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Improved Material Removal with Thermal - Assisted Abrasive Flow Machining (Th-AFM) Process

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Abstract:- A precise finishing technique called abrasive flow machining is mostly used to polish intricate interior and external surfaces of metallic components. Because of the low rate of material removal, this procedure is likewise slow, just like the majority of finishing operations. This method began in the aerospace industry, but it is currently used in the die-making, automotive, and biomedical implant industries, among others. Recently, there has been research into hybridizing the abrasive flow machining (AFM) process with other non-conventional machining (NCM) techniques in an effort to overcome the primary drawback of the AFM process—namely, the low material removal—and meet the demanding functional and finish requirements. The current study focuses on the creation of a thermal setup and abrasive flow machining (AFM) technique for internal hole or prismatic recess fine finishing. The novel technique is known as thermally assisted abrasive flow machining, or Th-AFM, and it was found to cause greater material abrasion because of the combined effects of AFM and temperature. Using the standard L_{27} orthogonal array (OA) for the experimentation plan, the various process parameters have been further optimized for the response characteristic of material removal in the current investigation, based on the Taguchi method and found to be 9.9 mg. All things considered, the Th-AFM process has a very bright future in the industries because of its ability to complete quickly, even when dealing with thin, delicate, and hard alloy components.

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

1. Introduction

Since the quality of a product is now more important than ever in the modern world, there are strict requirements for creating beautiful finished products with intricate shapes and a variety of functionalities. Because of its high polish, tight dimension controls, and strength endurance, a finely finished part has superior aesthetics, life, and functional performance. In the production of precision parts, finishing operations are labor-intensive, least controllable, and cost roughly 15% of the total machining cost[1] The conventional techniques of grinding, lapping, honing, and superfinishing work well for simple surface geometries but fall short when it comes to finely finishing complex or hard surfaces. The abrasive flow machining (AFM) procedure is a good fit for the finishing problems listed above. The abrasive flow finishing (AFF) procedure is another name for this unconventional polishing method. [2] mostly as a result of a little amount of material being removed during the metallic components' fine polishing. The aerospace industry first recognized the AFM or AFF method for deburring and polishing vital hydraulic and fuel system components of aircraft. Anywhere that gasoline, liquid, or air flows, it can polish. [2]

Using two vertically oriented hydraulic actuators, a self-deforming, abrasive-laden semi-liquid paste consisting of gel, abrasive particles, and viscoelastic polymer is extruded over the surface that needs to be polished through a regulated route. When abrasive-laden media is extruded through the limiting passage produced by the workpiece and the tooling, a large number of randomly oriented cutting edges of the abrasives erode the necessary surface, resulting in machining action. This method works best for complicated or interior cavities, holes, or slots that require delicate finishing. It can also be used to polish several fine slots simultaneously. The newest manufacturing techniques are using hybrid machining processes (HMPs) to solve the problems of high surface quality and tolerance requirements, which are frequently combined with high production rates of products with complicated shapes and curves.[3] as well as for hard material finishing. In an effort to create hybrid AFM processes, researchers have effectively combined AFM with several nonconventional machining techniques. This has allowed them to remove more material—as low material removal is an AFM process limitation—and create better polished surfaces more quickly. Ultrasonic flow polishing (UFP) was created by Jones and Hull. They employed an ultrasonically energized tool and an abrasive-laden media flow to polish complex dies and molds, and they saw a tenfold improvement. [4] Singh and Shan developed the magnetic-assisted abrasive flow machining (MAAFM) technology with success [5] to increase the amount of active grains owing to magnetic aid compared to AFM alone. By combining the polymer base with ferromagnetic material, the required rheology of the abrasive-laden media and magnetic forces on the iron particles were achieved, together with the desired magnetic action. Centrifugal force-assisted AFM (CFAAFM) was created by Walia et al. by simultaneously spinning the extruding AFM material using variously shaped rods and noting the intense abrasive effect. [1,6-9] In order to achieve better results, Sankar et al. developed the (DBG-AFF) process drill bit-guided abrasive flow finishing. They used a drill bit instead of prismatic rods to rotate abrasive-laden media simultaneously. This allowed for better media mixing, which in turn produced a higher number of active grains. [10] The rotational abrasive flow finishing (R-AFF) method was also created by Sankar et al. This procedure involved rotating the cylindrical workpiece, which improved the surface polish by shearing more peaks during the extrusion and applying more shearing forces [12]. The helical abrasive flow machining (HLX-AFM) technology was created by Brar et al. to polish internal cylindrical surfaces. During the abrasive flow machining process, using a coaxially fixed helical twist drill bit improved the material removal and surface finish. [14,15] M. Shergill and B.S. Brar developed the Th-AFM process for finishing internal surface of brass by temperature setup around media cylinder to increase or decrease the temperature of media used in machine [16] M.Shergill and B.S. Brar experiment with different organic media in abrasive flow machining using parameters. Media type, Grit Size and Number of cycles for optimizing parameters for material removal and percentage improvement in surface roughness [17] According to a study by Rajurkar et al., electrochemical machining (ECM) has been effectively combined with a variety of conventional and non-traditional machining techniques, including turning, grinding, electro discharge machining, abrading, ultrasonic machining, and grinding. [19] The Taguchi approach has been applied for additional parametric optimization as well as to investigate the impact of different process parameters on material removal during machining. The Taguchi technique is frequently used in engineering analysis to create high-quality systems. It aids in the development of resilient goods and manufacturing processes that are insensitive to daily and seasonal variations of environment, machining wear, etc.[3,25-27] Similar to the general AFM, this procedure can be used to quickly finish hard alloys, remove burrs and round the edges of slots, and fine-finish workpieces with through internal holes, slots, or cavities with prismatic sections. It may also find use in the automotive, aerospace, hydraulic, and pneumatic industries, as well as in the medical technology and space and aviation industries [23]. H.S. Mali and Jai Kishan examined the media as one of the main factors that controls finishing behavior in AFF. However, the high cost of commercially available abrasive media makes them unaffordable, particularly for businesses where cost is a critical consideration. Alternative AFM media that are less expensive are created by uniformly mixing liquid synthesizer, base polymers, and additives to create flexible polymer abrasive gels. In order to define the rheology of produced gels, the effects of temperature, abrasive concentrations, abrasive mesh size, and percentage of liquid synthesizer on the viscosity of polymer abrasive gel have been examined. [34]. Liang Fang et.al found in abrasive flow machining, work efficiency is thought to be the most important goal (AFM). Numerous elements might affect it, including temperature, viscosity of the medium, hardness of the abrasive, density and sharpness of the particles, hardness of the workpiece, pressure, and piston movement speed. The most important factor affecting job efficiency is temperature [35].

