Development of a Robust Abrasive Flow Machining Process Setup

Brar B.S.[1*], Walia R.S.[2], Singh V.P.[3] and Singh Mandeep[4]
[1]*Research Scholar (Mech. Engg.),*
[2]*Asst. Prof. (Prod. Engg.),*
[3]*Assoc. Prof. (Mech. Engg.),* [4]*Research Student (Prod. Engg.),*
PEC University of Technology, Chandigarh, India
*E-mail: *brarbalraj@yahoo.com*

Abstract—*Finishing of complex, miniaturized parts, especially of internal recesses is very difficult and time consuming process. Abrasive Flow Machining (AFM) is an appropriate finishing process for such finishing requirements. It uses abrasives laden polymeric putty with other ingredients to polish the surfaces. This media is extruded back-and-forth over the surface employing the hydraulic pressure system. Using the Taguchi method, the main parameters of abrasives-to-media ratio, extrusion pressure and number of cycles have been optimized for the better signal-to-noise ratio for the quality characteristics of material removed (MR) and the percentage improvement in the surface finish (ΔRa) respectively. Taguchi's experimental design based on L9 orthogonal array has been taken for the experimentation and on the basis of maximum Signal-to-Noise (S/N) ratio, the optimal parameters have been selected leading to the robust AFM setup.*

Keywords: *Robust, Optimization, Abrasive Flow Machining (AFM), Taguchi Method*

Introduction

Abrasive Flow Machining (AFM) is widely used in the fine finishing of complex inaccessible shapes, miniaturized parts, and for simultaneous finishing of many areas of a part or many parts itself. It avoids the need of time consuming or sometimes hazardous manual finishing techniques with low damage to mechanical surface. Abrasive flow machining process is a process to polish metallic components using a semi-liquid paste which can reach inaccessible undercut areas of a complicated component. It is a process for surface finishing, deburring, radiusing, removing cast layers, and to produce compressive residual stresses in a complex (or delicate) work-piece [1]. Starting with the deburring of hydraulic control blocks, AFM has rapidly diversified into automobile, pharmaceutical, chemical, production, defense, space and aeronautics industry [2].

This technique uses a liquid polymer containing abrasive particles as grinding media. This media is also known as an abrasive laden medium, not-so-silly putty [3], or a liquid file. The abrasive media is extruded through the passages formed by the work-piece and tooling with the help of hydraulic pressure system employing hydraulic actuators. Abrasion occurs wherever the medium enters and passes through the most restrictive passages. The media act as a self-modulation abrasive medium with good fluidity and viscosity so the cutting tools are flexible [4]. Consequently, the medium abrade the work-piece in the work holder and fixture.

It has been reported in a number of studies that abrasion is more pronounced in some initial cycles after which improvement in the surface finish stabilize or reduce in some cases [5, 6]. Jain and Jain [7] reported that at higher pressure the improvement in material removal just tends to stabilize probably due to localized rolling of abrasion particles. It has been found that keeping all other process parameters constant, a larger volume of media will cause more abrasion [8]. Williams and Rajurkar [9] has reported that viscosity of the media is one of the significant parameters of the AFM process. Keeping all other parameter constant, an increase in viscosity improves both material removal and surface roughness. Smaller size abrasive gives better surface finish and can reach into complex and narrow passages, while larger one cut faster [10]. Siwert [11] suggested that abrasive particle to base material ratio (by weight) should vary from 4:1 to 1:4 with 1:1 as the most appropriate ratio. As the concentration of abrasive in the media increase, material removal increases. Jain and Adsul [12] in their study mentioned that material removal is governed by initial surface roughness and work piece hardness. Softer material has higher material removal and more improvement in surface finish as compared to harder material. The pseudo-plastic nature of media used in AFM process has been indicated by some studies [13].

From the stochastic analysis, it is concluded that the mechanism of material removal in AFM is considered to consist of ploughing responsible for creation of characteristics flow lines and micro-cutting [14].

Singh and Shan [15, 16] and Singh et al. [17] employed a magnetic field around work-piece in abrasive flow machining process to improve the machining performance.

