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Finishing of Bevel Gears using Abrasive Flow Machining

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Abstract

Abrasive flow machining (AFM) is a precision finishing process with a deforming tool. In this process, a semi viscous carrier material that holds the abrasive particles acts as a multi-point flexible tool with tiny cutting edges. In the present study, effects of few important parameters such as extrusion pressure, abrasive mesh size, processing time and media flow rate on finishing EN-8 steel bevel gears have been investigated. A new tooling for fixing bevel gears has been designed and developed in such a way that the abrasive media passage is thoroughly restricted to abrade the gear tooth surface only. The initial surface roughness of the as received bevel gears was 1.4 to 1.8 micrometers. Taguchi orthogonal array was used to investigate the signal to noise ratio, main effect and parametric optimization. Finished gears were monitored using an optical profiler to assess the surface roughness. Finished gear surfaces were subjected to roughness measurements at five different locations (for each sample) and average of those values was considered. The results indicated that the improvement in surface finish was more than 50%, however, the enhancement in material removal was marginal. It was observed that the extrusion pressure has the highest contribution of about 73 % on the process output; the other significant parameters being abrasive mesh size and processing time.

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Keywords: AFM, bevel gears, surface finish, abrasion time

1. Introduction

The AFM process consists of pumping an abrasive-laden medium through or over the surfaces of the component to be finished. In this process, a suitable workpiece tooling is used to hold the workpiece and also to direct the abrasive to where the flow is constricted, or where the media is forced to change direction [1]. The media is pushed by means of two hydraulic cylinders, positioned suitably either vertically or horizontally. Media flows from one cylinder, through the tooling into the other cylinder, and then returns. This complete step can be considered as one contacting processing cycle. In the process, the hard abrasives under controlled pressure carry changes to the contacting workpiece surfaces through micro-cutting and micro-ploughing that eventually results in improved characteristics of the target surface.

Bevel gears are used to transfer motion from a machine to another part of two intersecting shafts. The effect of surface finish on gear tooth plays a major role [2]. In order to improve the performance, finishing of a gear member through proper process is required. Generally, gears are finished using processes like lapping, honing, elecrochemical honing [3] etc.

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In the present work, simulation of media flow on the gear teeth was carried out in order to understand the media flow behavior in a complex bevel gear AFM tooling. Further, experiments were planned according to Taguchi L9 orthogonal array; a set of 9 experiments were conducted on finishing of bevel gear using natural polymer media. Extrusion pressure, abrasive mesh size, processing time and media flow rate were selected as input variables whereas surface finish improvement (SF) and material removal (MR) were considered as process responses. The response curves of illustrating the main effect plots, signal to noise ratio, Analysis of variance (ANOVA), local and global solutions were predicted using response optimizer. The conformity trials reveal a neat agreement between the experimental data and the predicted value and evidences that the model selected is acceptable

2. Simulation of AFM in finishing of bevel gears

It is important to know the behavior of media in AFM process not only for improving its active grain density but also to maintain uniform flow. Therefore, a numerical model was created by finite element modelling (FEM) of the abrasive media flow to estimate wall shear and pressure losses on gear tooth surface. Computations were performed using the ANSYS FLUENT CFD tool (version-14). Navier-Stokes equations and transport equations were used for fluid flow simulation in order to define the fluid flow characteristics. The medium used in this study consists of a silicon carbide abrasives mixed with a natural polymer material whereas naphthenic based processing oil was used for mixing thoroughly. In actual processing, the working pressure of the abrasive flow was set to 15 bar; the initial density of the abrasive media was 1260 kg/m3, combined with the media performance parameters. The properties of the media used in the work are: temperature = 300 K, thermal conductivity = 0.8 W/m-K, specific heat coefficient = 1800 J/kg-K, media viscosity = 730 poise. The cross section of the half thickness of the bevel gear of EN8 steel material was used to demonstrate the simulated results as shown in the Fig. 1. The distribution of the pressure and the shear rates of the abrasive medium on gear tooth are as shown in Fig.1 and Fig. 2. It is also observed that the pressure decreases with increase in length of media flow travel. This behavior of pressure is common in AFM processing as claimed by other authors [4]. On the other hand, from Fig. 2 it is observed that wall shear is high at the edges of the gear teeth at the small diameter end of the bevel gear. The rise in observed wall shear is associated with increase in media flow velocity or fall in the extrusion pressure as illustrated in Fig. 1. Results also reveal reasonable uniformity of media flow on the flank, tip, left and right side wall of the gear tooth surface.

