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Experiments with Distinct Abrasive Flow Machining Media at Different Operating Temperatures

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Abstract:- Amongst the Non Conventional Machining Processes, Abrasive flow machining (AFM) is famous for its ability to finish internal passages which are difficult to finish by other finishing tools.Beginning of this process started with aerospace industry,but now it finds its uses in automotive,bio-medical implants, die making industry, etc. In the present investigation, the effect of three different AFM media and variations in the experimental temperature have been studied for the quality characteristics of Material Removal and Percentage Improvement in Surface Roughness. The experiment was designed on the basis L9 orthogonal array and the various parameters have been optimized using the concept of robust engineering as suggested in Taguchi method.

Keywords*:* – Abrasive aluminiun oxide; abrasive flow machining; Types of media; Thermal AFM.

1. Introduction

Abrasive flow machining (AFM) also known as Extrude Honing, is a precision finishing process used in various industries to improve the surface quality of complex and intricate components. It involves the controlled removal of material from the interior surfaces of workpieces using a mixture of abrasive media and a viscous, polymer-based carrier fluid. This process is particularly valuable in applications where achieving precise and consistent surface finishes is crucial for performance and longevity of the parts [1]. one of the primary advantages of Abrasive Flow Machining is its ability to address intricate and difficult--to-reach areas that are challenging to finish using traditional methods. This is particularly relevant in industries such as aerospace, automotive, medical, and mold-making, where components often have complex internal geometries that require uniform surface finishes for optimal performance. The process begins by selecting an appropriate abrasive media based on the material and geometry of the workpiece. The chosen abrasive, typically silicon carbide or aluminum oxide, is mixed with a polymer-based carrier fluid to create a highly viscous, putty-like substance. This mixture is then forced through the workpiece's internal passages using hydraulic pressure, controlled by a specialized machines the abrasive-laden fluid flows through the component, it abrades the surfaces it comes into contact with. The rate of material removal can be precisely controlled by adjusting parameters such as pressure, flow rate, and dwell time. This level of control allows for the achievement of extremely tight tolerances and consistent surface finishes [2,3,4]

Benefits of AFM

Improved Surface Finish: Extrude honing can achieve surface finishes down to sub-micron levels. This is critical in applications where smooth surfaces are essential for reducing friction, improving fluid flow, or enhancing fatigue resistance, Uniform Material Removal: Unlike some other finishing processes, extrude honing provides uniform material removal across the entire surface of the workpiece. This ensures that no localized stress concentrations or irregularities are introduced, deburring and radiusing: The process is highly effective at removing burrs, sharp edges, and irregularities, which is crucial for enhancing the durability and performance of components, **in**creased performance and efficiency: Components subjected to extrude honing often exhibit improved fluid flow characteristics, reduced friction, and enhanced fatigue resistance. This can lead to increased operational efficiency and longevity, complex geometry. Accessibility: Extrude honing can reach and finish internal surfaces that would be nearly impossible to access using conventional methods like milling or grinding [4,5]

The pursuit of high-quality products and processes has always been a paramount objective in manufacturing and engineering. The Taguchi Method, pioneered by Dr. Genichi Taguchi, has emerged as a seminal approach to achieving this goal. This statistical technique transcends traditional quality control measures by not only detecting and rectifying defects but by fundamentally designing robust processes that are inherently resistant to variation. This article delves into the essence of the Taguchi Method, its key principles, and its widespread application across industries. Focus on robustness is one of the fundamental tenets of the Taguchi Method and it emphasis on creating products and processes that are robust to sources of variation. Instead of striving to eliminate variability entirely, the approach acknowledges that some level of variation is inevitable. Thus, the goal is to design systems that perform reliably even in the presence of these variations. Signal-to-Noise Ratio, instead of relying solely on traditional quality metrics that focus on defects or deviations, the Taguchi Method introduces the concept of Signal-to-Noise Ratio. This metric assesses the variability relative to the desired performance, providing a more nuanced and comprehensive measure of quality [6,7].

