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Experimental Investigation into MRR of Polished Zinc Plate with Ultrasonic Vibrations Using Single Pole Magnetic Abrasive Finishing Process

Arsh Siddiqui[1], Mragank Sharma[2], Kheelraj Pandey[3,*], Ashwani Sharma[4]

Abstract

The present research examines the material removal rate (MRR) in finishing zinc plates on the experimental framework called Single Pole Magnetic Abrasive Finishing Process (SPMAFP) by inducing ultrasonic vibrations. By means of a Flexible Magnetic Abrasive Brush (FMAB) composed of 40% alumina and 60% iron elements, the investigation estimates the effect of key process parameters on surface finishing excellence. An L-16 factorial study design was applied to examine the FMAB speed, working gap, feed rate, and pulse-on time effect on MRR. Statistical examination shows that higher FMAB speed and smaller working gap significantly increases the material removal by increasing magnetic flux concentration and abrasive indentation force. The optimal parameters are 1500 RPM speed, 6mm working gap, 5.5mm/s feed rate, and 7.3 minutes pulse-on time, yielding an MRR of 9.8 mg/min. SEM analysis confirmed the procedure successfully eliminated the surface deficiencies, producing a smooth surface roughness (SR). Ultrasonic vibrations increase the MRR by abrasive particle agitation thus reducing the frictional resistance at the contact surface. The maximum MRR attained without ultrasonic vibration was 6.4 mg/min, but ultrasonic-assisted trials got 9.8 mg/min, indicating a 53% increase in material removal rate. Experimental results closely matched theoretical predictions, validating effectiveness of the chosen process parameters.

Keywords: Flexible magnetic abrasive brush (FMAB), Magnetic abrasive finishing process (MAFP), Material removal rate (MRR), Single-pole magnetic abrasive finishing process (SPMAFP), Surface roughness (SR)

INTRODUCTION

MAF is an unconventional surface finishing method in which the magnetic field and abrasive particles are used to produce superior surface quality. This method is ideal for complex shapes and hard-to-reach surface geometries, which are employed in precision industries, such as aerospace, electronics, and medical device manufacturing. By combining chemical mechanical polishing (CMP) with MAF, the MRR is increased using the combined action of chemical and mechanical processing. New methods like SPMAF give better MRR and hence improve surface quality and finish. The flexibility offered by MAF made it an ideal method for finishing zinc plates. Shinmura et al[1]. proposed an innovative magnetic abrasive finishing process in which the executing pressure is produced using a magnetic field. The result of abrasive grain magnitude on stock removal and surface finish was examined. Using a diamond-coated abrasive, they obtained better SR and fine finishing at edges on Si_3N_4