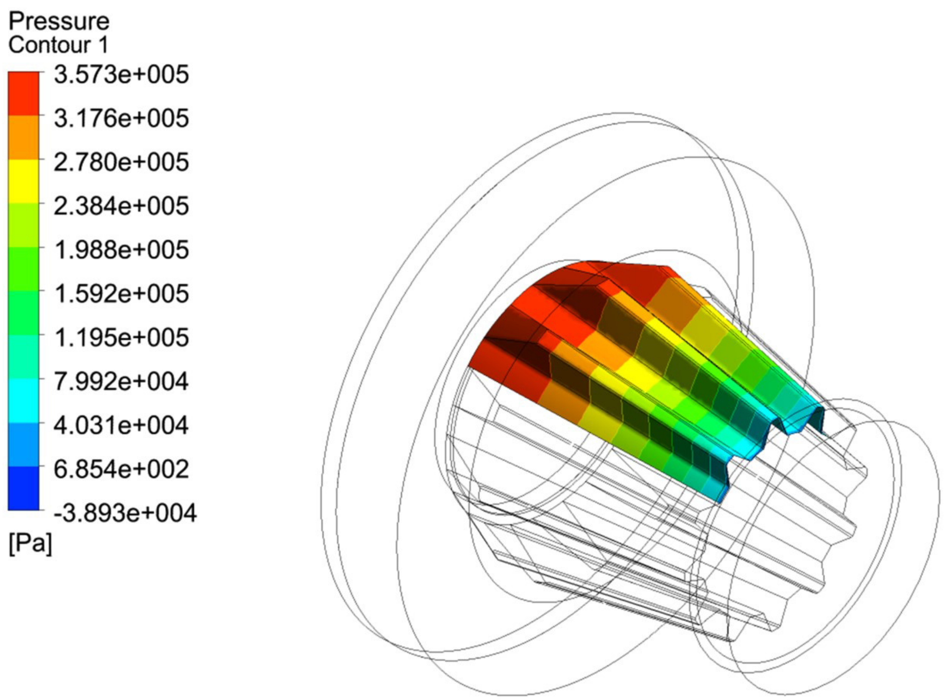


Fig. 1. Dynamic Pressure distribution of AFM media on bevel gear outer surface

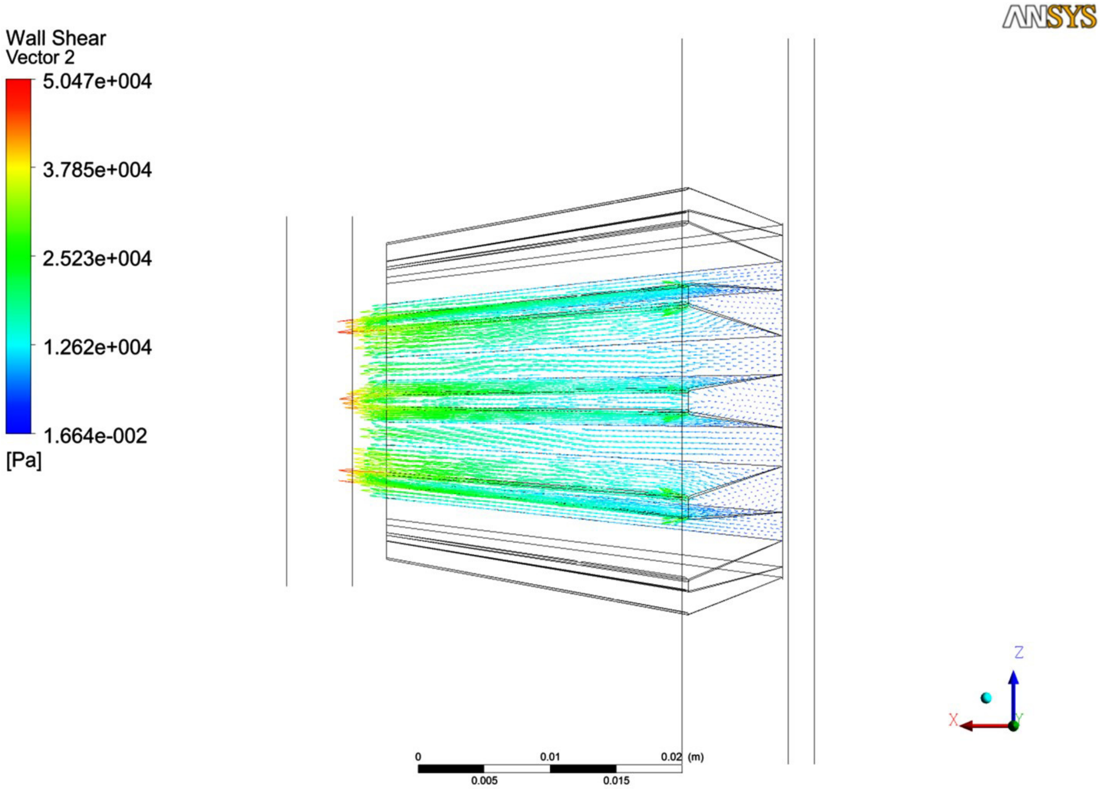


Fig. 2. Wall shear distribution of AFM media on bevel gear outer surface

3. Experimental Procedure

The AFM set-up used for experimentation is shown in Fig. 3(a). It consists of hydraulic unit which controls the movement of cylinders filled with media, mounted on the cast iron bed. The reciprocating motion is controlled by the control panel. In AFM, it has been reported that enhancement in performance could be achieved by improved fixturing [5]. Accordingly, a special tooling was designed to hold the workpiece and guide the media to flow through it by restricting its passage appropriately. The Teflon tooling developed in this study and the bevel gears used as specimens are shown in Fig.3 (a & b). A Solid Work 3D model of the tooling used is presented in Fig.3(c).

The objective of this set of experiments conducted in the present study was to explore the performance of simple AFM on finishing of bevel gears of EN8 material. The effect of newly developed fixture on surface finish and material removal rate was also investigated. The final roughness after finishing and weights after machining were measured to calculate the percentage improvement in Ra and MR by using the equations (1) and (2) respectively.

$$SF = \frac{Intial\ Ra - final\ Ra}{intial\ Ra} \ X\ 100\ \% \tag{1}$$

$$MR = Initial\ weight - Final\ weight\ (mg) \tag{2}$$

3.1. Taguchi analysis

The process parameters and their ranges were selected after an extensive literature survey on the developments and then conducting a series of pilot runs. The main experiments were planned using the parametric approach of the Taguchi's method. Table 1 shows the factors and levels preferred for the experimental trials. Table 2 shows the experimental data conducted based on Taguchi orthogonal array L9. The standard procedure to analyse the data as suggested by Taguchi was employed. The average values and S/N ratio of the quality/response characteristics for each parameter at different levels were calculated from the experimental data. The main effect of process parameters both for raw data and S/N ratio were plotted as shown in Fig. 4. The response curves (main effects) were used for examining for parametric effects on the response characteristics. The most favourable conditions (optimal settings) of process parameters in terms of mean response characteristic were established by analysing response curves and the ANOVA. Tables 3 and 4 present the ANOVA calculations for both surface finish improvement and material removal, respectively.