In the present investigations, effect of different AFM media (viz. common toothpaste, paraffin wax and silicone based polymer) and temperatures have been studied in the finishing of internal cylindrical hole in the brass work-pieces. Special fixtures was designed to maintain the required temperatures and the developed AFM setup has been names as Thermal-AFM process. The different parameters have been optimised to achieve optimal material removal and percentage improvement in the surface finish.

2. Experimental Materials

In the present investigation a hollow cylindrical work-piece of brass (yellow brass :65 % Cu,35%Zn having BHN hardness 156) is finished. The inner surface of the workpiece has been prepared by drilling operation. Initial surface roughness of the specimens is in the range of (2.2 -2.4) microns. Workpiece is a hollow cylindrical piece with I.D.10 mm, O.D.13.8 mm and length 16 mmfor abrading the material of brass. During the experimentation, abrasive laden media is extruded through the hollow cylindrical workpiece. The workpiece is held in the setup with the help of designed nylon fixtures.

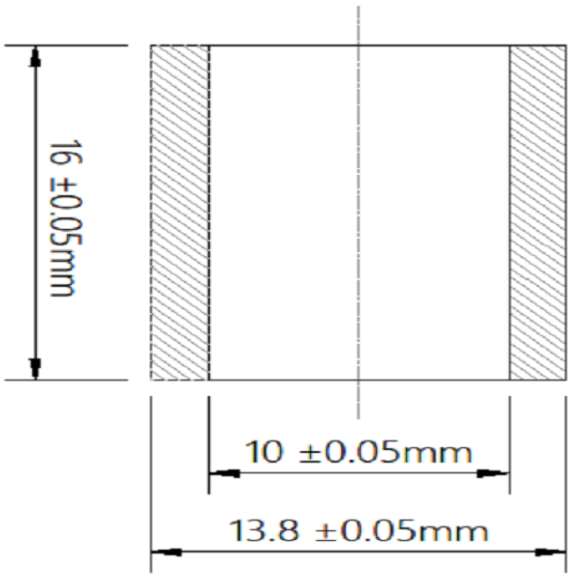


Fig.1. Dimensions of the hollow cylindrical work-piece.

Equipment and Procedure

The inhouse designed and developed setup has the highest extrusion pressure of 25N/mm². Media is pushed by two actuators which are connected to two media cylinders, media passes from one media cylinder to another media cylinder through the workpiece. when this stroke is complete reverse stroke occurs and both upward and downward strokes complete one cycle. Thermal jackets are provided around media cylinders and to check temperature digital thermometer is used of range 0°C to 100°C. The temperature is achieved with the help water dispenser of Voltas 500W to supply hot and cold water. The stroke length is permanent value of100 mm and media volume has been taken as 310 cc. Media cylinder I.D 63 mm. when media passes through the work-piece,it aims to finish the inner surface of the work-piece.The internal cylindrical surface of the work piece is finished by the abrasion process,when the abrasives laden media extrudes through this.Each workpiece was machined for a predetermined number of cycles.The workpieces were measured by a precisionelectronic balance(CX220) with 0.1mgresolution before and after each experiment to calculate the material removal.The measurement of surface roughness(avg of three values) employeda precision profilometer (Mitutoyo SJ-201) to evaluate the quality of the machined surface.

Fig. 2. Developed Thermal-AFM setup at (Yadavindra Department of Engineering, Talwandi Sabo). The media temperature is maintained at 15°C,25°C&35°C.

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 and Number of cycles (N), Temprature(T), Media type (M) were varied to determine their effect on the machining characteristics of material removal (MR) and %age improvement in the surface roughness. The experiments were designed to study the effect of these on response characteristics of AFM process. Table 1shows the various levels of process parameters, and values of other fixed parameters

Table 1. Process Variables and their Values at Different Levels

Character	Process Parameters	Unit	Level tent 1	Level 2	Level 3
N	Number of Cycles	Number	3	6	9
T	Temprature	°C	15	25	35
M	Media	-	Toothpaste	Paraffin Wax	Silicone based polymer
Polymer-to-Gel Ratio: 1:1 of, Work-piece material: Brass, Abrasive type: Al_2O_3, Grit Size: 150. Media Flow Volume: 310 cm^3, Reduction Ratio: 0.97, Initial Surface Roughness of Work-piece: 2.2 -2.4) microns.					

