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Study the Effects of Centrifugal Force on Abrasive Flow Machining Process

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Abstract
Abrasive flow machining is a non-conventional machining process and was developed in late 1960's as a method to deburr, polish and radius difficult to reach surfaces such as intricate geometries by flowing a semi-liquid paste over them. Abrasion occurs wherever the medium passes through the highly restrictive passage. The key components of AFM process are the machine, tooling and abrasive medium. The AFM is capable of economically producing high surface finish. One serious limitation of this process is its low productivity in terms of rate of improvement in surface roughness. Till now limited efforts have been done towards enhancing the productivity of this process with regard to better quality of work piece surface. In recent years, hybrid-machining processes have been developed to improve the efficiency of such processes. This paper discusses centrifugal force as a technique for productivity enhancement in terms of surface roughness (Ra). A rotating Centrifugal Force Generating (CFG) rod was used inside the cylindrical work piece, which provides the centrifugal force to the abrasive particles normal to the axis of work piece. The effect of the key parameters on the performance of process has been studied.

Keywords
Abrasive Flow Machining (AFM), CFAAFM, CFG Rod

I. Introduction

Abrasive Flow Machining (AFM) is one of the latest non-conventional finishing processes, which possesses excellent capabilities for finish-machining of inaccessible regions of a component. It has been successfully employed for deburring, radiusing, and removing recast layers of precision components by extruding an abrasive laden polymer medium with very special rheological properties. High levels of surface finish and sufficiently close tolerances have been achieved for a wide range of components [7]. The polymer abrasive medium which is used in this process possesses easy flowability, better self deformability and fine abrading capability. A special fixture is generally required to create restrictive passage or to direct the medium to the desired locations in the workpiece.

The basic principle behind AFM process is to use a large number of random cutting edges with indefinite orientation and geometry for effective removal of material. The extremely thin chips produced in abrasive flow machining allow better surface finish upto 50nm, close tolerances in the range ± 0.5µm, and generation of more intricate surface [2]. In this process tooling plays very important role in finishing of material.

In order to cater to the requirement of high-accuracy and high-efficiency finishing of materials, AFM is gaining importance day by day. The AFM process has a limitation too, with regard to achieving required surface finish. With the aim to overcome the difficulty of longer cycle time, the present paper reports the findings of a hybrid process, which permits AFM to be carried out with additional centrifugal force applied onto the cutting media. The Abrasive Flow Machining process is a process that involves extruding an abrasive-filled semisolid media through a workpiece passage. The elements required for AFM process are the machine, workpiece fixture (tooling) and media. The machine used in AFM process hydraulically clamps the work-holding fixtures between two vertically opposed media cylinder. These cylinders extrude the media back and forth through the workpiece(s).Two cylinder strokes, one from the lower cylinder and one from the upper cylinder, make up one process cycle. Both semiautomatic machines and high-production fully automated system are widely used. The extrusion pressure is controlled between 7-200bars, as well as the displacement per stroke and the number of reciprocating cycles are controlled. AFM process is an efficient method of the inner surface finishing process. In practical application, it has an obvious effect on surface finishing of the industrial valves, and the parts/components of die, etc.

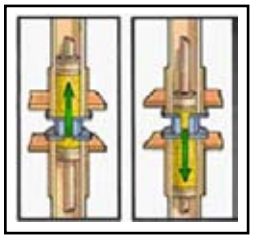


Fig. 1: AFM Process

The AFM process can largely help automation of surface finishing, saving manpower and promoting product quality. Generally speaking, the control parameters of the AFM process are extrusion pressure, media flow volume, number of working cycle etc. The result of the surface quality will be harmfully affected if improperly control the parameters in the process. It is necessary that an engineer must work on accumulating experience of the test results and does his/her best to understand the control parameters of the process such as engaging in the parameter experiment of the AFM process in order to identify the dominant factors, supporting the on-sight operation as consultant, promoting the efficiency of manufacture process and reducing the variables.