Taguchi has built upon W E Deming's observation that 85% of poor quality is attributable to the manufacturing process and only 15% to the worker. Thus, his attempt has been to develop robust manufacturing systems that are insensitive to daily and seasonal variations of environment, machining wear etc. [18]. Taguchi method has been widely used in engineering analysis, and is a powerful tool to design a high quality system. Moreover, Taguchi method employs a special design of orthogonal array to investigate the effects of the entire machining parameters through small number of experiments. The array forces all experimenters to design almost identical experiments [19, 20].

In the present investigation the feasibility and reliability of the developed AFM have been investigated. For this experimentation the essential AFM parameters such as abrasives-to-media ratio, extrusion pressure and number of cycles have been selected. The quality characteristics under the consideration are material removal (MR) and the percentage improvement in the surface finish (ΔR_a).

Experimental Design

Experimental Materials

In the present investigation, brass (Yellow brass: 65% Cu, 35% Zinc, having 156 BHN hardness) as work-piece material was used [2, 15, 16, 21]. The internal cavity to be machined in the test specimen was prepared by drilling operation followed by boring to the required size. Initial surface roughness of the specimens is in the range of 3.8 to 4.2 micron. The work-piece is a hollow cylindrical piece with I.D. 8mm, O.D. 10 mm and Length 16mm [2, 21]. The work-piece is held in the setup with the help of designed nylon fixtures.

Equipment and Procedure

In this investigation, a developed AFM setup has been used. This setup has been designed for the maximum extrusion pressure of 25 N/mm². It employs two hydraulic actuators for the extrusion of media from one media cylinder to the other, through the work-piece during the forward stroke. Once a stroke is complete the procedure is reversed and the combination of these forward and backward strokes constitutes a cycle. The media volume has been taken as 290 cm³, and the stroke length has been kept constant at 100mm. Figure 1. shows the developed experimental apparatus for an AFM process.

The internal cylindrical surface of the work-piece is finished by the abrasion process, when the abrasives laden media extrudes through this. Each work-piece was machined for a predetermined number of cycles.

The work-pieces were measured by a precision electronic balance (CAS India CAY220) with 0.1mg resolution before and after each experiment to calculate the material removal. The measurement of surface roughness (avg. of five values) employed a precision profilometer (Mitutoyo SJ-2, L.C. 0.01 micron) to evaluate the quality of the machined surface.

Fig. 1: Developed AFM Setup

Experimental Conditions

The effects of machining parameters associated with AFM on machining characteristics were extensively investigated in this study. Moreover, the significant parameters and the optimal combination levels of machining parameters were determined.

Process Parameters

The machining parameters, such as abrasives-to-media ratio (C), Extrusion pressure (P) and Number of cycles (N) were varied to determine their effects on the machining characteristics material removal (MR) and % age improvement in surface finish [22]. The experiments were designed to study the effect of these on response characteristics of AFM process. Table 1. shows the various levels of process parameters, and values of other fixed parameters.

Table 1: Process Parameters and their Values at Different Levels

Symbol	Process Parameters	Unit	Level 1	Level 2	Level 3
C	Abrasives to Media Ratio	% by weight	1:1.25	1:1	1.25:1
P	Extrusion Pressure	N/mm²	5	10	15
N	Number of Cycles	Number	5	10	15
Polymer-to-Gel Ratio: 1:1, Work-piece material: Brass, Abrasive type: Al_2O_3, Grit Size: 600 (13-16 micron), Media Flow Volume: 290 cm³, Reduction Ratio: 0.95, Temperature: 32 ± 2°C, Initial Surface Roughness of Work-piece: 3.8 -4.2 micron, Media Viscosity: 810 Pa.s.					

Response Parameters

The effect of selected process parameters was studied on the following response characteristics of AFM process:

Percentage Improvement in Surface Roughness (Δ**Ra***):* The average of Ra value was calculated and the percentage improvement in roughness was estimated as:

$$\Delta R_a = \frac{(Initial\ Roughness - Roughness\ after\ machining) x\ 100}{Initial\ Roughness}$$

Material Removal in mg (MR): The material removal signifies the amount of material that has been removed from a specimen in a specified number of process cycles. It was estimated by calculating the difference between initial weight of the specimen and final weight of the specimen after processing at a specified set of conditions by AFM.

