

Experimental Investigation into Surface Roughness of Polished Zinc Plate with Ultrasonic Vibration Using Single Pole Magnetic Abrasive Finishing

Puneet Singh¹, Ashwani Sharma², Kheelraj Pandey^{3,*}, Chitra Bajpai⁴

Abstract

This research investigates how applying ultrasonic vibrations influences the surface finish quality of zinc plates when using the Single Pole Magnetic Abrasive Finishing (SP-MAF) method. In SP-MAF, magnetic abrasive particles (MAPs)—amalgamation of ferromagnetic and abrasive materials—are guided by a magnetic field to achieve precise surface finishing. Introducing ultrasonic vibration improves the effectiveness of the flexible magnetic abrasive brush (FMAB), which forms as the MAPs align along the magnetic field lines. This enhancement leads to better material removal and improved surface quality. The research examines the effects of key process variables, including polishing speed (ranging from 250 to 1250 RPM), feed rate (1.5 to 5.5 mm/sec), and working gap (4 to 6 mm), on the final surface finish. A comprehensive analysis across various operating conditions institutes that ultrasonic assistance significantly augments finishing efficiency and gives smoother and better surfaces compared to those obtained through traditional process of MAF. These outcomes show that ultrasonic-assisted SP-MAF is an effective method for achieving superior finishes on zinc and other soft materials. The SEM images at experimental optimum parameters shows that the irregularities and the scratches appearing in form of holes and patches in the raw sample have been reduced and the polished surface appears to be defect free in the finishing direction.

Keywords: Single pole magnetic abrasive finishing (SP-MAF), flexible magnetic abrasive brush (FMAB), surface roughness (SR), surface texture analysis, and ultrasonic-vibration-assisted MAF

INTRODUCTION

The smoothness of a surface greatly affects how good a machined component will perform, how long it will last, and how it looks. In fields requiring high-precision like aerospace, medical implants (prosthetics), and electronics industries, achieving ultra-smooth finish is very crucial. To meet this mandate, cutting-edge polishing methods have been developed including Magnetic Abrasive Finishing. In MAF, MAPs typically a blend of ferromagnetic iron particles and hard abrasives like alumina—are aligned in the magnetic field to form a semi-flexible tool also known as the FMAB. This FMAB acts as a dynamic polishing medium that conforms to the workpiece surface and facilitates uniform material abstraction. Ultrasonic vibrations, when applied to the polishing system, introduce high-frequency oscillations that enhance the relative motion amidst abrasive particles and the surface of the workpiece. This not only improves the impact

*Author for Correspondence

Kheelraj Pandey

¹UG scholar, Department of Mechanical Engineering, Amity University, Lucknow, Uttar Pradesh, India

^{2,3}Assistant Professor, Department of Mechanical Engineering, Amity University, Lucknow, Uttar Pradesh, India

⁴Assistant Professor, Department of Mechanical Engineering, Shri Ramswaroop Memorial College of Engineering and Management, Lucknow, Uttar Pradesh, India

