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The effect of polishing slurry parameters on the surface finish obtained using a novel compliant polishing technique

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Abstract

Compliant polishing techniques are class of finishing techniques which exhibit some degree of compliance during the work-tool interaction. This compliant nature of the polishing process allows the tool to exercise some degree of adaptability during finishing thus allowing it to finish complex macro-features on work surface. Pneumatically Configurable Polishing (PCP) is a novel compliant finishing technique where the tool compliance degree and the polishing forces can be precisely controlled using pneumatic pressure. The final surface finish obtained on the work surface is an important outcome of the finishing process.

The present study investigates the effect of the polishing slurry parameters such as abrasive concentration, abrasive type, and the volume of polishing slurry on the final surface finish obtained on an EN31 workpiece surface. The surface finish is analysed at varying values of the aforesaid parameters. The percentage reduction in surface roughness obtained using diamond abrasives (~ 88%) is found to be the highest when compared to those obtained using silicon carbide (~ 60%) and alumina (~ 55%).

The volume of polishing slurry applied during finishing is found to significantly affect the final surface finish. A threshold value of polishing volume (0.2 mL) is needed to achieve a substantial value of percentage reduction in surface finish below which no improvement in surface finish is observed in the case of Al_2O_3 and SiC abrasive slurries. On the other hand, as the applied volume of slurry increases, the percentage reduction increases and gets saturated beyond a limit. The value of the saturation volume is found to be 0.65 mL for diamond abrasive slurry and 0.5 mL for both Al_2O_3 and SiC abrasive slurries.

1 Introduction

Many enabling technologies have been developed for polishing of industrial components which find applications in sectors such as automotive, aerospace, dies, molds and optics etc. The past few years have witnessed the development of many finishing processes like bonnet polishing, BEMRF, MRF have been developed to achieve nano scale surface finish on substrate surfaces. These finishing processes need a certain level of surface finish to begin with. If the initial surface roughness of the part is high (order of a few microns), the polishing becomes inefficient as the material removal rate in these processes is quite low. As a result, there is a need of primary finishing processes to generate sub microns surface roughness. The commonly employed primary finishing processes can be lapping, belt grinding, manual polishing, etc. However, producing a high-quality surface finish using these manual polishing or conventional finishing techniques is difficult [1,2]. The secondary finishing processes then further reduce the sub-micron surface roughness down to few nano meters.

In finishing processes, the slurry parameters and slurry volume play a vital role. The effect of slurry parameters and slurry volume on surface roughness has been investigated in literature. The major outcome of few papers is discussed here. Miao et al. [3] investigated the influence of nano-diamond abrasive concentration in the polishing fluid during the polishing of borosilicate glass. An increase in the MRR was observed as the nano-diamond abrasives concentration in the MRP fluid increased. Sidpara et al.[4] examined the effect of change in fluid composition on surface finish in case of single crystal silicon material and found that the water based MRP fluid significantly improved surface finish. Alam et al. [5] studied the effect of slurry volume on the surface finish and the size of the polished spot obtained during the finishing of mild steel workpieces using the BEMRF process. The authors observed that when a higher volume of MR slurry was used the surface roughness deteriorated as the spot containing deep scratches was formed. The primary reason for such an observation was that when the slurry volume is high in the working gap the centrifugal forces force the fluid to flow outside in a radial direction. This leads to the development formation of a ring-shaped structure around the tool periphery producing deep indentations on the spot periphery thus causing a deterioration of the surface quality. On the other hand, if a very low volume of slurry was used negligible polishing is observed as the EIPs were not sufficient to hold the abrasives in the polishing spot. Optimum slurry volume can help in reducing of polishing time as well as reduction in slurry volume. Singh et al. [6] conducted investigations using different secondary finishing process on different workpiece materials and the effects of slurry parameters and slurry volume on surface roughness. The authors reported an increase in the percentage surface roughness reduction as abrasive mesh size is lowered or the volume concentration of abrasive particle is increased.

Pneumatically Configurable Polishing process is a recent addition to the class of compliant finishing processes. It provides the convenience of manipulation provided by the controlled inflating of a thin membrane in substrate polishing [7]. The PCP process uses a slurry of abrasives suspended in a viscous medium which provides them the necessary mobility for material removal. The reduction in surface roughness obtained using PCP process is a critical parameter for determining the process suitability for an application and the abrasive slurry properties are important in determining the same. In literature, a study of abrasive slurry composition in PCP is not yet explored. Therefore, the present paper investigates the effect of slurry volume, abrasive type and abrasive concentration on the surface roughness reduction in the Pneumatically Configurable Polishing process.

