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Chemo Assisted Magnetic Abrasive Finishing: Experimental Investigations

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Abstract

In modern industries with advancement of technology advanced engineering materials are needed to be used like Tungsten, Titanium alloys, ceramics, various composites etc. These materials possess some special characteristics such as high hardness, high wear resistance, high toughness, high strength etc. which make them preferred over conventional materials in modern industries. Due to the stringent properties these materials are difficult to process. Different conventional finishing processes like grinding, lapping, honing, buffing etc. are generally inefficient in finishing these materials. Although processes like abrasive flow machining, magnetic field assisted finishing processes and chemo-mechanical finishing may be used but these may be less productive. Therefore a new process which uses combination of chemical oxidation and magnetic field assisted abrasion (magnetic abrasive finishing) has been conceived in the present work for faster processing.
To establish the process experiments have been conducted on tungsten work piece and the effects of various process parameters like percentage weight of abrasive, oxidizing agent concentration, rotational speed of magnet and working gap on process response namely percentage change in average surface roughness value (ΔR_a) was recorded. The experiments were planned using Taguchi L_9 orthogonal array. Experimental data was analyzed using analysis of variance to understand contribution of various process factors on process response. SEM micrographs have also been obtained to study the surface morphology of the finished work piece. Regression model was developed to predict the percentage change in surface roughness in terms of significant process factors.

*Keywords:*Magnetic abrasive finishing; Chemical mechanical polishing; Taguchi L_9 orthogonal array.

1. Introduction

As technologies in modern industries advance, the machining processes involved are required to be more precise and efficient to obtain a quality product whilst maintaining high productivity. Life and functionality of a product is directly influenced by its surface finish. Now-a-days, non-conventional materials like Titanium alloys, Tungsten, various composites etc. are used widely in industries because of their special properties such as high strength, high hardness, better wear resistance, high toughness etc. However these properties make them difficult to be processed. Various conventional finishing processes such as grinding, honing, lapping etc. are used in industries for long time, but they are not efficient in finishing these materials. Some advanced finishing processes like AFM (Abrasive flow machining), MAF (Magnetic abrasive finishing), CMP (Chemical mechanical polishing) etc. can be employed for finishing these materials [1], but they may be less productive.
MAF is a finishing process in which magnetic abrasive particles (MAP's) are forced against work piece in the presence of magnetic field and material is removed in form of microchips [1-2].

CMP is a process of finishing surfaces with the combination of chemical and mechanical forces. It is a hybrid of chemical etching and free abrasive polishing. In CMP abrasive and corrosive chemical slurry is used in conjunction with a polishing pad. Slurry is applied to the work piece surface, so that a softer oxide layer can be formed over the surface. Being softer, this oxide layer is much easier to be removed as compared to the parent material. Then the polishing pad is rotated with different axes of rotation to remove material and even out any irregular topography.

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Both MAF and CMP have several advantages due to which they are widely used by the industries. But they also have the limitation of low efficiency and low MRR, specially when applied to hard materials. A recent trend in precision surface finishing is to combine several processes together to obtain surface of superior quality. Therefore, a need is felt by industries to develop a combined finishing process, which produces an improved surface quality with greater efficiency. In the present work, a new process is developed by combining CMP and MAF, and is termed as Chemo Assisted Magnetic Abrasive Finishing (CMAF).

Nomenclature

CMP	Chemical mechanical polishing
DF	Degree of freedom
F	Fisher value
FMAB	Ferromagnetic abrasive brush
MAF	Magnetic abrasive finishing
MAPs	Magnetic abrasive particles
MRR	Material removal rate
P	p-value
R_a	Average surface roughness value
Seq.SS	Sequential Sum of square

1.1. Literature review

Several combined polishing processes have been reported recently. Some of the important literature in the field is discussed below.

El-Taweel [3] integrated the electrochemical turning (ECT) process and magnetic abrasive finishing (MAF) to produce a combined process that improves the material removal rate (MRR) and reduces surface roughness (SR). He used 6061 Al/Al_2O_3 (10% wt) composite as work material.The results demonstrated that addition of ECT resulted in increased machining efficiency of MAF by 147.6% and improved surface quality by 33%.

