International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 09, RTMSE-2026

Improved Surface Finish with Thermal - Assisted Abrasive Flow Machining (Th-AFM) Process

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Abstract— The complicated exterior and inner surfaces of metallic components are often polished using abrasive flow machining, a precision finishing technique. Similar to most finishing processes, this process is also slow due to the low rate of material removal. Originally developed in the aerospace sector, this technique is now employed, among other industries, in the die-making, automotive, and biomedical implant sectors. In an attempt to overcome the main disadvantage of the abrasive flow machining (AFM) process—namely, its low material removal—and satisfy the exacting functional and finish requirements, recent research has looked into hybridizing the AFM process with other non-conventional machining (NCM) techniques. The development of an abrasive flow machining (AFM) technology and thermal setup for internal hole or prismatic recess fine finishing is the main goal of the current study. Thermally aided abrasive flow machining, or Th-AFM, is a revolutionary process that has been discovered to increase material abrasion due to the combined effects of temperature and AFM. The different process parameters have been further adjusted for the response characteristic of percentage improvement in surface roughness in the current inquiry, based on the Taguchi method, and were determined to be 42.1% using the standard L_{27} orthogonal array (OA) for the experimentation plan.

Keywords— Abrasive aluminium oxide; abrasive flow machining; Types of media; Thermal AFM

I. INTRODUCTION

The current world has tight standards for producing beautiful completed products with complicated shapes and a range of functionality because product quality is more crucial than ever. A beautifully completed part has better life, functionality, and aesthetics due to its high polish, precise dimension controls, and strength endurance. Finishing procedures are labour-intensive, the least controlled, and account for around 15% of the total machining cost when producing precision parts [1]. For basic surface geometries, the traditional methods of grinding, lapping, honing, and superfinishing are effective; however, they are inadequate for complicated or hard surfaces. The aforesaid finishing issues are well suited for the abrasive flow machining (AFM) process. This non-traditional polishing technique is also known as the abrasive flow finishing (AFF) process [2]. mostly due to a little amount of material being removed during the precise polishing of the metallic components. The AFM or AFF technique for deburring and polishing essential aviation fuel and hydraulic system components was initially acknowledged by the aerospace industry. It may polish any surface where air, liquid, or gasoline moves [2]. A self-deforming, abrasive-laden semi-liquid paste made of gel, abrasive particles, and viscoelastic polymer is extruded over the surface that needs to be polished via a controlled process using two hydraulic actuators that are aligned vertically.

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Numerous randomly oriented cutting edges of the abrasives erode the required surface when abrasive-laden media is extruded via the restricting route created by the workpiece and the tooling, producing machining action. For intricate or internal cavities, holes, or slots that need delicate finishing, this technique is ideal. Additionally, it can be used to polish multiple tiny slots at once. High surface quality and accuracy requirements, which are commonly coupled with high production rates of goods with intricate shapes and curves, are being addressed by the newest manufacturing techniques through the use of hybrid machining processes (HMPs) [3]. Brar et al. developed the helical abrasive flow machining (HLX-AFM) technique to polish internal cylindrical surfaces. Using a coaxially fixed helical twist drill bit enhanced the surface finish and material removal during the abrasive flow machining process [4,5]. M. Shergill and B.S. Brar experimented with various organic media in abrasive flow machining using parameters to develop the Th-AFM process for finishing the internal surface of brass by setting the temperature around the media cylinder to raise or lower the temperature of the media used in the machine. Grit size, media type, and number of removal and surface roughness improvement percentage optimization [6,7].

II. EXPERIMENTATION

A. Conducting Experiment

The work-piece was secured in the arrangement using the custom nylon fixture designed for the Th-AFM setup. Throughout the experimentation, the material was extruded through the cavity within the workpiece. The inner cylindrical surface of the work-piece was polished through the rubbing effect of aluminium oxide abrasive (internal media).

