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Original Article

Influence of MQL and hobbing parameters on microgeometry deviations and flank roughness of spur gears manufactured by MQL assisted hobbing

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ABSTRACT

Conventional cutting fluids used in gear hobbing have negative impacts on the environment and health of the machine operators thereby adversely affecting the sustainability of the gear hobbing process. This paper reports on MQL assisted hobbing (MQLAH) using environment friendly fatty alcohol-based lubricant to manufacture superior quality spur gears. Experimental investigation was conducted to study of influence of six parameters of MQLAH namely hob cutter speed, axial feed, depth of cut, lube flow rate, air pressure, and nozzle angle on microgeometry deviations, avg. and max. values of flank surface roughness, and material removal rate to identify their optimum ranges to manufacture better quality spur gears with maximum productivity. Deviations in total profile, lead, cumulative pitch and radial runout were used to evaluate microgeometry of the spur gears. It revealed that depth of cut has no considerable effect on the spur gear quality. It identified that higher value of hob cutter speed, lower value of axial feed, optimum values of lube flow rate as 100 ml/h, nozzle angle as 30°, and air pressure in a range from 3 to 5 bar yield superior quality of spur gears by MQLAH.

1. Introduction

Gear is regarded as the most basic mechanical component used for transmission of motion and/or toque between two shafts. Most of the machines used in day to day life such as bikes, cars, bicycles, clocks, toys, washing machines, mixer grinder etc. use different types of gears. Also, there has been an increasing demand for high quality gears in various industries such as automobile, aeronautical, pharmaceutical sector etc. Quality of a gear is primarily evaluated based upon its microgeometry deviations or geometrical tolerances and surface roughness of its flank surfaces [1,2]. Gear microgeometry deviations are expressed in terms of form deviation parameters i.e. deviations in profile (F_a) and lead (F_β), and location deviation parameters namely deviations in cumulative pitch (F_p) and radial runout (F_r). Form deviations (i.e. F_a and F_β) refer to the deviations in form or shape of gear teeth whereas location deviation parameters (i.e. F_p and F_r) denote the deviations or errors related to the position of teeth on a gear. Flank surface roughness parameters such as average roughness (R_a) and

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maximum roughness (R_{max}) denote unevenness or coarseness of gear flank surface which determine performance of a gear. Higher values of tooth flank roughness parameters are responsible for gear failure through crack formation and initial wear whereas deviations in profile, lead, cumulative pitch and radial runout respectively affect noise generation, load carrying capacity, motion transfer and transmission accuracy of a gear [1,2].

Subtractive (i.e. material removal) manufacturing processes such as hobbing, milling, shaping, planning, broaching constitute one of the most important and widely used processes in manufacturing of different types of the gears. But these processes are incapable of producing good quality gears without any finishing processes which extends the process chains [2].

Gear hobbing is the most extensively used subtractive manufacturing process for the cylindrical (i.e. spur and helical) gears. Its schematic is shown in Fig. 1. It uses synthetic cutting fluids by means of flood lubrication (FL) and cooling technique to minimize and regulate the heat generation by improving the frictional behavior at the machining zone besides assisting in chip evacuation. Cutting fluids also play a vital role in improving the product quality, reducing the power consumption and enhancing tool life [3,4]. But, FL technique adversely affects the environment and human health [5–9]. Moreover, necessity of the subsequent finishing processes to achieve the desired gear quality results in longer process chains thus upsetting the economic advantages of the process.

All the aspects of economic, social (human health) and environmental sustainability must be satisfied efficiently for a manufacturing process to be considered as sustainable. To improve sustainability of gear hobbing process and to enhance its performance, continuous efforts are being made to eliminate or minimize the consumption of synthetic cutting fluids and to reduce the process chain by finding potential alternatives to the conventional FL technique [10]. Although elimination of cutting fluids has its own disadvantages because gear hobbing without cutting fluid lead to more deviations in gear microgeometry due to thermal expansion caused by intense heat accumulation in the machining zone thus leading to poor quality of gears [11]. Studies are being conducted to replace FL technique with an environment friendly lubrication technique referred as minimum quantity lubrication (MQL) and use it in gear hobbing to improve its sustainability without compromising with quality of the hobbed gears.