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frequency and uniformity of the FMAB but also assists in the localized softening of the zinc surface, hence allowing for smoother shearing of micro-indentation. Shinmura et al. [1] conducted revolutionary research on the fundamental mechanisms of SR enhancement in magnetic abrasive finishing. Their work established that the finishing pressure generated by magnetic forces controls the interaction between abrasive particles and the workpiece surface, resulting in micro-cutting actions that selectively remove peaks from surface irregularities. They also demonstrated that MAF could further reduce SR from several micrometres to manometer levels under optimized conditions. Yamaguchi and Shinmura [2] examined the influence of magnetic field distribution on surface finish quality, demonstrating that uniform magnetic flux density across the working area contributes to a consistent SR. Their research provided design guidelines for magnetic field generators to achieve homogeneous surface finishes across complex geometries. Jain et al. [3] examined the micro-mechanics of surface modification in MAF processes. Using Scanning Electron Microscopy (SEM) and surface Profilometry, they documented how abrasive particles create microscopic cutting paths that progressively reduce surface severities. Their work established correlations between the finishing time and SR improvement, identifying characteristic three-phase behaviour: rapid initial improvement, steady-state reduction, and eventual saturation. Chang et al. [4] examined the influence of abrasive grain size on final SR. Their systematic experiments with different mesh sizes established that finer abrasives produced better surface finishes but at condensed material abstraction rates. They proposed a two-stage finishing strategy using progressively finer abrasives to optimize processing efficiency. Mori et al. [5] investigated nanoscale finishing capabilities of advanced MAF processes. Using specially formulated ultra-fine abrasive media and precisely controlled magnetic fields, they demonstrated capabilities for reducing SR to Ra values below 10 nm on metallic mirror components. Singh et al. [6] investigated abrasive concentration effects on SR outcomes in MAF. Their research established optimal volumetric concentrations (typically 25-35% by volume) that balanced sufficient cutting action with proper magnetic brush formation. Higher concentrations resulted in diminished improvement due to restricted particle mobility, while lower concentrations provided insufficient cutting action. Yin and Shinmura [7] investigated surface finishing characteristics of titanium alloys using modified magnetic abrasive processes. Their research demonstrated that conventional MAF techniques required adaptation for these materials, with specially formulated abrasive compositions achieving SR reductions from initial Ra values of 0.5-0.8 μm to final values of 0.04-0.07 μm . Judal and Yadava [8] combined electrochemical principles with magnetic abrasive finishing, creating a hybrid process for difficult-to-machine materials. Their approach leveraged electrochemical reactions to soften the surface layer while simultaneous MAF action removed the reaction products, resulting in SR improvements up to 95% from initial values. Xing et al. [9] made a study on Pulse Electrolytic Magnetic Abrasive Finishing (P-EMAF) of SUS304 stainless steel using rectangular wave pulse voltage explored the effects of varying frequencies (1 Hz–1 kHz) and duty ratios (25%–75%) on SR and material removal. Optimum results were achieved at 1 Hz and 50% duty ratio with 6 V, showing improved surface texture and efficiency on the higher side as compared to traditional MAF. This revolutionary research highlights the potential of P-EMAF in advanced surface finishing. Yamaguchi et al. [10] conducted extensive studies on SR improvement in hardened steel components using MAF. Their research also demonstrated capabilities for reducing SR from initial Ra values of 0.8-1.2 μm to final values of 0.02-0.05 μm . They identified optimal processing conditions for the different steel grades based on the various hardness levels and initial surface conditions. Purohit et al. [11] studied SR improvements in aluminium alloy components using magnetic abrasive finishing. They identified challenges related to the non-magnetic nature of the workpiece material and developed modified techniques incorporating ferromagnetic fixtures to enhance magnetic field effectiveness at the finishing zone. Fox et al. [12] conducted comprehensive parametric studies on the relationship between magnetic field strength and SR outcomes. Their research revealed that increasing magnetic flux density improved surface finish up to a threshold value (typically 0.4-0.6 Tesla), beyond which diminishing returns or even deterioration in surface quality occurred due to excessive finishing pressure causing surface damage. Wang and Hu [13] developed and investigated a vibration-assisted magnetic abrasive finishing process. By introducing ultrasonic vibrations to either the workpiece or

the magnetic field source, they achieved 30-40% additional improvement in SR compared to conventional MAF. Their research established optimal vibration parameters including frequency and amplitude ranges for different material types. Sun et al. [14] developed a hybrid finishing method combining electrochemical effects with magnetic abrasive finishing (EMAF) was proposed for hard alloy metals. The EMAF process, divided into EMAF and MAF stages, relies on forming and removing passive films to enhance surface finish. Results showed over 75% improvement in efficiency and significant SR reduction—from 178 nm to 20 nm. The MRR was about seven times as that of conventional MAF, indicating the much higher performance of EMAF. Wang et al. [15] reported the growing demand of the parts with complex internal surfaces manufacture through metal additive manufactured, especially in aerospace and defence industry. They highlighted the limitations of conventional methods and laid emphasis on MAF for making complex shapes. Their study was concentrated on the evolution in MAF technology, abrasive materials, mechanism. The study also discussed the prospects of composite MAF systems, abrasive particle dynamics and high-performance abrasives for optimizing the MAF process. Dixit et al. [16] explored the process of Ultrasonic-Assisted Magnetic Abrasive Flow Machining (UA-MAFM) and examined that UAMAFM has better machining ability compared to traditional MAF. They formulated predictive models for material removal (MR) and SR, considering both stable and changing operational conditions. The application of external ultrasonic and magnetic fields enhanced the speed of abrasive particles and extended their contact with the workpiece. The models incorporated factors like abrasive dynamics and work material hardness. Experimental validation showed strong agreement, with only 7.80% and 2.44% deviation for MR and Ra predictions, respectively. Kala and Pandey [17] examined composite abrasive media incorporating lubricants and explored their effects on SR. Their studies showed that self-lubricating magnetic abrasives reduced friction during finishing, resulting in 15-20% improvements in surface smoothness compared to conventional abrasives under identical processing conditions. Gupta et al. [18] investigated Magnetic Abrasive Finishing (MAF) as a cost-effective, advanced process for reaching surface finishes at nanometric level on both magnetic and non-magnetic materials. Their study focused on the impact of key parameters such as machining gap, voltage, abrasive properties, and binder composition on surface quality. Emphasizing flat surface applications—an underexplored area—they reviewed past and recent research to analyses how variations in magnetic abrasive powder composition impact the surface texture and overall finishing performance. Wu et al. [19] developed magnetic nano-abrasive finishing techniques for optical components. Their research demonstrated capabilities for producing surfaces with roughness values below 5 nm Ra while simultaneously controlling form accuracy for precision optical applications. Hashmi et al. [20] highlighted the growing importance of additive manufacturing due to its efficiency in producing complex prototypes and customized products. Although it has been proved to be beneficial, there are still some problems such as low surface. Therefore, post-treatments and process parameters optimization are required. Rajput et al. [21] used ANN methods for SR prediction in MAF operations. Based on the extensive experimental dataset, they trained models that can estimate final SR with more than 92% of accuracy under a wide range of processing conditions and material families.