2. Experimentation

A. Initial Stage

For the present study The effect of abrasive media has been studied, and so the experimental design is according to the Taguchi orthogonal array L_{27} approach. the L_{27} orthogonal array within the Taguchi method offers a structured approach to optimize Abrasive Flow Machining processes by systematically varying parameters and levels, thereby improving process efficiency, quality, and reliability. A Nylon Fixture is designed in Cylindrical shape as shown in Figure 1. Nylon cylinder of diameter 4 inch is taken and machining is done on lathe. Length of fixture is 110 mm and fixture is made in two parts .Specimen was put in fixture and two parts of fixture is assembled with three screws of hardened steel fitted at 120° each; the taper angle in fixture is 80° .In the present investigation a hollow cylindrical work piece of brass (yellow brass: 65 % Cu, 35% Zn, having BHN hardness 156) is taken. drilling operation was done on the inner surface of workpiece. Work-piece is made of hollow cylindrical piece with O.D.13.8 mm,I.D.10 mm and length 16 mm for abrading the material of brass. while doing experiment media was extruded through the hollow workpiece maintaining the temperature across media cylinder.

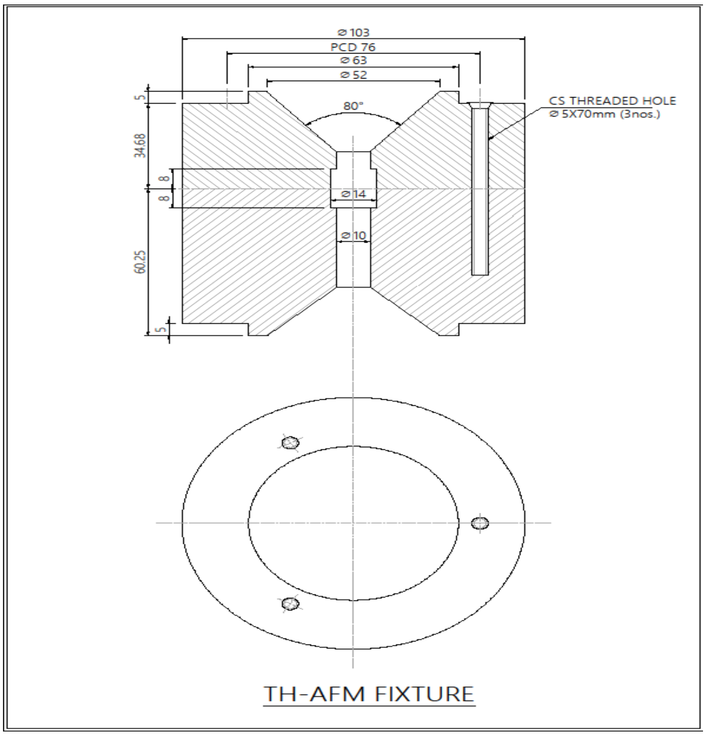


Figure 1

B. Specifications of Machine

Maximum pressure for hydraulic Actuators: maximum 25 N/mm²

I.D. of Hydraulic actuators (D_i): 100 mm

Stoke length of piston (l): 300 mm

The media cylinder's outer diameter: 73 mm

The media cylinder's inner diameter: 63 mm

Pillar-to-pillar distance longitudinally is 320 mm

It is possible to conduct experiments at different levels of the process parameters of media temperature, media flow rate, media flow volume, stroke length, and number of cycles using this specially designed Th-AFM equipment.