MQL supplies only a precise amount of lubricant to the machining zone in aerosol form thereby minimizing the harmful effects of large amount of synthetic based cutting fluids based conventional FL technique [10]. Precise amount of lubricant supplied along with the compressed air ensures more effective lubrication and penetration of the lubricant thereby improving the frictional behavior at the work-tool and tool-chip interfaces [12]. Limited research has been reported on sustainable manufacturing of gears by hobbing process. Kadashevich et al. [11] developed 3D based-simulation model to calculate thermal deviations in dry hobbing. Modified 3D model and abacus-based thermo-mechanical solver were used to identify the zones of extreme deformations and to compensate them for improving the gear quality manufactured by dry hobbing. Sato et al. [13] performed simulated hobbing for manufacturing spur gears using fly tool cutter in MQL and dry lubrication environment. They found that the tool wear rate and the cutting forces obtained in MQL assisted hobbing (MQLAH) were less than that obtained in the dry hobbing. Matsuoka et al. [14] conducted experimental research to manufacture spur gears by hobbing using coated tools in dry and MQL lubrication environments. It was observed that MQLAH resulted in lower tool wear and surface roughness values as compared to that obtained with dry hobbing. Stachurski [15] did comparative study of MQLAH and flood lubrication assisted hobbing (FLAH) during manufacturing of spur gears. His results revealed that cutting forces were less in MQLAH thereby yielding better tool life as compared to FLAH. Zhang et al. [16] compared performance of flood, dry, MQL and cryogenic lubrication assisted hobbing of helical gears and concluded that there was significant improvement in tool life with MQLAH than other lubrication techniques.

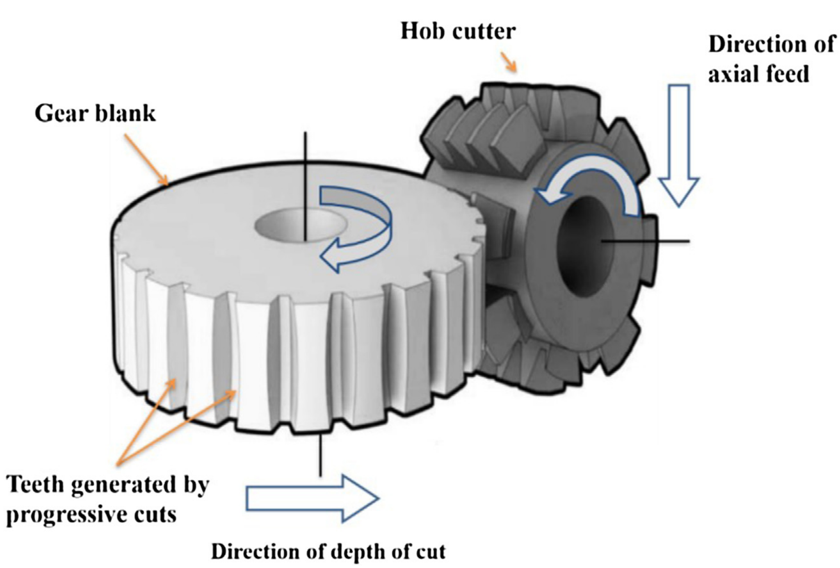

Fig. 1 – Schematic of gear hobbing process.

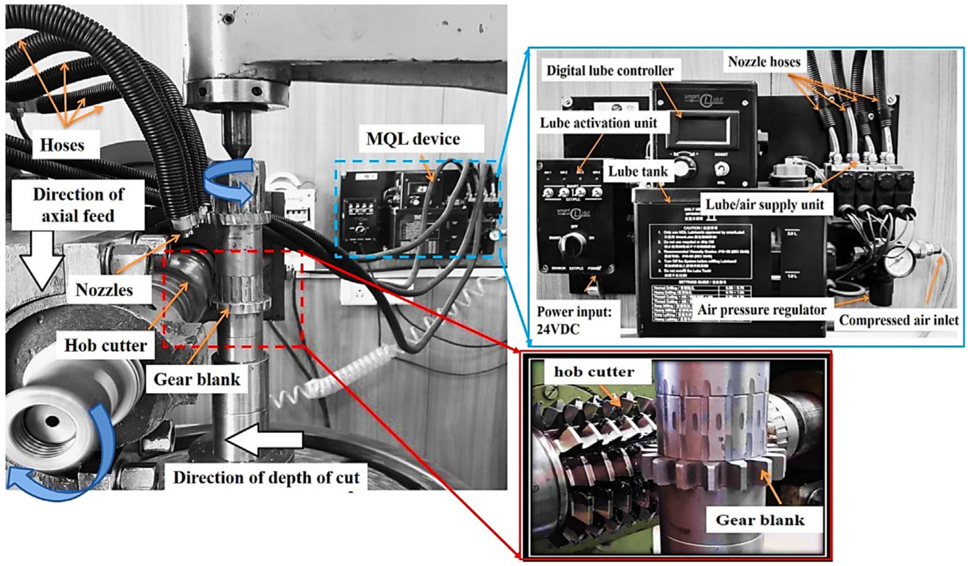

Fig. 2 – Experimental apparatus for minimum quantity lubrication assisted hobbing.