II. Literature Survey

A number of studies [4,6,10,12-13,27-28,31], show that the material removal rapidly increases during the initial cycles and there after it stabilized at higher number of cycles. This is due to the fact that higher peaks are removed during the initial process cycles when abrasive particles abrade these peaks; later the peaks become somewhat flatter and the rate of material removal and that of ΔRa reduce. Increased extrusion pressure, with all other parameters remaining constant, has significantly affected the work surface roughness [4-5,17]. Jain and Jain [13], reported that at higher pressure the improvement in material removal just tends to stabilize probably due to localized rolling of abrasion particles. The media flow rate has been reported to be a less-influential parameter in respect to material removal [2]. It has also been observed that greater the reduction ratio the more is the material removal from the work piece for a specified number of cycles. It has been noted that the fine grain size of the abrasive particles results in greater improvement of surface finish and the material

removal decreases. The reason for this seems obvious as the fine grains are expected to make finer but large number of cuts on the high spots on the work surface, thus generating smoother surface. There exists the possibility of using a large range of concentration of abrasive particles in carrier media (2–12 times the weight of carrier media)[14]. However, it has also been suggested that abrasive grain to base material ratio (by weight) should vary from 4:1 to 1:4 with 1:1 as the most appropriate ratio [1]. The media viscosity and geometrical shape of the work piece also affect the flow pattern.

The concept of Hybrid Machining Processes (HMP) is currently gaining attention with the aim to improve the performance by clubbing the advantages of different machining processes and to avoid or to reduce the limitations or adverse effects (if any) of the constituent processes [14]. A lot of work has been done in integrating non-traditional machining method like magnetic assistance, application of ultrasonic, incorporation of centrifugal force and electrochemical aid.

In Ultrasonic Flow Polishing (UFP), which is the combination of AFM and USM [11], is a hybrid process; surface finish improvements up to 10:1 were recorded. Another hybrid-machining process is the orbital flow machining process, which utilises the principle of orbital grinding and AFM [9]. The finishing of metals by Magnetic Abrasive Machining (MAM) was studied by many researchers [3,8,16]. The characteristic feature of MAM is that it employs very small machining pressure and is easily controllable with the help of input current to the electromagnet. Magnetically Assisted Abrasive Flow Machining (MAFM), which is the combination of AFM and MAF has been shown to give better results than obtained from individual AFM or MAF [17-18]. Magnetorheological Abrasive Flow Finishing (MRAFF), is basically a combination of Abrasive Flow Machining (AFM) and Magnetorheological Finishing (MRF), has been developed for nano-finishing of parts even with complicated geometry for a wide range of industrial applications. MRF is used for external finishing of optical lenses to the nanometer level in which forces are controlled by magnetic field [1-20,23]. Electrochemically Assisted Abrasive Flow Machining (ECAFM) using polypropylene glycol PPG with NaI salt share and the ethylene glycol PEG with KSCN salt share shows the larger material removal [21-22]. Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM), which is the combination of AFM and centrifugal force [24-27] was studied to improve the surface finish. To improve the performance efficiency of Abrasive Flow Finishing (AFF) process, Drill Bit Guided (DBG) AFF process has been proposed [29], here the cylindrical slug gets divided in two halves while entering in the finishing zone; at the exit side these two halves recombine resulting in better intermixing of the medium. The abrasive intermixing depends not only on the medium self-deformability but also on the pressure from the drill bit being exerted on the medium. Another hybrid process (R-AFF) in which externally rotated tooling and the reciprocation of medium with the help of hydraulic actuators was done to improve the surface finish [30-31].

III. Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM)

The fixture employed for the CFAAFM process is shown in fig. 2. In the current investigation the work piece was placed in between the media cylinders to create an artificial dead zone and increase the pressure required for extruding the media. The fixture was made in three parts and the work piece and rotating attachment were placed in between the three parts. During the operation, the media containing the abrasive particles was made to flow from one cylinder to the other cylinder through the central hole in the work piece. The work piece was surrounded by an attachment specially designed to give necessary rotary motion to CFG rod. While the media passed through the work piece cavity, the rotation of the CFG rod caused a centrifugal force to act on the abrasive particles so as to throw them on the internal surface (normal to the axis) of the work piece. Thus the media was thus subjected to the extrusion pressure as well as to the additional centrifugal pressure