Yin and Shinmura [4] developed three modes (horizontal vibration, vertical vibration and compound vibration) of vibration-assisted magnetic abrasive polishing process and studied the process for stainless steel (SS 304) sample. They confirmed a realization of efficient polishing of a 3D micro-curved surface. With their results they reported a significant improvement in surface quality by addition of vibrations in specific direction with MAF. Mulik and Pandey [5] developed a new process, namely ultrasonic-assisted magnetic abrasive finishing (UAMAF). This technique integrates the use of ultrasonic vibrations and magnetic abrasive finishing (MAF) process to finish surfaces to nanometre order within a short time span. They obtained surface roughness value as low as 22nm within 80 s on a hardened steel work piece (AISI 52100) by UAMAF. Kim and Choi [6] developed magnetic electrolytic abrasive polishing (MEAP) system to finish Cr-coated roller and reported that addition of magnetic field improved the finishing efficiency.

Wrschka et al. [7] used four different types of slurries to describe the CMP of copper damascene structure. They evaluated two alumina based slurries and two silica based slurries. They examined the topography of finished surface using scanning electron microscopy after successful removal of excess copper. By experimental results, they found that in order to yield reproducible removal rates, low etch rates of the slurry chemistry should be used, i.e. of the order 10 nm/min. Furthermore, low etch rates are required to prevent recess and corrosion of the copper line.

Nanz and Camilletti [8] described and compared various models of CMP and investigated different assumptions of the models. They reported that whether primary removal mechanism is mechanical or chemical, it will also depend on the layer being removed and must be modeled accordingly. Forsberg [9] examined the effect of changing process parameters on the material removal rate in CMP of Silicon. With the help of obtained results, he reported that the silicon removal rate increases sub linearly with applied pressure, plate speed and slurry silica content. The removal rate increases in the beginning for new stock removal pads. For planarization pads, in contrast, the oxide removal rate decreases from the beginning. A lapped wafer was found to have a lower removal rate. The removal of poly-silicon on top of thermal oxide was found to be non uniform.

Literature discussed above shows various attempts to improve the machining performance. In present study a hybrid process namely chemo assisted magnetic abrasive finishing, is developed to enhance machining performance and productivity. The objective of present work is to analyze the effect of process parameters (percentage weight of abrasive, oxidizing agent concentration, rotational speed of magnet and working gap) on process response (percentage change in surface roughness). To perform the experiments the required set up was designed and fabricated. Scanning electron microscope (SEM) images were taken to further analyze the results.

2. Experimental Set-up

Figure 1 show the experimental set up used for present study. The set up consisted of two permanent magnetic disks and workpiece holding fixtures, which were designed and fabricated as required in the present set up. An aluminium disk having four blind holed was taken and to fabricate permanent magnetic tool, a set of NdBFe magnetic disks (Φ25mm X 3 mm thick) were inserted in each hole making arrangement of alternative north and south pole.

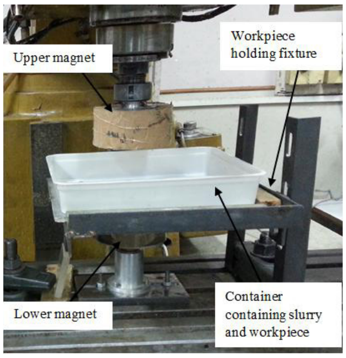

Fig.1 Actual photograph of experimental set up fabricated to perform CMAF

To provide the required rotational motion to upper magnet, it was held in CNC vertical milling center. The lower magnet is fixed on the machine table opposite to the upper magnetic disk. Two magnetic disks were placed opposite to each other and work piece was placed between them. To allow the formation of passive oxide layer over the work piece surface, it was kept in contact with the oxidizing agent before starting the experiments. In the present work H_2O_2 was selected as oxidizing agent to oxidize tungsten [10]. Then work piece was held with help of specially designed fixtures. A mixture of ferromagnetic and abrasive particles is filled in the gap between workpiece and upper magnet. Cutting action is performed by the flexible magnetic abrasive brush formed by these particles. The FMAB formed is shown in figure 2.

Fig.2 FMAB formed on four magnetic poles of upper magnetic disk

3. Experimental Procedure

To analyse the performance of CMAF four process parameters were selected namely percentage weight of abrasive, oxidizing agent concentration, rotational speed of magnet and working gap. To decide the levels of these parameters, some preliminary experimentation was done. Also these experiments helped in deciding the finishing time for each experiment as 20 minutes. Detail of process factors is given in table 1.