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ceramic bars. Singh et al[2]. established the fundamentals of the material removal mechanism in MAF. They emphasized that the MRR in such a process is also correlated with the magnetic pressure on abrasive particles, which are moving and rubbing against the workpiece surface. Mathematical models were developed that correlated MRR with several process constraints, such as magnetic field strength, working gap, and abrasive particle concentration. Wang and Hu [3] also proposed MAF to obtain excellent surface finish of tubes. Their work indicated that traditional abrasives and ferrous particles were excellent in finishing the internal surface of a variety of metallic tubes like Ly12 aluminum alloy, 316-L stainless steel, and H-62 brass. Mulik and Pandey [4] studied the combination of ultrasonic vibrations with the MAF procedure to have improved surface finish. An experiment was carried out to investigate the process constraints like supply of voltage, abrasive mesh grade, magnet rotation speed, abrasive weight, and on-time of the ultrasonic pulse. It was obtained that by using UAMAF, an SR of 22 nm could be achieved after 80 seconds on AISI 52100 steel; compared to MAF, there was also a significant improvement. Using SEM and AFM, the surface texture and finishing mechanism were also analyzed. Vahdati and Rasouli [5] developed an MAF system for finishing aluminum surfaces through a CNC integrated setup. They employed mechanically alloyed magnetic abrasives and investigated parameters, such as gap, feed rate, rotation speed, and the amount of powder. Based on response surface methodology (RSM), the significant factors were determined, and the finite element technique was used to analyze the magnetic field concentration. Results showed that efficient finishing was achieved at optimal parameters. Misra et al[6]. studied the ultrasonic-assisted MAF (UAMAF) to improve efficiency. They simulated the material removal mechanisms using a combination of steady and transient phenomena and studied the influence of several parameters. The magnetic forces were obtained by finite-element analysis, and the model revealed that MRR is exponentially dependent on finishing time. Ahmad et al[7]. studied the MAF process with sintered abrasives of alumina and iron powders. The impact of process constraints rotational velocity, electromagnet voltage, machining gap, and abrasive particle size on the surface finish of Stainless Steel 202 were investigated. The sintering process improved the quality of abrasive particles by strongly bonding them together. The results demonstrated that sintered abrasive is beneficial for the SR, making it ideal for a super-fine finishing tool. Babbar et al[8]. examined the consequence of boron carbide abrasives on SR and MRR in MAF for flat brass plates. They conducted a full factorial experiment with four factors: rotation speed, amount of abrasive, mesh number, and duration. Both ANOVA and regression modeling revealed that the spindle speed has the main influence on SR, while MRR was dependent on machining time. A minimum SR of 0.061μm and MRR of 3 mg/min was achieved by the study. Mousa et al[9]. utilized MAF to determine MRR for an Al-1050 alloy plate. Their work analyzed the effects of current, percentage abrasive weight, working gap, and feed rate and found that input parameters had a great impact on MRR. Dhakar et al[10]. investigated the application of MAF on cylindrical stainless steel with an emphasis on surface finish and MRR. They studied the effects of current, magnetic abrasive amount, rotation speed, and proportion of diamond abrasive using RSM. All parameters had a significant effect on the responses, with magnetic abrasive quantity having the greatest influence. An SR of 17.7 nm was obtained, which confirms the effectiveness of the process. Guo et al[11]. proposed a vibration-assisted magnetic abrasive polishing (VAMAP) way to finish complex internal surfaces of aerospace and automobile components, by taking double-layered tube Inconel 718. This device made use of external magnets and a central cylindrical magnet to attract magnetic abrasives and obtained good polishing efficiency. Results indicated an improvement in SR from 7 to 0.5 μm with even material exclusion on both the inner and outer tube surfaces. Kadhum et al[12]. studied how the magnetic abrasive finishing process affects the temperature rise and material removal rate during polishing of AISI 304 steel, using Taguchi design and ANOVA analysis, and found the optimum contact temperature of 70.7°C. Gao et al[13]. applied magnetic abrasive finishing (MAF) using diamond-embedded spherical magnetic abrasive powders (MAPs) developed via atomization to improve the finishing of SS304. The study demonstrated that higher MRR correlates with a finer surface finish in MAF. Ahmadi et al[14]. examined the consequence of abrasive particle morphology and process parameters on SR in magnetic abrasive finishing (MAF) for medical implants. Using Ti-6Al-4V, AZ31, and 316LVM stainless steel, they compared rod-shaped and spherical abrasive particles. Results showed rod-shaped abrasives and