Most of the previous works on sustainable manufacturing of gears were carried out using fly tool cutters and have used synthetic cutting fluids and have been focused on evaluating parameters such as tool wear rate, thermal deviations, cutting forces. There is a scarcity of work on study of MQLAH using environment friendly lubricants with an objective to identify the optimum ranges of MQLAH process parameters (i.e. hob cutter speed, axial feed, depth of cut, lube flow rate, air pressure and nozzle angle) for commercial production of superior quality spur gears. The present research work fulfils this gap. Therefore, the objectives of the present investigation are (i) to study feasibility of MQLAH as a sustainable process to manufacture superior quality spur gears using environment friendly green fatty alcohol-based lubricants, and (ii) to study influence of MQL parameters such as lube flow rate ‘Q’, air pressure ‘P’, nozzle angle ‘α’ and hobbing parameters such as hob cutter speed ‘V’, axial feed ‘f’, depth of cut ‘D’ on quality of gears manufactured by MQLAH in order to identify the optimum parametric ranges for commercial production of spur gears and for future investigations.

2. Materials and methods

Fig. 2 illustrates the experimental apparatus for MQLAH developed by integrating MQL system MT-MQL V2.2 to a manual gear hobbing machine by means of four micro-nozzles. Environment friendly and biodegradable fatty alcohol-based lubricant “Hyspray A 1536” (having kinematic viscosity as 28 mm^2/s at 40 °C; flash point as 194 °C) was used to manufacture spur gears from 20MnCr5 alloy using solid type single start hob cutter made of high-speed steel (HSS) Emo5Co5. Table A1 compares properties of “Hyspray 1536” lubricant used in present investigation with the water-mix lubricant “Servocut S” used in conventional fluid lubricated hobbing. Specifications of the hob cutter and manufactured spur gears are shown in Table 1.

The alloy steel 20MnCr5 is one of the most commercially used material for commercial production of heavy-duty gears, shafts, axles etc. It has higher tensile strength of 1000−1300 N/mm^2 and a good wearing resistance as compared to other gear materials. Therefore, it was selected as material for manufacturing spur gears. Environment friendly fatty alcohol-based lubricant “Hyspray 1536” was used in the present investigation as it is recommended by the manufacturer of MQL system MT-MQL V2.2 (i.e. MECHATRONIK, Singapore) and it is safe to the operators and possess desirable properties for effective lubrication in MQL. Total 24 experiments were conducted to study the influence of six parameters of MQLAH (three parameters related to hobbing namely hob cutter speed ‘V’, axial feed ‘f’, depth of cut ‘D’ and three parameters of MQL i.e. lube flow rate ‘Q’, air pressure ‘P’, nozzle angle ‘α’) on the considered parameters of microgeometry deviations (i.e. F_a, F_β, F_p, F_r) and flank surface roughness (i.e. R_a and R_{max}) of the spur gears. The experiments were designed using one-factor-at-a-time approach which involves varying one variable parameter at a time and keeping the other parameters constant at their mid-level values. Hob cutter speed, axial feed, lube flow rate, and air pressure were varied at five levels each whereas depth of cut and nozzle angle were varied at

Table 1 – Specifications of hob cutter and manufactured spur gear.

Specification of the spur gear	Specifications of the hob cutter
Material: 20MnCr5 alloy steel	Material: Emo5Co5
Chemical composition: 0.8–1.1% Cr; 1–1.3% Mn; 0.14–0.19% C; 0.035% P and S; 0.15–0.40%; and balance Fe	Chemical composition: 6.40% W; 5% Mo; 4.80% Co; 4.10% Cr; 1.90% V; 0.92% C; and balance Fe
Module: 3 mm	Module: 3 mm
Profile: involute	Helix angle: 2.5°
Number of teeth: 16	Number of starts: 1
Pitch circle diameter: 48 mm	Number of gashes: 12
Pressure angle: 20°	Outer diameter: 80 mm
Face width: 10 mm	Bore diameter: 32 mm
Tip diameter: 54 mm	Length: 69 mm

Table 2 – Details of variable input parameters and responses used in the experimentation.

Variable parameters	Levels					Responses
	I	II	III	IV	V	
Hob cutter speed (m/min)	8	15	22	29		Total profile deviation 'F_a'
						Total lead deviation 'F_β'
Axial feed (mm/rev)	0.2	0.32	0.44	0.56		Accumulative pitch deviation 'F_p'
Depth of cut (mm)	0.75	1.125	2.25			
Lube flow rate (ml/h)	40	60	80	100	120	Runout deviation 'F_r'
Air pressure (bar)	2	3	4	5	6	Average surface roughness 'R_a'
Nozzle angle (degrees)	15	30	45			Maximum surface roughness 'R_{max}'
						Material removal rate (MRR)

Table 3 – MRR for different combinations of hobbing parameters.