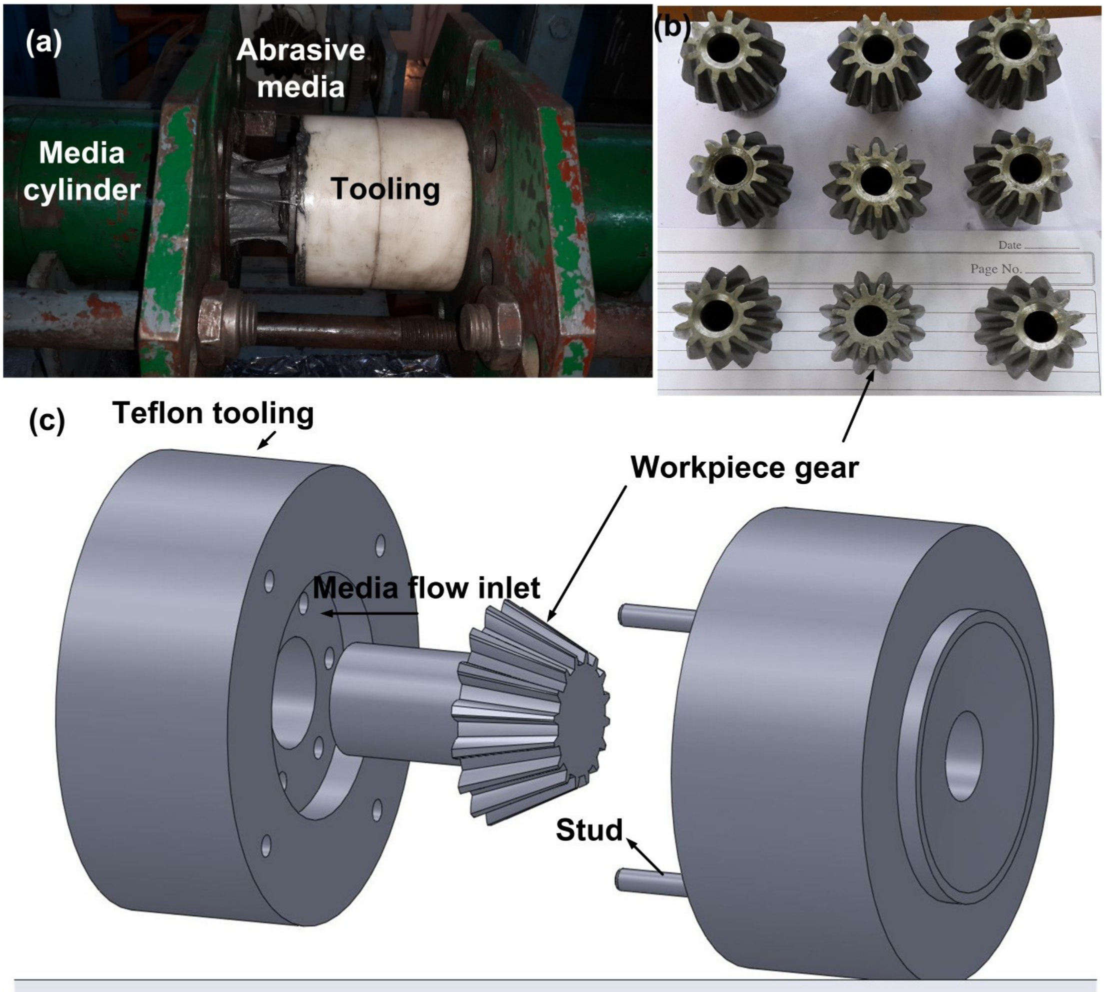


Fig.3. (a) A close view of the tooling and a media cylinder as attached to the two way AFM experimental setup, (b) image of the bevel gears prior to machining and (c) a 3D model of the tooling and the bevel gear.

Table 1. Process parameters and their levels

S. No.	Process parameters	Range	Unit
	Independent parameters		
1	Extrusion Pressure	20-30-40	bar
2	Abrasive size	100-150-200	mesh size
3	Processing Time	5-7-9	Min
4	Media Flow Rate	567-796-995	cm^3/min
	Constant parameters		
5	Media Viscosity	510	Pa-s
6	Abrasive to media concentration	50:50	% by weight
7	Temperature of media	32 ±2	^{0}C
8	Initial surface roughness of a gear	1.4 – 1.6	µm
	Response parameters		
9	Improvement in Surface roughness		%
10	Material removal		mg