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longer finishing times significantly improved surface quality. Among materials, 316LVM achieved the best surface finish. ANOVA interaction plots revealed material–morphology and material–machining time interactions had a notable impact on finishing performance. Xing et al[15]. examined the Pulse Electrolytic MAF (P-EMAF) process on SUS304 using rectangular wave pulse voltage. They analyzed the effects of different frequencies and duty ratios on SR and MRR. Results showed P-EMAF outperformed traditional MAF in efficiency and surface quality under optimal conditions. Dixit et al[16]. proposed the mathematical models for MRR and SR in the ultrasonic-assisted magnetic-abrasive-flow-machining (UAMAFM) process. By including both transient and steady-state effects, they demonstrated that ultrasonic vibrations and magnetic fields impose a high abrasive velocity and contact length. The physics of the model was supported by kinematic and force analyses. The predicted value by the model has an error of 7.80% and 2.44% for MRR and SR, respectively. Majeed and Khadum [17] studied the influence of MAF of aluminum alloy on temperature rise and MRR by utilizing a Taguchi L16 (4^4) orthogonal arrangement. Four process parameters: cutting speed, finishing time, working gap, and current were changed. Significant factors on temperature rise and MRR were found using ANOVA analysis. The optimal contact temperature was 70.7°C, which indicated that thermal control and material removal of SS304 were effectively regulated during MAF. Singh and Kumar [18] studied magnetic abrasive flow machining (MAFM) for finishing Al/SiC/B_4C based hybrid metal matrix composites (HMMCs). Silicon carbide abrasive and a silicon rubber-hydraulic oil slurry were used in the experiment. Procedure variables, namely extrusion pressure, magnetic field concentration, abrasive size, and number of cycles were studied, and SR and MRR were used as response parameters. ANSYS simulations and SEM study demonstrated that MAFM can effectively improve the surface quality for complex geometries with improved SR. Wang et al[19]. presented an overview of the difficulties related to the post-processing of Additive Manufactured (AM) metallic parts with complex internal features and proposed magnetic abrasive finishing (MAF) as a suitable solution. Special attention was paid to MAF for non-standard geometries, and progress on MAF equipment, mechanisms of removal processes, and abrasive materials were reported. Prospects include hybrid MAF systems, particle dynamics, and high-performance abrasives specifically engineered for complex internal cavities, which is in accordance with present needs of the market, particularly in the aerospace and defense sectors. Liu et al[20]. utilized the abrasive force under a magnetic field to propose a model for the removal of material from tubular workpieces while using MAF. They developed a predictive model based on an active abrasive amount and a penetration depth for the MRR. The experimental results demonstrated a high level of model accuracy with significant improvement in surface finish.

From the above, it can be concluded that both SR and MRR can be improved using magnetic abrasive finishing (MAF) by controlling process parameters, using hybrid processes, and with novel abrasives. The present work studies MRR using ultrasonic-assisted single-pole magnetic abrasive finishing (UA-SPMAF) for zinc plate. Polishing speed, working gap, feed rate, and pulse-on time were input process parameters while MRR is the output process parameter. Ultrasonic-assisted SP-MAF might have a potential to increase MRR by enhancing finishing speed and efficiency. High-frequency vibration promotes abrasive particle dynamics in the finishing zone;, therefore, improved MRR is obtained.

METHODOLOGY

Framework and Procedure

Experiment Setup Overview

The framework, as demonstrated in Figure 1, is designed for precision polishing using a Flexible Magnetic Abrasive Brush (FMAB). The setup has the following key components:

- *Machine Spindle*: Powers the polishing tool for controlled surface finishing.
- *Polishing Tool*: A 25mm diameter cylindrical aluminum disk holding magnetic stacks to generate a strong magnetic field in the polishing area.
- *FMAB (Flexible Magnetic Abrasive Brush):* The core polishing mechanism influenced by the magnetic field.
- *Vibrating Platform*: Enhances abrasive action for uniform surface finishing.
- *Machine Bed*: Provides controlled feed motion for the polishing process.

- Iron stacks placed below the polishing tray strengthen the magnetic field, ensuring effective polishing.
- *Polishing Tray*: Holds the workpiece securely.
- *Zn Workpiece*: A 150mm × 50mm × 2mm zinc plate, positioned for experimentation.
- *Iron Block*: Supports magnetic field stabilization.
- *Vibrator*: Ensures consistent abrasive action.
- *Earthing Wire*: Prevents black spots caused by eddy currents induced during the magnetic tool's rotation over the zinc surface and counters unwanted EMF generation, which could otherwise oppose the external magnetic field and destabilize FMAB, causing surface scratches.
- *Spring*: Helps maintain tool stability and consistent contact with the workpiece.

Flexible Magnetic Abrasive Brush (FMAB) – Composition and Functionality

Material Composition: Consists of 40% alumina + 60% iron particles (by weight) with a total weight of 5g, forming a flexible magnetic brush for precision finishing.

Mechanism of Operation: The tool is placed on a milling machine spindle. As the spindle rotates, it causes circular motion of the FMAB, which then causes tangential cutting action. The abrasive elements actively eliminate material from the zinc work sample. Iron particles exert a downward force, increasing penetration depth and enhancing material removal efficiency for improved surface finishing.