S. no.	Hobbing parameters			MRR (mm^3/min)
	V (m/min)	f (mm/rev)	D (mm)	
1	8	0.44	1.125	31.42
2	15			61.27
3	22			90.22
4	29			120.3
5	22	0.20	1.125	41.02
6		0.32		65.62
7		0.44		90.22
8		0.56		114.83
9	22	0.44	0.75	60.15
10			1.125	90.22
11			2.25	180.45

three levels each. Table 2 presents details of the variable input parameters and their corresponding levels, fixed parameters and responses used in this investigation.

Microgeometry deviation parameters of the spur gears were measured on SmartGear 500 computer numerical controlled (CNC) gear metrology machine from *Wenzel GearTec, Germany* whereas surface roughness parameters were evaluated using 3D-coutour-tracing-cum-measuring instrument MarSurf LD-130 from *Mahr Metrology, Germany*. Multiple measurements for each of the considered responses were taken corresponding to each parametric combination i.e. (i) total deviation in profile (F_a) and total deviation in lead (F_β) were measured on both the left and right flanks of the randomly selected four teeth for each manufactured spur gear i.e. total 8 values for F_a and F_β each for each experiment, (ii) deviation in cumulative pitch (F_p) and total radial runout (F_r) were measured on left and right flanks of 16 teeth of each manufactured spur gear and their corresponding average value was used for analysis purpose, and (iii) average and maximum values of flank surface roughness (R_a and R_{max}) were measured on both left and right flank surfaces of any two teeth located on radially opposite ends of each manufactured spur gear i.e. 4 values for R_a and R_{max} each and their average values was considered for the analysis. Volumetric material removal rate (MRR) is the volume of the material removed per unit time and determines the productivity of any subtractive manufacturing process. It was evaluated by using the following equation [17]:

$$MRR = \frac{W_b - W_g}{\rho_g\, t}\left(\frac{mm^3}{min}\right) \quad (1)$$

where, W_b' is weight of the gear blank (g); 'W_g' is weight of the manufactured gear (g); ρ_g is density of the gear material (g/mm^3); and t is the total time to manufacture a spur gear (minutes). W_b and W_g were measured on a precision weighing instrument having least count of 10 mg. Hobbing time was measured using a stopwatch having a least count of 0.01 s. Tooth flank surface topography of the manufactured spur gear was studied using scanning electron micrograph (SEM) images obtained from SUPRA 55 FE-SEM from *Carl Zeiss, Germany*.

3. Results and discussion

Table 3 presents MRR values obtained while varying only three parameters of hobbing whereas Table 4 presents values of parameters of microgeometry deviations and surface roughness obtained for each experimental run. Figs. 3–5 illustrate the effect of MQLAH process parameters on form deviations (i.e. F_a and F_β), location deviations (i.e. F_p and F_r) and flank roughness parameters (i.e. R_a and R_{max}) by means of best fit curves obtained using the experimental results of Tables 3 and 4 and along with values of the constant parameters.

3.1. *Influence of MQL and hobbing parameters*

Figs. 3(a–c); 4 (a–c); and 5 (a–c) present effect of hobbing parameters (hob cutter speed, axial feed, and depth of cut respectively) on form deviations, location deviations, and flank surface roughness of the MQLAH manufactured spur gears. It can be observed from Figs. 3(a) and 4 (a) that gear

Table 4 – Values of the considered responses for all the experiments.

S. no.	Hobbing parameters			MQL parameters			Responses					
							Microgeometry deviations (μm)				Surface roughness (μm)	
	V (m/min)	f (mm/rev)	D (mm)	Q (ml/h)	α (deg)	P (bar)	F_a	F_β	F_p	F_r	R_a	R_{max}
1	8	0.44	1.125	80	30	4	63.5	31.9	131.1	144.3	0.66	6.94
2	15						55.3	25.1	116.1	127.7	0.60	6.05
3	22						52.5	20.2	110.5	121.2	0.55	5.63
4	29						51.2	19.0	106.1	118.3	0.53	5.34
5	22	0.20	1.125	80	30	4	50.1	16.7	101.2	120.8	0.54	5.57
6		0.32					51.3	17.0	105.2	121.5	0.55	5.68
7		0.44					52.1	20.7	111.3	122.3	0.59	5.79
8		0.56					62.5	27.5	129.7	139.3	0.65	6.64
9	22	0.44	0.75	80	30	4	52.1	20.6	109.4	120.4	0.53	5.75
10			1.125				51.9	19.7	108.9	119.9	0.54	5.77
11			2.25				52.7	19.6	109.6	119.5	0.52	5.68
12	22	0.44	1.125	40	30	4	61.4	24.7	125.2	136.2	0.63	7.41
13				60			54.9	18.9	116.5	126.9	0.59	6.33
14				80			51.6	18.7	112.7	120.9	0.55	5.84
15				100			49.8	14.0	99.7	117.3	0.51	5.23
16				120			50.3	15.9	101.2	120.1	0.53	5.52
17	22	0.44	1.125	80	15	4	53.8	19.6	113.3	126.7	0.56	6.03
18					30		52.4	17.8	112.2	124.0	0.55	5.85
19					45		56.3	18.5	115.0	125.4	0.58	6.43
20	22	0.44	1.125	80	30	2	54.3	19.0	114.4	122.9	0.57	6.34
21						3	52.7	17.2	110.6	118.6	0.53	5.95
22						4	51.1	16.9	109.3	119.7	0.54	5.79
23						5	51.3	16.7	108.9	119.2	0.52	5.73
24						6	52.7	17.4	111.1	120.6	0.55	5.84