The consequence of MAF technique on surface unevenness is due to combined influence of magnetic field, abrasive particles, relative movement, and nature of work material. By optimizing these parameters, performance can be enhanced for different applications. In this work, UA-MAF application on the polished zinc plates is evaluated. The main control parameters were magnetic field intensity, the frequency of vibration, type of abrasive and finishing time. Ultrasonic vibration was shown to enhance finishing rate, surface quality with an increase efficiency.

METHODOLOGY

Slurry Preparation

In MAF process, Flexible Magnetic Abrasive Brush (FMAB) is prepared by blending iron powder (Fe) and alumina powder (Al_2O_3). This combination is critical for achieving suitable and smooth SR.

Each of these elements performs upon a specific action in finishing. Since the iron powder is ferromagnetic material, it will directly react to the external magnetic field. And this gets aligned with the lines of magnetic force, resulting in a semi flexible brush called FMAB. This brush is designed to support the abrasives and adapt to the workpiece. On the other hand, alumina powder (Al_2O_3) is a non-magnetic material with several sharp edges that perform cutting & polishing action. When it is mixed with iron powder, it can be used to eliminate surface imperfections and obtain the desired surface finish. Ultrasonic vibration enhances the FMAB flexibility ensuing in a uniform exclusion of material from the workpiece. Slurry obtained through mixing of Nitric acid (2.5 ml), alumina (5 g), hydrogen peroxide (2 ml) and distilled water (50 ml) assists in minimising friction, cooling the reaction medium and preventing zinc oxidation which leads to enhanced material removal.

Experimental Framework and Procedure

Figure 1 shows the experimental set-up with parts including a machine spindle, the polishing-tool, Flexible Magnetic Abrasive Brush (FMAB), vibrating platform and a machine bed for providing feed rate. The polishing tool is a 25 mm thick aluminium cylinder, having disc magnets which form a stack inside the cylinder and generates the necessary magnetic field in the polishing zone. The FMAB is formed on the polishing tool and composed of 60% of iron and 40% of alumina particles. Additional iron stacks are placed under the polishing plate to enhance the magnetic field. The zoomed-in view depicts the zinc workpiece, polishing tray, iron block, vibrator, spring and earthing wire. The earthing wire is provided to prevent blacking of Zn surface due to formation of eddy currents and emf, generated when the tool is revolved. These undesired currents oppose the external magnetic field and can destabilize the FMAB, leading to destruction. The earthing wire drains unwanted current.

The workpiece in this experiment is a 150 mm × 50 mm × 2 mm zinc plate having initial SR of 0.291 μ m. It is clamped tightly on the polishing tray during machining operation. When tool rotates, the FMAB also rotates and tangential cutting force act on abrasive which gradually grinds material from the Zn surface. Large iron particles produce more weight (downward pressure) on alumina abrasive which leads to greater penetration and better surface finish. Continuous slurry is provided after every 5 min to regulate the amount heat produced due to relative motion between workpiece and FMAB.

Initial Experimental Observations

The process conditions used in the present work were optimized using the Design of Experimentations (DOE) method along with Response Surface Method (RSM). Some of the key findings are summarised in Table 1

Table 1. Initial experimental observation.

Parameter	Range tested	Observations	Optimal range/condition
Polishing Speed	250 – 1250 rpm	< 500 rpm - poor removal, high SR.	500 – 1250 rpm for smooth, consistent finish.
		> 1250 rpm - uneven material removal.	
Working Gap	6 – 8 mm	Proper gap essential for stable magnetic field formation and accurate material removal.	6 – 8 mm maintained for high-quality surfaces.
Feed Rate	1.5 – 5.5 mm/sec	< 1.5 mm/sec - excessive abrasion and scratches.	1.5 – 5.5 mm/sec for balance of efficiency and quality.
		> 5.5 mm/sec - poor removal efficiency.	
Pulse on Time	1 – 5 minutes	Short times: shallow indentation, inadequate removal.	Moderate duration (within 1–5 min) for consistent finish.
		Long times - deep indentations, risk of over-finishing.	