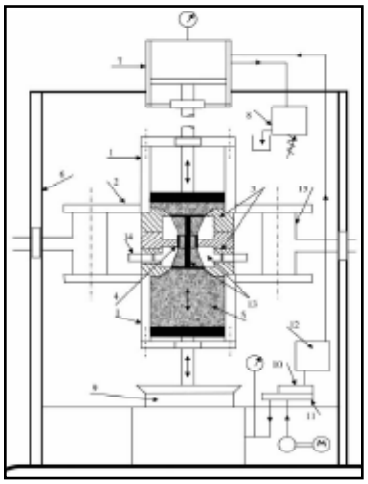


Fig. 2: Schematic illustration of the CFAAFM setup: 1. Cylinder containing media; 2. Flange; 3.Fixture; 4.Work piece; 5. Abrasive laden media; 6. Hydraulic press; 7. Auxiliary cylinder; 8. Modular relief valve; 9. Piston of hydraulic press; 10. Directional control valve; 11and12. Manifold blocks; 13. Rotating CFG rod assembly; 14. Idle gear, and 15. Eye bolt

A. Work-piece

In the present investigation, brass as work-piece material was used. The cavity to be machined in the test specimen was prepared by drilling operation followed by boring to the required size. The test work piece is shown in fig. 3. The internal cylindrical surface was finished by AFM process. Each work-piece was machined for a predetermined number of cycles. The work-piece was taken out from the setup and cleaned with acetone before the subsequent measurement.

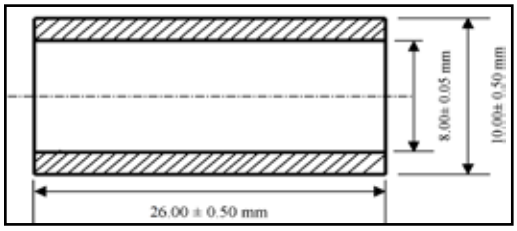


Fig. 3: Test Piece

The selected parameters and their range for the detailed experiments are shown in Table 1.

Table 1: Selected Process Parameters and their Range

S.No.	Process Parameter	Range	Unit
1	Shape of the CFG rod	Triangular-Rectangular-Spline	NIL
2	Rotational speed of CFG rod	0-60	RPM
3	Extrusion Pressure	5	N/mm^2
4	Number of cycles	2-6	No.
5	Abrasive particle size	13-16	Micron
6	Media Flow Volume	290	cm^3
7	Abrasive to media concentration	1:1	% by weight
8	Polymer-to-Gel Ratio	1:1	% by weight
9	Temperature of media	32 ± 2	°C
10	Reduction Ratio	0.95	---
11	Initial Surface Roughness	0.6-1.1	µm

4. Scheme of Experiments

The experiments were designed to study the effect of some of the AFM parameters on response characteristics of AFM process. Taguchi parametric design methodology was adopted [32-33]. The experiments were conducted using appropriate Orthogonal Array (OA).

The non-linear behavior, if exists, among the process parameters can only be studied if more than two levels of the parameters are used. Therefore, each parameter was analyzed at three levels. The selected number of process parameters and their levels are given in Table 2.

Each three level parameter has 2 degree of freedom (DOF = Number of levels-1), overall mean has a degree of freedom of 1, and the total DOF required for three parameters each at three levels is 7 =1+ [3 x (3-1)]. As per Taguchi's method the total DOF of selected OA must be greater than or equal to the total DOF required for the experiment. So an L9 (a standard 3-level OA) having 8 = (9-1) degree of freedom was selected for the present analysis. Standard L9 OA with the parameters assigned by using linear graphs is given in Table 3.

Table 2: Process Parameters and their Values at Different Levels

Symbol	Process Parameters	Unit	Level 1	Level 2	Level 3
C	Type of CFG rod	Nil	Triangular(T)	Rectangular(R)	Spline(S)
P	Rotational speed of the rod	RPM	0	30	60
N	Number of Cycles	Number	2	4	6

Polymer-to-Gel Ratio: 1:1, Work-piece material: Brass, Abrasive type: Al_2O_3, Grit Size: 150 (13-16 micron), Extrusion pressure: $5N/mm^2$, Media Flow Volume: 290 cm^3, Reduction Ration: 0.95, Temperature: 32 ± 2°C, Initial Surface Roughness of Work-piece: 3.8 -4.2 micron, Media Viscosity: 810 Pa.s.