For Enhancing the Finishing Process, alumina slurry is introduced every 5 minutes to aid in lubrication and cooling and maintains optimal finishing conditions by reducing friction and heat build-up. The continuous contact between FMAB and workpieces generates frictional heat;, therefore, this temperature rise must be controlled to ensure effective and damage-free finishing.

Preliminary Observation

Table 1 shows the preliminary experimental observation which determines the range of each parameter within which the operating parameter works.

Planning of Experiment

The study examined the impact of four key process parameters—FMAB speed, machining gap, workpiece feed rate, and pulse-on time—on material removal efficiency. An L-16 factorial design guided 16 trials, systematically varying these factors to optimize SR. MRR was quantified by measuring the weight alteration of zinc workpieces before and after machining. The results, compiled in Table 2 and Table 3, provided insights into parameter interactions, ensuring a comprehensive evaluation of machining efficiency and optimal conditions for enhanced performance.

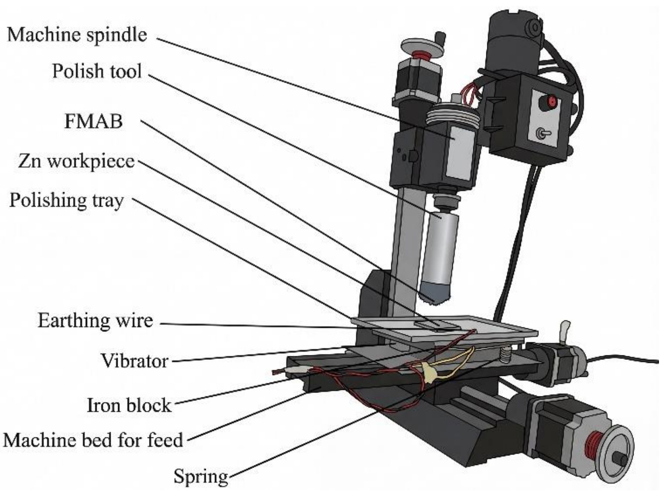

Figure 1. Schematic diagram of experimental setup.

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Table 1. Preliminary Observations.

Parameter	**Evaluation & Findings**
Polishing Speed	Evaluated from 250 to 1250 rpm. Speeds <500 rpm increased roughness, while >1250 rpm caused uneven removal. Optimal range: 500–1500 rpm.
Working Gap	Maintained at 6–8 mm to ensure effective magnetic flux density, enabling controlled MRR and SR for precision manufacturing.
Workpiece-Feed-Rate	Set between 1.5–5.5 mm/sec. Slower rates (<1.5 mm/sec) caused excessive erosion, while faster rates (>5.5 mm/sec) reduced efficiency, leading to poor finishes.
Pulse On Time	Chosen between 1–5 min. Lower pulse-on time led to shallow abrasive indentation and inadequate MRR, while higher pulse-on time resulted in excessive material removal, affecting SR. In this context, pulse-on time' refers to the active duration of ultrasonic vibration applied during each machining cycle. It defines how long the ultrasonic transducer remains engaged to assist the FMAB action, analogous in function but distinct from pulse control in EDM

Table 2. Process parameter details.

Signs	**X_1**	**X_2**	**X_3**	**X_4**
Explanation	FMAB speed (in r.p.m)	Working Gap (in mm)	Feed rate (in mm/s)	Pulse on time (mins)
Low Level	250	4	1.5	1
High Level	1250	6	5.5	5

Table 3. Measured value of MRR for the experimental trials.

Exp. no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
FMAB Speed (RPM)	250	1250	1250	1250	1250	250	1250	250	250	1250	1250	250	1250	250	1250	1250
Working Gap (mm)	4	4	4	6	6	4	6	6	6	6	4	6	4	4	4	4
Feed rate (mm/s)	1.5	1.5	5.5	5.5	1.5	5.5	1.5	1.5	1.5	5.5	5.5	5.5	1.5	1.5	1.5	5.5
Pulse on Time (Min)	1	1	5	5	1	1	5	5	1	1	1	1	5	1	1	5
MRR (mg/min)	2	3	0.8	2.4	9	8.5	5.5	6	1.5	6.8	1.3	1	5	8	0.5	9.8

Table 4. Analysis of variance for response.