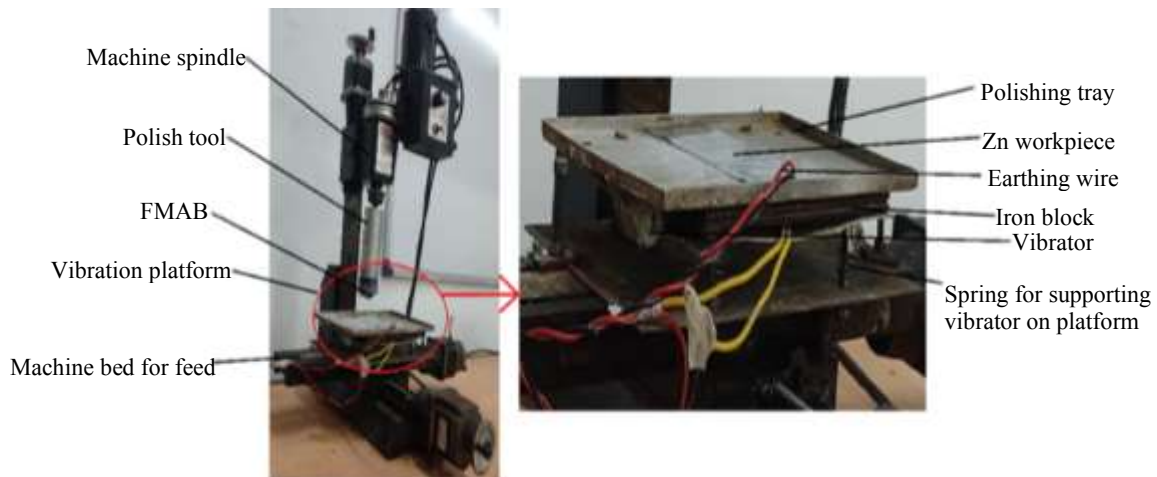


Figure 1. SPMAF experimental setup.

Table 2. Process parameter details.

Signs	Explanation	Low Level	High Level
X1	Tool speed (RPM)	250	1250
X2	Working Gap (mm)	4	6
X3	Feed rate (mm/s)	1.5	5.5
X4	Pulse on time	1	5

Table 3. Measured the value of SR of zinc workpiece for each experimental trial.

Exp. No.	FMAB Speed (RPM)	Working Gap (mm)	Feed rate (mm/s)	Pulse on time(min)	SR (μm)
1	250	4	5.5	5	0.171
2	250	4	1.5	5	0.160
3	250	6	5.5	5	0.169
4	250	4	1.5	1	0.167
5	1250	4	1.5	1	0.143
6	1250	4	5.5	5	0.141
7	1250	6	5.5	5	0.146
8	1250	6	1.5	1	0.150
9	250	4	5.5	1	0.174
10	1250	6	1.5	5	0.147
11	250	6	1.5	5	0.168
12	250	6	1.5	1	0.175
13	1250	6	5.5	1	0.149
14	1250	4	5.5	1	0.142
15	250	6	5.5	1	0.170
16	1250	4	1.5	5	0.140

Planning of Experiment

The experiment utilized key process parameters—tool speed, working gap, workpiece feed rate, and pulse-on time—following L-16 factorial design to evaluate the SR of a zinc workpiece. Table 2 outlines the experimental strategy, specifying selected parameters and their levels. SR measurements were taken using a Mitutoyo tester, capturing data across a 2 mm transverse length with a 0.08 mm cut-off. The recorded roughness values for each trial, presented in Table 3, offer insights into the process's effectiveness

Table 4. Analysis of variance for response.

Source	DF	Adj. SS	Adj. MS	F	p	Remark
Model	11	0.02650	0.000241	481.82	0.00	$F_{(0.05,11,4)}^{standard} = 5.93$ $F^{model} = 481.82$ $F^{model} > F_{(0.05,11,15)}^{standard}$ $\Rightarrow 481.82 > 5.93$ The statistical model for the SR is accurate
Linear	04	0.002540	0.000635	1270.00	0.00	
X_1	1	0.002401	0.002401	4802.00	0.00	
X_2	1	0.000081	0.000081	162.00	0.00	
X_3	1	0.00009	0.00009	18.00	0.013	
X_4	1	0.000049	0.000049	98.00	0.001	
2-Way interaction	5	0.000081	0.000016	32.40	0.002	
$X_1 \times X_2$	1	0.000016	0.000016	32.00	0.005	
$X_1 \times X_3$	1	0.000016	0.000016	32.00	0.005	
$X_1 \times X_4$	1	0.000004	0.000004	8.0	0.047	
$X_2 \times X_3$	1	0.000036	0.000036	72.00	0.001	
$X_3 \times X_4$	1	0.000009	0.000009	18.00	0.013	
3-Way interaction	2	0.000029	0.000015	29.00	0.004	
$X_1 \times X_2 \times X_3$	1	0.000004	0.000025	50.00	0.002	
$X_1 \times X_3 \times X_4$	1	0.000004	0.000005	8.00	0.047	
Error	4	0.0000002	0.000000			
Total	15	0.002652				

Analysis of Experimental Data

An L-16 factorial design was utilized in Minitab 17 to carry out experiments. A linear model was applied within this design framework, leading to the development of Response Equation 1. The regression equation derived from the model analysis is presented as Equation 2

$$SR (\mu\text{m}) = \alpha_o + \sum_{i=1}^n \beta_i x_i + \epsilon \tag{1}$$

In this study, SR (μm) signifies the SR of the zinc workpiece, while n represents the number of process parameters. The coefficient β_i defines their influence, x_i denotes the linear terms of process variables, and ϵ accounts for random error. Experimental data were analysed through Analysis of Variance (ANOVA), with Table 4 presenting the ANOVA results for SR. To further explore process parameter effects on MRR, a multivariable regression equation (Equation 1) was formulated. A strong correlation was observed between SR (μm) and process parameters (X_1, X_2, X_3, X_4), with an adjusted R^2 of 99.72% at a 95% confidence level and a minimal error of 0.