2 Materials and methods

2.1 Sample Preparation

The samples used for this study are made up of EN-31 work material whose properties are presented in Table 1. The sample size was kept 45 x 45 x 10 mm^3 and the initial sample preparation was done using surface grinding. The initial suface roughness value (Ra) was found to range between 0.420 to 0.450 µm.

Table 1: Properties of work material

Property description	**Value**
Material	EN-31 steel
Hardness	310 HV
Elastic Modulus	210 GPa
Shear Strength	450 MPa
Poisson’s ratio	0.30
Density	7800 kg/m^3

2.2 Experimental details

The PCP process makes use of a 5-axis CNC machine tool as illustrated in Fig. 1 which is designed to use pneumatic pressure for controlling the forces on abrasives present in a slurry. The applied pneumatic pressure leads to inflation of a membrane which further transmits forces to the polishing film. The extensible nature of the film allows it to sustain high expansion forces. The polishing film has two main roles to play: to transmit the finishing forces from the polishing tool to the abrasives present in the slurry and second is to hold the abrasive particles in the finishing zone thus preventing them from being expelled due to the centrifugal forces during finishing. The synthesis of the abrasive slurry and the experimental strategies used in this study have been described in the next two sub sections.

2.2.1 Polishing slurry preparation

The abrasive slurry is a homogeneous mixture of two components: abrasive particles and a carrier medium. The abrasive particles used in this study are Alumina, SiC and Diamond, while paraffin oil is used as the carrier medium. A precision weighing balance (AND GR200) having a least count of 0.1 mg was used to measure the desired mass of the abrasives and the carrier medium as per the concentration required for the study. The synthesis of various slurries having different abrasive concentration was conducted using a homogenizer. The homogenising setup ensures through mixing of the abrasive particles with the carrier medium so that no separation or sedimentation takes place during finishing. The prepared slurry is then filled in a cartridge-based fluid delivery system for polishing. The volume of slurry is controlled by using a fluid delivery system and is commanded via a specialised H-code through the CNC controller. The fluid delivery system makes use of an electric actuator which ejects a precise volume of polishing fluid in the polishing zone as per the user defined part program.

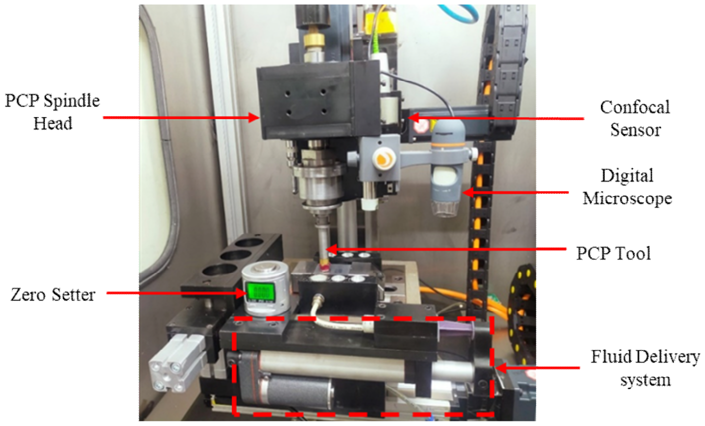


Figure 1: Experimental setup used

2.2.2 Polishing regimes used

The effect of the slurry parameters has been studied using two polishing strategies: constant slurry volume regime and constant slurry concentration regime. However, in both regimes three type of abrasives have been used: Diamond, Alumina (Al_2O_3) and Silicon Carbide (SiC). In the constant slurry volume regime, the effect of slurry abrasive concentration on the percentage roughness reduction is studied for the three abrasives using a fixed slurry volume for all experiments. On the other hand, the constant slurry concentration regime investigates the effect of slurry volume on the percentage roughness reduction using a fixed value of abrasive concentration. Few parameters such as pneumatic pressure, tool rotation speed, working gap etc. were kept constant throughout the study. The parameters used during experimentation have been summarised in Table 2. The surface roughness value (Ra) was measured before and after each experiment on 6 randomly selected locations. The device used was a Mahr M310 surface testing device keeping a sampling length of 4 mm and a cut-off length of 0.8 mm. The average of the six readings was used to obtain the values of initial and final surface roughness to ascertain the percentage Ra reduction.

