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Research Article

Surface roughness evaluation of copper material processed by single pole magnetic abrasive finishing process: A statistical factorial design study

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ABSTRACT

This study focuses on the enhancement of surface finish quality for copper material workpiece using a superfinishing technique based on single-pole magnetic abrasive finishing with and without the assistance of chemically aided oxidizers. Achieving ultra-smooth copper surfaces is significant for applications in electronics, optics, and precision tooling, where surface integrity plays an important role. A systematic investigation was carried out using a factorial design of experiments to evaluate the influence of key process parameters i.e., polishing speed, feed rate, and working gap viz. for dry and chemically aided conditions. Surface roughness was measured as a response variable. Results indicate that the introduction of chemical oxidizers in the chemically aided conditions significantly improved finishing performance, achieving a minimum surface roughness of 0.0166 µm, compared to 0.0621 µm in dry conditions. Analysis of variance revealed strong interaction effects among process variables, particularly between polishing speed and working gap. Scanning Electron Microscopy confirmed the improvement in surface morphology and uniformity under optimized conditions. This work advances beyond previous efforts signifying the contribution of newly induced finishing process called single-pole magnetic abrasive finishing by establishing the effect of chemical assistance in the finishing of copper workpiece.

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INTRODUCTION

Magnetic abrasive finishing process contains a mixture of ferromagnetic iron particles and abrasive of different mesh number to form a brush and utilizing a magnetic field to perform material removal from the workpiece at micro level to achieve superfinishing characteristics. The past literature suggest that complex geometries has been successfully

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addressed with the application of MAF process. The process parameters like magnetic field strength, particle size of abrasives, rotational speed, machining timing, working gap and their influence on finishing accuracy, material removal rate and surface roughness have been successfully studied by various researchers. In the present study a new variant tool in form of single pole magnetic abrasive finishing process with specific application to pure copper workpiece with simultaneous impact of chemical oxidizers considering Polishing speed, working gap and longitudinal motion of workpiece on surface roughness have been systematically analysed to address the real time monitoring of surface quality during a finishing process. Copper has versatile use in industrial applications as well as engineering design due to its light weight as well as its favourable properties such good conductor, resistance to corrosion, good reflector etc. Humans have utilized it for thousands of years, beginning with ancient civilizations. Copper is crucial in modern society due to its application in electrical systems, renewable energy technologies, and infrastructural development. Recently they are used in electric vehicles (EVs), solar panels, wind turbines, and other green technologies is fast increasing advancements, making it an essential component in the transition to a more sustainable future. Furthermore, copper's recyclability enhances its environmental significance, as recycled copper requires substantially less energy to create than primary copper. Copper's distinct qualities and broad applications make it one of the most valuable and indispensable metals in modern engineering and industry. The recent developments have created new uses for copper in high-speed internet connectivity and data transmission. Copper's electrical properties are crucial in the networking infrastructure, particularly in fibre optics and antennas. Copper's demand in data transfer networks is expected to grow globally due to its inherent properties and recyclability. Copper remains one of the most crucial metals of the modern era due to its unmatched electrical and thermal conductivity, recyclability, and versatility. Recent developments, especially in green technologies, electric vehicles, and telecommunications, have further cemented copper's importance in global industries. As the world pushes toward a sustainable future, copper's demand will continue to grow, supported by innovative applications, efficient recycling methods, and advancements in cutting edge technologies. It makes it very useful in handling for some of its uses in defence sector as well as in aerospace industries. To be very precise, they are used and applied for the communication networks and also used as antennas as laser beam reflecting mirror. They can be used as focussing as well as reflecting mirrors to generate the signal intensity. Copper can also be employed for testing and calibration of optical systems which is used in defence equipment for their accuracy. The surface finishing of the copper material is indeed important due to its versatile application. The advancement in finishing application of copper material is thus important for improving the surface topographical variations. In this direction chemical assisted finishing process is applied on single pole magnetic abrasive finishing and is used in the present work to finish and obtain high surface accuracy with minimum topographical variations to enhance the wide applications of copper material in various industries. Chemical mechanical polishing (CMP) has gained popularity, since it combines chemical etching with mechanical abrasion to create better surface planarity and low defectivity. Studies have shown that adjusting CMP process parameters such as abrasive type, slurry composition, and applied pressure can greatly improve copper surface polish while limiting corrosion and dishing effects [1]. Precision component finishing to specifications is a time-consuming and complex production process. Traditionally, pre-machined surfaces undergo various finishing procedures such as grinding, superfinishing, and honing with hard tools. Due to the lack of tool flexibility, these methods not only have intrinsic limitations in finishing complicated surfaces, but they can also cause surface damage. To overcome these challenges, numerous attempts were done in the past for various machining and finishing procedures. Non-traditional finishing methods often have flexible abrading mediums and can finish complicated surfaces. Magnetic abrasives combined with abrasion grits in a paste or fluid medium may give the necessary ideas and ability to smoothen complicated surfaces [2]. Magnetic abrasive powder used under a magnetic zone or abrasive particles used on fluidized bed are effective finishing mediums. To create abrasive powder for magnetic field aided finishing, abrasive powder along with pure iron powder are mixed together and applied for finishing process of complicated surfaces [3]. A flexible abrasive brush of magnetic nature is used under a magnetic field to polish the surface. The magnetic field will be varied by adjusting the current flow, which ultimately is used as force used for finishing the surface. The particles are placed along magnetic lines to create a flexible magnetic abrasive brush (FMAB) is serving as a multi-point cutting tool and as the brush rotates, this FMAB removes microchips from the surface to be polished, thereby resulting in a finished workpiece. MAF has a significant impact in the area of generating for high-quality finished and mirror-like surfaces from basic to complicated surfaces and is widespread use in industries.