3. Response Parameters

The effect of selected process parameters was studied on the following response characteristics of AFM process: Percentage Improvement in Surface Roughness (%ΔR_a): The average of R_a value was calculated and the percentage improvement in roughness was estimated as:

$$\%\Delta R_a = \frac{(InitialRoughness - \ FinalRoughness) \ \times 100}{InitialRoughness}$$

A. 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.

B. Experimental design based on Taguchi Method: The L_9 orthogonal array has been chosen. It had four columns and 9 rows, and three parameters have been assigned to the first three columns, and the rows designate nine experiments with various combination levels of the selected machining parameters. In this investigation only three parameters at three levels each were considered. Three observed values of MR and Percentage improvement in surface finish (ΔR_a) were examined for each experiment. The levels of each machining parameter were set according to the L_9 orthogonal array, based on the Taguchi method. Moreover, the significant machining parameters associated with MR and % Improvement in (ΔR_a) 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 (2.2 – 2.4 micron). In each of the trial conditions and for every replication, the percentage improvement in surface roughness and material removal were measured

C.For preparation of media: (M_1) 250 g of toothpaste and 250g Al_2O_3 abrasive is taken of grit size 150, (M_2) 250 g of paraffin wax and 250g Al_2O_3 abrasive, (M_3) 250 g of polymer and 250g Al_2O_3 abrasive.

Silicon based Polymer was prepared from Silicon oil, lewis acid, Pyroboric acid, ammonium carbonate and gel was prepared from napthenic oil and aluminium stearate after preparation and cooling, then these were mixed in the ratio 1:1[20].

Fig. 3. Materials for preparing silicone based polymer.

4. 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 given in Table 2. The standard method to analyze the data based on S/N ratio, as suggested by Taguchi, is worked out. 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.

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

where

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

, R = Number of repetitions, y_j = 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 (M1, M2, M3). 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. Number of cycles 3,6,9; Temprature set around media cylinders is 15°C,25°C,35°C; 1 means Toothpaste, 2 means paraffin wax, 3 means Polymer (Polyborosiloxane)[21,22,23] for media type

Effect on Material Removal (MR)

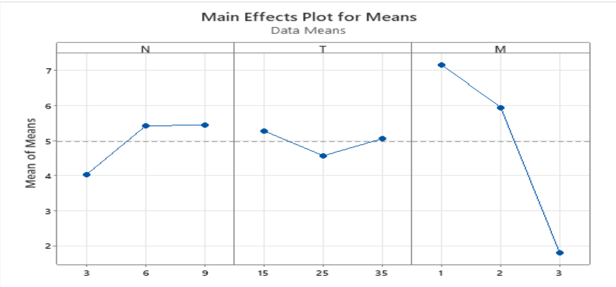
Number of cycles: it is clearly shown in figure as number of cycles increases from 3 to 9 the material removal increase. More number of cycles means more abrasion action and higher material removal.

Temprature: at a temprature 15°C, more material removal is observed than 25°C and 35°C, it is due to the increased viscosity of the media at the low temperatures.

Type of media: It is observed that the toothpaste gives more material removal and is followed by paraffin wax and polymer in this order.

Table 2.