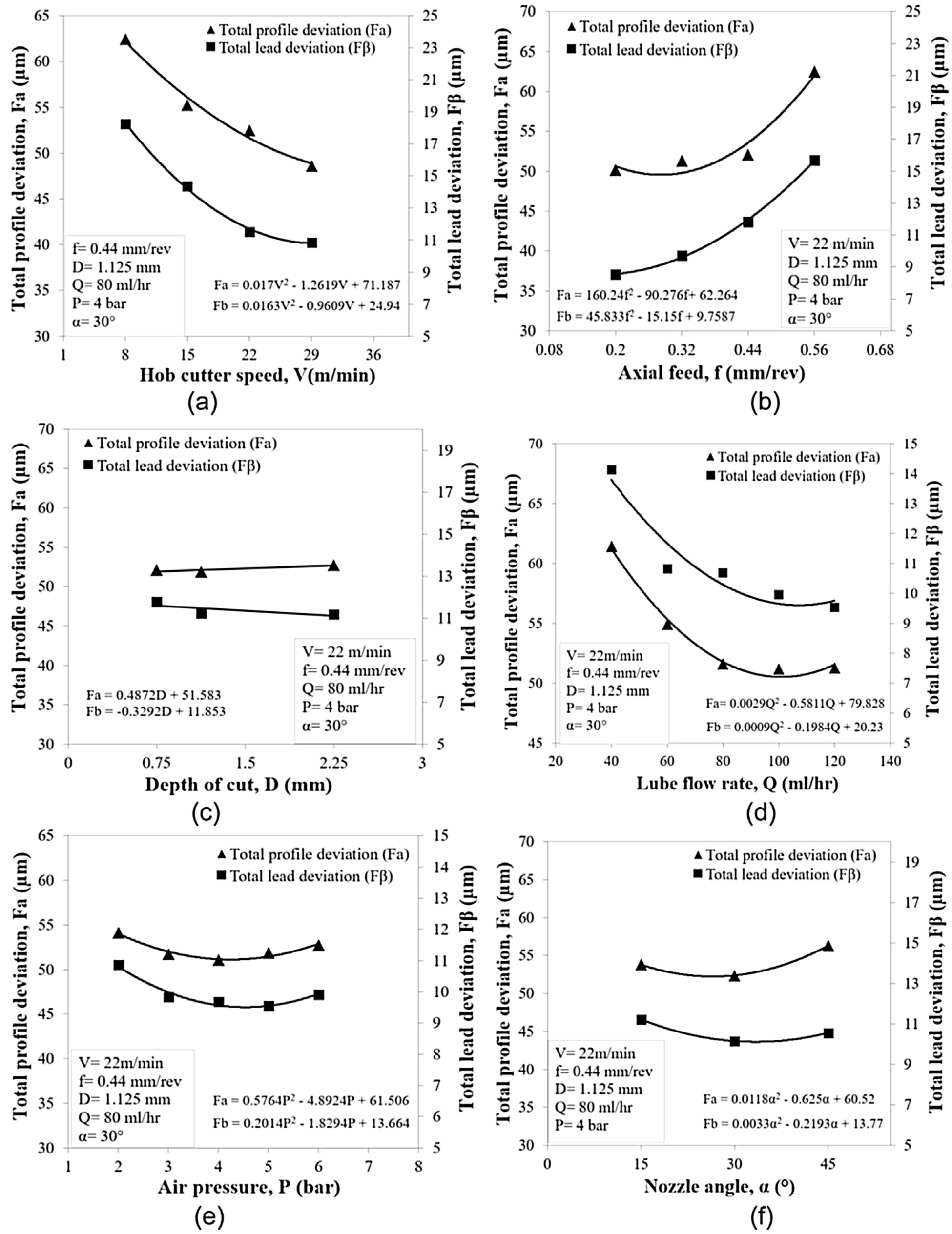

Fig. 3 – Variation in form deviations i.e. deviations in profile 'F_α' and lead 'F_β' with MQLAH parameters: (a) hob cutter speed; (b) axial feed; (c) depth of cut; (d) lube flow rate; (e) air pressure; and (f) nozzle angle.