Table 3: Orthogonal array for L9 with responses (raw data and S/N ratios)

Trial No.	Input parameters: Type of CFG rod	Rotational speed of the rod	Number of Cycles	Response (Raw Data) (ΔR_a)			S/N Ratio (dB)
	1	2	3	R_1	R_2	R_3	
	Trial Conditions						
1	T	0	2	15.23	14.8	15.89	23.69
2	T	30	4	30.16	25.53	27.23	28.83
3	T	60	6	23.84	22.36	21.12	27.02
4	R	0	4	24.21	29.95	25.13	28.44
5	R	30	6	29.47	33.64	26.60	29.51
6	R	60	2	16.26	14.35	13.48	23.34
7	S	0	6	32.00	38.02	33.83	30.78
8	S	30	2	21.42	25.3	25.16	27.58
9	S	60	4	37.50	31.56	33.82	30.70
	Total			230.09	235.51	222.26	

R_1, R_2, R_3 represent percentage improvement in surface roughness value for three repetitions of each trial. $\bar{T}_{\Delta Ra}$: Grant average of percentage improvement in surface roughness = ΔR_a=25.47 %

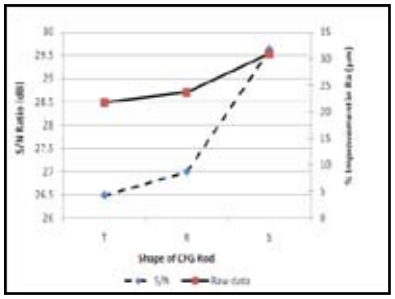
V. Results and Discussions

The average values of %age improvement in surface roughness and S/N ratio for each parameter at Level L_1, L_2 and L_3 are calculated and given in Table 4. These values have been plotted in fig. 4(a), fig. (b), fig. (c).

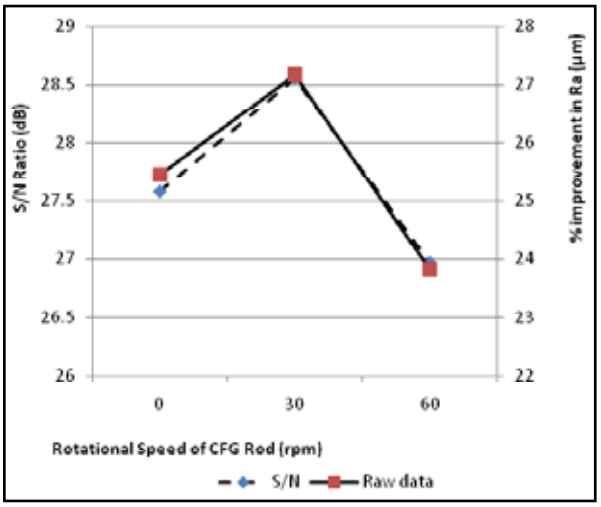
Table 4: Average Values and Main Effects: %age Improvement in R_a (ΔR_a)

Type of Data		Shape of CFG rod (C)		Rotational speed of CFG rod (P)		Number of cycles (N)	
Process Parameter	Level	Raw Data	S/N Ratio	Raw Data	S/N Ratio	Raw Data	S/N Ratio
Average Values (% R_a)	L_1	21.79	26.48	25.45	27.58	17.98	24.82
	L_2	23.67	26.99	27.16	28.56	29.45	29.24
	L_3	30.95	29.62	23.81	26.96	28.98	29.03
Main Effects (% R_a)	$L_2 - L_1$	1.88	0.51	1.71	0.98	11.46	4.42
	$L_3 - L_2$	7.28	2.62	-3.36	-1.59	-0.46	-0.21
Difference {($L_3 - L_2$) - ($L_2 - L_1$)}		5.39	2.10	-5.07	-2.57	-11.93	-4.64

L_1, L_2 and L_3 represent levels 1, 2 and 3 respectively of parameters. L_2-L_1 is the average main effect when the corresponding parameter changes from level 1 to level 2. L_3-L_2 is the main effect when the corresponding parameter changes from level 2 to level 3.