A continuous design has been done using various methods and designs for planarizing the complicated surfaces. In some systems, complicated surface is being finished while coupled with the vibratory motion as well as rotation of the workpiece and is transmitted to the poles used or the yoke bearing the magnetic poles. Magnetic abrasives can be used to polish flat surfaces in a different arrangement [4,5]. Magnetic lines of flux form chains of magnetic particles and used to grasp the abrasives to polish the surface. Magnetic abrasive finishing (MAF) [6] is a magnetic field-assisted finishing procedure designed for nano-finishing of the surface. Superfinishing of non-ferrous materials with magnetic fields remains challenging due to their lower relative permeability compared to ferrous materials [7]. Jha and Jain

[8] performed abrasive mixed with magnetorheological fluid (MR fluid) flow machining with the goal of efficiently managing the finishing qualities by altering the magnetic intensity. In another arrangement, Seok et al. [9] used MR fluid along with abrasives on the surface of the workpiece to be superfinished by applying pushed up and down the flat surface. MR fluid alone was used to fabricate and polish curved silicon-based microstructures. Girma et al. [10] had done experimental analysis for planarizing with the help of MAF. They had given an idea of MAF process for polishing the surface. Sadique A et al. had developed magnetorheological abrasive honing (MRAH) setup and made experiments on austenitic stainless-steel and Aluminium for surface finishing by the equipment keeping in mind the effect of workpiece rotation, initial roughness, and duration time for finishing. They had observed improvement in finishing surface with higher workpiece rotation and at the same time a decrement in roughness in consistent with duration time [11]. Jain V. K. et al. had developed a new process named as chemo-mechanical magneto-rheological finishing (CMMRF) for finishing surface of silicon workpiece. They used two techniques i.e. chemical mechanical polishing (CMP) as well as magneto-rheological finishing (MRF) for the process. They found that by using this method they were able to finish the workpieces with minimum defects, nano-finishing and also increase in material removal rates [12]. Bissey-Breton S.et al. made a model and applied on pure copper to calculate temperature, residual stress and dislocation on the finished material after superfinished turning of copper. They included structural evolution, thermal-mechanical and dynamic recrystallisation method for their model and found a good agreement on the numerical as well as experimental data [13]. Ranjan P.et al. had used hybrid finishing process named as chemo-mechanical magnetorheological finishing (CMMRF) for finishing operations on metals. After studying the variables, analysing and optimizing, they found better copper alloy surface finish. They found as the pH values of the chemical slurry decreases, then surface finishing increases. It happened only at certain level after that surface finishing starts decreasing. For the better result for surface finishing, pH value plays critical role [14]. Khan et al. [15] had used ball end magnetorheological finishing (BEMRF) process over ferromagnetic material and copper through magnetic simulation. They found through magnetic simulation that when copper was placed on a mild steel base, then there is slight improvement in flux density improves, which was used to finish the copper surface [15]. Maciag T.et al. had found the time required and the optimal current required for conducting electropolishing process for improvement of surface micro-geometry. They discovered that the experiment allows optimizing the current parameter for the electrochemical polishing process for non-ferrous materials [16]. Kansal H. et al. had used magnetorheological technique for diamagnetic materials surface finishing. They have used Two permanent magnets, filled with magnetorheological polishing fluid in the gap, rotated over surface of diamagnetic material and creating good surface finish [17]. Khan D. A. and Jha S. had found an optimum fluid composition named as magnetorheological polishing (MRP) fluid. They used fluid along with magnetically stiffened ball shaped mixed tool, named electrolytic iron powder (EIP) based fluids for finishing of soft material like copper. They found that type of material selection for polishing gives the direction of preparation on MRP fluid composition [18]. Qian C.et al. had done critical review on magnetic abrasive finishing (MAF) for different parameters such as magnetic abrasive preparation, principles of MAF, various tools for MAF, modelling, simulation, characteristics of finished surface and various challenges faced. They also covered some optimal processing parameters for better surface finishing processes. They had given idea of future directions [19]. Pineiro et al. had used two oxidizers, potassium peroxydisulphate ($K_2S_2O_8$) and Oxone for pH-value and chemical effect on surface finishing of silicon wafers for better material removal rate (MRR). They found that use of oxidizers improves surface finishing quality, if there is lower surface roughness and MRR value. MRR falls at lower concentrations of oxidizer. Decreasing pH and MRR is implied by increasing oxidizer content [20]. Guo, X. et.al. had studied about chemical effects of glycine and H_2O_2 on copper. They had found that copper atoms on upper surface weakens under the action of glycine and H_2O_2, which was beneficial to the metal removal. Under the pure water case, the removal rate was lower as compared to the solution used as glycine plus aqueous H_2O_2 during chemical mechanical polishing (CMP). Thus, they provided an idea to choose and make CMP slurry preparation for better metal removal from copper surface [21]. Ghosh G. et.al. had conducted theoretical and experimental research on residual stress and surface roughness for copper in oxygen free high conductivity (OFHC) under magnetorheological finishing (MRF). Wheel speed, gap and rate of feed were chosen variables to observe variations in surface roughness, tangential force and residual stress. They observed that in MRF process, a good surface roughness with decremental residual stress could be achieved with lower speed, lower feed rate, higher working gap [22]. Babbar, A. et.al had used grey relational analysis to optimize the magnetic abrasive finishing process. They found how different process factors affected the material removal rate (MRR) and surface roughness during the finishing. They used a combined approach of Taguchi technique and grey relational analysis to find out the optimum solution [23]. Pandey et al. had done a thorough review on silicon wafer to find out different finishing processes used. They had studied about different experimentation used for various finishing processes, recent developments and related mathematical modelling used for the processes [24]. Sharma et al. had recently done an experiment on surface finish over silicon wafer with single pole magnetic abrasive finishing using chemical oxidizers and alumina slurry. They found satisfactory result for

surface roughness values from the experimental data over the silicon wafer [25]. Sharma et al. had done the experimental analysis on silicon wafer to forecast the roughness by making use of a fuzzy model that is part of the MATLAB toolbox. The experimental data obtained, and derived model had closely matched with a slight deviation of 8.70%. Using SEM Images, they expanded the investigation for surface morphology of unpolished as well as polished surfaces. Under optimized case, defect free surfaces could be seen for polished surfaces [26]. Ergene B. and Bolat Ç. had done a review on the recent investigation trends in abrasive waterjet cutting and turning of hybrid composites. They compiled recent studies from technical literature to provide inclusive overview of methods feasibility and potential specially for abrasive waterjet cutting and also for abrasive waterjet turning with a goal to clarify the intricacies of the process and the effects of key input parameters such as water pressure, traverse speed, abrasive flow rate, standoff distance, and abrasive particle size [27]. Gupta S. K. and Rathore V. had done a review on nanofluid lubrication as a cutting fluid in machining operations. They reviewed and explored the current state of nanofluid lubrication in machining, covering synthesis methods, nanoparticle types, and their impact on cutting forces, tool wear, surface finish, and overall machining performance. They had discussed about the challenges and future prospects of implementing nanofluids in different machining processes [28].