Table 2. Experimental results based on orthogonal array

	Process Parameters				Process Response			
Run	A:Extrusion Pressure (bar)	B:Abrasive Size (µm)	C:Processing Time (min)	D:Media Flow Rate (cm^3/min)	Surface Finish Improvement (%R_a)	S/N (SF)	Material Removal (mg)	S/N (MR)
1	1	1	1	1	18.62	20.59	11.38	16.26
2	1	2	2	2	29.95	24.73	12.64	17.26
3	1	3	3	3	37.19	26.6	8.51	13.79
4	2	1	2	3	38.51	26.93	20.03	21.25
5	2	2	3	1	50.43	29.28	16.26	19.44
6	2	3	1	2	46.12	28.49	13.4	17.74
7	3	1	2	2	48.32	28.9	22.03	21.22
8	3	2	1	3	50.02	29.2	20.81	21.57
9	3	3	3	1	59.82	30.76	20.92	21.59

4. Effect of variable parameters on surface responses

The effect of variable parameters such as extrusion pressure, abrasive mesh size, processing time and media flow rate were explored while machining a bevel gear surface using traditional abrasive flow machining process. The process responses such as surface finish improvement and material removal were evaluated. The average values of percentage improvement in surface finish and the S/N ratio for each parameter at three levels were calculated and trend characteristics were plotted in the Fig. 4 (a-h).

Fig. 4(a and b) show that at lower pressure, surface finish and material removal are low due to the fact that the shearing energy produced through abrasive particle at 20 bar extrusion pressure is not enough to shear the peeks. It is observed that the shear strength of the tool material (abrasive media) should be more than that of the resistance offered by the work material. In the process, the top edge of the peek will get sheared off and remaining part of the peek will contribute to the observed surface roughness. At 30 bar pressure, the rate of improvement of surface finish and MR is quite significant. On further increase in the pressure, the surface finish as well as MR improve further. But the rates of improvement in surface finish as well as MR decline when compare to 20 to 30 bar pressures (Fig. 4(b)).

In Fig. 4(c) and (d), the characteristic curves show that surface finish increases with increase in abrasion mesh size whereas material removal decreases with increase in mesh size. Abrasive size decreases with increase in mesh size, thus more number of active abrasive particles participates during the abrasion process (with higher mesh size). This leads to removal of material at even finer level resulting in smoother surface. Large abrasive particles yield greater improvement in material removal while surface finish gets deteriorated (Fig. 4(d)).

The interaction of abrasive media with the target surface was calculated in terms of time of interaction and termed as processing time or abrasion time. It is the total time the gear surface is exposed to abrasive action during the AFM process. Figs. 4(e) and (f) show that during the initial stages of processing time, surface finish and material removal improve sharply. Further drop in percentage surface finish improvement and MR can be attributed to the fact that the sharp abrasive edges get blunt as machining progresses, this eventually results in marginal improvements in finish on continued machining. Such effects on micro finishing of surfaces were also explored in other work elsewhere [6].

Effects of media flow rate on surface finish and MR are graphically shown in the Fig. 4(g) and (h). Surface finish improvement is seen lean from level 1 to level 2. Further, it improved significantly from level 2 to 3. This is due to machining surface being exposed to more abrasives with fresh cutting edges taking active part in abrading the work piece surface. Further, velocity of the abrasive particles increases with the media flow rate leading to removal of asperity peeks in sub-micron level. These results in fine surface finish and low MR; whereas MR remains constant with increasing media flow volume which indicates that its role is insignificant.