(a)



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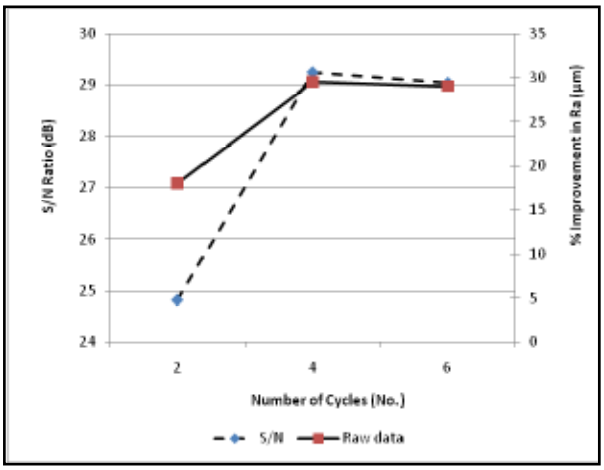

(c)

Fig. 4: Effect of process parameters on percentage improvement in surface roughness (ΔRa) and S/N ratio (main effects). (a) Effect of shape of CFG rod on raw data and S/N ratio; (b) effect of rotational speeds on raw data and S/N ratio and (c) effect of number of cycles on raw data and S/N ratio

Fig. 4(a), shows that with the change in the shape of CFG rod the percentage improvement in surface roughness varies in the sequence of Triangular, Rectangular and Spline rod. The percentage improvement in surface roughness is nominal by using Rectangular CFG rod as compared to Triangular CFG rod but using Spline shape CFG rod there is a huge improvement in the surface roughness of the work-piece. The probable reason for improvement in the surface roughness with Spline Shape CFG rod can be the number of edges to push the abrasive media particles on the work-piece are more as compared to Traingular and Rectangular shape of CFG rods. It can be observed from the Fig. 4(b), that increase in Rotational speed of CFG rod first improves the surface finish and after the second speed level surface finish starts deteriorating. The maximum surface finish is achieved at 30 rpm. Both the analysis predicts the deterioration of surface finish after the middle level of 30 rpm. This can be attributed to the fact that at with higher rotational speed of CFG rod, abrasives dig deeper into the material i.e. the abrasives are thrown on the work-piece and produces deep scratches. But before middle level of rotational speed of CFG rod the media moves in a block and individual abrasives are not as much digging into the work-piece so an improvement in the surface finish is observed. From fig. 4(c), it can be 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 (4 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 abrasion by abrasive particles.

As ΔRa is the 'higher the better' type quality characteristic, higher values of ΔRa were sought. From fig. 4(a), fig. 4(c), it can be seen that the third level for 'shape of CFG rod' parameter i.e. (A_3), second level for 'rotational speed of CFG rod' and 'number of cycles' parameters, i.e., (B_2) and (C_2) may provide maximum value of percentage improvement in surface roughness. As in the case of all the parameters A, B and C the highest values of mean response correspond to the highest values of S/N ratio.

In order to study the significance of the process parameters towards the percentage improvement in ΔR_a, analysis of variance (ANOVA) was performed. The pooled versions of ANOVA of the raw data and the S/N data for ΔR_a are given in Tables 5 & 6. From these tables, it is clear parameters A, B and C significantly affect both the mean and the variation in the percentage improvement in ΔR_a values. The percentage contribution of Number of cycles is highest (54.64%) followed by Shape of CFG rod (29.94%), and Rotational speed of CFG rod (2.74%). It is clear from the figure the fig. 4, that the percentage improvement in ΔR_a for raw data is highest at the third level of Shape of CFG rod (C_3), second level of Rotational speed of CFG rod (P_2) and second level of number of cycles (N_2).