This study introduces a novel single pole magnetic abrasive finishing technique with chemical assistance to evaluate the surface roughness of pure copper under both dry and wet finishing conditions. Key parameters such as polishing speed, working gap, and feed rate are explored, which have not been reported in previous literature. The research emphasizes the role of chemically assisted slurry in improving surface texture, which is critical for enhancing copper's electrical, thermal, and mechanical properties. This method aims to meet the durability and performance standards required in modern industrial applications, highlighting the significance of precise surface roughness assessment. Further to improve the process efficacy, the parameter optimization using response surface methodology based on design of experiments can be explored. The investigation of hybrid single pole magnetic abrasive finishing process with ultrasonic assistance utilizing the influence of chemical oxidisers can be investigated to improve the surface finishing of pure copper workpiece.

PRELIMINARY EXPERIMENTAL OBSERVATIONS

In the present investigation dry and wet polishing of copper material was carried out on the SPMAF experimental framework. A total of eight preliminary experiments were designed using factorial design available with MiniTab17 software for the two cases i.e. Dry and Wet polishing. The experimental data obtained was used to investigate how process parameters behaved with surface roughness. The polishing speed between 500 and 1500 rpm was taken into consideration. According to preliminary testing, the workpiece's hillocks could not be sheared off at speeds lower than 500 rpm, which resulted in poor roughness. Also, FMAB disintegrated at polishing rates greater than 1500 rpm. So, the range for the speed is chosen to be 500 rpm to 1500rpm. The workpiece feed rate between the range of 1.5 mm/sec and 5.5 mm/sec was taken. This range was chosen because feed-rate less than 1.5 mm/sec increased the duration that abrasive particles are in touch with the copper workpiece and thus increases the frictional force between them. This makes more erosion as well as uneven scratch marks over the finished workpiece. However, feed rates greater than 5.5 mm/sec drastically reduces contact duration between the workpiece and finishing tool, which decreases MRR and gives a poor surface finish. A working gap of 6 mm to 7 mm has been maintained between the workpiece and the finishing tool. Now a magnetic field has been generated between the copper workpiece and finishing tool, which in turn creates magnetic flux density and causes of polishing on the copper surface.

EXPERIMENTAL FRAMEWORK AND PROCEDURE

Polishing a copper was done on the experimental equipment shown in Figure 1(a). An unpolished (cut and lapped) copper workpiece measuring 100 mm by 100 mm is taken with a thickness of about 2 mm is chosen for the experimental work.

A tool with a single pole magnet is used for this experiment. A magnet having 25mm diameter disk (NdBFe) is chosen for the polishing machine's tool design. An inner cylindrical hole is used to insert the magnetic disk. As per the strength of magnetic field required, a number of magnetic stacks in the aluminium cylindrical holder are chosen to polish copper. The machine's moving platform will have an iron block installed, which is composed of a number of iron plates and providing the workpiece feed for polishing. The workpiece is positioned between the single pole magnet and iron block, and tool is mounted on computer operated miller machine. Between work piece and the pole, a brush is formed to carry out the polishing activity. This is accomplished by employing the magnetic field produced by single pole magnets and the iron block. To facilitate the material's simple removal, chemical solution would be put on the copper surface to create an etching action. While FMAB is displayed in Figure 1(b), which shows how magnetic abrasive particles (MAPs), composed of 60% iron particles and 40% alumina, are combined to generate FMAB. The experimental configuration is shown in Figure 1(a). The rotatory motion of FMAB in tandem with the magnet remove the uneven peaks on the copper workpiece due to the magnetic field generated. The peak can be removed from copper surface with the help of formation of abrasive particle's continuous chain, that is produced by

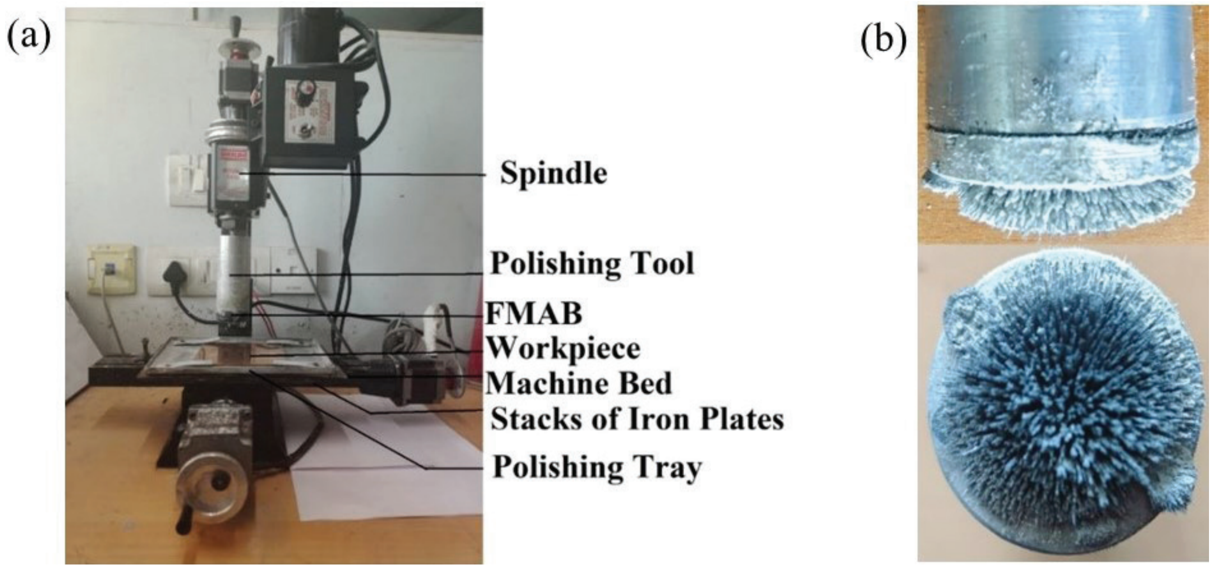


Figure 1. (a) Experimental setup (b) FMAB.

the enhanced magnetic flux-density. Alumina slurry along with chemical solution pass through the working gap while polishing. Roughness value was manually taken by surface roughness tester (Mitutoyo SJ-201) after completion of the polishing process, which takes a completion cycle of a total of 60 minutes duration. The surface roughness measurement is important to examine because it describes the surface finishing behaviour of the polished copper surface under various trials.