Experimental Design Based on Taguchi Method

The experimental design was according to an orthogonal array (OA) based on the Taguchi method as the total degrees of freedom associated with the three parameters at three levels each (without interaction) is 7, which is less than 8, total degrees of freedom of L9 OA. The L9 orthogonal array had four columns and 9 rows, thus, four machining parameters can be apportioned to the columns and the rows designate nine experiments with various combination levels of the machining parameters. In this investigation only three machining parameters were considered, so one column was empty. The orthogonality is preserved, even if one column of the array remained empty. Three observed values of MR and Percentage improvement in surface finish (ΔRa) were examined. The levels of each machining parameter were set in accordance with the L9 orthogonal array, based on the Taguchi experimental method. Moreover, the significant machining parameters associated with MR and % Improvement in (ΔRa) were determined by ANOVA based on S/N ratio.

Experimentation

Experiments were conducted according to the test conditions specified by the L_9 OA (Table 2.) Each experiment was repeated three times in each of the trial conditions. Thus, twenty seven work-pieces were selected having initial surface in close range of (3.8-4.2 micron). In each of the trial conditions and for every replication, the percentage improvement in surface roughness and material removal were measured. The data is recorded in Table 2.

Analysis and Discussions

Analysis by Taguchi Method

The experiments were planned by using the parametric approach of the Taguchi's Method. The response characteristic data is provided in Table 2. The standard procedure to analyze the data based on S/N ratio, as suggested by Taguchi, is employed. The average values of the S/N Ratio of the quality/response characteristics for each parameter at different levels are calculated from experimental data. Both the response parameters viz. material removal and %age improvement in surface finish, are of "higher the better" type of machining quality characteristics, hence the S/N ratio for these types of responses is given below.

$$\left(S/N\right)_{HB} = -10\ \log(MSD_{HB})$$

Table 2: The L_9 (3^4) OA (Parameters Assigned) with Experimental Results of Various Response Characteristics

Exp No.	Run Order	Parameter Trial Conditions				Responses for Material Removal MR				Responses for % Improvement in (ΔR_a)			
		1	2	3	4	Raw Data for Material Removal (mg)			S/N Ratio (dB)	Raw data for % Improvement in (ΔR_a)			S/N Ratio (dB)
		C	P	N	e	R_1	R_2	R_3		R_1	R_2	R_3	
1	1	1	1	1	1	0.82	0.33	0.456	-7.13	8.77	11.02	9.21	19.58
2	3	1	2	3	2	1.13	1.78	1.65	3.11	25.59	8.01	15.53	21.49
3	2	1	3	3	3	2.17	2.6	2.68	7.79	12.49	14.37	14.57	22.74
4	4	2	1	2	3	2.97	3.1	3.35	9.91	23.49	52.95	34.26	29.97
5	6	2	2	3	1	5.98	5.9	6.56	15.74	25.73	28.02	27.14	28.60
6	5	2	3	1	2	3.17	3.1	3.66	10.33	14.69	38.59	32.00	26.79
7	9	3	1	3	2	17.77	27.01	20.73	26.41	61.74	79.09	65.58	36.61
8	7	3	2	1	3	8.9	10.53	9.54	19.63	34.20	44.63	35.61	31.46
9	8	3	3	2	1	20.35	29.35	24.65	27.59	75.56	68.64	72.25	37.14
Total						63.26	83.7	73.28	---	282.26	345.22	306.15	---
						$\bar{T}_{MR}$= Overall mean of MR = 8.16 mg			---	$\bar{T}_{\Delta Ra}$ = Overall mean of ΔRa = 34.58 %			---
R_1, R_2, R_3 represent response value for three repetitions of each trial. The 1's, 2's, and 3's represent levels 1, 2, and 3 of the parameters, which appear at the top of the column. (e) represents no assignment in the column													

where

$$MSD_{HB} = \frac{1}{R} \sum_{j=1}^{R} (1/y_j^2)$$

R = Number of repetitions

yj = Response value

The main effects of process parameters for S/N Ratio for each response are plotted by calculating the average values of response characteristics for each parameter at level one, level two and level three (L1, L2, L3). The analysis of variance (ANOVA) of S/N Ratio data is performed to identify the significant parameters and to quantify their effect on the response characteristics.