$$SR (\mu\text{m}) = 0.14584 - 0.000013X_1 + 0.006656 X_2 + 0.008437X_3 - 0.002563X_4 - 0.000002X_1X_2 + 0.000006X_1X_3 + 0.000001X_1X_4 - 0.001687X_2X_3 + 0.000375X_3X_4 + 0.000001X_1X_2X_3 - 0.000000X_1X_3X_4 \tag{2}$$

RESULT AND DISCUSSION

Figure 2(a) demonstrates the relationship between polishing speed and SR. As the polishing speed rises, SR decreases, resulting in a smoother surface. This is because higher speeds increase the material removal rate (MRR) by generating stronger tangential cutting forces on the abrasive particles, which efficiently shear off surface irregularities such as hillocks. Figure 2(b) shows that increasing the working gap leads to higher SR values, indicating a decline in surface finish quality. This implies that smaller working gaps are more effective for polishing zinc, as they allow the magnetic abrasive particles (MAPs) to apply greater indentation pressure. A narrower gap strengthens the magnetic field, enabling more controlled and precise material removal. In contrast, a larger gap weakens the magnetic force, leading to reduced cutting effectiveness and increased roughness. Figure 2(c) depicts the influence of workpiece feed rate on SR. As the feed rate goes up, SR also increases.

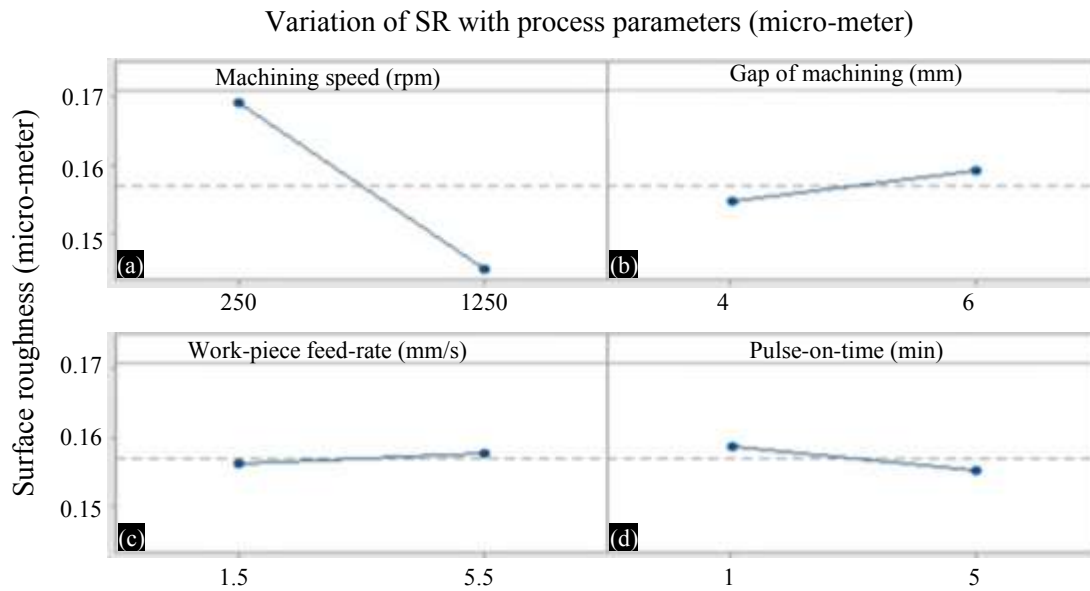


Figure 2. The main effect plot and the outcomes from the optimization analysis are presented.

This can be attributed to the tangential cutting action of the FMAB tool and the rapid movement of the workpiece, which together cause uneven shearing of surface peaks. These results highlight the rank of maintaining an optimal feed rate to achieve a uniform and smooth finish. Figure 2(d) illustrates how pulse on time impacts SR. With longer pulse durations, the abrasive elements penetrate deeper inside the surface, increasing material elimination rates. As a result, the surface becomes smoother, confirming that extended pulse on time contributes to improved surface finish