Exp. No.	1	2	3	Responses for Material Removal MR			
	N	T	M	R1	R2	R3	S/N Ratio
1	1	1	1	6.2	6.7	6	15.95
2	1	2	2	4.9	4.7	5	13.73
3	1	3	3	1.3	0.7	0.8	-1.45
4	2	1	2	7	6.7	6.4	16.51
5	2	2	3	1.3	1.6	1.9	3.76
6	2	3	1	7.9	8.2	7.8	18.01
7	3	1	3	2.7	2.8	3	9.02
8	3	2	1	7.3	7.1	7.3	17.18
9	3	3	2	6.3	6	6.5	15.92



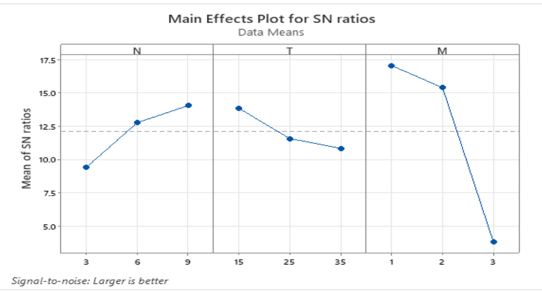


Table 3. Response Table for Means of Material Removal (MR)

Level	N	T	M
1	4.033	5.278	7.167
2	5.422	4.567	5.944
3	5.444	5.056	1.789
Delta	1.411	0.711	5.378
Rank	2	3	1

Table 4. ANOVA (S/N Ratio of material removal)

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Number of Cycles	34.32	2	17.16	9.15	2.78	NO (SIGNIFICANT)
Temprature	14.65	2	7.32	3.91	1.18	NO
Media	313.83	2	156.92	83.65	25.45	YES (SIGNIFICANT
ERROR	24.62	2	12.32	3.28		
T	375.13	8				
* Significant at 95 % confidence level, $F_{critical}$ = 19						
SS – Sum of Squares, DOF – Degree of Freedom, V – Variance, SS' – Pure Sum of Squares						

The percentage contribution of media is 83.65%, temprature is 3.91% and number of cycles 9.15%. Media is the most significant parameter.

Table 5. ANOVA of raw data

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Number of Cycles	11.76	2	5.88	7.37	91.25	YES(SIGNIFICANT)
Temprature	2.38	2	1.19	1.49	18.48	YES(SIGNIFICANT)
Media	143.05	2	71.52	89.69	1109.86	YES(SIGNIFICANT)
ERROR	2.29	20	0.115			
T	159.48	26				
* Significant at 95 % confidence level, $F_{critical}$ = 3.5 SS – Sum of Squares, DOF – Degree of Freedom, V – Variance, SS' – Pure Sum of Squares						

Effect on Percentage Improvement in Surface Roughness

Number of cycles: it is visible in figure below as number of cycles increases from 3 to 6 the % improvement in surface roughness increases but as number cycles increases from 6 to 9 % improvement in surface roughness decreases. This means that as we increase number of cycles more than 6 material starts deteriorating

Temprature: Temprature 15°C gives more % improvement in surface roughness than 25°C and 35°C

Type of media: Polymer gives more % improvement in surface roughness than Toothpaste and Paraffin wax.