Table 2: Process parameters used during the experimental study in different polishing regimes

Parameter	**Constant Slurry Volume**	**Constant Slurry Concentration**
Pneumatic pressure (bar)	2	2
Tool rotation speed (RPM)	1000	1000
Working gap (mm)	1	1
Abrasives used	Diamond, Al_2O_3, SiC	Diamond, Al_2O_3, SiC
Abrasive size	5-7 µm	5-7 µm
Tool diameter	12 mm	12 mm
Abrasive concentration (% wt)	10,30,50,70,90	50
Polishing Time	20 min	20 min
Polishing slurry volume (ml)	0.6	0.2, 0.4 , 0.6 , 0.8 , 1

3 Results and Discussion

3.1 Effect of abrasive concentration on percentage reduction in surface roughness

The constant slurry volume regime makes use of a fixed volume of slurry i.e 0.6 mL for each experiement. The abrasive concentration in the slurry (%wt) was varied between 0 % and 90 % starting from a value of 10 % and was subsequently incremented by a value of 20 % in the next experiment run. The results of this experimental regime have been presented in Table 3. It is evident that if only the carrier medium was used during finishing i.e. without any abrasive addition, no change in roughness was observed. However, it was found that as the abrasive concentration increases there is gradual increase in the percentage reduction in roughness. Fig. 2 illustrates the results of the constant slurry volume polishing regime. It is observed that after a certain optimal abrasive concentration value the percentage reductionin roughness starts declining for each abrasive. The reason for such an observation is that as the abrasive concentration in the slurry increases, the number of abrasives particpating in finishing (active abrasives) also increases. This leads to an increase in the microscopic material removal of the surface peaks. However, after this optimal concentration level the viscosity of the slurry increases causing a decline in the mobility of the abrasives. As a result, the percentage reduction in roughness starts declining, so much so that around 90 % abrasive concentration the slurry becomes so viscous that hardly any finishing is observed in case of SiC.

Table 3: Effect of abrasive concentration in the slurry on percentage roughness reduction (constant slurry volume regime)

			Percentage reduction in surface roughness		
S.No.	**Abrasive Concentration in slurry (% wt)**	**Slurry Volume (mL)**	**Al_2O_3**	**SiC**	**Diamond**
1	0	0.6	0.00	0.00	0.00
2	10		16.39	26.53	30.72
3	30		38.53	60.61	69.34
4	50		47.58	51.28	88.18
5	70		54.39	16.15	70.00
6	90		23.27	8.90	29.91

It is also evident from Fig. 2, that the optimal value of concentration for diamond abrasives is around 52 % while for Alumina and SiC this value is approximately 30 % and 70 % respectively. This is because the density of SiC, Diamond and Alumina are 3.21 g/cm^3 , 3.51 g/cm^3 and 3.95 g/cm^3 respectively. As the density of the SiC abrasives is lowest amongst the three, even at low abrasive %wt concentration, the amount of abrasives added to the slurry are sufficient enough to increase the slurry viscosity, thus reducing the active abrasives' mobility as discussed above. Since the abrasive size is kept same for each abrasive type (5 – 7 µm), a higher abrasive %wt concentration is required for the same effect of reduced mobility to occur in the case of Al_2O_3 because its density is lowest amongst the three.