Source	**DF**	**Adj. SS**	**Adj. MS**	**F**	**p**	**Remark**
Model	6	159.189	26.531	1035.37	0.00	
Linear	4	156.203	39.051	1523.93	0.00	$F^{standard}_{(0.05,6,9)} = 3.37$
X_1	1	132.826	132.926	5183.44	0.00	F^{model}= 1035.37
X_2	1	18.706	18.706	729.98	0.00	$F^{model} > F^{standard}_{(0.05,11,15)}$
X_3	1	3.516	3.516	137.20	0.000	$\Rightarrow 1035.37 > 3.37$
X_4	1	1.156	1.156	45.10	0.000	
2-Way interaction	2	2.986	1.493	58.27	0.000	
$X_1 \times X_2$	1	2.806	2.806	109.49	0.000	
$X_1 \times X_3$	1	0.181	0.181	7.05	0.026	The statistical model for the MRR is accurate
Error	9	0.231	0.026			
Total	15	159.419				

The study employed an L-16 factorial design with Minitab 17 for precise analysis and optimization. A linear model given by Equation 1 was integrated to derive a predictive equation, capturing parameter interactions and material removal efficiency. This approach ensured accuracy, deep insights, and refined process optimization for superior performance.

$$MRR = \alpha_o + \sum_{i=1}^{n} \beta_i x_i + \epsilon \quad (1)$$

The MRR is influenced by multiple process parameters. In the formulated linear model, *n* represents the count of process parameters, βi denotes the regression coefficients, xi corresponds to the linear elements of the process variables, and ε accounts for the error occurring randomly. The regression equation obtained from the model is given by Equation 2.

$$MRR = 2.526 + 0.010322X_1 - 0.4531X_2 - 0.1547X_3 + 0.1344X_4 - 0.000.838X_1X_2 - 0.000106X_1X_3 \quad (2)$$

A precise mathematical model was formulated, and ANOVA (Table 4) was applied to assess parameter significance. Table 2 details their contributions to material removal efficiency, ensuring a structured evaluation of the polishing process. A multivariable regression model (Equation 2) with a 99.76% adjusted R² at a 95% confidence level and a ±0.34 error margin confirmed a strong correlation between MRR and process variables (X_1, X_2, X_3, X_4). This high accuracy validates the model's reliability, offering deep insights into optimization.

RESULT AND DISCUSSION

Result of Process Parameters on MRR

Figure 2 illustrates the effect of process parameters on MRR. Higher FMAB speed increases MRR as larger iron particles exert downward force on smaller abrasives, aiding peak removal on the zinc workpiece. A smaller machining gap (X_2 = 6 mm) enhances magnetic flux density, intensifying indentation force and boosting MRR, while a larger gap weakens flux, reducing force and increasing SR. As the workpiece feed rate rises, MRR declines due to non-uniform shearing from the FMAB tool's tangential cutting action, hindering effective material removal. Additionally, increased pulse-on time enhances the indentation effect, further improving MRR. The findings highlight the significance of optimizing the machining gap and feed rate for efficient MRR and superior finishing. Maintaining an optimal machining gap ensures effective abrasive penetration, preventing SR while maximizing MRR. These insights contribute to refining the finishing process for improved performance and efficiency. The indentation effect of abrasive particles increases due to an increase in pulse-on time, which leads to an increase in MRR.