Table 5: Pooled ANOVA (Raw Data (ΔR_a)

SOURCE	SS	DOF	V	F-RATIO	SS'	P %
Shape of CFG rod	421.39	2	210.69	31.73*	408.11	29.94
Rotational speed of CFG rod	50.74	2	25.37	3.82*	37.46	2.75
Number of Cycles	758.03	2	379.01	57.08*	744.76	54.64
E (Pooled)	132.79	20	6.64	--	172.63	12.66
Total (T)	1362.96	26	--	--	1362.96	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 Data (ΔR_a)

SOURCE	SS	DOF	V	F-RATIO	SS'	P %
Shape of CFG rod	17.03	2	8.51	88.66*	16.83	28.78
Rotational speed of CFG rod	3.88	2	1.93	20.19*	3.68	6.30
Number of Cycles	37.38	2	18.69	194.66*	37.19	63.59
E (Pooled)	0.19	2	0.096	--	0.77	1.31
Total (T)	58.48	8	--	--	58.48	100

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

VI. Estimation of Optimum Response Characteristics

As observed the optimum values for maximum percentage improvement in R_a are $A_3B_2C_2$ for both raw and S/N data. The mean at the optimal percentage improvement in ΔR_a (optimal value of the response characteristic) is estimated [30-31] as:

$$\Delta R_a = \overline{A_3} + \overline{B_2} + \overline{C_2} - 2 \times \overline{T}$$

where,

$\overline{T}$ = overall mean of the response = 25.47 % mg (Table 3)

$\overline{A}$ = Average value of % age improvement in ΔRa at the third level of shape of CFG = 30.95 %

$\overline{B}$ = Average value of % age improvement in ΔRa at the second level of rotational speed of CFG rod = 27.16 %

$\overline{C}$ = Average value of % age improvement in ΔRa at the second level of number of cycles = 29.45 %

Substituting these values of various terms in above equation,

% age improvement in ΔR_a = 30.95 + 27.16 + 29.45 – 2 x 25.47 = 36.62 %

The Confidence Interval of Confirmation Experiments (CICE) and of Population (CIPOP) is calculated by using the following equations:

$$CI_{CE} = \sqrt{F_\alpha(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \text{and}$$

$$CI_{POP} = \sqrt{\frac{F_\alpha(1, f_e) V_e}{n_{eff}}}$$

where,

$F_\alpha(1, f_e)$ = The F-ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom f_e = 4.35 (Tabulated F value)

f_e = error DOF = 20 (Table 4)

N = Total number of result = 27 (treatment = 9, repetition = 3)

R = Sample size for confirmation experiments = 3

V_e = Error variance = 6.64 (Table 4)

$$n_{eff} = \frac{N}{1 + [\text{DOF associated in the estimate of mean responce}]}$$

= 3.86

So, CI_{CE} = ± 4.10 and CI_{POP} = ± 2.73

The 95% confirmation interval of predicted optimal range (for confirmation run of three experiments) is:

$$\text{Mean } \Delta R_a - CI_{CE} < \%age\ improvement\ in\ \Delta \mathbf{Ra} >$$

$$\text{Mean } \Delta R_a - CI_{CE}$$

$$32.53 < \%age\ improvement\ in\ \Delta \mathbf{Ra} > 40.73$$

The 95% confirmation interval of the predicted mean is:

$$\text{Mean } \Delta R_a - CI_{POP} < \%age\ improvement\ in\ \Delta \mathbf{Ra} >$$

$$\text{Mean } \Delta R_a - CI_{POP}$$

$$33.9 < \%age\ improvement\ in\ \Delta \mathbf{Ra} > 39.36$$

The optimal values of process parameters for the predicted ranges of optimal % age improvement in ΔR_a are as follows:

- Shape of the CFG rod (A, 3rd level) = Spline
- Rotational speed of CFG rod (B, 2nd level) = 30rpm
- Number of cycles (C, 2nd level) = 4

VII. Confirmation Experiments

In order to validate the results obtained, three confirmation experiments were conducted at the optimum setting of the process parameters. The shape of CFG rod was set at the third level (A_3), rotational speed of CFG rod (rpm) was set at the second level (B_2) and number of cycles was kept at the second level (C_2). The average ΔR_a of the CFAAFM process was found to be 36.18%, which was within the confidence interval of the predicated optima of ΔR_a.

