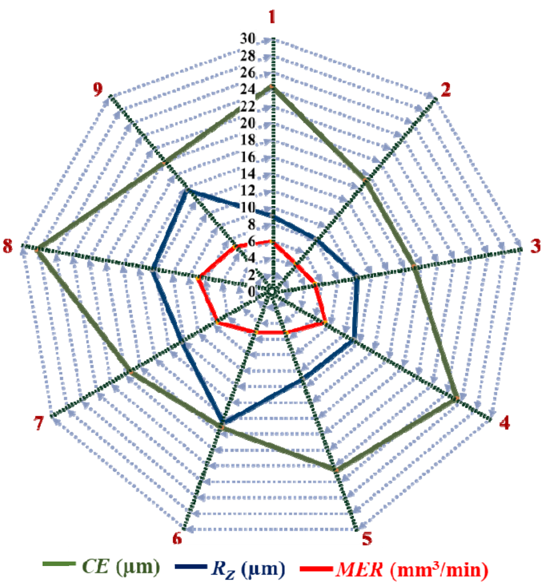
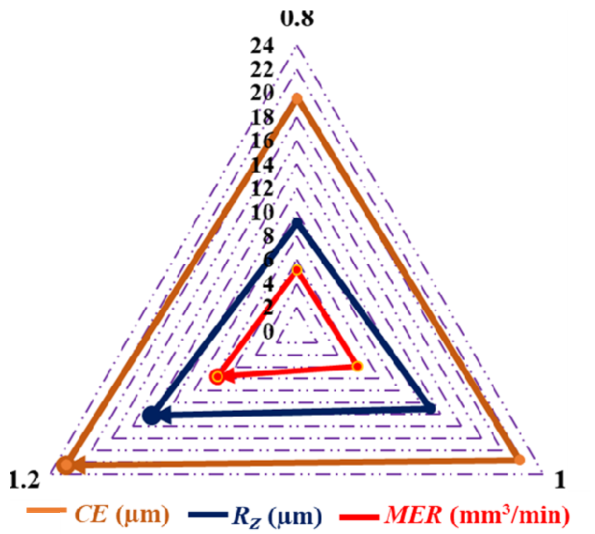


Figure 5. Variation in circularity error; mean surface ir– regularity depth; and machining erosion rate with machining combinations.

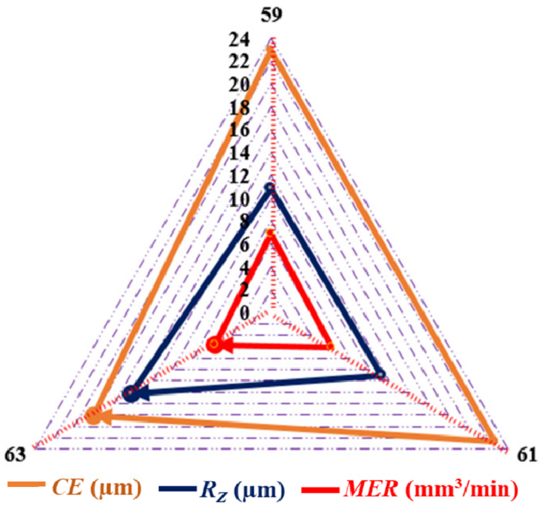
This study focuses on optimizing the turning of cylindrical mild steel bars using wire electrical discharge turning (wire-EDT) by addressing conflicting perfor– mance measures. The objectives are to minimize the circularity error (CE) and mean surface irregularity dep– th (R_z) while maximizing the machining erosion rate (MER). Figure 5 presents the variations in CE, R_z, and MER across nine experimental runs. Runs 2 and 3 yielded the lowest CE (17.12 µm) and R_z (8.1 µm), res– pectively, while the highest MER was observed in run 8.