Figure.2 Photograph of Th-AFM setup with nylon fixture

The hybrid Th-AFM process setup has been developed with necessary modification over the basic AFM setup, media cylinder have been modified by providing hollow jacket around the media cylinder and cold/hot water is circulated around the media cylinder to increase or decrease the temperature of media. Temperature of water is measured with digital thermometer by attaching a sensor in outlet pipe of water jacket, temperature is achieved by circulating water and waiting for 10 minutes to get proper temperature of media .water dispenser has range of temperature 10°C to 75°C,but we have used in range from 10°C to 40°C. Machine is installed in the Laboratory at YDOE Talwandisaboo Bathinda campus of Punjabi university patiala .The AFM action part is achieved due to the back and forth extrusion of the abrasive laden media through the work-piece. A hydraulic system designed for the basic AFM setup controls this extrusion with reversal of stroke. A combination of one upward and downcast stroke completes a cycle of AFM process.To achieve the thermal abrasive machining along with the abrasive cutting action, the necessary nylon fixture has been developed (Figs. 1 and 2).The modified nylon fixture is made in two parts and axially holding the tightly held hollow cylindrical work-piece with the help of necessary retainers and fasteners.

C. Experimental Details

For Th-AFM Method, a thorough investigation was conducted into how different related machining parameters affected the machining characteristic of Material Removal (MR).

D. Process Parameters

Based on the parametric optimization of the developed basic AFM setup (using L_9 OA of Taguchi method) [16,17], pilot ex- perimentation (using one-factor-at-a-time approach) [18] for the developed Th-AFM process setup and literature re- view [16,17], five process parameters of Media (*M*), Temperature (*T*), Number of cycles (*N*), Abrasive concentration in media (*C*) and abrasives grain size (*G*) were selected for the experimentation. The three selected levels of the selected process parameters along with values of the fixed process parameters are given in 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, 1.97–2.25 µm (Ra).

Table 1

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 (Ab/media)	Nil	0.75	1	1.25
5	G	Abrasive grain Size	Mesh size	100	150	200

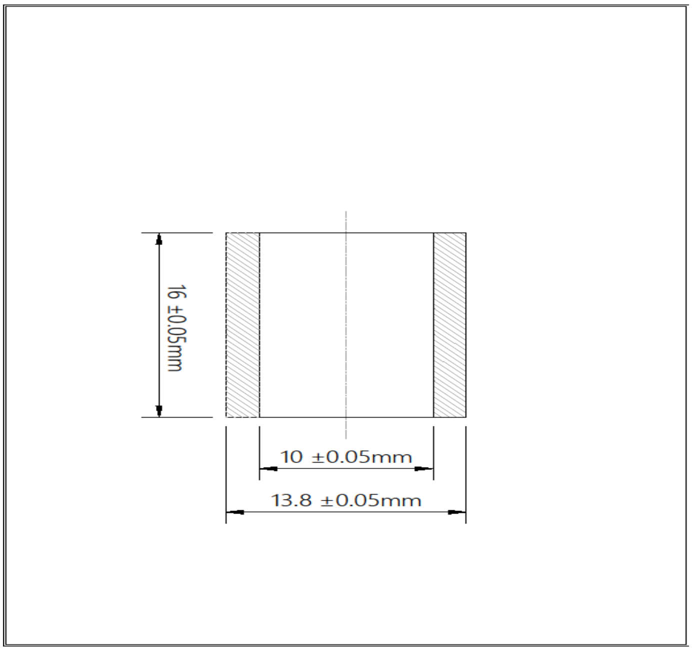


Fig.3 Specimen of length 16 mm and O.D =13.8mm, I.D=10mm, made of brass

E. Response Parameter

The response parameter chosen was material removal (MR). The term "material removal" refers to the quantity of material (measured in milligrams) extracted from a specimen over a predetermined number of process cycles. It was calculated by subtracting the specimen's initial weight from its final weight following processing under a predetermined set of parameters using the Th-AFM technique. An electronic balance with precision was used to measure the weight (CX220) with 0.1mg resolution (available at our campus).

Material Removal (MR) = (Initial Weight- Final Weight) * 1000 (mg)

F. Experimental Materials

The term "work-piece" refers to a hollow cylindrical piece of yellow brass that has been selected based on a survey of the literature [1, 5–8] (see Fig. 3). The test specimen's internal cylindrical surface was produced by drilling and then boring to the desired size using a set of fixed boring parameters, such as spindle speed, cut depth, and longitudinal feed. To avoid the impact of size variation and/or initial roughness of the work-piece, a very narrow range of bore size and initial roughness was selected from a large number of specimens for the test specimens. From a large batch of specimens, those with an initial surface roughness value between 1.97 and 2.25 µm were chosen. We have tried Media: Synthetic Polymer, toothpaste and p.wax for optimization of the media in Th-AFM setup and found toothpaste to more suitable for material removal [16], and pilot experiments using organic media such as Guar gum, Locust bean gum, Agar-Agar with L_9 OA [16, 17]