VIII. Conclusions

Rotating CFG rod used inside the hollow cylindrical work piece provides the centrifugal force to media is being processed by CFAAFM and an increase in percentage improvement in surface roughness was achieved. The following conclusions can be drawn from the study:

1. The result shows that the process parameter number of cycles has the highest contribution towards the response characteristic and is 54% for the percentage improvement in ΔRa. As the number of cycles increases from 2 to 6, the percentage improvement in ΔRa is maximum at the second level of 4. So lesser number of cycles led to better surface finish.
2. The percentage contribution of Shape of CFG rod is 29.94% for the %age improvement in ΔR_a. The percentage improvement in surface roughness increases in the sequence of Triangular, Rectangular and Spline rod.
3. The Rotational speed of CFG rod is also significant for the present setup and its shows 2.74% improvement in ΔR_a . At lower rotational speed of 30 rpm the surface finish is the best.
4. The 95% confidence interval of the predicted mean for ΔR_a is CICE: 32.53 < ΔRa(%) < 40.73
5. The predicted optimal range for ΔR_a is CIPOP: 33.9 < ΔR_a (%) < 39.36.

References

[1] Siwert, D.E.,"Tooling for the extrude hone process", Proceeding SME International Engineering Conference, WA, pp. 302–315, 1974.

[2] L.J. Rhoades,"Abrasive flow machining and its use". Proceedings of Non Traditional Machining Conference, Cincinnati, OH, December, pp. 111–120, 1985.

[3] Takazazawa, K., Shinmura, T., Hatano, E. ,"Deve-lopment of magnetic abrasive finishing and its equipment", Proc. Deburring and Surface Conditioning, SME Conference, Orlando,USA, 1985.

[4] Przyklenk,"Abrasive flow machining: a process for surface finishing and deburring of workpiece with a complicated shape by means of an abrasive laden medium", Advances in Non-traditional Machining, PED, Vol. 22, ASME, pp. 101–110, 1986.

[5] Williams, R.E., Rajurkar, K.P., Rhoades, L.J.,"Performance Characteristics of Abrasive Flow Machining", SME Technical Paper No. FC 89-806, 1989.

[6] Williams, R.E. Rajurkar, K.P.,"Stochastic modeling and analysis of abrasive flow machining", Trans. ASME, J. Engg. for Ind., Vol. 114, 1992, pp. 74–81

[7] Jones A.R., Hull J.B.,"A Model of the Pressure Distribution within Ultrasonically Energised, Polymer Suspended Abrasive Used for Surface Finishing Moulds and Dies", Key Engg. Materials, Vol 99-100, 1995, pp. 355-362.

[8] Loveless T.R., Williams R.E., Rajurkar K.P.,"A study of the effects of abrasive-flow finishing on various machined surfaces", Journal of Materials Processing Technology, Vol. 47, 1994, pp. 133-151.