3.2 Effect of wire-EDT variable parameters on CE, R_z, and MER

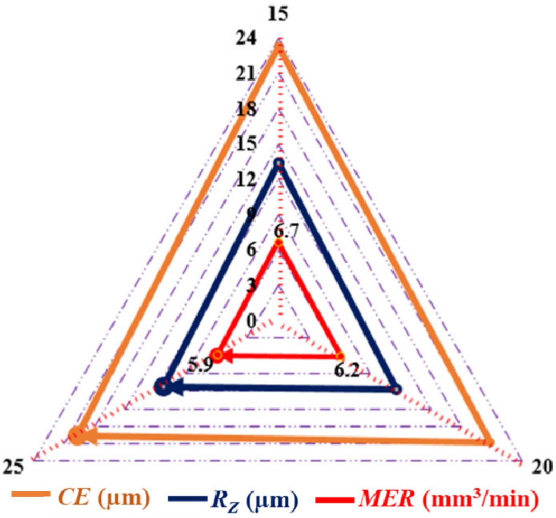
This section examines the impact of variable wire-EDT parameters namely spark-on duration 'T_{on}', spark-off duration 'T_{off}', and servo voltage 'S_V' on circularity error 'CE', mean surface irregularity depth 'R_z', and machining erosion rate 'MER'. The discussion is supported by graphical representations in Fig. 6. These graphs depict circularity error and mean surface irregularity depth in µm, and machining erosion rate in mm³/min on the ordinate, while the abscissa illustrates the variable wire-EDT parameters. The findings reveal that: (i) circularity error tends to increase with longer spark-on duration but decreases with increased spark-off duration and servo voltage (Fig 6a); (ii) mean surface irregularity depth increases with longer spark-on duration and spark-off duration but decreases with higher servo voltage (Fig 6b). (iii) the machining erosion rate increases with a longer spark-on duration, while decreases with a longer spark-off duration and higher servo voltage (Fig 6c). A longer spark-on duration allows more energy to be transferred to the workpiece, resulting in a more significant material removal per discharge cycle. A longer spark-on duration also formed nonuniform deep craters on eroded surfaces. Hence, a longer spark-on duration not only raises the machining erosion rate but also amp– lifies the mean surface irregularity depth and circularity error. A longer spark-off duration indicates more time between the occurrence of two consecutive sparks. Furthermore, a longer spark-off duration allows the electrode and workpiece to cool between discharges.



(a)



(b)



(c)

Figure 6. Variation in *CE, R_z,* and *MER* with (a) pulse-on duration; (b) pulse-off duration; and (c) servo voltage.

This cooling reduces the overall heat input and hence decreases the erosion rate. But, a longer spark-off duration avoids the wire chatters, forming uneven deeper carters, wire breakage, and short-circuiting due to blocking of debris in wire passage. Therefore, a longer spark-off duration lowers the erosion rate while also diminishing the circularity error and mean surface irregularity depth.

3.3 Confirmation experiments

It was found from experimental results that the mini–mum *CE* and R_z, as well as the maximum *MER*, are achieved at experimental run 3 (0.8 µs T_{on}, 63 µs T_{off}, 25 V S_V); experimental run 2 (0.8 µs T_{on}, 61 µs T_{off}, 20 V S_V); and experimental run 8 (1.2 µs T_{on}, 61 µs T_{off}, 15 V S_V), respectively. Each combination was tested twice, and the average values were used to validate the optimal results. The optimum and confirmation results demonstrate strong agreement, with a variance of less than 6%, for the values of circularity error, mean surface irregularity depth, and machining erosion rate.

Fig. 7 presents the circularity error graph of the turned cylindrical bar at the optimal combination (run 3), which shows a deviation of 17.06 µm. Fig. 8 shows the SEM images of the cylindrical bar turned at the optimum combination (run 2) using wire-EDM. Fig. 8(a) displays the cross-section of the turned bar, which has an accurate and precise profile, free from burrs and sharp edges. Fig. 8(b) illustrates a smooth surface, free from uneven deep craters, burrs, and cracks.