Effect on Material Removal (MR)

The av\erage values and main effects (S\N Data) for material removal (MR) are shown in figure 2.

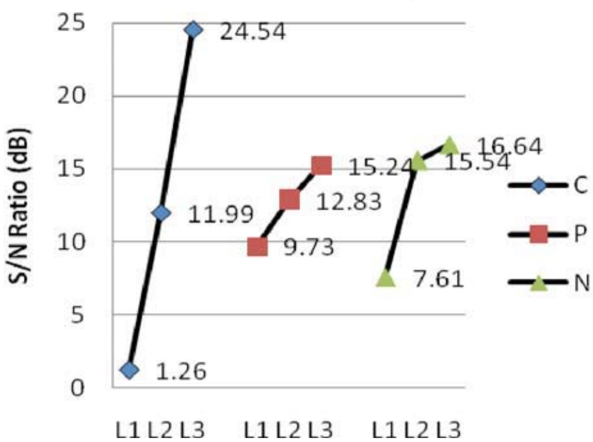

Fig. 2: Main Effects (S/N Ratio) for Material Removal

Tables 3 and 4. show the results of ANOVA for Raw Data and S/N Ratio associated with MR obtained from the L_9 orthogonal array based on Taguchi method.

Table 3: Pooled ANOVA (Raw Data, Material Removal)

Source	SS	DOF	V	F- Ratio	SS'	P %
C	1549.90	2	774.95	68.68*	1527.3	75.75
P	89.45	2	44.725	3.96*	66.89	4.37
N	180.99	2	90.495	8.02*	158.43	8.85
E (Pooled)	225.65	20	11.28	--	293.35	11.03
Total (T)	2145.6	26	--	--	2045.6	100

* Significant at 95 % confidence level

$F_{critical}$=3.4928

SS –Sum of Squares, DOF–Degree of Freedom, V–Variance, SS' Pure Sum of Squares

As shown in these tables, all the selected three parameters of abrasives-to-media concentration ratio (C), extrusion pressure (P) and number of cycles N) significantly affect both the mean and the variation in the MR values. The percentage contribution of Abrasives-to-media concentration is highest (75.75%) for MR followed by number of cycles (8.85%), and extrusion pressure (4.37%).

Table 4: Pooled ANOVA (S/N Ratio, Material Removal)

Source	SS	DOF	V	F- Ratio	SS'	P %
C	815.15	2	407.575	353.52*	812.85	82.38
P	45.73	2	22.87	19.83*	43.43	4.62
N	126.36	2	63.18	54.8*	124.05	12.77
E (Pooled)	2.31	2	1.155	--	9.22	0.23
Total (T)	989.55	8	--	--	989.55	100

* Significant at 95 % confidence level, $F_{critical}$ = 19

SS–Sum of Squares, DOF–Degree of Freedom, V–Variance, SS'–Pure Sum of Squares

It is evident that MR increases with the increase in the abrasives-to media ratio as more abrasives hence cutting edges are available in the media. With the increase in the extrusion pressure upto 10 MPa decrease in MR is attributed to the fact that with increased pressure there is lesser rolling of abrasives in media and media glides as a block without new cutting edges of abrasives coming in contact with the material surface. Further increase MR after 10 MPa pressure is due to the fact that more extrusion pressure enables the abrasive particles to strike the surface with the greater cutting forces.As observed in literature increase in the number of cycles, initially increases the MR faster and then the material removal rate decreases.

The optimum levels of the parameters for the higher MR are the third level of Abrasives-to-Media concentration ratio (C_3), third level of extrusion pressure (P_3) and also third level of number of cycles (N_3).

Effect on %Age Improvement in Ra (ΔR_a)

The average values and main effects (S/N ratio) for percentage improvement in surface finish ($\Delta \mathbf{R}_a$) are shown in Figure 3.