INTERACTION BETWEEN PROCESS PARAMETERS

Effect of interaction amid Tool-Speed and Working-Gap

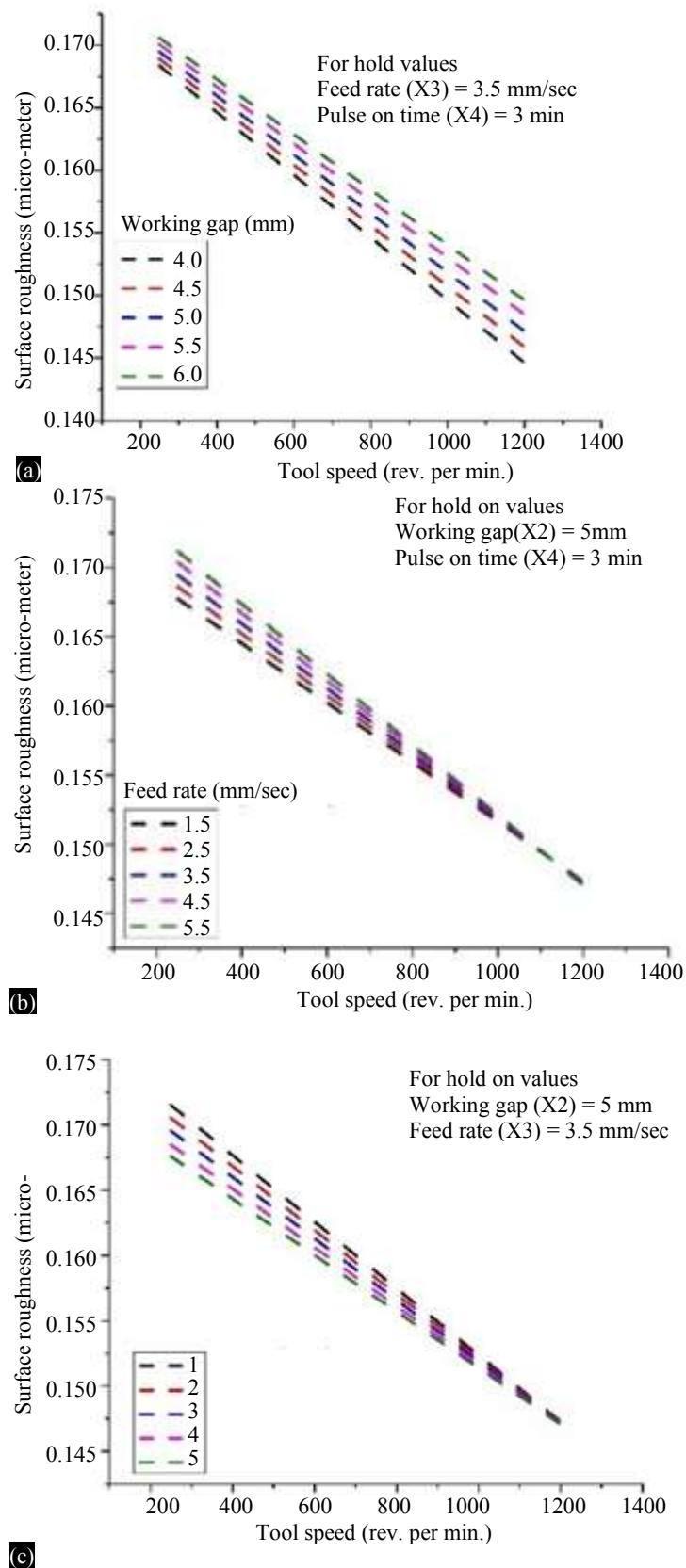
When the working gap is small ($X_2 = 4$ mm), increasing the polishing speed results in a noticeable decrease in SR, as illustrated in Figure 3(a). This improvement can be attributed due to the stronger magnetic region generated in the narrow gap between the revolving magnetic tool and the workpiece. The higher magnetic flux concentration pushes the abrasive particles downward more effectively, leading to deeper penetration into the workpiece surface. As the tool rotates, these particles perform a tangential cutting action that enhances the material removal rate, thereby producing a smoother surface finish.

Effect of interaction amid Tool-Speed and Workpiece Feed-Rate

At lower polishing speeds ($X_1 = 250$ rpm), an increase in the workpiece feed rate tends to enhance surface finish, as shown in Figure 3(b). This improvement occurs because the tangential cutting forces generated by the FMAB effectively activate the abrasive grains to remove surface irregularities in a controlled manner. However, at higher polishing speeds ($X_1 = 1250$ rpm), increasing the feed rate results in poorer surface quality. This is attributed to the intensified cutting action per abrasive grain, which causes aggressive and less controlled material removal. On the other hand, lowering the feed rate at high polishing speeds increases the contact duration between the FMAB and the workpiece, allowing for more refined abrasion and yielding a smoother surface.

Interaction amid Tool-Speed and Pulse on Time

Figure 3(c) illustrates that when pulse-on time is extended alongside higher tool speeds, the abrasive particles create deeper indentations on the workpiece. This enhances the material removal rate (MRR), resulting in a superior surface finish.