Table 3 ANOVA table for Surface finish improvement (SF)

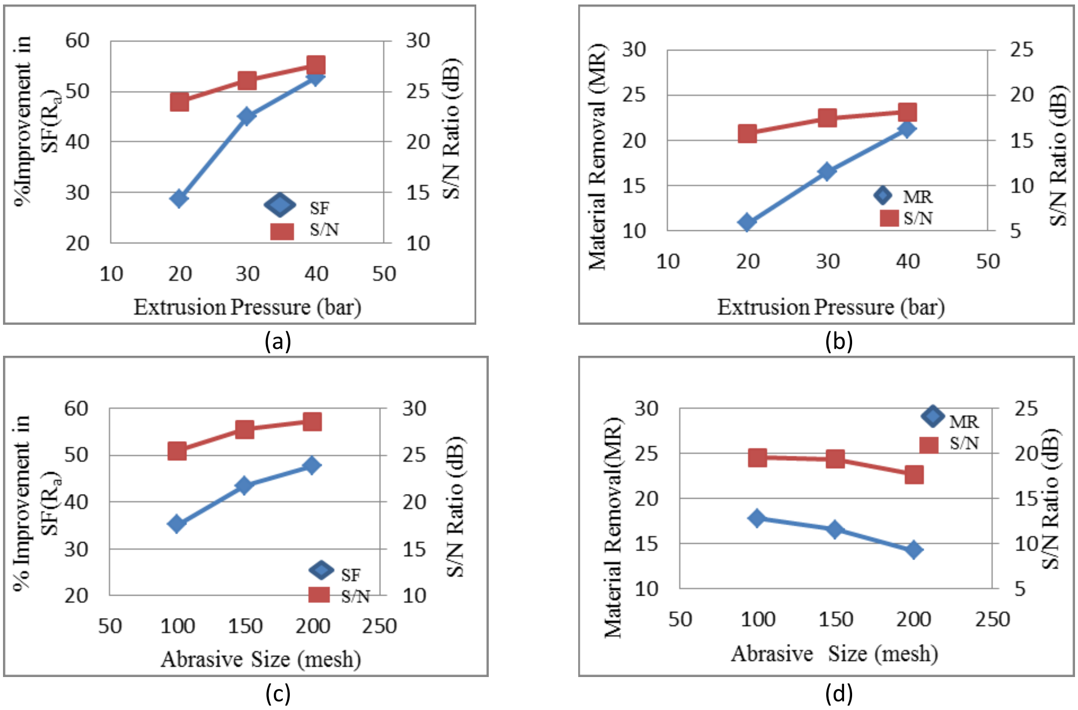
Source	Sum of Squares	DF	Mean Square	F-ratio	Pure Sum	% of contribution
A	911.76	2	455.88	258.36*	19.83	73.71
B	244.93	2	122.46	69.40*	7.94	19.80
C	76.67	2	38.34	21.73*	6.20	6.20
Error	3.53	2	1.76			0.29
Total	1236.89	8				100.00
Std. Dev.	1.33			R-Squared	0.9971	
Mean	42.11			Adj R-Squared	0.9886	
C.V.	3.15			Pred R-Squared	0.9422	

*Significant at 95% confidence level

Table 4 ANOVA table for Material removal rate (MR)

Source	Sum of Squares	DF	Mean Square	F-ratio	Pure Sum	% of contribution
A	163.08	2	81.54	586.49	163.08*	83.60
B	19.31	2	9.66	69.46	19.31*	9.90
C	12.40	2	6.20	44.58	12.40*	6.35
Error	0.28	2	0.14			0.15
Total	195.07	8				100.00
Std. Dev.	0.37		R-Squared	0.9986		
Mean	16.22		Adj R-Squared	0.9943		
C.V.	2.30		Pred R-Squared	0.9711		