The temperature surrounding the media cylinder was regulated by a water jacket encasing it, and the water kept at a specific temperature was achieved by activating the water dispenser. During the experimentation, three distinct media have been utilized: Guar Gum, Colgate Toothpaste, and Paraffin wax. Temperature is attained by circulating water and allowing 10 minutes for the media to reach the desired temperature. The water dispenser has a temperature range of 10°C to 75°C, but we utilized it within the range of 10°C to 40°C. The machine is situated in the laboratory at YDOE Talwandisabo Bathinda campus of Punjabi University Patiala. The AFM action occurs from the back-and-forth extrusion of the abrasive-laden media through the workpiece. A hydraulic system created for the standard AFM configuration manages this extrusion by reversing the stroke cycles for material

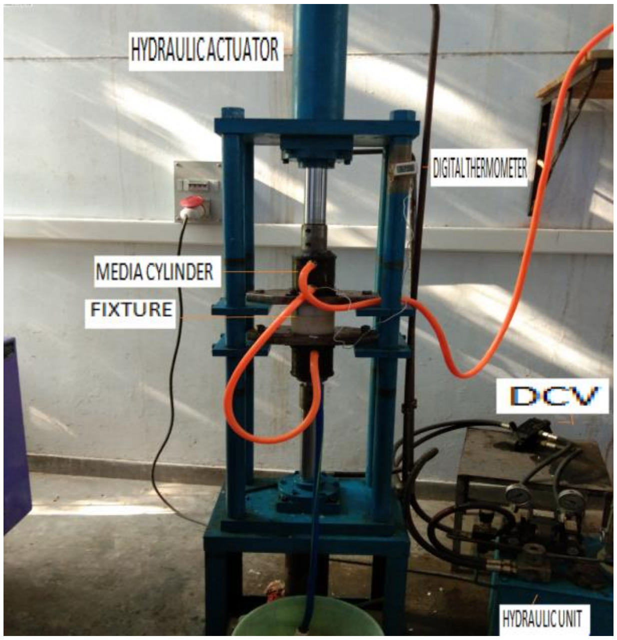

Fig.1: Th-AFM Setup

Fig.2: Nylon Fixture

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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Table 1: Types of parameters

Sr. No	Symbol	Process Parameters	Unit	Level 1	Level 2	Level 3
1	M	Media	Nil	guar gum	toothpaste	paraffin wax
2	T	Temperature	°C	10	25	40
3	N	Number of cycles	Nil	3	6	9
4	C	Concentration	Nil	0.75	1	1.25
5	G	Abrasive grain Size	Mesh size	100	150	200

work-piece material, brass; abrasive type, Al_2O_3; mesh size, 100–200 (150–75 µm) ; media flow volume,310 cm^3 ; reduction ratio, 0.97 initial surface roughness of work-piece,1.97–2.25µm(Ra)

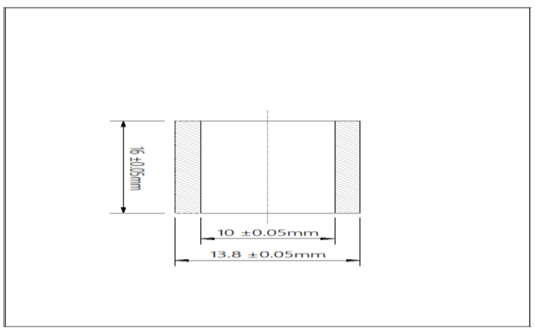

Fig.3: Specimen of length 16 mm and O.D=13.8mm, I.D=10mm,made of brass

B. Response Parameter

The response parameter chosen was Surface Roughness Improvement (%ΔRa)- change in surface roughness (ΔRa): is estimated as the difference between the initial surface roughness of the work-piece and the final surface roughness of the work-piece after finish-machining with Th-AFM. This characteristic was chosen considering that drilling, turning, boring operations usually results in unavoidable variability in the machined surface which affects the final surface roughness values. The surface roughness, Ra value of multiple internal holes on each specimen was measured by using roughness tester (available at our campus).