[9] Kremen, G.Z., Elsayed, E.A., Rafalovich, V.I.,"Mechanism of material removal in MAP and the accuracy of machining", Int. J. Prod. Research, Vol. 34, No. 9, 1996, pp. 2629–2638.
[10] Gilmore J.R.,"Orbital polishing - an emerging technology", SME, Buff and Polish Clinic, Schaumburg, IL, 1997.
[11] Shan, H.S., Dubey, A.K.,"Micro Machining by Flow of Abrasives", Proceedings 17th AIMTDR Conference, Warrangal, India, pp. 269–275, 1997.
[12] Jones A.R., Hull J.B.,"Ultrasonic flow polishing", Ultrasonics, Vol. 36, 1998, pp. 97- 101.
[13] Jain R.K., Jain V.K.,"Abrasive fine finishing processes- a review", Int. J. of Manufacturing Science and Production, Vol. 2(1), 1999, pp. 55-68.
[14] Jain, R.K., Jain, V.K., Dixit, P.M.,"Modelling of material removal and surface roughness in abrasive flow machining process", Int. J. Machine Tool and Manufacture, Vol. 39, 1999, pp. 1903–1923.
[15] Rajurkar, K.P., Kozak, J.,"Hybrid Machining Process Evaluation and Development", Proceeding 2nd Int. Conf. on Machining and Measurement of Sculptured Surfaces, Poland, 2000, pp. 501-536.
[16] Khairy, A.B. (2000),"Aspects of surface and edge finishing by magneto abrasive particles", Proc. Int. Conf. on Advanced Manufacturing Technology, Malaysia, pp. 77–84.
[17] Yamaguchi, H., Shinmura, T.,"Study of magnetic abrasive finishing using a pole rotationsystem", Precision Engineering Journal, Vol. 24, 2000, pp. 237–244.
[18] Singh Sehijpal (2002),"Studies in metal finishing with magnetically assisted abrasive flow machining", PhD thesis, IIT Roorkee.
[19] Singh S., Shan H.S.,"Development of magneto abrasive flow machining process", Int J Mach Tools Manuf, Vol 42, 2002, pp: 953–959.
[20] Jha S., Jain V.K.,"Design and development of the Magnetorheological Abrasive Flow Finishing (MRAFF) process", International Journal of Machine Tools & Manufacture, Vol. 44, 2004, pp. 1019–1029.
[21] Singh D.K., Jain V.K., Raghuram V., Koanduri R., "Analysis of surface texture generated by a flexible magnetic abrasive brush", Wear, Vol. 259, 2005, pp. 1254–1261.
[22] Dabrowski L., Marciniak M., Szewczyk T.,"Analysis of Abrasive Flow Machining with an Electrochemical Process Aid", Proceedings of the Institution of Mechanical Engineers - Part B, Vol. 220, Issue 3, 2006, pp. 397-403.
[23]. Akagami Y., Umehara N.,"Development of electrically controlled polishing with dispersion type ER fluid under AC electric field", Wear, Vol. 260, 2006, pp. 345–350.
[24] Jha S., Jain V.K.,"Modeling and simulation of surface roughness in Magnetorheological Abrasive Flow Finishing (MRAFF) process", Wear, Vol. 261, 2006, pp. 856–866.
[25] Walia R.S. ,"Ph.D. Thesis: Development and Investigations in Centrifugal Force Assisted Abrasive Flow Machining Process", IIT, Roorkee, 2006.
[26] Walia R.S., Shan H.S., Kumar P.,"Parametric optimization of Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM) By the Taguchi Method", Journal of Materials and Manufacturing Processes, USA. Vol. 21, Issue 4, 2006, pp. 375-382.
[27] Walia R.S., Shan H.S., Kumar P.,"Multi-response optimization of centrifugal force assisted abrasive flow machining (CFAAFM) process through Taguchi method and Utility concept", Journal of Materials and Manufacturing Processes, Vol. 21, 2006, pp. 907-914.
[28] Walia R.S., Shan H.S., Kumar P.,"Abrasive flow machining with additional centrifugal force applied to the media", Machining Science and Technology an International Journal, Vol.10, 2006, pp. 341-354.
[29]. Wang AC, Tsai L., Liang KZ, Liu C, Wang SH,"Uniform surface polished method of complex holes in abrasive flow machining" Trans. Nonferrous Met. Soc. China, (2006), Vol. 19, 2009, pp. 250−257.
[30] Sankar R.M., Monda, S., Ramkumar J., Jain V.K., "Experimental investigations and modelling of drill bit-guided abrasive flow finishing (DBG-AFF) process", International Journal of Advanced Manufacturing Technology, Vol. 42, 2009, pp. 678–688.
[31] Sankar M.R., Jain V.K., Ramkumar J.,"Experimental investigations into rotating workpiece abrasive flow finishing" Wear, Vol. 267, 2009, pp: 43–51.
[32] Sankar M.R., Jain V.K., Ramkumar J.,"Rotational abrasive flow finishing (R-AFF) process and its effects on finished surface topography", International Journal of Machine Tools and Manufacture, Vol. 50, 2010, pp. 637-650.
[33] Ross P.J.,"Taguchi Techniques for quality engineering", McGraw Hill, New York, 1996.
[34] Roy R.K.,"A primer on Taguchi method", Van Nostrand Reinhold, New York, 1990.