microgeometry deviation parameters decrease with increase in hob cutter speed. This is due to decrease in cutting forces with increase in hob cutter speed from 8 to 29 m/min which minimize the inherent vibrations between the hob cutter and the gear blank thus decreasing microgeometry deviations of the manufactured spur gear [18]. Fig. 5(a) depicts reduction in average and maximum values of flank surface roughness (R_a and R_{max}) with increase in hob cutter speed. It can be attributed to the rapid chip flow action which reduces formation of built-up edge (BUE) resulting in burr-free and smoother surface. Microgeometry deviations and flank surface roughness values are maximum at hob cutter speed of 8 m/min and MRR value is also minimum as can be observed from Table 3. It will significantly increase the hob cycle time thus reducing the productivity of the process. Figs. 3(b) and 4 (b) show that the microgeometry deviations increase with axial feed. This is due to increase in MRR (Table 3) as the axial feed is increased from 0.2 to 0.56 mm/rev which increases the cutting forces thereby generating a significant amount of heat in the machining zone. This heat leads to thermal expansion of the workpiece which results in geometrical distortions thereby increasing the microgeometry deviations. Fig. 5(b) depicts increase in R_a and R_{max} of tool flank surface with increasing axial feed which is due to occurrence of rapid tool wear which increases the radial force and vibrations thereby increasing the surface roughness of tooth flank surface [19]. Microgeometry devia-