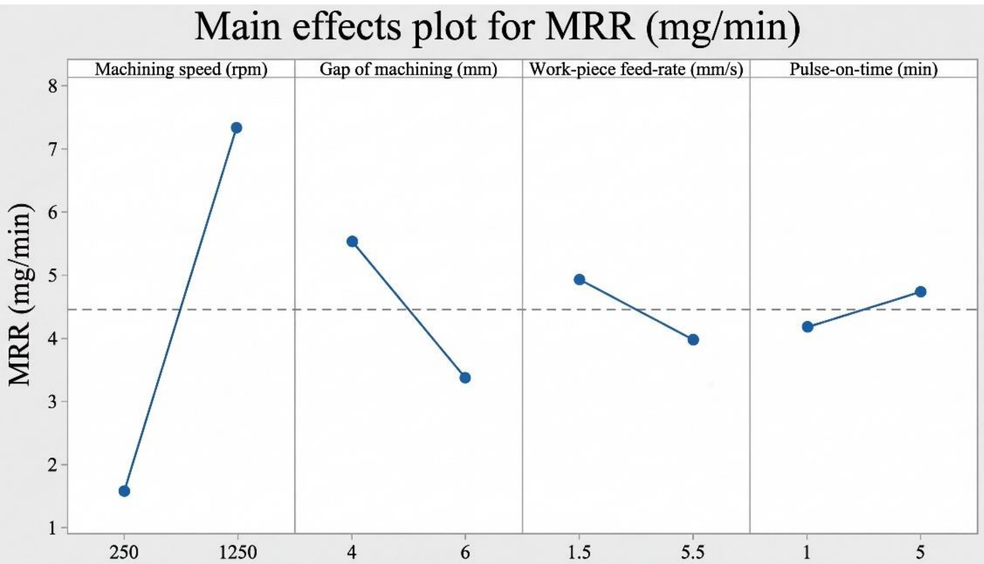

Figure 2. Main effect plot.

Interaction Between Process Parameters

Effect of Interaction Between Tool Speed and the Working Gap

At a small working gap (X_2 = 4 mm), with a rise in the speed of polishing, the MRR is found to increase (Figure 3.1) since at a small working gap, the magnetic field concentration between the rotating magnetic tool and the workpiece is high. The rise in magnetic flux density causes greater penetration by abrasive particles on the workpiece and hence a greater MRR. The magnetic flux weakens as the gap is increased;, therefore, MRR decreases.

Effect of Interaction Between Tool Speed and Workpiece Feed Rate

At lower polishing speeds (X_1 = 250 rpm), increasing the workpiece feed rate results in decreased MRR (Figure 3.2). When the feed rate is low, the interaction time between the abrasive grains and the workpiece rises; hence, better removal of material. So MRR is better at low feed rates. On the other side, a rise in the feed rate decreases the contact time, leading to less removal of material, and hence MRR decreases at low speed.

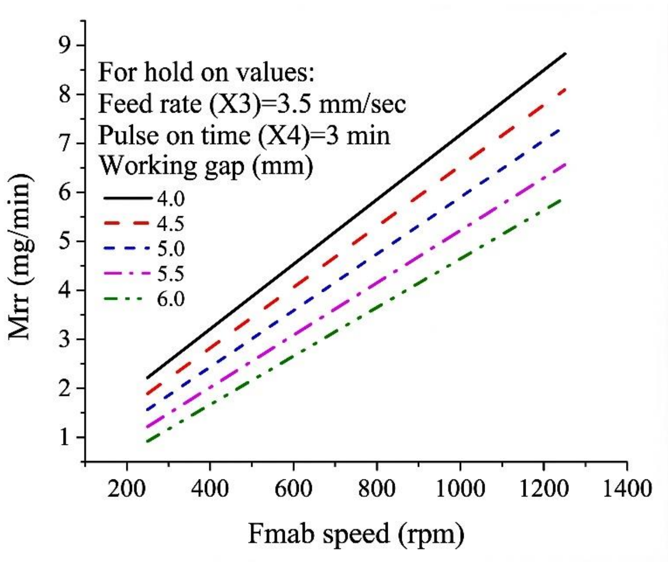

Figure 3.1. Tool speed- working gap.

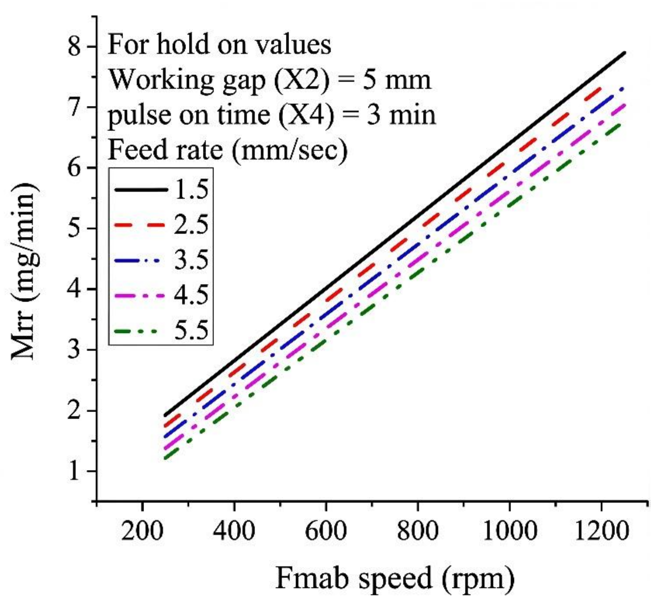

Figure 3.2. Tool speed-feed rate.