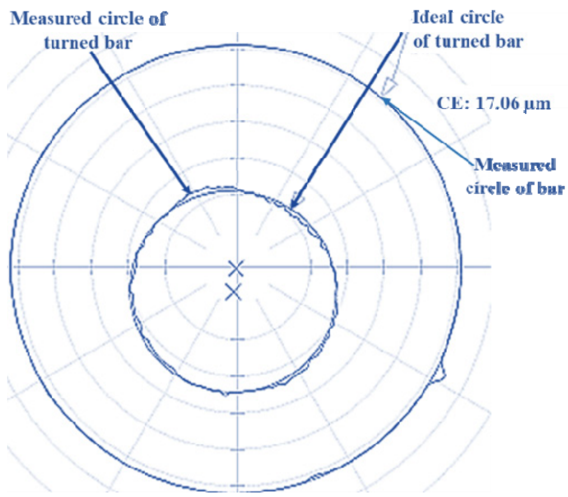
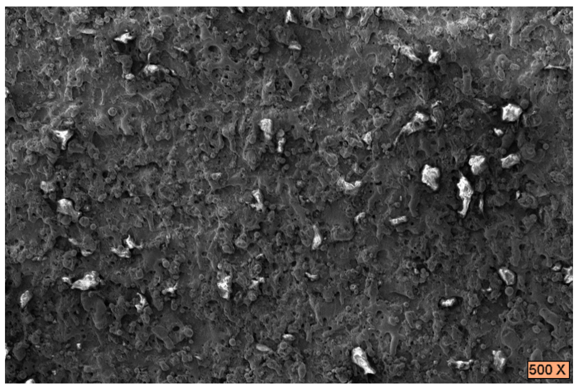


Figure 7. Circularity error in the geometrical profile of mild steel bar after turning at an optimum combination (i.e. run 3) by wire-EDT.

(a)



(b)

Figure 8. SEM graphs of a cross-section of a cylindrical mild steel bar turned at an optimum combination (i.e. run 3) by wire-EDT: (a) circular profile of bar; and (b) micrographs of the turned surface of the bar.

4. COMPARATIVE ANALYSIS

This section compares the results of this study with previous research on wire-EDT, highlighting the following key points.

- Previous work used belt-driven rotary setups [13, 19] and DC motors [10] for turning, while this study employed a low-speed, gear-driven rotary setup powered by a stepper motor to avoid slipping and power fluctuations.
- The turning accuracy achieved in this study (circularity error: 17.06) is superior to that in previous work (circularity error: 455) [21].
- Previous work focused on evaluating average surface roughness.
- The achieved surface roughness (8.1 μm) is lower than that reported in previous studies, such as 19 μm [12] and 8.53 μm [22].
- Optimum machining erosion rate (8.86 mm^3/min) achieved in this study is better than in previous work (MER 3.78 mm^3/min) [11].
- The maximum circularity error achieved in this study (28.31 μm) is lower than the maximum circularity error of 40 μm obtained through three-stage turning by low-speed wire-EDT [17].
- This comparative study concludes that a low-speed, gear-driven rotary setup with a stepper motor offers greater accuracy than belt-driven and DC motor-driven configurations, as belt slipping and power fluctuations are major issues in these setups.

5. CONCLUSIONS

This section summarizes the conclusions of this study and suggests potential directions for future research. The results demonstrate the effectiveness of wire-EDT for machining cylindrical mild steel bars.