G. Design of Experiments

The effect of five key process parameters of Media (*M*), Temperature (*T*), Number of cycles (*N*), Abrasive concentration in media (*C*) and abrasives grain size (*G*) and three prospective two-factor interactions, i.e. 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 material removal (MR) were investigated. The total degrees of freedom associated with the five parameters at three levels each (with three two-factor interactions) was 22 [5 ×(3–1) + 3(2 × 2) = 22], which is less than 26, total degrees of freedom of L27 OA. Therefore, the experimental design followed the standard L_{27} (3^{13}) orthogonal array (OA) of the Taguchi method. Since the L_{27} orthogonal array consists of 13 columns and 27 rows, five machining parameters were assigned to the columns after the interacting columns were identified using the standard L_{27} OA's linear graph [26]. This left the 12th and 13th columns unfilled (see Table 2). Even if the array's columns stay empty in one or more cases, the orthogonality is maintained.[36]

H. Experimentation

The work-piece was held in the setup with the help of the developed nylon fixture for the Th-AFM setup. During the experimentation, the media was extruded through the recess inside the workpiece. The internal cylindrical surface of the work-piece was finished by the rubbing action of aluminium oxide abrasive (inside media). The required.

Temperature around the media cylinder was maintained by water jacket around media cylinder and this water maintained at particular temperature was done by switching on water dispenser. Three different types of media have been used during experimentation i.e. Guar Gum, colgate Toothpaste and Paraffin wax. The material removal (MR) values for the respective experiment were obtained after processing the work-piece at a specified set of conditions by the Th-AFM process For the experimentation, the process parameters and run order were planned in accordance with the L_{27} OA as per Table 2, based on the Taguchi experimental method. Each experiment was repeated three times, and the response for the three observed values of MR for the respective experiment is also enlisted in the Table 2. The order of the trials was randomized to minimize the time error variations.

Table 2. The L_{27} (3^{13}) OA (parameters assigned) with experimental results of response characteristic

Exp no.	Run order	Parameter trial conditions													Material removal (MR)			
		1	2	3	4	5	6	7	8	9	10	11	12	13	Raw data (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	8.2	7	8.1	17.736
2	21	1	1	1	1	2	2	2	2	2	2	2	2	2	10.9	8.7	10.1	19.797
3	16	1	1	1	1	3	3	3	3	3	3	3	3	3	10.4	13.2	9.8	20.723
4	27	1	2	2	2	1	1	1	2	2	2	3	3	3	8.9	9.4	5.1	16.820
5	24	1	2	2	2	2	2	2	3	3	3	1	1	1	7.2	5.8	7.3	16.460
6	13	1	2	2	2	3	3	3	1	1	1	2	2	2	4.7	6.2	7.3	15.226
7	26	1	3	3	3	1	1	1	3	3	3	2	2	2	8.1	6	5.9	16.213
8	17	1	3	3	3	2	2	2	1	1	1	3	3	3	4.2	4.9	4.3	12.940
9	14	1	3	3	3	3	3	3	2	2	2	1	1	1	9.8	8.6	10	19.464
10	07	2	1	2	3	1	2	3	1	2	3	1	2	3	6.9	8.6	4.1	15.039
11	19	2	1	2	3	2	3	1	2	3	1	2	3	1	6.4	4.8	3.6	13.158
12	08	2	1	2	3	3	1	2	3	1	2	3	1	2	4.3	6	3.8	12.978

Exp no.	Run order	Parameter trial conditions													Material removal (MR)			
		1	2	3	4	5	6	7	8	9	10	11	12	13	Raw data (mg)			*S/N* ratio (dB)
		M	*T*	MxT		*N*	MxN		TxN	*C*	*G*	TxG	*e*	*e*	R_1	R_2	R_3	
13	12	2	2	3	1	1	2	3	2	3	1	3	1	2	9.6	5.1	5.4	15.549
14	10	2	2	3	1	2	3	1	3	1	2	1	2	3	4.8	4.1	1.8	8.627
15	02	2	2	3	1	3	1	2	1	2	3	2	3	1	4.4	6	6.4	14.607
16	01	2	3	1	2	1	2	3	3	1	2	2	3	1	1.4	1	1.7	2.084
17	18	2	3	1	2	2	3	1	1	2	3	3	1	2	9.1	8.3	4.6	16.087
18	23	2	3	1	2	3	1	2	2	3	1	1	2	3	5.2	3.8	4.4	12.787
19	20	3	1	3	2	1	3	2	1	3	2	1	3	2	3.9	2.5	2.3	8.593
20	05	3	1	3	2	2	1	3	2	1	3	2	1	3	2.7	3.8	3.2	9.941
21	06	3	1	3	2	3	2	1	3	2	1	3	2	1	6.5	3	5.4	12.490
22	25	3	2	1	3	1	3	2	2	1	3	3	2	1	1.9	1.8	2.1	5.673
23	15	3	2	1	3	2	1	3	3	2	1	1	3	2	5.4	5.8	2.4	11.012
24	09	3	2	1	3	3	2	1	1	3	2	2	1	3	1.5	3.3	4.8	7.139
25	03	3	3	2	1	1	3	2	3	2	1	2	1	3	0.8	2.4	2	1.791
26	22	3	3	2	1	2	1	3	1	3	2	3	2	1	1.7	2.1	1.9	5.478
27	04	3	3	2	1	3	2	1	2	1	3	1	3	2	2.1	1.9	1.5	5.002