Table 1 Details of process parameters

Symbol	Description	Level		
		-1	0	1
X_1	Rotational speed (RPM)	50	100	150
X_2	Working gap (mm)	1	2	3
X_3	Concentration of oxidizing agent(%wt/wt)	3	5	7
X_4	Percentage weight of abrasive(%wt)	20	25	30

Then experiments were conducted to analyze the performance of CMAF process. As initial surface roughness for all the samples was not same so this variation was taken into account by considering ratio of change in surface roughness to the initial surface roughness as response. The initial surface roughness of the samples varied between 0.25micron to .35 microns. This variation was not substantial to affect the performance. The surface roughness was measured using Talysurf profilometer with a sampling length of 2mm.

Process response, i.e. percentage change in surface roughness is calculated by the following formula.

$$\Delta R_a = \frac{\text{Initial surface roughness} - \text{Final surface roughness}}{\text{Initial surface roughness}} \text{x}100 \qquad (1)$$

Tungsten was selected as the work piece material (10 mmx10mmx1mm) for present study. It has hardness of 440 Hv and density 17.5 g/cm^3. It is 1.9% ferromagnetic. Due to its magnetic properties high finishing force was produced, which caused effective finishing. Alumina powder of mesh number 1200 was used as abrasive.

Once the levels of process factors were decided, experiments were designed and performed based on Taguchi L_9 orthogonal array. The experiments were replicated twice in order to observe the repeatability of the results and the results for the same setting of process parameters lied within ±5%. A linear model was involved with Taguchi L_9design and Response equation of following form is obtained.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \epsilon \qquad (2)$$

Where, Y represents the response variable, k is number of variables, β_0, β_i are constants, X_i represents linear terms of process variables, and ϵ is the random error.

To measure the surface roughness (R_a) of work pieces an average $R_a$value of three points was calculated. The variation in $R_a$value at these three points was within ±5%. After all this preparation, experiments were conducted and percentage change in surface roughness for each set of process factors was recorded.

4. Analysis of experimental data

The data obtained by experimental results was analyzed with help of analysis of variance (ANOVA). The ANOVA table for percentage change in surface roughness (ΔR_a) is shown in Table **2**.

In order to have a better understanding of the effect of process factors onΔR_a the multivariable regression equation was obtained and is given below as equation 3.

$$\Delta R_a = 70.6 + 0.183 * X_1 - 5.99 * X_2 + 2.77 * X_3 - 1.57 * X_4 (3)$$

Where, ΔR_a is percentage change in surface roughness, X_1 is rotational speed of magnet (RPM), X_2 is working gap (mm), and X_3 is concentration of oxidizing agent (% w/w) and X_4 is percentage weight of abrasive.

Table 2Analysis of variance (ANOVA) for ΔR_a

Terms	DF	Seq SS	F	P	R^2
Regression model	4	1274.34	20.36	0.006	90.60%
Rotational speed (RPM)	1	504.17		0.005	
Working Gap (mm)	1	215.52		0.021	
Conc. of H_2O_2 (%w/w)	1	183.82		0.027	
%wt of abrasive	1	370.83		0.008	
Residual error	4	62.60			
Total	8	1336.94			

5. Results and discussion

Figure 3 shows percentage contribution of each process factor on process response. It is concluded from figure that that the rotational speed has the highest influence on ΔR_a .

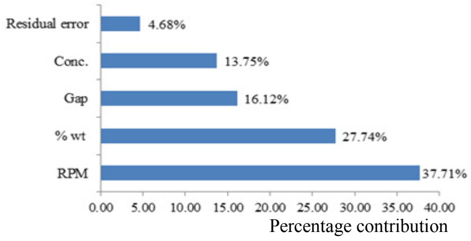

Fig. 3 percentage contribution of process factors on ΔR_a

5.1. Effect of process factors on ΔR_a

The main effect plot of the process is shown in figure 4. It can be seen from figure 4that ΔR_a linearly increasing relation with rotational speed of magnet. This may be because at higher RPM, the rate at which magnetic abrasive particles hit the work piece surface increases. Therefore, more peaks are sheared at higher RPM resulting in higher surface finish. The available normal force, which is responsible for finishing, is reduced at higher working gap. This may be the reason of reduction in ΔR_a with increase in working gap, as shown in figure 4. Also ΔR_a was found to increase with increasing concentration of H_2O_2. This may be because at lower concentration of H_2O_2, it is not sufficient to oxidize all the tungsten atoms on the work piece surface. This leads to formation of non-uniform oxide layer and hence deteriorated surface. As concentration of H_2O_2 increases, more tungsten atoms will be oxidized and a uniform oxide layer will be formed over the surface. This layer can be removed uniformly by FMAB resulting in higher surface finish. ΔR_a decreases with increase in percentage weight of abrasive, as seen by figure 4. This may be because at higher percentage of abrasive particles, the number of iron particles is reduced. As a result the magnetic chain starts disintegrating making FMAB less effective. As a result ΔR_a is reduced.