Comparative Analysis with and Without Ultrasonic Assistance

To quantify the benefit of ultrasonic integration, control experiments were performed without applying vibration under otherwise identical process parameters. The maximum MRR obtained without ultrasonic vibration was 6.4 mg/min. In contrast, ultrasonic-assisted trials yielded an MRR of 9.8 mg/min, reflecting a 53% improvement. This enhancement can be attributed to increased abrasive mobility, better surface interaction, and reduced resistance at the finishing interface.

Objective Functions Optimization

The equation of regression analysis is attained from the experimental information presented in Table 2 and was optimized using the tool available with Minitab under the constraints as mentioned:

$$250 \leq X_1 \leq 1250;\ 4 \leq X_2 \leq 6;\ 1.5 \leq X_3 \leq 5.5;\ 1 \leq X_4 \leq 5 \quad (3)$$

An MRR of 9.66 ± 0.34 mg/min was then predicted. Optimum process parameters, shown in Table 5, at which the maximum value of the MRR was predicted. The outcome of MRR was found by Equation 2, at optimum parameters, shown in Figure 4.

Table 5. MRR at Optimum process parameters with experimental validation.

FMAB speed (X_1) in rpm	Working gap (X_2) in mm	Feed rate(X_3) in mm/s	Pulse on time (min)	Model MRR (mg/min)	Experimental MRR (mg/min)
1500	6	5.5	7.3	9.66±0.34	9.8

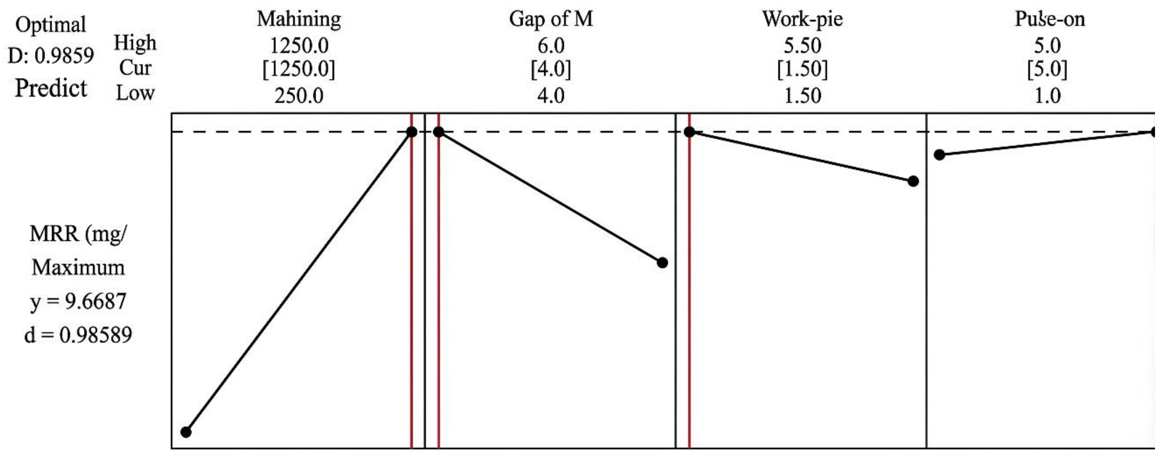

Figure 4. Minitab screenshot of MRR at optimized parameters.