$T_{MR} = 5.239$ *mg*

Table 3. ANOVA of Raw Data

Source	SS	DOF	V	P- value	F-Value	Fcritical
M	321.652	2	160.82	50.01	80.26*	3.15
T	47.7158	2	23.85	7.42	11.90*	3.15
N	10.8921	2	5.45	1.69	2.71	3.15
C	88.798	2	44.39	13.81	22.15*	3.15
G	7.63432	2	3.81	1.18	1.90	3.15
MxT	19.5323	4	4.88	3.04	2.43	2.53
MxN	14.3338	4	3.58	2.22	1.78	2.53
TxN	16.3857	4	4.09	2.54	2.04	2.53
Error	130.539	62	2.11	20.29		

*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, *and P%* percentage contribution of a treatment

According to raw data media, temperature and abrasive to media concentration are significant

Table 4

ANOVA CALCUALTIONS (S/N Ratio Data)						
Source	SS	DOF	V	P- value	F-Value	Fcritical
M	432.79	2	216.39	59.38	37.86*	3.89
T	82.80	2	41.40	11.36	7.24*	3.89
N	25.24	2	12.62	3.46	2.21	3.89
C	79.74	2	39.87	10.94	6.97*	3.89
G	19.96	2	9.98	2.73	1.74	3.89
MxT	16.78	4	4.19	2.30	0.73	3.26
MxN	12.49	4	3.12	1.71	0.54	3.26
TxN	36.11	4	9.03	4.95	1.58	3.26
Error	52.12	12	4.34	7.15		
Total	728.8	26		100		

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

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 to media concentration are significant

Table 5

Process parameter	Level1		Level2		Level3	
▼ Type of data ➔	RAW	S/N	RAW	S/N	RAW	S/N
Media, *M*	7.78	17.264	5.022	12.324	2.914	7.457
Temperature, *T*	6.22	14.495	5.129	12.346	4.359	10.205
Number of cycles, *N*	4.82	11.055	5.181	12.611	5.714	13.380
Concentration, *C*	3.88	10.023	6.429	14.123	5.407	12.900
Abrasives grain size, *G*	5.07	12.521	4.977	11.220	5.670	13.305

3. Analysis

In order to determine the significant factors and measure their impact on the process performance characteristic of MR, the results were analyzed using the Taguchi method, which applied Fisher's test (F ratio), and analysis of variance (ANOVA) to both the raw and signal-to-noise (S/N) ratio data. Material removal's (MR) response characteristic is of the "higher-the-better" variety. Of machining quality characteristics; hence, the *S/N* ratio for this is given below [26]:

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

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

where y_j, j=1, 2,... R are the response values under the repeated R times of the trial condition. A high value of the S/N ratio indicates a higher signal effect than the random effects. The S/N ratio is a summary statistic that measures the performance characteristic's sensitivity to noise factors in a controlled manner. It is computed using data from all replications of a trial condition

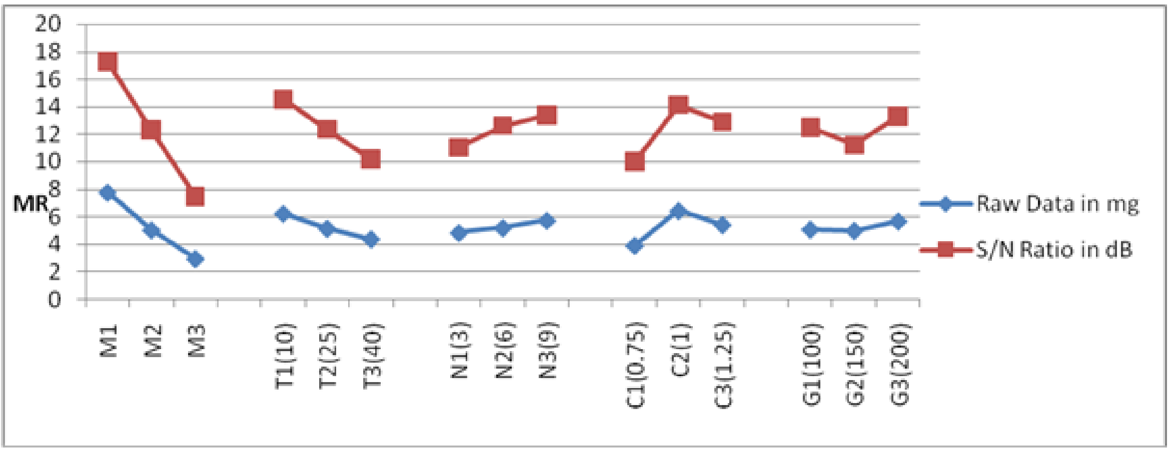
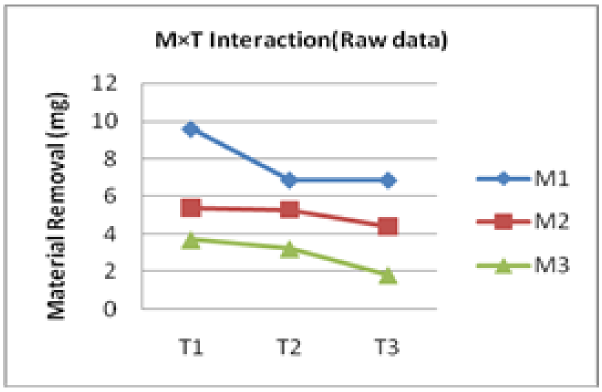