Surface Roughness Improvement (%ΔRa) = (Initial Ra – Final Ra)/(Initial Ra) * 100

III.DESIGN OF EXPERIMENTS

The influence of five main process parameters: Media (M), Temperature (T), Number of cycles (N), Abrasive concentration in media (C), and abrasive grain size (G), along with three potential two-factor interactions—Type of Media and Temperature of Media (MxT), Media and Number of cycles (MxN), and Temperature of media and Number of cycles (TxN)—on the response parameter of Surface Roughness Improvement (%ΔRa) were examined. The overall degrees of freedom related to the five parameters at three levels each (including three two-factor interactions) was 22 [5 ×(3–1) + 3(2 × 2) = 22], which is fewer than 26, the total degrees of freedom for L_{27} OA. Consequently, the experimental setup adhered to the standard L_{27} (3^{13}) orthogonal array (OA) of the Taguchi approach. The L_{27} orthogonal array features 13 columns and 27 rows, with five machining parameters allocated to the columns after determining the interacting columns through the standard linear graph of the L_{27} OA [10]. The 12th and 13th columns remained empty (refer to Table 2). The orthogonality is preserved even if some columns of the array remain empty in one or more instances.

Percentage improvement in surface roughness (%ΔRa) values for the respective experiment were acquired after processing the work-piece under a defined set of conditions through the Th-AFM process. For the experiment, the parameters and run sequence were organized according to the L_{27} OA as outlined in Table 2, following the Taguchi experimental methodology. Every experiment was conducted three times, and the response for the three recorded values of %ΔRa for the respective experiment is also listed in Table 2. The sequence of the trials was randomized to reduce variations in time errors

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Table2:The L_{27} (3^{13}) OA(parameters assigned) with experimental results of response characteristic % improvement in surface roughness

		1	2	3	4	5	6	7	8	9	10	11	12	13	Rawdata(mg)			*S*/*N*ratio(dB)
		M	*T*	MxT		*N*	MxN		TxN	*C*	*G*	TxG	*e*	*e*	R_1	R_2	R_3	
1	11	1	1	1	1	1	1	1	1	1	1	1	1	1	28.71	34.9	33.67	32.426
2	21	1	1	1	1	2	2	2	2	2	2	2	2	2	43.55	39.36	33.04	38.650
3	16	1	1	1	1	3	3	3	3	3	3	3	3	3	51.45	48.93	45.43	48.603
4	27	1	2	2	2	1	1	1	2	2	2	3	3	3	43.99	38.34	34.66	38.99
5	24	1	2	2	2	2	2	2	3	3	3	1	1	1	25.29	18.67	18.57	20.843
6	13	1	2	2	2	3	3	3	1	1	1	2	2	2	17.41	14.04	26.02	19.156
7	26	1	3	3	3	1	1	1	3	3	3	2	2	2	18.27	23.81	27.8	23.293
8	17	1	3	3	3	2	2	2	1	1	1	3	3	3	18.71	12.79	20.38	17.293
9	14	1	3	3	3	3	3	3	2	2	2	1	1	1	40.88	35.78	27.43	34.696
10	07	2	1	2	3	1	2	3	1	2	3	1	2	3	13.56	18.7	8.71	13.656
11	19	2	1	2	3	2	3	1	2	3	1	2	3	1	26.2	34.95	20.53	27.226
12	08	2	1	2	3	3	1	2	3	1	2	3	1	2	35.3	22.23	28.02	28.516
13	12	2	2	3	1	1	2	3	2	3	1	3	1	2	17.43	12.27	10	13.233
14	10	2	2	3	1	2	3	1	3	1	2	1	2	3	18.19	23.44	28.2	23.283
15	02	2	2	3	1	3	1	2	1	2	3	2	3	1	17.25	21.18	26.08	21.503
16	01	2	3	1	2	1	2	3	3	1	2	2	3	1	23.87	19.21	15.24	19.44
17	18	2	3	1	2	2	3	1	1	2	3	3	1	2	9.24	6.93	15.21	10.46
18	23	2	3	1	2	3	1	2	2	3	1	1	2	3	6.45	10.81	19.03	12.096
19	20	3	1	3	2	1	3	2	1	3	2	1	3	2	16.41	23.51	21.01	20.310
20	05	3	1	3	2	2	1	3	2	1	3	2	1	3	13.48	17.5	23.6	18.193
21	06	3	1	3	2	3	2	1	3	2	1	3	2	1	14.55	16.84	22.65	18.013
22	25	3	2	1	3	1	3	2	2	1	3	3	2	1	7.6	5.9	12	8.50
23	15	3	2	1	3	2	1	3	3	2	1	1	3	2	9.7	15.34	8.7	11.246
24	09	3	2	1	3	3	2	1	1	3	2	2	1	3	18.21	27	36.27	27.16
25	03	3	3	2	1	1	3	2	3	2	1	2	1	3	7.1	14.59	8.25	9.98
26	22	3	3	2	1	2	1	3	1	3	2	3	2	1	19.3	11.67	13.24	14.736
27	04	3	3	2	1	3	2	1	2	1	3	1	3	2	11.47	6.97	5.58	8.006