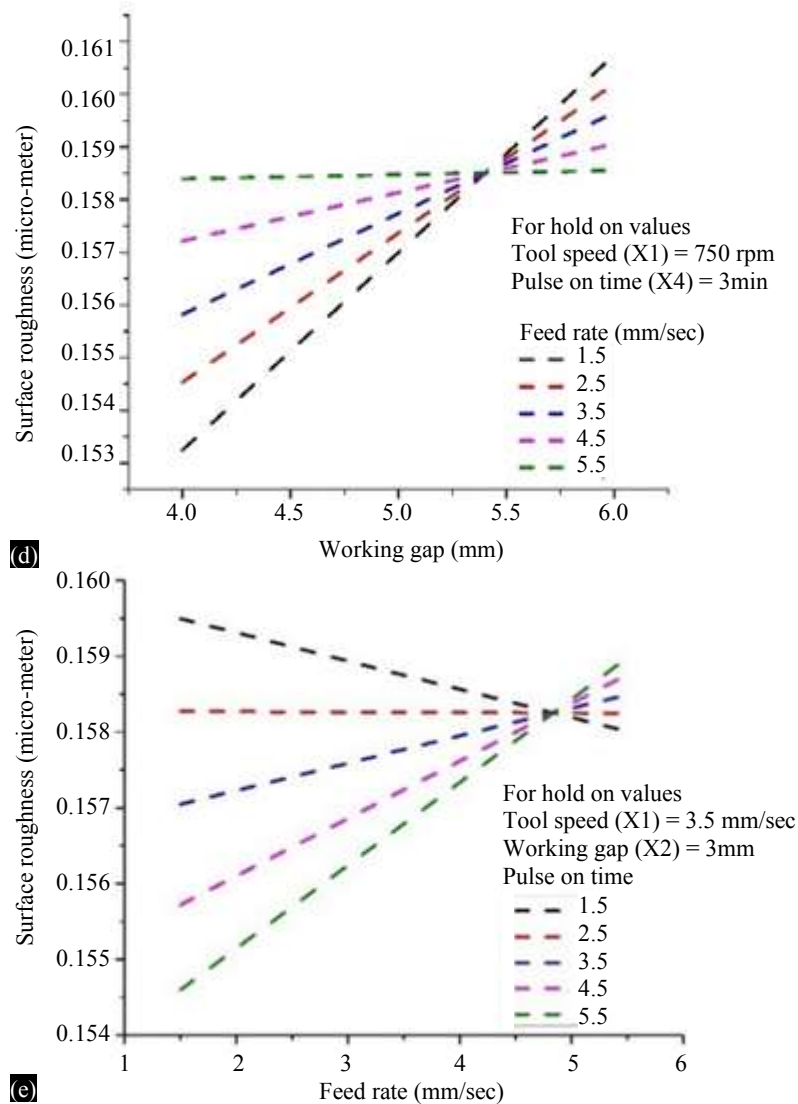


Figure 3 (a). Tool speed- working gap; (b) Tool speed-feed rate; (c) Tool speed- pulse on time. (d) Working gap-feed rate; (e) Feed rate-pulse on time; Interaction between process parameters.

Interaction amid Working Gap and Feed-Rate

Figure 3(d) shows how the working gap interacts with the feed rate. At lower feed rates, a larger gap tends to increase SR due to a weaker magnetic field between the tool and the workpiece, which lowers the force applied by the abrasive particles and leads to a rougher surface. However, at higher feed rates, even with a wider gap, the enhanced tangential cutting action slightly improves the surface finish.

Interaction amid Workpiece-Feed-rate And Pulse on Time

As shown in Figure 3(e), at lower pulse on times, increasing the feed rate enhances the surface finish. This is likely because the combination of a higher feed rate and tool speed increases the indentation force, leading to more effective polishing. However, this trend reverses when pulse on time is extended. The likely reason is that the combined influence of a longer pulse duration and high feed rate causes uneven material removal, resulting in a deteriorated surface finish.

Optimization of Objective Functions

Using response surface optimizer available with Minitab subjected to following constraints

$$250 \leq X_1 \leq 1250; 4 \leq X_2 \leq 6; 1.5 \leq X_3 \leq 5.5; 1 \leq X_4 \leq 5 \tag{3}$$

Table 5 presents the comparison between theoretical and experimental values of SR determined at the optimal process parameters. These results were derived from the Minitab optimization output, as illustrated in Figure 4.

Table 5. Validation of theoretical and experimental SR at optimum process parameters.

FMAB speed (X_1) in rpm	Working Gap (X_2) in mm	Feed rate(X_3) in mm/s	Pulse on Time (X_4) in min	SR from model equation (μm)	Experimental SR (μm)
1500	6	1.5	5	0.140	0.140

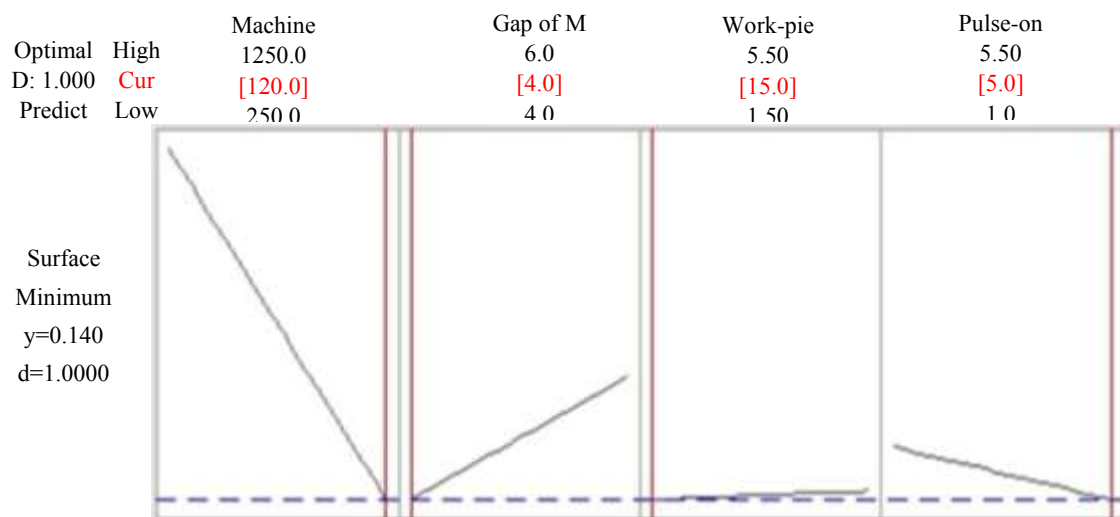


Figure 4. Minitab screen shot of optimized SR at optimized parameters.