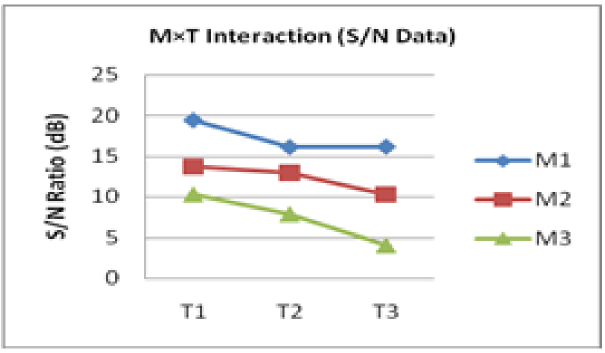
Figure 4

By looking at first graph and relating it to table5 guar gum gives better material removal in comparison to toothpaste, and paraffin wax. second graph elaborates material removal decreases with increase in temperature it is better at 10°C and third graph shows MR increases with increase in number of cycles fourth graph shows MR value is better at concentration of 1:1 and fifth graph shows grit size of 200 is better for optimum Material removal (Figure plotted according to table 5)

A. Effects of Two-Factor Interactions

The Th-AFM process is not very interactive. The effects of three two-factor interactions, i.e. Media and Temperature (MxT), Media and Number of cycles (MxN) and Temperature and Number of cycles (TxN), on the response parameter of material removal (MR) are plotted by calculating average values of response characteristics for respective two-factor interaction at different level combinations. None of the interaction is significant based on ANOVA (raw data) and ANOVA of (S/N ratio data) according to table 6,7,8





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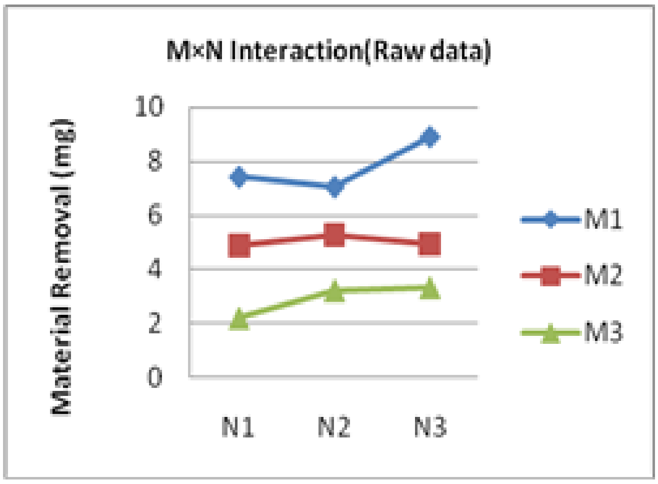