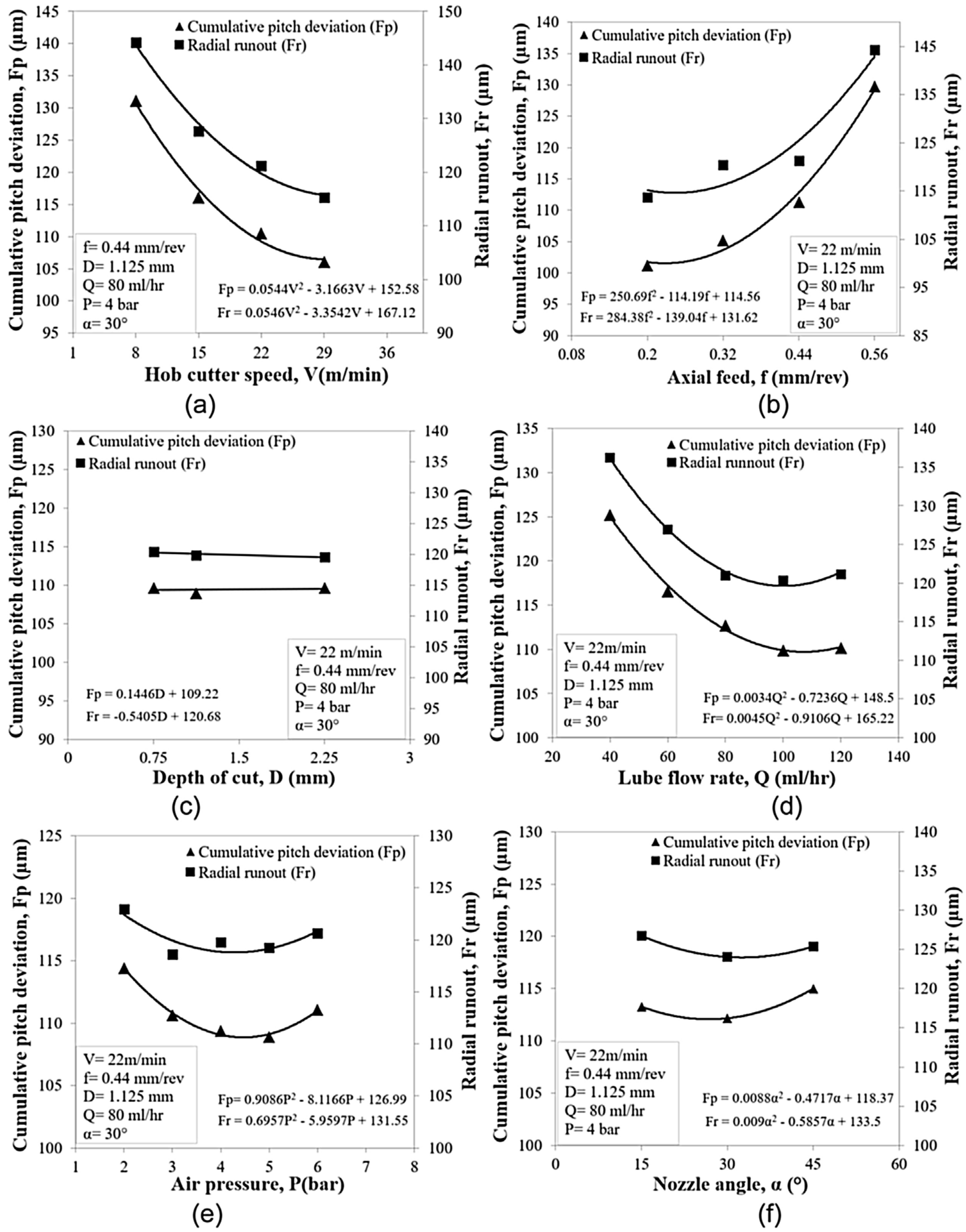

Fig. 4 – Variation in location deviations i.e. deviations in cumulative pitch 'F_p' and radial runout 'F_r' with MQLAH parameters: (a) hob cutter speed; (b) axial feed; (c) depth of cut; (d) lube flow rate; (e) air pressure; and (f) nozzle angle.

tions and flank roughness parameters of the manufactured gears showed insignificant variation with change in depth of cut as observed in Figs. 3(c), 4 (c) and 5 (c) however MRR increased very significantly with depth of cut values of 0.75; 1.125; and 2.25 mm as can be seen in Table 3.

Figs. 3(d–f); 4 (d–f); and 5 (d–f) illustrate influence of three parameters (lube flow rate, air pressure, axial feed, and depth of cut respectively) of MQL on form deviations, location deviations, and flank surface roughness of the spur gears manufactured by MQLAH. Graphs presented in these illustrate existence of optimum ranges of the MQL parameters for all the considered response. Figs. 3(d), 4 (d) and 5 (d) show that there exists an optimum value of lube (or lubricant) flow rate as 100 ml/h because form deviations, location deviations and tooth flank roughness values decrease with increase in lube flow rate and then increase slightly at 120 ml/h. lube flow rate. This can be attributed to significant improvement in the frictional behavior at the tool-work interface with increased lube flow rate which reduces heat generation thereby minimizing formation of BUE and thermal deviations. Figs. 3(e), 4 (e) and 5 (e) reveal that microgeometry deviations and flank surface roughness parameters gradually decrease as the pressure is increased from 2 bar, attain their minimum values in a range from 3 to 5 bar, and then increase on increasing the air pressure. This can be explained by the following phenomena:

- Low air pressure results in non-uniform distribution of the lubricant particles in the aerosol medium and inefficient