$T_{\%\Delta Ra} = 21.46$

Table 3: ANOVA Calculations (Raw Data)

International Journal of Engineering Research & Technology (IJERT)
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Vol. 14, Issue 09, RTMSE-2026

ANOVA CALCUALTIONS (Raw Data)						
Source	SS	DOF	V	P- value	F-Value	Fcritical
M	3447.6	2	1723.818	35.67	53.9871*	3.15
T	1565.8	2	782.9029	16.2	24.51922*	3.15
N	302.79	2	151.3968	3.133	4.741	3.15
C	186.19	2	93.09283	1.927	2.916	3.15
G	1409.8	2	704.885	14.59	22.07583*	3.15
MxT	313.14	4	78.28377	3.24	2.452	2.53
MxN	304.66	4	76.16436	3.152	2.385	2.53
TxN	282.25	4	70.56309	2.921	2.21	2.53
Error	1852	58	31.93018	19.16		
Total	9664.2	80		100		

*Significant at 95% confidence level, F critical=F(0.05,2,62) =3.15,F(0.05,4,62) =2.52

SS sum of squares, *DOF* degree of freedom, *V* variance, *SS* ’pure sum of squares,

P% percentage contribution of a treatment

According to raw data media, temperature and abrasive grain size are significant

Table 4: S/N Ratio Data

ANOVA CALCUALTIONS (S/N Ratio Data)						
Source	SS	DOF	V	P- value	F-Value	Fcritical
M	214.923	2	107.4617	39.9882	14.14194*	3.89
T	111.849	2	55.92468	20.81045	7.359674*	3.89
N	9.72594	2	4.862971	1.809588	0.639966	3.89
C	9.7197	2	4.859851	1.808427	0.639555	3.89
G	110.062	2	55.03076	20.47781	7.242033*	3.89
MxT	11.4833	4	2.870823	2.136557	0.3778	3.26
MxN	17.199	4	4.299754	3.200012	0.565846	3.26
TxN	22.1097	4	5.527436	4.113691	0.727409	3.26
Error	30.3952	4	7.598799	5.655265		
Total	537.467	26		100		

*Significant at 95% confidence level, F (0.05,4,12) =3.26
Fcritical=F(0.05,2,12) =3.89,

SS sum of squares, *DOF* degree of freedom, *V* variance, *SS* ’pure sum of squares, *P%* percentage contribution of a treatment
According to S/N data media ,temperature and abrasive grain size are significant

Table 5: Process parameters at three different level (Mean value)