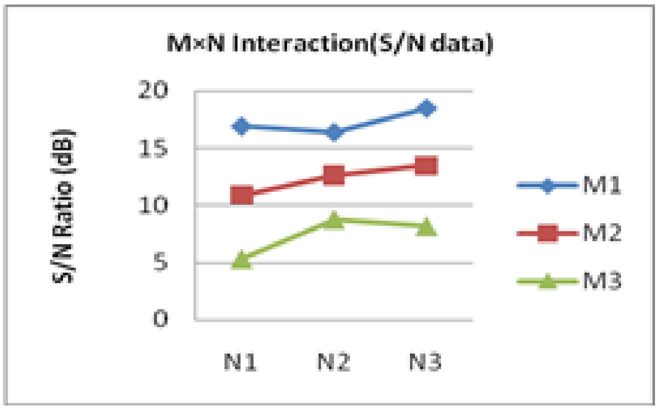

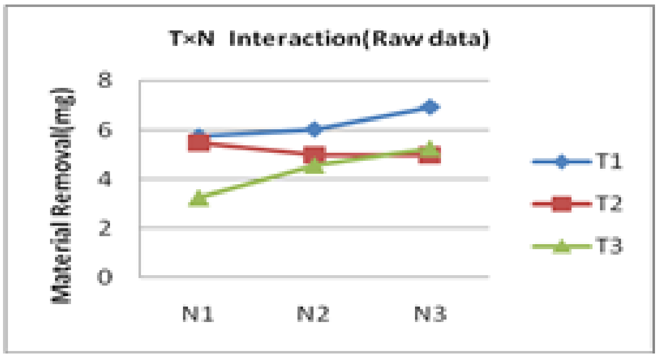

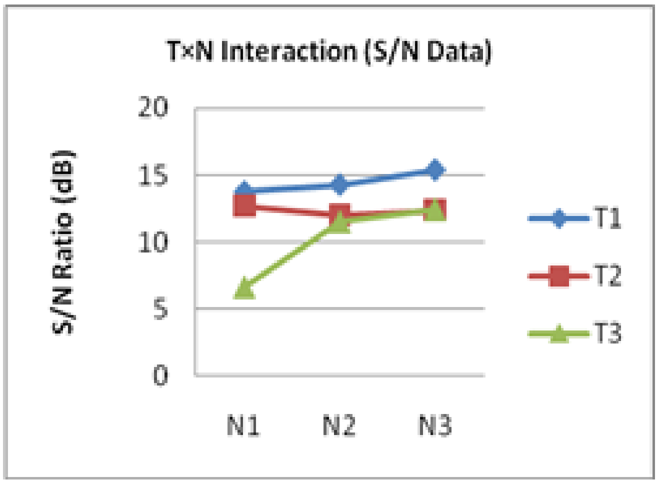

Table 6. Average values of material removal, *MR* in mg (*S*/*N* ratio in dB) for the interaction of MxTparameters

Levels of Media↓ Levels of Temperature→	T_1		T_2		T_3	
Type of data	Raw data	S/N ratio	Raw data	S/N ratio	Raw data	S/N ratio
M_1	9.60	19.419	6.87	16.168	6.86	16.206
M_2	5.38	13.725	5.28	12.928	4.38	10.320
M_3	3.70	10.341	3.22	7.941	1.82	4.091

Table 7. Average values of material removal, *MR* in mg (*S*/*N* ratio in dB) for the interaction of MxN parameters

Levels of Media↓ Levels of Cycles→	N_1		N_2		N_3	
Type of data	Raw data	S/N ratio	Raw data	S/N ratio	Raw data	S/N ratio
M_1	7.41	16.923	7.04	16.399	8.88	18.471
M_2	4.86	10.891	5.27	12.624	4.92	13.457
M_3	2.18	5.352	3.22	8.811	3.33	8.211

Table 8. Average values of material removal, *MR* in mg (*S*/*N* ratio in dB) for the interaction of TxN parameters

Levels of Temperature↓ Levels of Cycles→	N_1		N_2		N_3	
Type of data	Raw data	S/N ratio	Raw data	S/N ratio	Raw data	S/N ratio
T_1	5.73	13.789	6.02	14.299	6.93	15.397
T_2	5.47	12.681	4.95	12.033	4.95	12.324
T_3	3.25	6.696	4.56	11.502	5.25	12.418

4. Optimization Calculations

To determine the significant parameters and measure their impact on the response characteristic, the analysis of variance (ANOVA) of raw data and S/N ratio data is conducted. The pooled ANOVA findings for the material removal based on raw data and S/N ratio data are shown in Tables 3 and 4, respectively. By treating the pooled unimportant values as noise, the pooling in the ANOVA raises the confidence level of the significant parameters [25]. Three parameters Media, Temperature, Concentration had a significant impact on the mean of MR, according to the ANOVA based on raw data and S/N ratio data whereas three interactions have no effect. According to the *S*/*N* ratio data, Media(*M*,59.38%) has the maximum percentage contribution towards the MR followed by Temperature (T, 11.36%) and Concentration (C, 10.94 %)

$$MR = \overline{M}_1 + \overline{T}_1 + \overline{C_2} - 2\overline{T}$$

$\overline{T}$ = overall mean of the response = 5.24 mg (Table 2)

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

=7.78 mg

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

= 6.229 mg

C_2 = Average value of MR at the second levelof concentration

= 6.42 mg

Substituting these values, MR = 9.958 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 (Standard tabulated F ratio value,25)

f_e = error DOF = 62 (Table 3)

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

R = Confirmation experiments sample size = 3

V_e = Error variance = 2.11 (Table 3)

= 11.57

So, CI_{CE} = ±1.879

And CI_{POP} = ±0.854

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

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

8.079 mg $< MR <$11.837 mg

The 95% confirmation interval of the predicted mean is:

Mean MR – $CI_{POP} < MR <$ MR + CI_{POP}

9.104 mg$< MR <$10.812

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

Table 9. 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)
MR	$M_1T_1C_2$	9.958 mg	CI_{CE}:8.08 <MR< 11.84 CI_{POP}:9.10 <MR< 10.81	9.9 mg

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

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

M_1 average value of MR at the First level of Media parameter, T_1 average value of MR at the First level of Temperature parameter, C_2 average value of MR at the second level of Concentration parameter.

A. Confirmation experimentation

In order to validate the results obtained, it was observed that the 2nd experiment in the Table 2 corresponds to the optimal process parameters for the response characteristics of MR at the optimal levels of M_1,T_1,C_2 of process parameters based on *S*/*N* ratio and the average of the noted MR for the three repetitions is 9.9 mg (Refer to Table 9).The average values of MR obtained through the confirmation experiment of 9.9 mg and is within95%of $CI_{CE}$and CI_{POP}.