5.2. Optimization of objective function

By observing main effect plot effect of various process parameters on ΔR_a is analyzed. Based on this a set of optimum process parameter were selected and experiment was performed using this data. The optimum result obtained with the experiment is shown in table**3**.

Figure 5(a) shows the surface roughness profile of rough sample and figure 5(b) shows the surface roughness profile of the same sample after finishing with optimum set of parameters. To support the analysis, SEM images of rough and finished surfaces were taken and shown in figure 6.

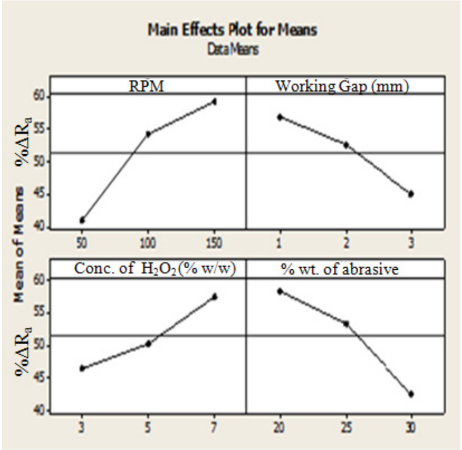

Fig. 4 Main effect plot of process parameters during CMAF

Table 3 Optimization results for Tungsten.

Sample	Tungsten
RPM	150 rpm
Working gap (mm)	1 mm
Concentration of H_2O_2 (% w/w)	7%
% weight of abrasive	20%
$\%\Delta R_a$	79.52%

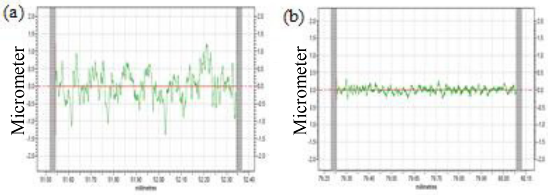

Fig.5 R_a plot of specimen with (a) R_a =0.3351 µm (b) R_a =0686µm

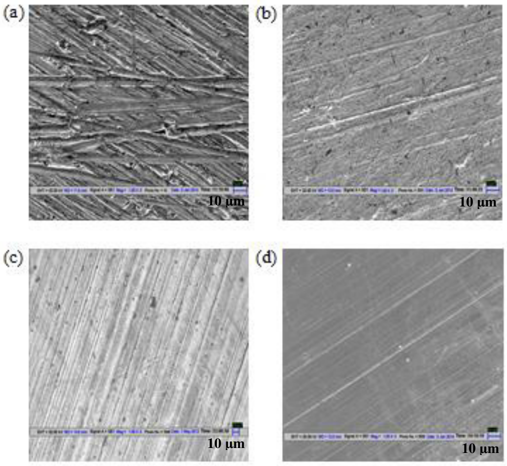

Fig.6(a) shows SEM (at 2000X) image of unfinished tungsten sample; Fig. 6(b,c,d) show SEM images of the same sample when it is finished using processing conditions given in table 4.

Table 4 Conditions at which SEM images shown in figure 6 are obtained

Fig. No.	RPM	Gap (mm)	Conc. of H_2O_2 (%w/w)	%wt of abrasive	% ΔR_a
6(b)	100	1	5	30	49.64
6(c)	150	3	5	20	58.44
6(d)	150	1	7	20	79.52

By SEM it can be observed that CMAF has noticeably reduced the surface roughness.

6. Conclusion

In the present work, tungsten work piece (1.9% ferromagnetic) is successfully finished using the developed process (CMAF). H_2O_2 is used to form a softer oxide layer over the surface. Combination of chemical oxidation and magnetic force resulted into better surface quality with minimum surface defects.

It is observed that during CMAF percentage change in surface finish is affected maximum by rotational speed of magnetic disk (37.71%) followed by %weight of abrasive (27.74%), working gap (16.12%) and concentration of H_2O_2 (13.75%). With optimum conditions surface finish is improved by 79.52%. Surface roughness profiles show maximum peak to valley height for finished sample is approximately 1/5th of the same for unfinished sample.

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