EXPERIMENT TRAILS

Eight trials, one for dry polishing and one for wet polishing, were carried out using variables including working gap (mm), polishing speed (rpm) and feed rate (mm/sec). Alumina abrasive with a mesh size of 1200 was used throughout the entire experiment. Alumina abrasive and iron particles were mixed in 40:60 ratio to form MAPs, which were used to create FMAB between iron block and the magnet. For experiment, slurry with a pH of 12.26 was selected (For wet experiments only). Chemical slurry was prepared using 100ml distilled water mixed with 5gm sodium hydroxide pallets, 1.5ml Hydrogen peroxide solution and 1.5gm Potassium persulphate along with 10gm Alumina abrasive. Table 1 shows the data from experimental trials for polishing under dry condition (without slurry). Whereas, Table 2 illustrates the experimental trials for the polishing under wet condition (with slurry). A surface roughness tester was used to record the surface roughness after each polished surface. Every trial lasted for 60 minutes. During the experimental trials, for dry polishing i.e. without the use of alumina mixed chemical oxidizers slurry, the surface roughness of finished copper material was obtained on the higher side and also there was black marks were observed on the finished surface due to temperature rise between FMAB and copper material. Whereas, for wet polishing i.e. with the use of alumina mixed chemical oxidizers slurry improved surface roughness for finished copper material. The factorial design based (L-8 array) experimental data for dry polishing has been presented in Table 1 The Table 2 represents the experimental obtained from wet finishing of copper workpiece.

MATERIAL REMOVAL MECHANISM

The combined application of mechanical polishing and oxidizer impact contributed to the material removal mechanism in attaining lower value of surface roughness. The simultaneous application of aforesaid processes was executed simultaneously to attain the finishing application. The slurry constituted by 100ml distilled water mixed with 5gm sodium hydroxide pallets, 1.5ml Hydrogen peroxide solution and 1.5gm Potassium persulphate along with 10gm Alumina abrasive, making altogether alkaline solution having pH of 12.26.The addition of aluminium hydroxide $Al(OH)_3$ in 100 ml distilled water attained the pH of solution around 8.16 was not preferred to be used as a slurry for polishing application due to formation of layer of hydration resulted due to chemical reaction with Al_2O_3. Addition of sodium hydroxide 5gm was further added to the mixture of alumina and distilled water, which resulted the slurry solution to achieve the alkaline state to a pH value around 12.36. The oxidizer Potassium persulphate of amount 1.5gm was added to the amalgamation of distilled water, alumina and sodium hydroxide to enhance the oxidizing power capability of copper atoms from the work specimen. At this stage the pH of slurry solution was around 12.41. Hydrogen peroxide(H_2O_2) 1.5 ml had been added to the solution to reach a pH value

Table 1. Data from experiment under polishing (dry condition)

Polishing speed (X_1) (RPM)	Working gap (X_2) (mm)	Feed-rate (X_3) (mm/sec)	Surface roughness (micro meter)
1500	7	1.5	0.0760
500	7	1.5	0.0780
1500	6	1.5	0.0621
1500	6	5.5	0.0680
500	7	5.5	0.0860
1500	7	5.5	0.0720
500	6	5.5	0.0790
500	6	1.5	0.0730

Table 2. Data from Experiment under polishing (wet condition)

Polishing speed (X_1) (RPM)	Working gap (X_2) (mm)	Feed-rate (X_3) (mm/sec)	Surface roughness (micro meter)
500	6	1.5	0.0185
1500	6	5.5	0.0168
500	7	1.5	0.0240
500	7	5.5	0.0270
1500	7	5.5	0.0179
500	6	5.5	0.0250
1500	7	1.5	0.0203
1500	6	1.5	0.0166

12.26, which formed the passivation layer and protect finished surface from attack of OH^- ions. Generally, the alkaline state of slurry solution with pH value between 12-12.5 is preferable to attain good polished quality surface [29]. The aforesaid chemistry for slurry helps to soften the surface of copper material which has to be polished by the SPMAF. Under the effect of a magnetic field, the FMAB imparts a moderate finishing pressure on the copper surface, while the iron particle exerts a force on the abrasive particle. Force exerted by the abrasive particle causes it to penetrate the contact surface of the copper without harming its base substrate.

The rotatory motion of the magnet pole having abrasive particles (1200 mesh size) causes the elimination of the peaks from the copper surface. Material is removed from the copper surface using microchips [30], which can be machined in the ductile mode to achieve nanometric surface level whereas the depth of cut may go to the nanoscale.

RESULTS AND DISCUSSION

The Figure 2(a) and Figure 2 (b) represents the main effect plot for dry and wet polishing of copper workpiece respectively. The data presented in Table.1 and Table.2 with the help of ANOVA analysis reveals that the value of surface roughness decreases as the polishing speed increases. The possible reason can be that as the speed increases the tangential cutting forces on the abrasive particles also increases which strikes off the peaks present on the copper workpiece effectively. Further as increase in working gap also increases value of surface roughness. This indicates that due to the increase in working gap the magnetic flux density in the finishing zone decreases as a result the downward force applied on the abrasive particle also decreases. As a result, the penetration of abrasive particle on the copper workpiece reduces and thereby reducing the tangential cutting force by the abrasive particle, which is not sufficient to remove the peaks present on the copper workpiece. Finally, the main effect plot highlights that as the feed-rate given to the workpiece increases the surface roughness of copper work piece also increases. The possible reason behind this variation could be due to uneven shearing of peaks from the workpiece resulted due to the torque of abrasives used from the integrated effect in increase of movement of the workpiece and thereby non uniform tangential cutting by FMAB on the contact surface.

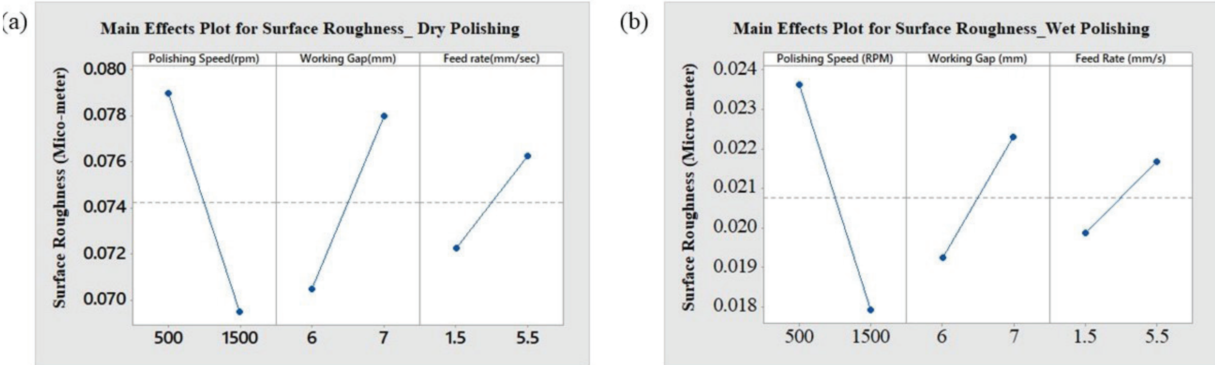


Figure 2. Main effect curve of process parameters for dry polishing and wet polishing.