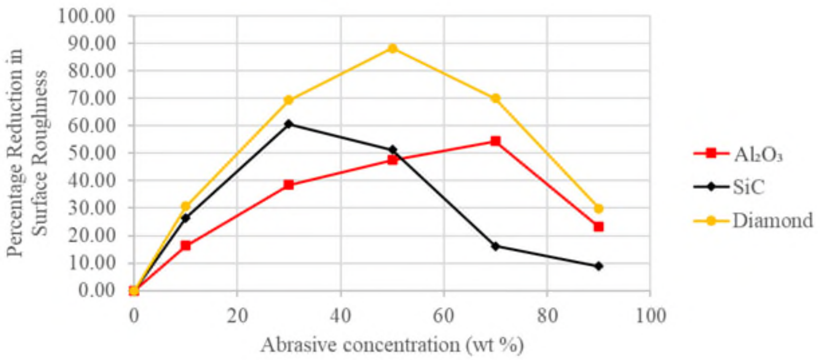
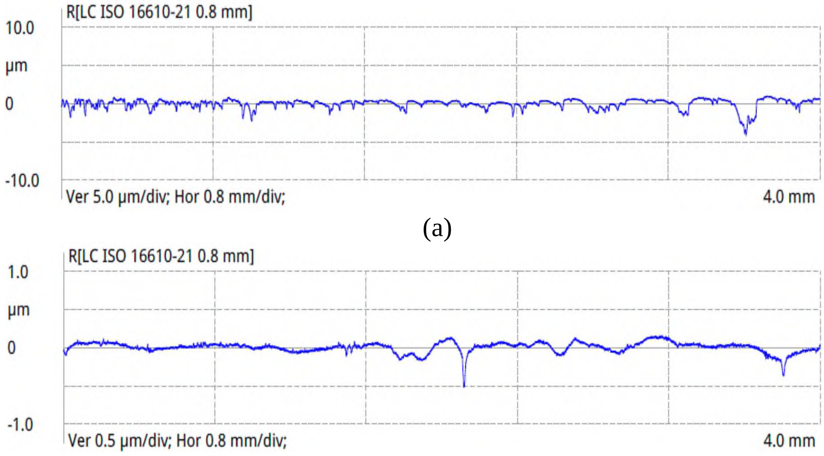


Figure 2: Variation of percentage reduction in surface roughness with increase in slurry abrasive concentration for different abrasives

It can also be observed from Fig. 2 that the value of percentage reduction in surface roughness is highest (~ 88%) for diamond while its comparable for both Alumina (~ 55%) and SiC (~ 60%). This because of the fact that the knoop hardness of diamond is highest amongst the three. As a result, diamond abrasives are able to remove more material surface peaks in the predefined polishing time as compared to the Al_2O_3 and SiC. The initial and final surface profiles for experiment 4 as presented in Table 3 are shown in Fig. 3.



(a)

(b)

Figure 3: Surface roughness profiles for Experiment 4 as per Table 3
(a) initial surface (Ra = 0.423 µm) (b) final surface (Ra = 0.050 µm)

3.2 Effect of slurry volume on percentage reduction in surface roughness

The constant slurry concentration regime was used to investigate the effect of slurry volume on the roughness reduction. The abrasive concentration (%wt) was kept constant at 50 % and the roughness evaluation was done at increasing levels of slurry volume starting from 0 ml and sequentially incremented in the next experimental run by a value of 0.2 ml going upto 1 ml.

Table 4: Effect of slurry volume on the percentage roughness reduction
(constant slurry concentration regime)

			Percentage reduction in surface roughness		
S.No.	**Slurry Volume (ml)**	**Abrasive Concentration (% wt)**	**Al_2O_3**	**SiC**	**Diamond**
1	0	50	0.00	0.00	0.00
2	0.2		3.67	4.86	10.75
3	0.4		35.55	40.37	54.76
4	0.6		48.14	50.93	87.82
5	0.8		46.64	49.64	87.65
6	1		45.41	49.65	87.50

The results for this study are presented in Table 4 and illustrated pictorially in Fig. 4. In the absence of abrasive slurry no finishing is observed. It is also obsverved that for Alumina and SiC abrasives a threshold volume of slurry is required below which no finishing is observed. Although this phenomenon is not observed in the case of diamond abrasives. However, after the threshold volume is crossed a gradual increase in the slurry volume leads to a proportional increase in the percentage reduction in surface roughness. This is due to that fact that, as the applied slurry volume in the polishing zone increases, the active abrasives which are responsible for finishing also increase in the finshing spot.