Process	Level 1		Level 2		level 3	
parameter	raw	S/N	raw	S/N	raw	S/N
Media, *M*	30.44	28.85	18.82	24.101	15.12	22.128
Temperature	27.28	27.62	20.43	24.78	16.66	22.849
, *T*						
Number of cycles	19.98	24.395	20.21	24.849	24.19	25.833
, *N*						
Concentration, *C*	19.42	24.345	21.91	24.928	23.05	25.805
Abrasives grain size, *G*	17.85	23.57	27.31	27.881	19.22	23.626

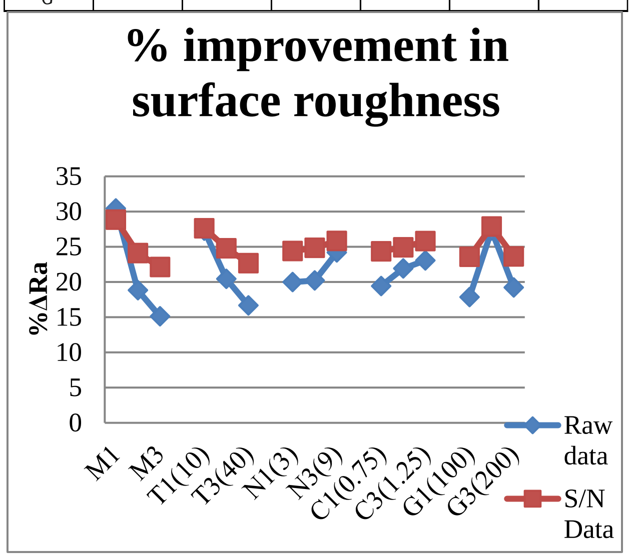

Fig.4: % Improvement in Surface Roughness for five parameters

By looking at first graph and relating it to Table 5Guar gum gives better percentage improvement in surface roughness in comparison to toothpaste, and paraffin wax. Second graph elaborates percentage improvement in surface roughness decreases with increase in temperature and third graph shows %ΔRa increases with increase in number of cycles fourth graph shows %ΔRa value is better at concentration of 1.25 and fifth graph shows abrasive grain size of 150 is better for optimum %ΔRa

Effect of Two way interaction

The Th-AFM method lacks significant interactivity. The impacts of three two-factor interactions, namely Media and Temperature (MxT), Media and Number of cycles (MxN), and Temperature and Number of cycles (TxN), on the response parameter of percentage improvement in surface roughness (%ΔRa) are illustrated by computing average values of response characteristics for the corresponding two-factor interaction at various level combinations. All interactions are not significant according to ANOVA (raw data) and the ANOVA of (S/N ratio data)

IV ANALYSIS

To identify the key factors and assess their effects on the $\%\Delta R_a$ process performance characteristics, the results were examined with the Taguchi method, which employed Fisher's test (F ratio) and analysis of variance (ANOVA) on both the raw data and the signal-to-noise (S/N) ratio data. The response characteristic of percentage improvement in surface roughness ($\%\Delta R_a$) is of the "higher-the-better" type regarding machining quality traits; a similar characteristic applies to the Material Removal, thus the S/N ratio for this is provided below []:

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

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

where yj, j=1, 2,... R represents the response values obtained under the repeated R times for the trial condition. A significant S/N ratio suggests that the signal effect outweighs the random effects. The S/N ratio is a summary statistic that quantifies the sensitivity of a performance characteristic to noise factors in a regulated way. It is calculated using information from all repetitions of a trial condition.

Impacts of two-variable interactions

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 09, RTMSE-2026

The Th-AFM method lacks interactivity. The impacts of three two-factor interactions, namely Media and Temperature (MxT), Media and Number of cycles (MxN), and Temperature and Number of cycles (TxN), on the percentage improvement in surface roughness response parameter are depicted by averaging the response characteristics for each two-factor interaction across various level combinations. None of the interactions show significance according to ANOVA results of both raw data and S/N ratio data.