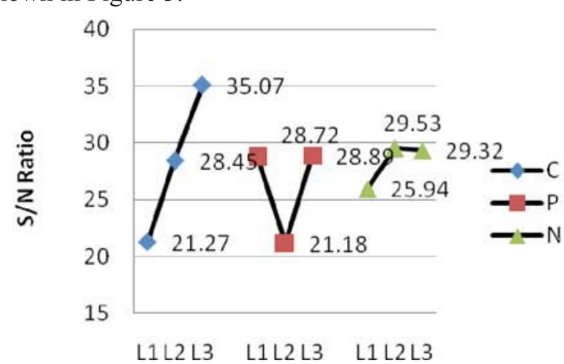

Fig. 3: Main Effects (S/N Ratio) for % Age Improvement in Surface Finish (ΔR_a)

Tables 5 and 6 show the results of ANOVA associated with %age improvement in Ra (ΔR_a) for Raw data and S/N ratio as obtained from the L9 orthogonal array based on Taguchi method.

Table 5: Pooled ANOVA (Raw Data, %Improvement in ΔR_a)

Source	SS	DOF	V	F- Ratio	SS'	P %
C	9887.5	2	4943.75	65.41*	9736.3	73.78
P	743.3	2	371.66	4.92*	592.15	5.55
N	1259.1	2	629.07	8.33*	1107.9	9.40
E (Pooled)	1511.6	20	75.58	--	1965.1	11.27
Total (T)	13401.6	26	--	--	13401.6	100

*Significant at 95 % confidence level, $F_{critical}$ =3.4928
SS–Sum of Squares, DOF–Degree of Freedom, V–Variance, SS'–Pure Sum of Squares

Table 6: Pooled ANOVA (S/N Ratio, % Age Improvement in ΔR_a)

Source	SS	DOF	V	F- Ratio	SS'	P %
C	285.74	2	142.87	1262.40*	285.52	90.54
P	5.32	2	2.66	23.51*	5.09	1.69
N	24.32	2	12.16	107.44*	24.09	7.71
E (Pooled)	0.23	2	0.115	--	0.91	0.06
Total (T)	315.61	8	--	--	315.61	100

*Significant at 95 % confidence level, $F_{critical}$=19
SS–Sum of Squares, DOF–Degree of Freedom, V–Variance, SS'–Pure Sum of Squares

As shown in the both the tables, all the selected three parameters C, P and N significantly affect both the mean and the variation in the %age improvement in Ra (ΔR_a). The percentage contribution of Abrasives-to-media concentration is highest (73.78%) for %age improvement in Ra (ΔR_a) followed by number of cycles (9.40 %) and extrusion pressure (5.55%).

It is observed that increase in the abrasives-to media ratio, improves the surface finish. This simultaneous increase in the MR and surface finish is very unique behaviour of AFM compared to other machining processes. It leads to lesser number of cycles and lesser pressures and thus leading to fast machining. One possible explanation for this could be that in AFM, the material removal takes place first from the hills or peaks of the surface profile. Further removal of more material produces smoother surface. The increase in pressure first deteriorates the surface finish and after the second pressure level surface finish starts improving. This can be attributed to the fact that at medium pressure the cutting edges are blunt and produce deep scratches. But at higher pressures the media flow is more viscous, thus leading to improvement in the surface finish. It is further noted that increase in the number of cycles initially leads to improvement in the surface finish and after the second level of number of cycles (10 cycles) the surface finish starts deteriorating. This fact can be attributed to the initial material removal from the peaks, which leads to the improvement in the surface finish. After the peaks are removed and a good surface finish has been achieved, the further cycles lead to deterioration of this surface due to abrasives. So the optimum levels of the parameters for the higher percentage improvement in Ra (based on S/N ratio) are the third level of Abrasives-to-Media concentration ratio (C_3), third level of extrusion pressure (P_3) and second level of number of cycles (N_2).

Estimation of Optimum Response Characteristics and Confirmation Experiments

The optimum values of the response characteristic along with their respective confidence intervals have been predicted using the Taguchi approach [19, 20, 22].

As observed the optimum values for maximum MR are $C_3P_3N_3$ and for maximum percentage improvement in ΔR_a are $C_3P_3N_2$ according to S\ N data.