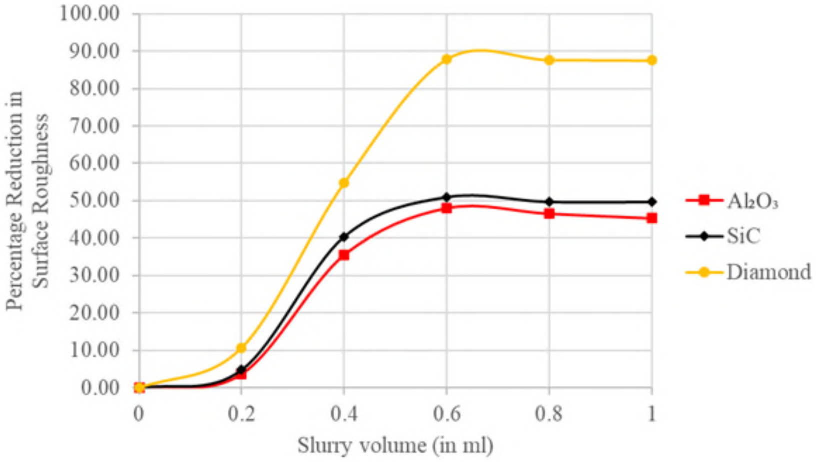
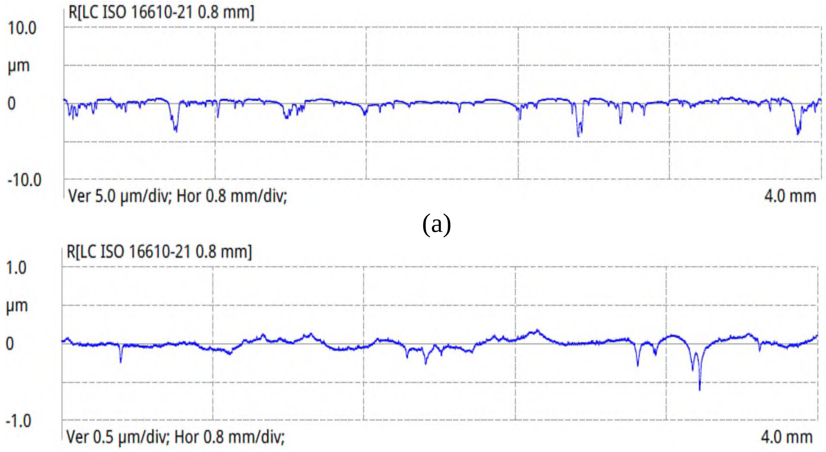


Figure 4: Variation of percentage reduction in surface roughness with increase in slurry volume for different abrasives

As evident from Fig. 4 this increase in percentage reduction in surface roughness becomes nearly constant after a certain slurry volume also known as saturation volume. A further increase in slurry volume doesnot lead to any change in the percentage reduction in surface roughness value as the polishing zone gets nearly saturated with active abrasives. Also, as observed in the previous section the percentage reduction in surface roughness at any given slurry volume is always higher than those obtained using SiC and Al_2O_3. The initial and final surface profiles for experiment 4 as presented in Table 4 are shown in Fig. 5.



(b)

Figure 5: Surface roughness profiles for Experiment 4 as per Table 4
(a) initial surface (Ra = 0.427µm) (b) final surface (Ra = 0.052µm)

4 Conclusions

A study on the effect of slurry parameters on percentage reduction in surface roughness has been conducted during PC polishing of EN-31 steel workpieces using three types of abrasives: Diamond, Al_2O_3 and SiC. Two polishing regimes: constant slurry and constant concentration regimes have been used for the investigation. Following conclusions have been drawn from this study:

1. The abrasive concentration in the polishing slurry is found to have a profound impact on the percentage reduction in surface roughness of the work material. As the abrasive concentration is increased in the slurry, the percentage reduction in surface roughness increases till an optimal value. If concentration is increased beyond this optimal value, a decline is observed in percentage reduction in surface roughness due to a decrease in abrasive mobility caused by an increase in slurry viscosity.

2. The maximum value of percentage reduction in surface roughness at the optimal concentration is observed to be highest for diamond abrasive slurry (~ 88%) owing to the abrasive's high Knoop hardness. On the other hand, this value is found comparable for Al_2O_3 (~ 55%) and SiC (~ 60%).

3. The study on the effect of slurry volume reveals that there exists a threshold slurry volume (0.2 mL) below which very little or negligible polishing is observed for Al_2O_3 and SiC slurries. However this threshold value is found to be negligible for diamond abrasive slurry.

4. After the threshold slurry volume a proprtional increase in percentage reduction in surface roughness is observed. However, beyond a certain saturation volume the percentage reduction in surface roughness does not change due to the saturation of the polishing zone by the active abrasives.

5. The value of the saturation volume is found to be 0.65 ml for diamond abrasive slurry and 0.5 ml for both Al_2O_3 and SiC abrasive slurries.

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