Interaction Effects Among Process Parameters over Surface Roughness

The interaction effect gives the combined variation among the significant process parameters over the surface roughness. The interaction effect among the significant process parameters shows the impact of one process parameter on the depended level of the other parameter. The following are the interaction among parameters verses the output responses.

Interaction among polishing speed verses working gap for dry and wet finishing

The interaction effects between polishing speed and working gap for dry and wet polishing of copper material is shown in Figure 3 and Figure 4 respectively. The Figure 3(a) and Figure 4(a) illustrates the surface plot and interaction among polishing speed and working gap verses output experimental response (surface roughness). This have been also represented through a 2-D plot in Figure 3(b) and Figure 4(b) respectively**.** The interaction effect shows that minimum surface roughness is obtained when polishing speed increases with consecutive decrement in the value of working gap. The variation could be due to the magnetic field in the finishing zone is high at the smaller working gap, which maintains a strong chain between large sized iron particles and small sized abrasive particles. The strong bonded chain of MAP particles allows greater penetration by abrasive particles through the copper due to the downward force exerted by iron particles. The aforesaid phenomena are assisted by greater tangential force on the abrasive particles due to the high polishing speed given by the rotating tool containing FMAB.

Interaction among polishing speed and feed-rate verses surface roughness for dry and wet finishing

The interaction effects among polishing speed and feed-rate over surface roughness, which have been shown in Figure 5 and 6 for dry and wet finishing respectively. The surface plot of interaction among polishing speed and feed-rate over experimental response i.e. surface roughness in the Figure 5(a) and 6(a) for dry and wet finishing respectively. Also, there are 2-D plot, which are also represented in Figure 5(b) and 6(b) for dry and wet finishing respectively**.** The interaction effect reveals that high polishing speed with low feed-rate is preferred to obtain good quality surface i.e. low value of surface roughness of copper

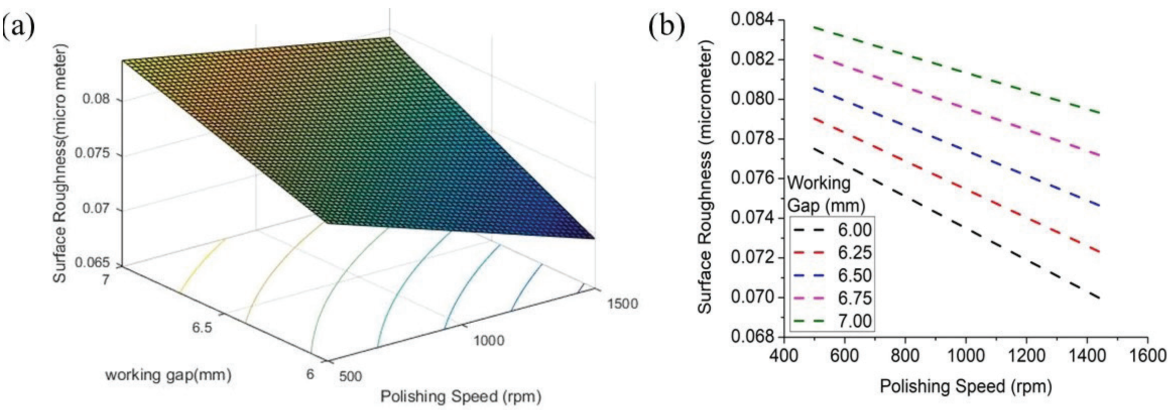


Figure 3. Interaction among polishing speed and working gap verses surface roughness for dry polishing.

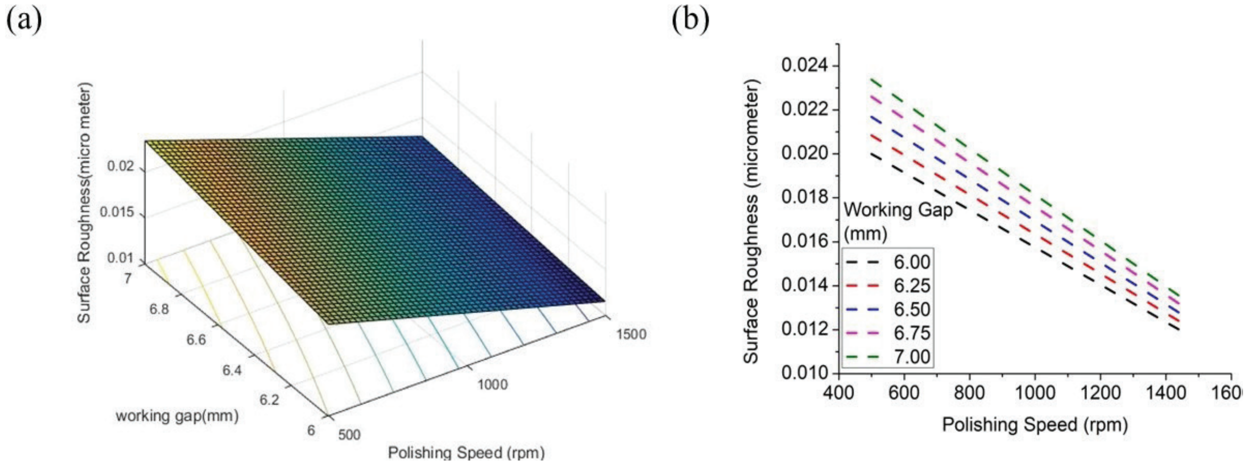


Figure 4. Interaction among polishing speed and working gap verses surface roughness for wet polishing.