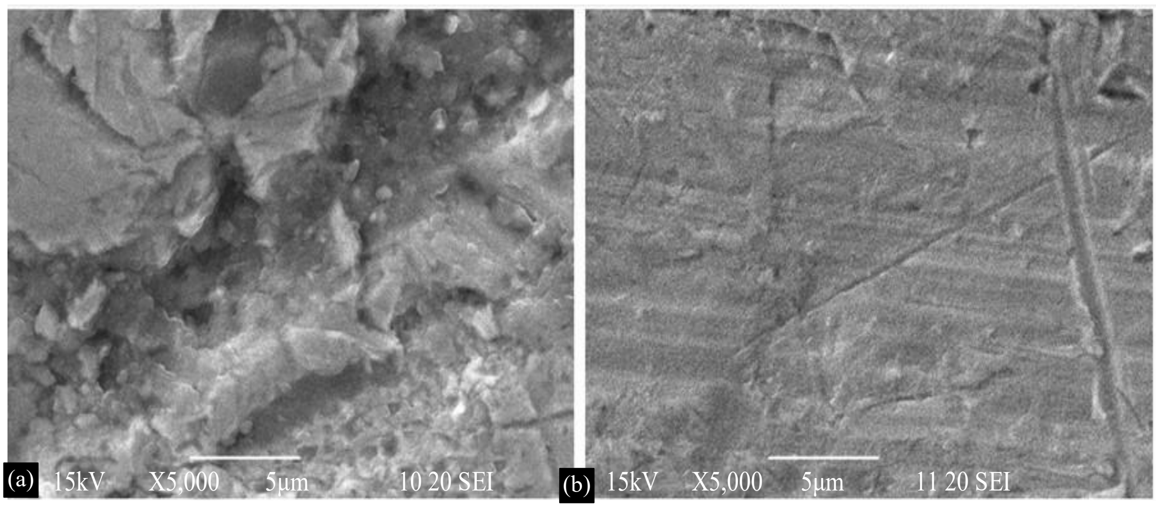

Figure 5. SEM Images (a) Unpolished zinc plate (b) Polished zinc plates.

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Surface Texture Study of Finished Zinc Sample

The correlation between the rough and polished images with the help of scanning electron microscopy has been shown in Figure 5(a) and 5(b) correspondingly. Figure 5(b) shows the SEM image at optimum parameters. By observing Figure 5(a), it can be interpreted that a rough and worn surface of raw and unpolished zinc plate with cracks and scratch marks indicates a rough morphology. Figure 5(b) shows a smoother perspective of a polished zinc plate with a uniform surface with fewer apparent cracks and voids which look smooth and less fractured. When a material is removed at a controlled rate, exhibiting fine and parallel lines indicates a smooth morphology with controlled MRR.

CONCLUSIONS

a. The SPMAFP process significantly enhanced the surface texture of the zinc plate while attaining a much higher MRR.
b. Optimal constraints for maximizing MRR were identified as an FMAB speed of 1250 RPM, a working gap of 4 mm, a feed rate of 5.5 mm/s, and a pulse-on time of 5 minutes.
c. Increased FMAB speed, reduced machining gap, and longer pulse-on time improved MRR, whereas a higher feed rate had the opposite effect.
d. SEM analysis confirmed the removal of surface defects, resulting in a smooth and refined finish.
e. Experimental results closely matched theoretical predictions, validating the effectiveness of the chosen process parameters.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval

NA

Abbreviations and Symbols

Abbreviation	Full Form/ Symbols with units
MRR	Material Removal Rate
MAF	Magnetic Abrasive Finishing
SPMAFP	Single-Pole Magnetic Abrasive Finishing Process
FMAB	Flexible Magnetic Abrasive Brush
CMP	Chemical Machining Process
SEM	Scanning Electron Microscopy
UAMAF	Ultrasonic-Assisted Magnetic Abrasive Finishing
VAMAP	Vibration-Assisted Magnetic Abrasive Polishing
MAP	Magnetic Abrasive Powder
P-EMAF	Pulse Electrolytic Magnetic Abrasive Finishing
UAMAFM	Ultrasonic-Assisted Magnetic Abrasive Flow Machining
HMMC	Hybrid Metal Matrix Composite
ANOVA	Analysis of Variance
X_1 FMAB	Speed (in RPM)
X_2	Working Gap (in mm)
X_3	Feed Rate (in mm/s)
X_4	Pulse-on Time (min)
mg/min	Milligrams per minute (Unit for MRR)
°C	Degrees Celsius (Temperature)
Ra	Average Surface Roughness
βi	Regression Coefficient in Model
ε	Random Error Term
n	Number of Process Parameters

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