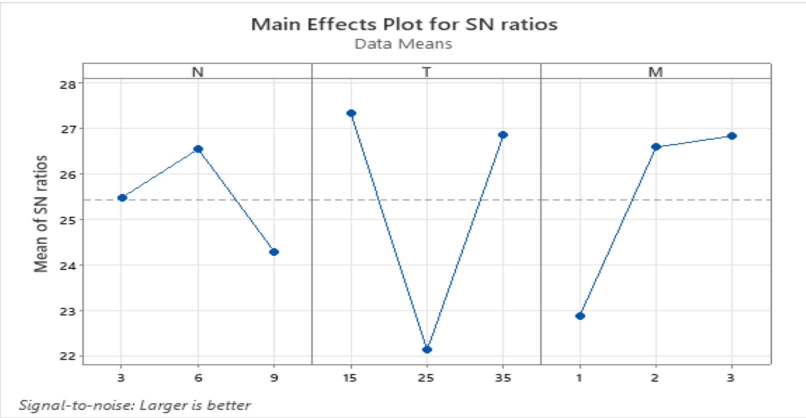
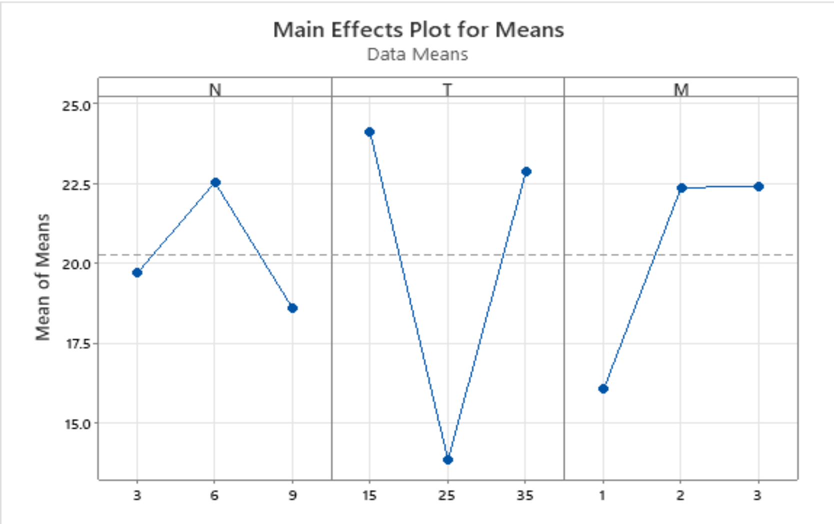


Table 6. Response Table for Means % Improvement in surface roughness

Exp. No.	1	2	3	% improvement in surface roughness			
	N	T	M	R1	R2	R3	S/N Ratio
1	1	1	1	17.68	23.07	15.19	25.03
2	1	2	2	17.28	18.11	12.77	23.79
3	1	3	3	23.79	25.48	24.48	27.81

4	2	1	2	26.59	28.83	30.42	29.09
5	2	2	3	17	18.97	16.74	24.85
6	2	3	1	14.245	24.73	25.25	25.66
7	3	1	3	21.45	27.36	26.4	27.83
8	3	2	1	9.59	7	7.65	17.92
9	3	3	2	23.2225	23.52	21.18	27.06



Level	N	T	M
1	19.69	24.11	16.05
2	22.53	13.83	22.37
3	18.6	22.88	22.41
Delta	3.93	10.28	6.36
Rank	3	1	2

Table 7. ANOVA of S/N Ratio % improvement in surface roughness

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Number of Cycles	7.72	2	3.86	8.87	6.43	NO (SIGNIFICANT)
Temprature	48.19	2	24.09	55.38	40.16	YES (SIGNIFICANT
Media	29.91	2	14.95	34.36	24.92	YES (SIGNIFICANT
ERROR	2.38	2	1.18	1.37		
T	87.02	8				

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

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

The percentage contribution of media is 34.36%, Temprature is 55.38% and Number of cycles 8.87%. Media and Temprature are significant parameter

Table 8. ANOVA of raw data

SOURCE	SS	DOF	V	P	F-Ratio	Pooling
Number of Cycles	73.49	2	36.74	7.01	4.01	YES (SIGNIFICANT)
Temprature	558.94	2	279.47	53.32	30.50	YES (SIGNIFICANT)
Media	243.98	2	121.99	23.27	13.32	YES (SIGNIFICANT)
ERROR	171.88	20	8.59			
T	1048.29	26				

* Significant at 95 % confidence level, $F_{critical}$ = 3.5

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

5. Estimation of Optimum Response Characteristics and Confirmation Experiments

Material Removal (MR)

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

$$MR = \bar{N}_3 + \bar{T}_1 + \overline{M_1} - 2\bar{T}$$

$\bar{T}$ = overall mean of the response = 4.967 mg (Table 3)

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

= 5.444 mg

$\bar{T}_1$ = Average value of MR at the first level of temprature

= 5.278 mg

M_1 = Average value of MR at the first level of media

= 7.167 mg

Substituting these values, MR = 7.955 mg

The confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{POP}) is calculated by using the following equations:

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

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

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 5)

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

R = Sample size for confirmation experiments = 3

V_e = Error variance = 0.115 (Table 5)

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

= 3.86

So, $CI_{CE} = \pm0.544$

And $CI_{POP} = \pm0.359$

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

Mean MR – $CI_{CE} < MR >$MR + CI_{CE}

$7.41 < MR > 8.499$

The 95% confirmation interval of the predicted mean is :

Mean MR – $CI_{CE} < MR >$MR + CI_{CE}

$7.596 < MR > 8.314$

Percentage improvement in ΔRa

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

$$\Delta Ra = \bar{N}_2 + \bar{T}_1 + \overline{M_3} - 2\bar{T}$$

$\bar{T}$ = overall mean of the response = 20.296 % mg (Table 7)

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

= 22.53 %

$\bar{T}_1$ = Average value of % age improvement in ΔR_a at the first level of temprature

= 24.11 %

M_3 = Average value of % age improvement in ΔR_a at the third level of media

= 22.41 %

Substituting these values, % age improvement in ΔR_a = 28.458 %

The confidence interval of confirmation experiments (CI_{CE}) and of population (CI_{POP}) is calculated by using the following equations:

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

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

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 8)

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

R = Sample size for confirmation experiments = 3

V_e = Error variance = 8.59 (Table 8)

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

= 3.86

So, $CI_{CE} = \pm 4.7$

And $CI_{POP} = \pm 3.1$

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

$23.75 < \%age\ improvement\ in\ \Delta \mathbf{Ra} > 33.15$

The 95% confirmation interval of the predicted mean is:

$25.35 < \%age\ improvement\ in\ \Delta \mathbf{Ra} > 31.55$

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 $N_3T_1M_1$ and %age improvement in ΔRaat the optimal levels of $N_2T_1M_3$ of process parameters based on S/N ratio. (refer table 4,7). The values of MR and % age improvement in ΔR_a obtained through the confirmation experiments are within 95% of CICE of respective response characteristic.

Table 9. Predicted Optimal Values, Confidence Interval and Results of Confirmaton Experiments

Response Characteristic	Optimal Process Parameters	Predicted Optimal Value	Confidence Interval 95%	Actual Value (Avg of Confirmation Exp)
MR	$N_3T_1M_1$ $N_2T_1M_3$	7.955 mg	CI_{CE}: $7.41 < MR > 8.49$ CI_{POP}: $7.59 < MR > 8.31$	8.1 mg
% Improvement in $\Delta \mathbf{Ra}$		28.458 %	CI_{CE}: $23.75 < \%\ \Delta \mathbf{Ra} > 33.15$ CI_{POP}: $25.35 < \%\ \Delta \mathbf{Ra} > 31.55$	30.1 %
CI_{CE} – Confidence interval for the mean of the confirmation experiments CI_{POP} – Confidence interval for the mean of the population M_3 – Media of third kind (Polymer), M_1-Media (Toothpaste) T_1 – Temprature at first level N_2 – Number of cycles at second level, N_3– Number of cycles at Third level				

6. Conclusions

The optimum values of the response characteristic along with their respective confidence intervals have been predicted using the Taguchi approach [6,7,19]. using Minitab software. The percentage contribution of media is 83.65%, temprature is 3.91% and number of cycles 9.15%. Media is the most significant parameter for the MR As observed the optimum values for maximum Material Removal are $N_3T_1M_1$ according to S/N data toothpaste media with Temperature 15°C and number of cycles 9 is better for material removal. The percentage contribution of media is 34.36%, Temprature is 55.38% and Number of cycles 8.87%. Media and Temprature are significant parameter for %ΔRa. Maximum percentage improvement in %ΔRa are $N_2T_1M_3$ according to S/N data. Polymer with Temprature 15°C and number of cycles 6 is better for % improvement in surface roughness

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