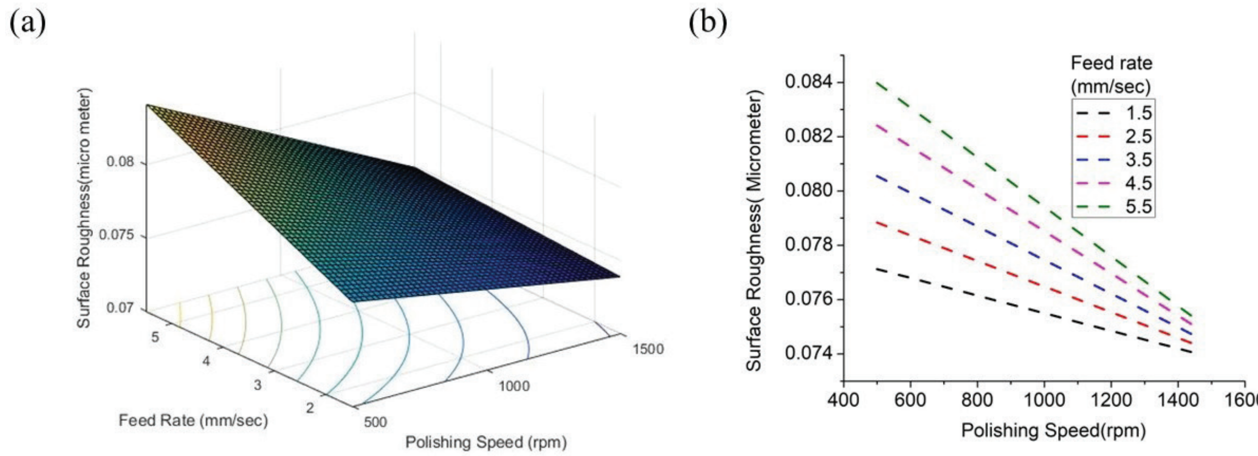


Figure 5. Interaction among polishing speed and feed-rate verses surface roughness for dry polishing.

workpiece. This is due to the increase in the contact time between abrasive particles and copper workpiece at smaller feed rate, which gives a sufficient tangential cutting force initiation for removal of peaks from the workpiece at high polishing speed.

Interaction among working gap and feed-rate verses surface roughness for dry and wet finishing

The interaction effects among working gap and feed-rate over surface roughness have been shown in Figure 7 and 8 respectively. The Figure 7(a) and 8(a) shows surface plot of interaction among working gap, feed-rate over experimental response i.e. surface roughness which is also represented through a 2-D plot in Figure7(b) and 8(b). The interaction between working gap and feed-rate shows that the increase in the working gap is also assisted with the increase in feed-rate given to the workpiece. The increase in the two parameters degrades the surface quality of copper material. This unusual variation causes increase in the surface roughness because increase in the gap decreases magnetic field on the polishing area and increasing the feed-rate decreases contact time between abrasive particles and workpiece, which is not favourable to remove the peaks existing in the copper material.

Interaction effect among the process parameters with the output response for two cases i.e. for dry and wet polishing on copper workpiece tends to follow the same trend , but the surface quality of finished copper material was found to be improved in case of wet polishing with the use of chemical oxidisers NaOH (Sodium Hydroxide), $K_2S_2O_8$ (Potassium persulphate) and H_2O_2 (Hydrogen Peroxide) mixed in Al_2O_3 slurry with distilled water reduced the surface roughness under optimum parameters mentioned in Table 3.

The following is the regression equation for surface roughness in case of dry polishing was obtained by the use of ANOVA for experimental data presented in Table.1.

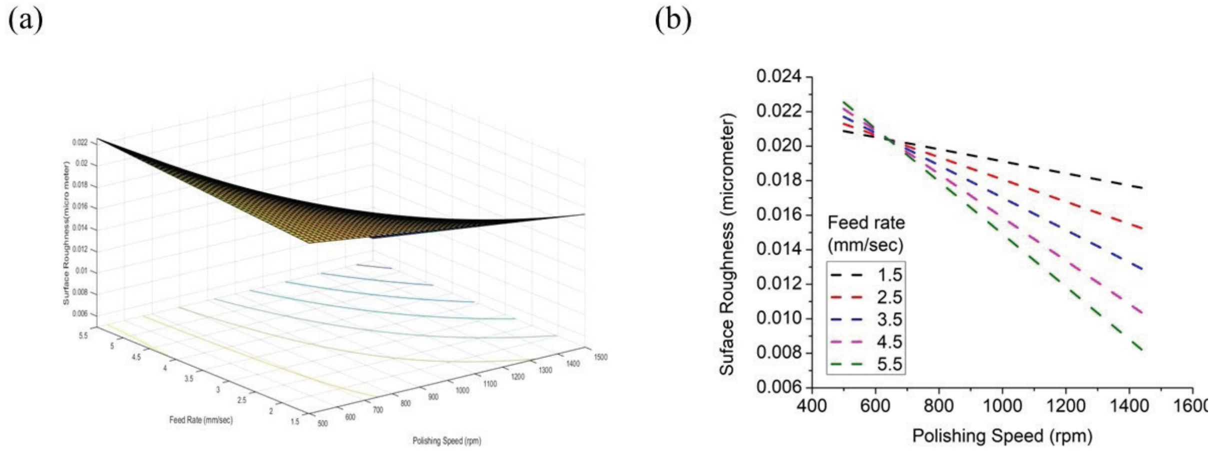


Figure 6. Interaction among polishing speed and feed-rate verses surface roughness for wet polishing.

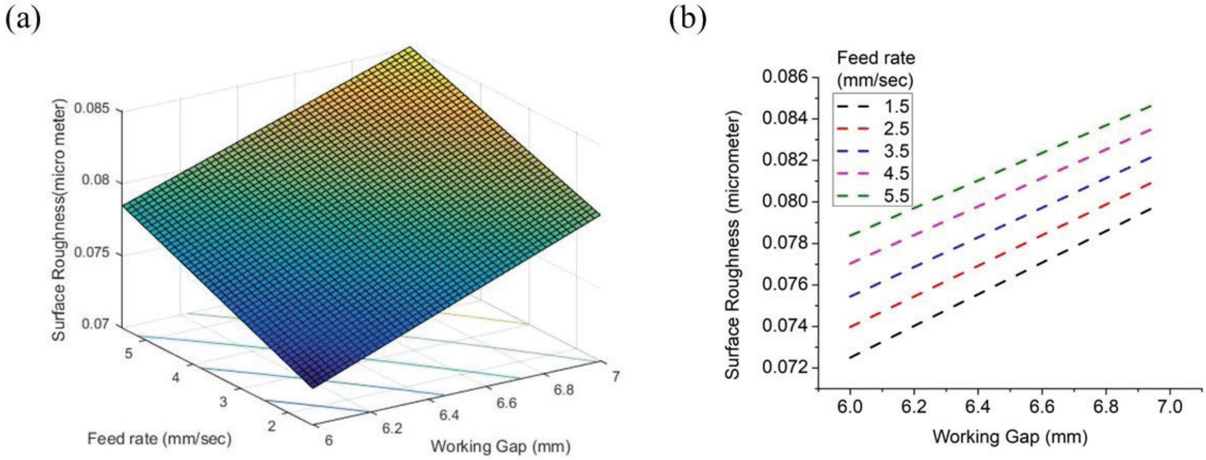


Figure 7. Interaction among working gap and feed-rate verses surface roughness for dry polishing.