*Significant at 95% confidence level



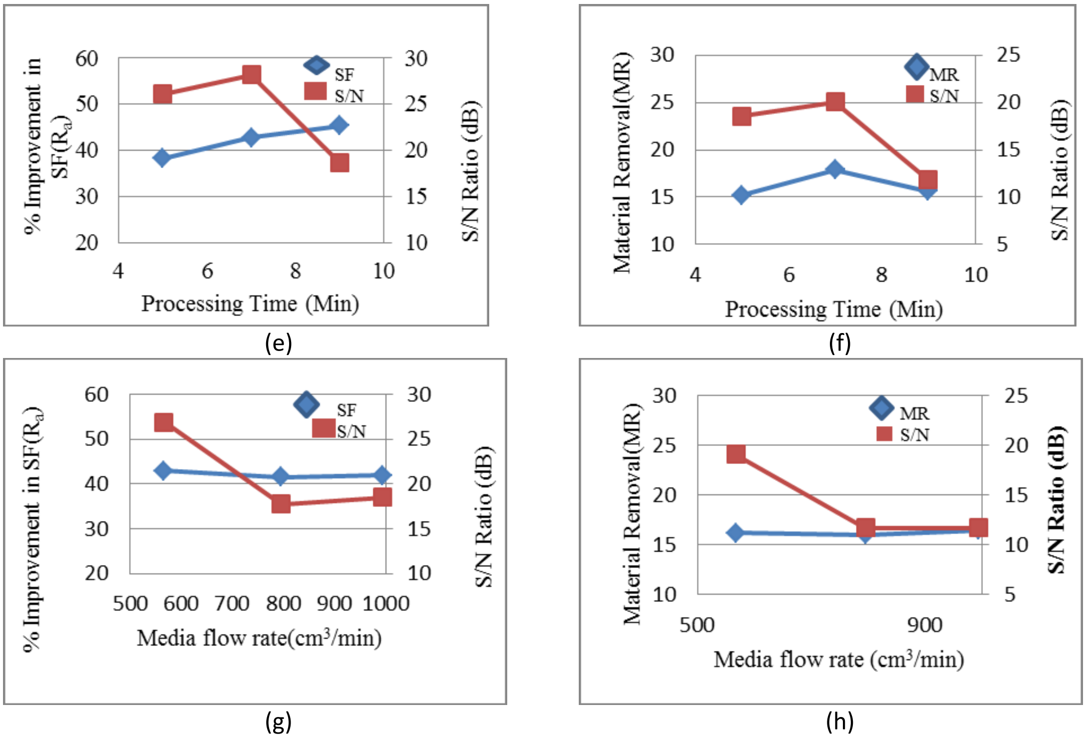


Fig. 4. Effect of process parameters on signal to noise ratio and main effect: (a) Extrusion pressure on SF improvement, (b) Extrusion pressure on MR, (c) Abrasive size on SF improvement, (d) Abrasive size on MR (e) Processing time on SF, (f) Processing time on MR, (g) Media flow rate on SF and (h) Media flow rate on MR.

4.1 *Optimality check*

Table 5 shows the predicted inputs, outputs and local as well as global solutions. The results reveal that the maximum composite desirability (D) in global solution is 0.99991. In order to confirm the result, a test was conducted, and the corresponding results are shown in Table 6. It is observed that the error percentage of surface finish improvement and material removal are 2.33% and 10.8% (Table 6). The obtained results appear within a practically achievable range. Therefore, the obtained result can be useful to predict the optimum values of the desired outputs in the same experimental condition. Thus, these results can be used by other researchers and practitioners in industries for developing their scheme for AFM machining of gears.

Table 5 Optimized results for predicted optimized inputs and responses

Local and global solutions	Predicted optimized inputs				Predicted optimized output		Composite desirability (D)
	A	B	C	D	SF,%	MR, mg	
Local solution	35	150	8	995	55.25	21.06	0.94600
Local solution	40	100	9	567	48.88	21.24	0.82390
Local solution	40	100	9	995	49.20	22.34	0.87099
Global solution	40	150	9	567	55.27	22.33	0.99991

Table 6 Error percentage of the predicted and measured responses

Predicted input				Predicted output		Measured output		Error %	
A	B	C	D	SF	MR	SF	MR	SF	MR
40	150	9	567	55.27	22.33	54.01	20.15	2.33	10.8

5. Surface morphology

Surface morphology of gear teeth was studied using optical profilometer. Figure 5 shows the typical surface topography in terms of 3D projection of bevel gear tooth surface profile before finishing and at some AFM conditions. The effect of significant parameters on the surface quality was analyzed using this profilometer. Fig. 5(b) shows that the average surface roughness (R_a) values change primarily with effect of extrusion pressure and also with mesh size and processing time to some extent. It is also observed from the Fig. 5(b), (c) and (d) that extrusion pressure significantly influences the surface finish improvement. Higher pressure at more processing time produces better surface finish improvement (Fig. 5(d)).