ANOVA calculations:

To identify the key parameters and assess their influence on the response characteristic, an analysis of variance (ANOVA) is performed on both the raw data and the S/N ratio data. The combined ANOVA results for percentage improvement in surface roughness, utilizing both raw data and S/N ratio data, are presented in Tables 3 and 4, correspondingly. By considering the combined insignificant values as noise, the pooling in ANOVA increases the confidence level of the important parameters [9]. Three factors—Media, Temperature, and Abrasive grain size—significantly affected the average of percentage improvement in surface roughness, as shown by the ANOVA using both raw data and S/N ratio data, while three interactions showed no impact. Based on the S/N ratio data, Media (M, 39.98 %) contributes the most to the $\%\Delta R_a$, followed by Temperature (T, 20.81%) and Abrasive grain size (G, 20.47 %)

Estimation of Optimum Response Characterstics Percentage improvement in Surface Roughness

$\%\Delta Ra = M_1 + T_1 + G_2 - 2T$

$\overline{T}$ = overall mean of the response = 21.46 % (Table 2)

M_1 = Average value of $\%\Delta R_a$ at the first level of Media = 30.44 %

$\overline{T}_1$ = Average value of $\%\Delta R_a$ at the first level of temperature = 27.28 %

G_2 = Average value of $\%\Delta R_a$ at the second level of Abrasive grain size = 27.31 %

Substituting these values, $\%\Delta R_a$ = 42.11 %

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 (Standard tabulated F ratio value,25)

f_e = error DOF = 62 (Table 3)

N = Total number of results = 81 (treatment = 27, repetition = 3)

R = Confirmation experiments sample size = 3, Ve = Error variance = 31.9 (Table 3)

= 11.57

So, $CI_{CE} = \pm 7.3$ And $CI_{POP} = \pm 3.32$

The 95% confirmation interval of predicted optimal range (for confirmation run of three experiments) is: Mean $\%\Delta Ra - CI_{CE} < \%\Delta Ra < \%\Delta Ra + CI_{CE}$

34.81 % $<\%\Delta Ra<$ 49.41 %,The 95% confirmation interval of the predicted mean is : Mean $\%\Delta Ra - CI_{POP} < \%\Delta Ra < \%\Delta Ra + CI_{POP}$

38.78 % $<\%\Delta Ra<$ 45.432

Table6: Predicted optimal values, confidence intervals and results of confirmation experiments

Response	Optimal process parameters	Predicted optimal value	Confidence interval 95 %	Actual value (avg of confirmation exp)
$\%\Delta R_a$	$M_1T_1G_2$	42.11%	CI_{CE}:34.81 <$\%\Delta R_a$< 49.41	42.10%
			CI_{POP}:38.78 <$\%\Delta R_a$< 45.432	

CI_{CE} confidence interval for the mean of the confirmation experiments based on raw data

CI_{POP} confidence interval for the mean of the population based on raw data

Parameters

M_1 average value of $\%\Delta R_a$ at the First level of Media parameter

T_1 average value of $\%\Delta R_a$ at the First level of Temperature parameter

G_2 average value of $\%\Delta R_a$ at the second level of Abrasive grain size parameter

V CONCLUSION

In This study effect of Thermal assisted abrasive flow machining parameters on $\%\Delta R_a$ of brass was studied using Taguchi method L_{27} OA. From the results, it was found that Media, Temperature and Abrasive grain size play a significant role in Th-AFM process operation related to % improvement in surface roughness. Number of cycles and Abrasive to media concentration has no significant effect on % improvement in surface roughness. Also it is found that for higher %ΔR the optimum levels of Media, Temperature, abrasive grain size are guar gum, 10°C, 150 respectively and its value is 42.1%. ANOVA is used to find the significance of machining parameters and their contributions on %ΔR individually. Media is found to be most significant parameter on %ΔR with 39.98% contribution followed by Temperature with 20.81 % contribution and Abrasive grain size with 20.47 % contribution

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