- Modified wire-EDM as wire-EDT using a low-speed gear-based rotary setup to execute straight turning on a cylindrical bar.
- Successfully executed straight turning on cylin–drical mild steel bars using the wire-EDT process with a newly designed gear-based rotary setup.
- Identified spark-on duration and spark-off duration as critical factors affecting surface roughness.
- Established that spark-on duration is a key factor impacting machining erosion rate.
- Observed that the residuals of *CE*, R_z, and *MER* are normally distributed.
- Observed that *CE*, R_z, and *MER* increase with longer spark-on duration.
- *CE* and *MER* decrease with increased spark-off duration.
- Higher servo voltage results in reduced *CE*, R_z, and *MER*.
- Achieved 17.06 μm *CE*, 8.1 μm R_z, and 8.86 mm^3/min *MER* at optimal wire-EDT parameters.
- SEM images of the optimum bar show a burr and crack-free turned surface with a consistent and accurate profile.
- Confirmed the optimal results through validation experiments.
- The results of this study highlight the potential of wire-EDM. This method can be used to manufa–cture a variety of features, including cylindrical and spherical parts, from a range of materials. These components are widely used in industries such as aerospace, automotive, biomedical, and marine.

Here are a few potential directions for future research:

- Developing a high-speed gear-driven rotary setup equipped with a stepper motor and controller.
- Investigations on turning of difficult-to-machine (DTM) materials and biocompatible materials such as titanium, stainless steel, shape memory alloys, and magnesium alloys.
- Application of artificial intelligence and machine learning-based techniques for optimization of wire-EDT.
- Investigations on wire-EDT for performing taper turning stepped turning, thread cutting, grooving, and parting-off operations.
- Manufacturing of various cylindrical, spherical, and conical structures from DTM and biocompatible materials using wire-EDT.
- Investigation of sustainability aspects of wire-EDT such as energy consumption, wire consumption, dielectric consumption, life cycle analysis, and exploration of dry wire-EDT.

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COMPETING INTERESTS

The authors declare that they have no conflict of interest.

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NOMENCLATURE

Wire-EDT	Wire electrical discharge turning
Wire-EDM	Wire electrical discharge machining
T_{on}	Spark-on duration
T_{off}	Spark-off duration
S_V	Servo voltage
CE	Circularity error
MER	Machining erosion rate
R_Z	Mean surface irregularity depth

ИСТРАЖИВАЊА О ЖИЧАНОМ-ЕДТ ЗА ПРЕЦИЗНО ОКРЕТАЊЕ ЦИЛИНДРИЧНИХ ШИПКИ ОД МЕКОГ ЧЕЛИКА КОРИШЋЕЊЕМ РОТАЦИОНОГ ПОДЕШАВАЊА СА ЗУПЧАНИКОМ

С. К. Цхаубеи

Овај рад наглашава аспекте кружне грешке „ЦЕ“, средње дубине површинске неправилности „Рз“ и стопе ерозије при машинској обради „МЕР“ за правокретне цилиндричне шипке од меког челика (ЦМСБ) стругањем жичаним електричним пражњењем (жичани-ЕДТ). Рз одражава квалитет површине, МЕР означава брзину обраде и продуктивност, а ЦЕ мери одступање од идеалног кружног облика. Микрографска анализа је изврше-на на шипки окренутом у оптималној комбинацији са минималном храпавости површине. Девет комбинација варијабилних параметара жице-ЕДТ - трајање импулса (T_{on}), трајање импулса (T_{off}) и серво напон (СВ) - распоређено је коришћењем Тагучи Л9 (33) ортогоналног низа, при чему је свака комбинација поновљена два пута. Ово је резултирало са осамнаест експеримената за процену потенцијала жичаног ЕДТ-а и утицаја промен-љивих параметара на ЦЕ, Рз и МЕР. Утврђено је да је трајање варничења значајно за брзину ерозије при обрађивању, док је и трајање варничења и трајање искре значајно за просечну дубину површинске неправилности. Грешка кружности од 17,06 μм, Рз од 8,1 μм и МЕР од 8,86 мм³/мин постигнути су у оптималним комбинацијама. Резултати тестова потврде се уско поклапају са оптимумом, показујући снажно слагање са варијансом мањом од 6% за ЦЕ, Рз и МЕР. Резултати овог истраживања су корисни за стругање цилиндричних шипки од различитих материјала.