6. Conclusions

. The following major conclusions could be drawn from the study.

1. Results reveal that micro-finishing of bevel gears is possible by AFM process attaching a special tooling.
2. The interaction of the tiny abrasive particles present in the AFM media with the asperities on the gear surface has been analyzed in terms of wall shear and pressure using the CFD technique. Wall shear is higher at the smaller diameter of the bevel gear due to decreased extrusion pressure (increased flow velocity).
3. The parameters such as extrusion pressure, abrasive mesh size, processing time are significant whereas media flow rate has no effect on the finishing process.
4. The extrusion pressure has the highest percentage contribution (73.71%) in surface finish improvement whereas 83.60 % in material removal rate.
5. The local and global solutions of the experimental set including with the conformity test showed the neat agreement between the predicted and actual experimental values.
6. The tooth surface morphology gets improved with an increase in extrusion pressure

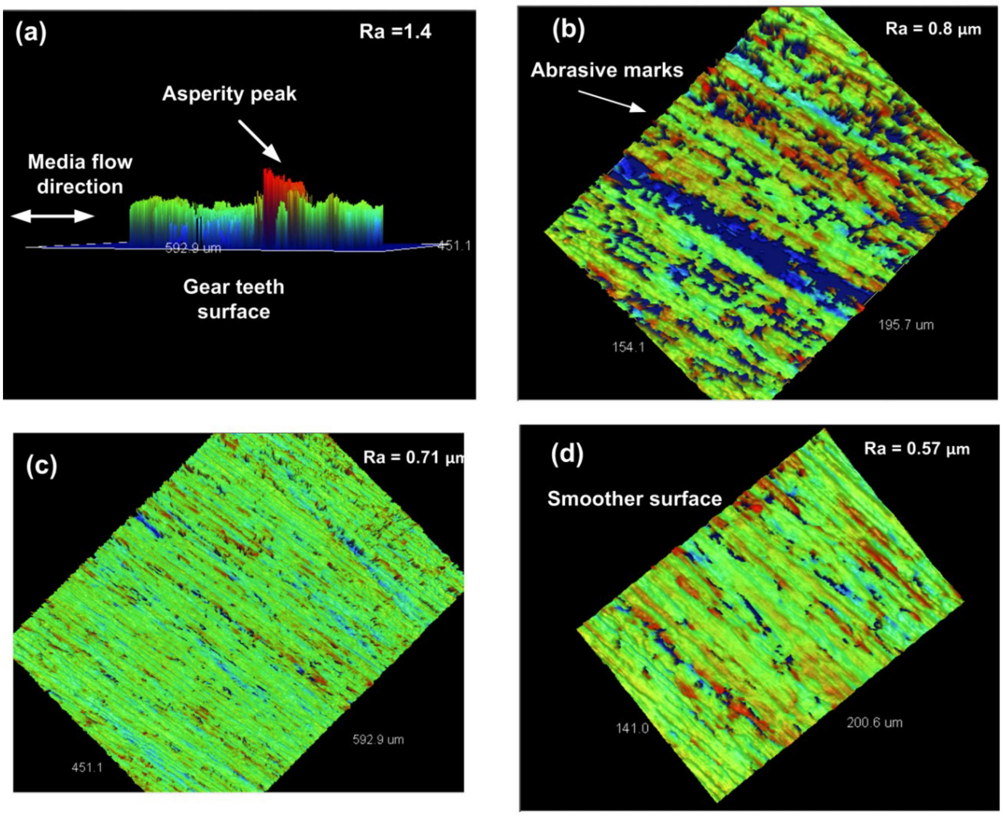


Figure 5 Typical surface topography in terms of 3D projection of bevel gear tooth surface profile: (a) Before AFM, (b) after AFM (Abrasion time 9 min, 200 mesh abrasive size, 20 bar extrusion pressure, media flow rate 796 (Run 3)), (c) at another condition after AFM (Run 5) and (d) fine finished surface (Run 9).

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