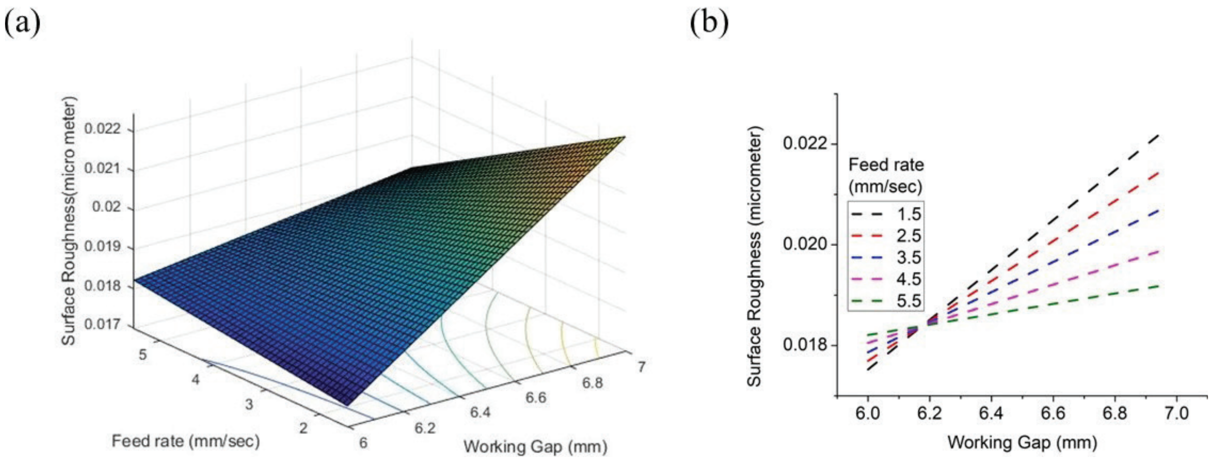
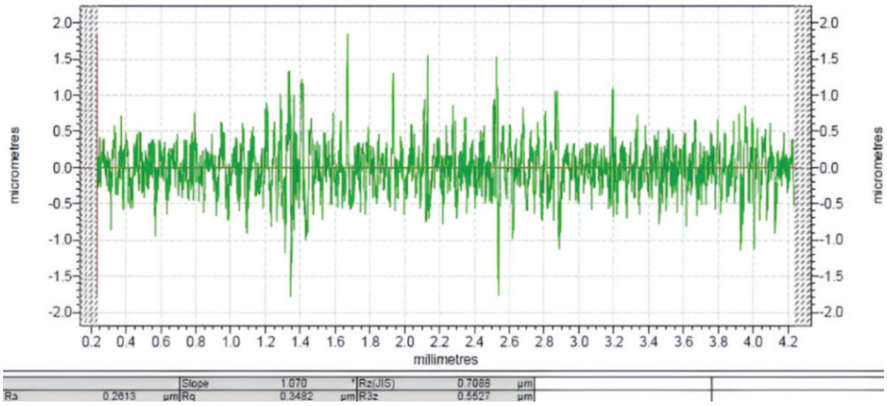


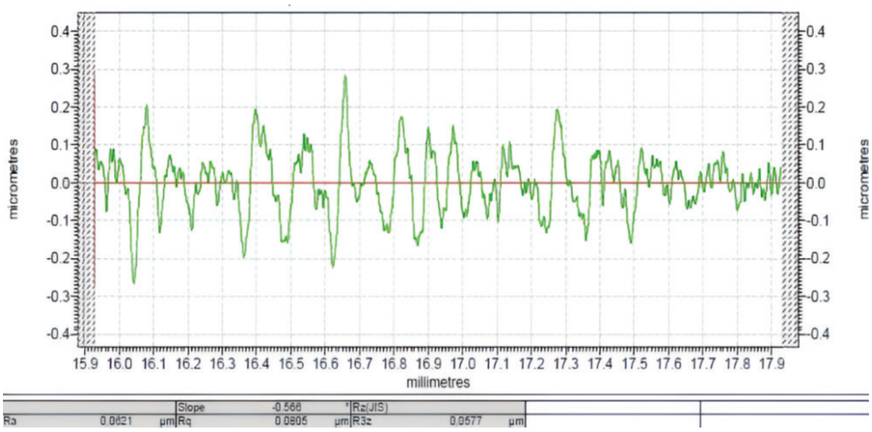
Figure 8. Interaction among working gap and feed-rate verses surface roughness for wet polishing.

Table 3. Optimum polishing condition

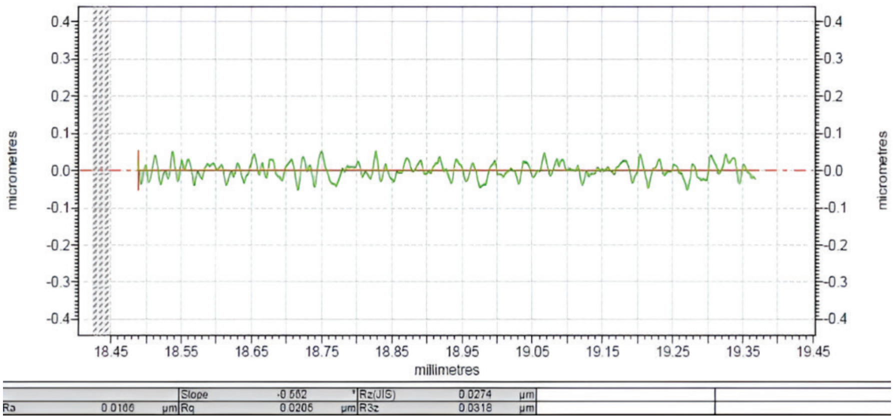
S.No.	Polishing condition	Polishing speed (X_1) (RPM)	Working gap (X_2) (mm)	Feed-rate (X_3)(mm/sec)	Surface roughness (micro meter)
1.	Dry polishing	1500	6	1.5	0.0621 (from equation 1)
2.	Wet polishing				0.0166(from equation 2)



(a)



(b)



(c)

Figure 9. Surface roughness images of (a) Raw copper sample, (b) Finished copper sample under dry condition and (c) Polished copper sample under wet condition.