B. SEM Micrographs and Discussion

Figure 5 displays a set of typical SEM micrographs (matching to various tests of L_{27} OA as per Table 2) That clearly demonstrate the impact of abrasion and thermal assistance on the inner surface of the hollow cylindrical work piece in the Th-AFM process. The experiment (27) was completed with the aid of temperature at 40°C using media paraffin wax at concentration of 0.75 as shown by the micrograph in Figure 5 a and b, which provides details both before and after completion.Since finishing is done solely by abrasive cutting action, the deep drilling tool marks are still discernible in this micrograph.The workpiece corresponding to the micrographs in Figure 5c and d, which correspond to experiment number 2, was finished with media guar gum at 10°C with an abrasive to media concentration of 1:1. The micrographs had ×500 and ×100 magnifications, respectively.Because of the greater temperature aid, more material was removed from the ridges, resulting in shallower tool marks

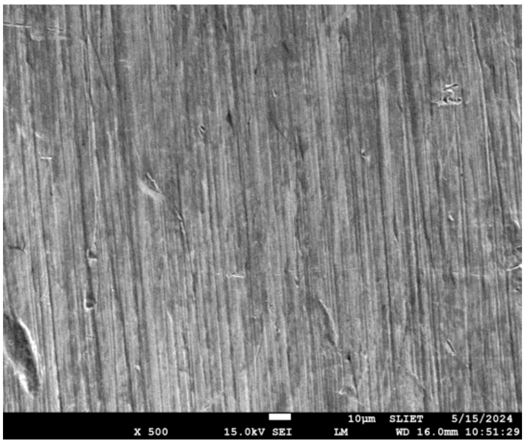
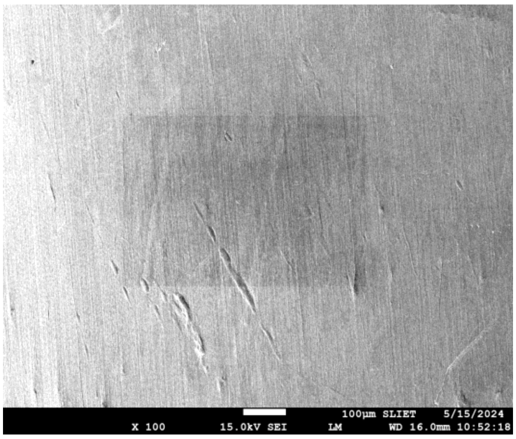
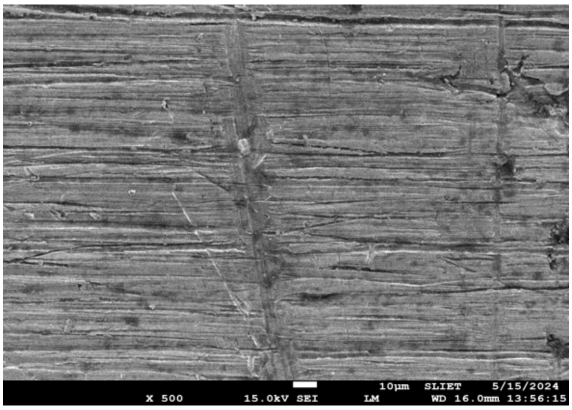


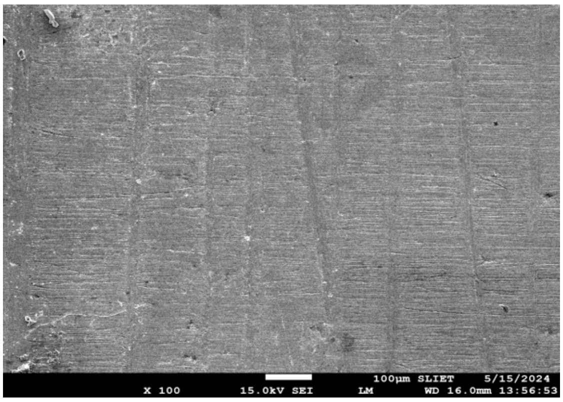
Fig. 5 (a) SEM BEFORE



(b) SEM AFTER Th-AFM process (P.wax) at 40°C



(c) SEM BEFORE



(d) SEM AFTER Th-AFM process (guar gum) at 10°C

5. Conclusion

In This study effect of Thermal assisted abrasive flow machining parameters on MR of brass was studied using Taguchi method L_{27} OA. From the results, it was found that Media, Temperature and concentration play a significant role in Th-AFM process operation related to material removal. Number of cycles and grit size has no significant effect on Material Removal. Also it is found that for higher MR the optimum levels of Media, Temperature, concentration are guar gum, 10°C, 1:1 respectively and its value is 9.9 mg. ANOVA is used to find the significance of machining parameters and their contributions on Material Removal individually. Media is found to be most significant parameter on MR with 59.38% contribution followed by Temperature with 11.36 % contribution and Concentration with 10.94 % contribution

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