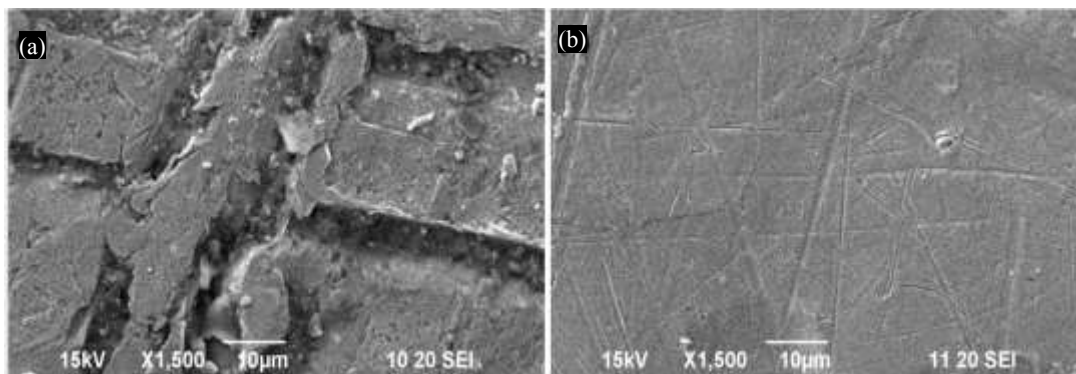


Figure 5. SEM images (a) Unpolished zinc plate; (b) Polished zinc plates.

Surface Morphology

Figure 5(a) illustrates the untreated sample, revealing a fractured surface characterized by deep cracks, irregular fragmentation, and a highly uneven texture with noticeable variations in depth. Additionally, small bright particles along the edges of the cracks suggest the presence of debris or exposed inclusions. In contrast, Figure 5(b) depicts the surface after polishing, which appears significantly smoother. The surface shows fine, shallow scratches or directional lines, indicating wear or polishing effects, and overall presents a much more refined appearance compared to the unpolished sample.

CONCLUSIONS

- (a) *Effect of tool speed:* An increase in FMAB speed results in greater friction between the abrasive particles and the workpiece, which in turn elevates the contact temperature.

- (b) Influence of working gap: A smaller gap between the FMAB and the workpiece generates more friction, resulting in higher contact temperatures, whereas a wider gap decreases friction and thus reduces the temperature.
- (c) Variation in feed rate: Slower feed rates prolong the contact duration between the FMAB and the surface, causing higher contact temperatures. Conversely, faster feed rates minimize interaction time and help maintain lower temperatures
- (d) Pulse on time: A longer pulse on time contributes to improved surface finish by enhancing the indentation effect of abrasive particles.
- (e) Optimized process parameters: Under optimal conditions, a SR value of 0.14 μm was achieved, indicating high finishing quality.
- (f) Surface morphology: Polishing significantly enhances the zinc surface by replacing deep cracks and irregularities with fine, shallow abrasions.

These results contribute to the refinement of the Magnetic Abrasive Finishing (MAF) process, aiming to improve machining efficiency and achieve better SR

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
MAF	Magnetic Abrasive Finishing
SPMAF	Single Pole Magnetic Abrasive Finishing
FMAB	Flexible Magnetic Abrasive Brush
CMP	Chemical Machining Process
MRR	Material Removal Rate
SEM	Scanning Electron Microscopy
UAMAF	Ultrasonic Assisted Magnetic Abrasive Finishing
MAP	Magnetic Abrasive Powder
VAMAP	Vibration-Assisted Magnetic Abrasive Polishing
P-EMAF	Pulse Electrolytic Magnetic Abrasive Finishing
UAMAFM	Ultrasonic-Assisted Magnetic Abrasive Flow Machining
HMMC	Hybrid Metal Matrix Composite
ANOVA	Analysis of Variance
DF	Degrees of Freedom
SS	Sum of Squares
MS	Mean Square
F	F-ratio (statistical significance)
p	p-value (significance level)
X_1	FMAB Speed (Revolutions per Minute - RPM)
X_2	Working Gap (Millimetres - mm)
X_3	Feed Rate (Millimetres per Second - mm/s)
X_4	Pulse-on Time (Minutes - min)
mg/min	Milligrams per Minute (unit of MRR)
β_i	Regression Coefficient (in model)
ε	Term / Random Disturbance
Ra	Surface Roughness (Micrometres - μm)
$^{\circ}\text{C}$	Temperature (Degrees Celsius)
n	Number of Process Parameters

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