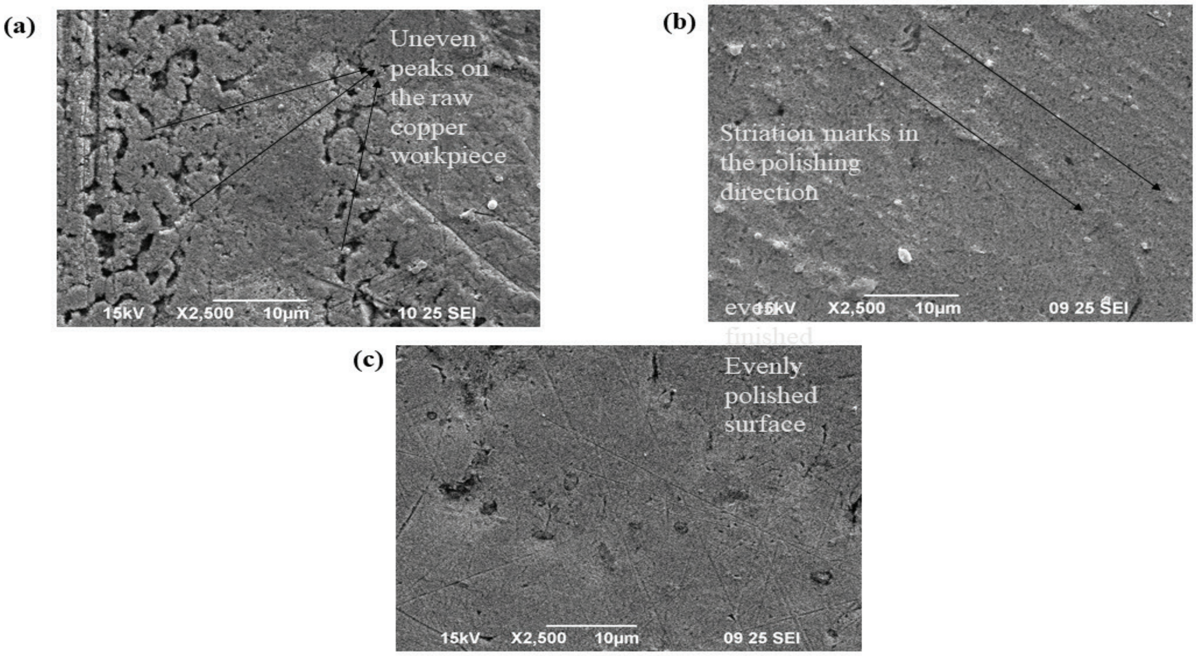


Figure 10. SEM images (a) Raw Copper Workpiece (b) Polished Copper workpiece with Dry Polishing (c) Polished Copper workpiece with Wet Polishing.

$$R_{a-dry} = 0.09125 - 0.000092 \times X_1 - 0.002500 \times X_2 - 0.01050 \times X_3 + 0.000014 \times X_1 \times X_2 + 0.000018 \times X_1 \times X_3 + 0.002000 \times X_2 \times X_3 - 0.000003 \times X_1 \times X_2 \times X_3 \quad (1)$$

The following is the regression equation for surface roughness in case of wet polishing was obtained by the use of ANOVA for the experimental data presented in Table.2.

$$R_{a-wet} = -0.03194 + 0.000014 \times X_1 + 0.007950 \times X_2 + 0.008425 \times X_3 - 0.000002 \times X_1 \times X_2 - 0.000003 \times X_1 \times X_3 - 0.001000 \times X_2 \times X_3 + 0.000000 \times X_1 \times X_2 \times X_3 \quad (2)$$

Where X_1 = polishing speed, X_2 = working gap and X_3 = feed-rate applied on copper workpiece.

Figure 9(a) shows the surface roughness image of raw copper sample whose average surface roughness of 0.2613 μm was obtained. The dry and wet polishing of the aforesaid raw copper sample at optimum parameters mentioned in Table 3 experimentally estimated the roughness of 0.0621μm and 0.0166μm respectively. The results comparatively shows that the finishing efficacy has been considerably improved utilizing the alumina slurry of 1200 mesh size mixed with chemical oxidizers viz. Sodium Hydroxide (NaOH,1.5%wt./wt.), Potassium sulphate ($K_2S_2O_8$, 1.5%wt./wt.) and Hydrogen peroxide (H_2O_2, 0.5%wt./wt.) at appropriate proportion attaining a pH of 12.26. Figure 9(b) and figure 9(c) show the surface roughness images of dry and wet polished copper at optimum polishing conditions respectively.

SURFACE TEXTURE OF POLISHED COPPER WORKPIECE

The scanning electron microscopy (SEM) of raw sample of copper workpiece along with the polished sample under dry and wet conditions at optimum parameters highlighted in Table 3 was carried out on JSM-6490 facility at a resolution of 2500X. Figure 10(a) shows the SEM image of raw copper sample. The uneven peaks and cracks are clearly visible. The uneven peaks and cracks have been efficiently reduced under dry polishing conditions, which can be clearly observed in Figure 10(b). Further striation marks which are comparatively at a larger distance show that effective finishing of copper workpiece has taken place. The surface is further improved, when wet polishing was effectively executed, which can be observed in Figure 10(c). The striation marks on surface have disappeared, which shows that the surface efficacy has been attained. However, some cracks are visible in Figure 10(c), which may be due to the non-removal of peaks as a result of weak MAP chains that had not executed the finishing process effectively.

CONCLUSION

This study introduces new method called chemically aided Single Pole Magnetic Abrasive Finishing Process for pure copper work-material, achieving ultra-smooth finishing, revealing key parameter interactions, and validating performance through Scanning Electron Microscopy in advanced micro-finishing techniques. The following are the major outcomes of the work:

i. The use of chemical oxidisers in alumina slurry with wet assisted polishing resulted in attaining high surface quality of polished copper material with surface roughness of 0.0166 μm in comparison to dry polishing attaining surface roughness of 0.0621 μm.
ii. Higher polishing speed, lower working gap and lower feed-rate is preferable for attaining good surface finish in dry and wet polishing respectively.
iii. scanning electron microscopy images drawn from surface morphology shows that surface quality in wet polishing is better than dry polishing subject to that no polishing marks exist on polished surface and the surface seems to be of improved quality. On the other hand, striation marks exist in the polishing direction in dry polishing of copper workpiece.

AUTHORSHIP CONTRIBUTIONS

Conceptualization**:** Dr. Kheelraj Pandey, Mr. Pravin Kumar Singh

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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