Predicted Material Removal (MR):

The mean at the optimal MR (optimal value of the response characteristic) is estimated as:

$$MR = \bar{C}_3 + \bar{P}_3 + \overline{N_3} - 2\bar{T} = 22.79 \text{ mg}$$

Where

$\bar{T}$=Overall mean of the response = 8.16 mg (Table 2)

$\bar{C}_3$=Average of MR at the third level of abrasives-to-media concentration ratio = 18.76 (Table 7a)

$\bar{P}_3$=Average of MR at the third level of extrusion pressure = 10.19

$\bar{N}_3$=Average of MR at the third level of number of cycles=10.16

Substituting theses values, MR = 22.79 mg

Table 7(a): Average Values and Main Effects (Raw Data) for Material Removal (MR) in mg

	Level 1	Level 2	Level 3
C	1.51	4.2	18.76
P	8.50	5.77	10.19
N	4.5	9.81	10.16

Predicted Percentage Improvement in ΔR_a:

The mean at the optimal percentage improvement in ΔR_a (optimal value of the response characteristic) is estimated as:

Table 7(b): Average Values and Main Effects (Raw Data) for Ercentage Improvement In Surface Finish (ΔR_a) in % Age

	Level 1	Level 2	Level 3
C	13.28	30.76	59.69
P	38.46	27.16	38.12
N	25.41	41.80	36.53

Table 8: Predicted Optimal Values, Confidence Intervals and Results of Confirmation Experiments

Response	Optimal Process Para-meters	Predicted Optimal Value	Confidence Interval 95%	Actual Value (Avg of Confirmation Exp)
MR	$C_3P_3N_3$	22.79 mg	CI_{CE}: 17.4 <*MR*>28.18 CI_{POP}: 19.23<*MR*>26.35	25.29 mg
% Improvement in ΔR_a	$C_3P_3N_2$	70.45 %	CI_{CE}: 56.54 <% ΔR_a >84.36 CI_{POP}: 61.22 <% ΔR_a > 79.68	78.09 %

$$\Delta \text{Ra} = \bar{C}_3 + \bar{P}_3 + \overline{N_2} - 2\bar{T}$$

Where

$\bar{T}$ =Overall mean of the response=34.58 (Table 2)

$\bar{C}_3$=Average of %age improvement in ΔR_a at the third level of abrasives-to-media concentration ratio = 59.69% (Table 7b)

$\bar{P}_3$=Average of %age improvement in ΔR_a at the third level of extrusion pressure = 38.12 %

$\bar{N}_2$=Average of %age improvement in ΔR_a at the third level of number of cycles = 41.80 %

Substituting theses values, MR = 70.45%

Confirmation Experiments

In order to validate the results obtained, three confirmation experiments have been conducted for response characteristics of MR at the optimal levels of $C_3P_3N_3$ and %age improvement in ΔR_a at the optimal levels of $C_3P_3N_2$ of process parameters based on S/N ratio. (refer table 8). The values of MR and %age improvement in ΔR_a obtained through the confirmation experiments are within 95% of CICE of respective response characteristic.

Conclusion

The important conclusions of this research work are enlisted below:

The results show that the process parameter Abrasives-to-media ratio has the highest contribution towards the response characteristics and is 75.75% and 73.78 %, respectively for the MR and %age improvement in ΔR_a. Increase in Abrasives-to-media ratio from 1:1.25 to 1.25:1 leads to improvement in both the response characteristics, which is the unique advantage of AFM, as it leads to faster finishing.

The percentage contribution of Number of Cycles is 8.85% and 9.40% respectively for the MR and %age improvement in ΔR_a. As the number of cycles increase from 5 to 15, the MR goes on increasing, but the %age improvement in ΔR_a is maximum at the second level of 10.

The Extrusion pressure is also significant but least effective for the present setup and its contribution is 4.37% and 5.55% respectively for the MR and %age improvement in ΔR_a. The MR and surface finish are more at the third level of 15 MP.

It is confirmed that at optimal process parameters of $C_3P_3N_3$, the MR improves by 22.79 %. Whereas the optimal process parameters of $C_3P_3N_2$, the percentage improvement in ΔR_a improves by 70.45%.

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