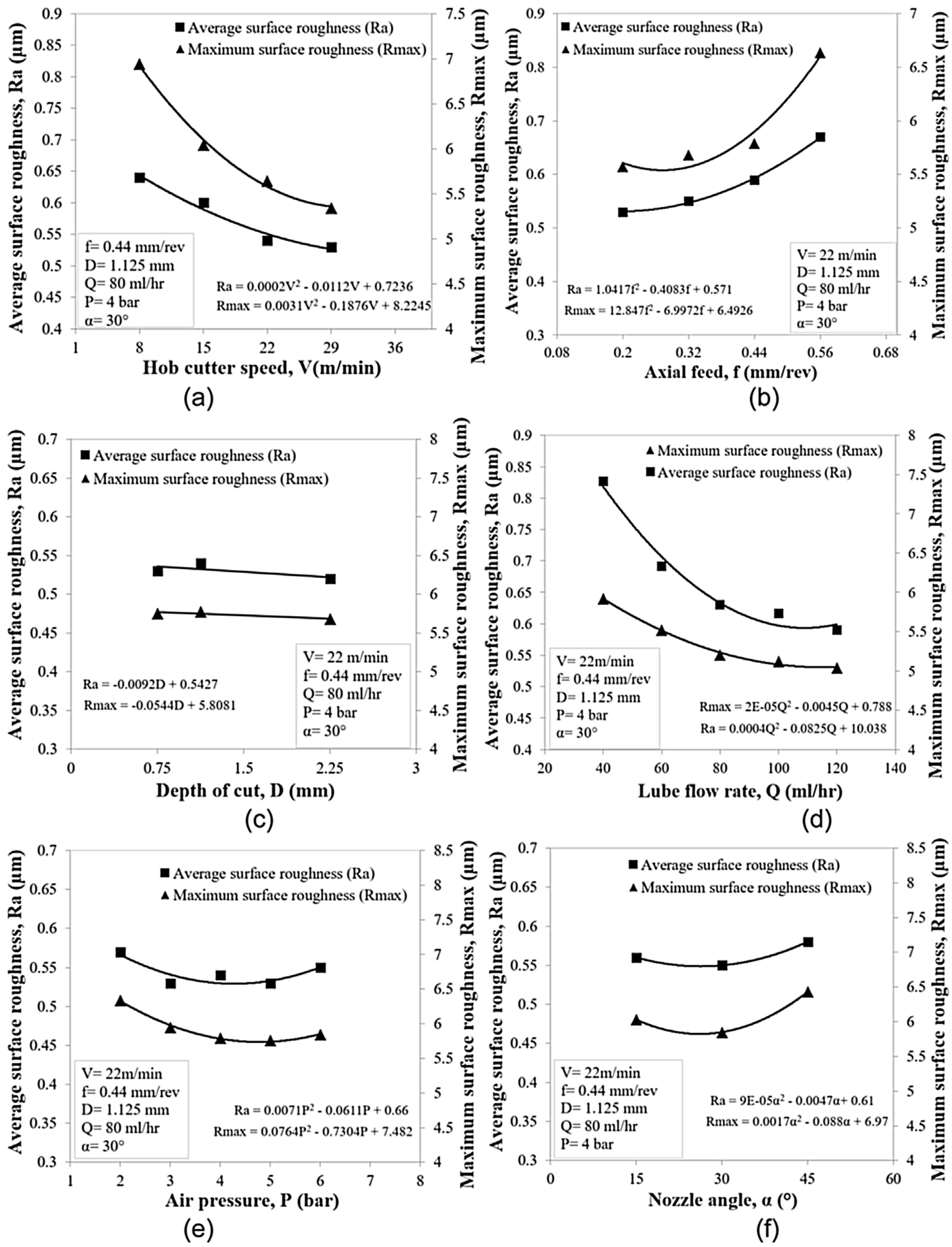

Fig. 5 – Variation in average and maximum values of flank surface roughness i.e. 'R_a' and 'R_{max}' with MQLAH parameters: (a) hob cutter speed; (b) axial feed; (c) depth of cut; (d) lube flow rate; (e) air pressure; and (f) nozzle angle.

penetration of the lubricant particles leading to higher values of microgeometry deviations and surface roughness parameters.

- Increased air pressure reduces the lubricant particle size thus improving penetrability of the aerosol mixture in the machining zone resulting in minimization of heat thereby reducing the microgeometry deviations.
- Uniform distribution of lubricant particles at higher air pressure leads to formation of a coating on the work-tool interface which minimizes formation of BUE and the inherent surface defects on the flank surface of the manufactured gear thus reducing tooth flank surface roughness (Fig. 5(e)). Moreover, at this favorable air pressure range, the superior kinematic viscosity of fatty alcohol-based environment friendly lubricant comes into play which facilitates prolonged retention of the coating over the tool work interface which probably is not the case with conventional lubricants having lower kinematic viscosity.
- More pronounced forced convective heat transfer at higher air pressure significantly reduces the heat generation and hence decreases microgeometry deviations and flank surface roughness.
- Very high value of air pressure causes the lubricant particles to bounce back after striking the tool-work interface thereby leading to ineffective lubrication and consequently

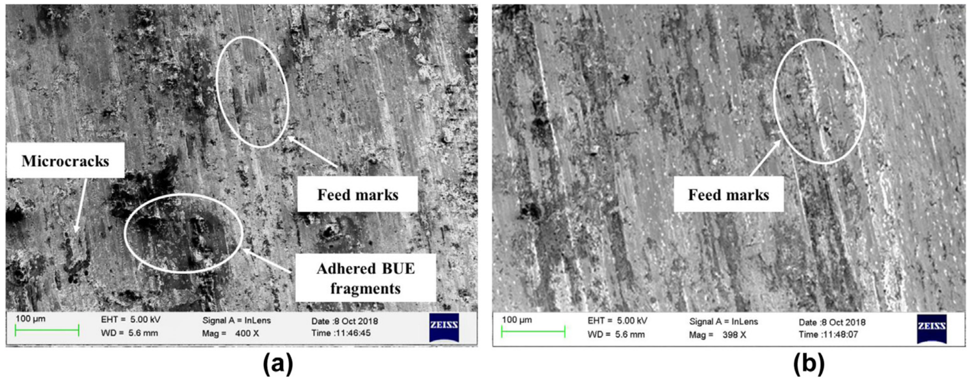

Fig. 6 – Morphology of tooth flank surface of MQLAH manufactured (a) the worst quality spur gear obtained using hob cutter speed of 8 m/min and lube flow rate of 80 ml/h, and (b) the best quality spur gear obtained using hob cutter speed of 22 m/min and lube flow rate of 100 ml/h (Constant parameters: axial feed = 0.44 mm/rev; depth of cut = 1.125 mm; nozzle angle = 30°; and air pressure = 4 bar).

increasing the microgeometry deviations and flank surface roughness of the MQLAH manufactured gears.

Figs. 3(f), 4 (f) and 5 (f) reveal that the form deviations, location deviations, and flank surface roughness parameters reduce as the nozzle angle is increased, reach their lowest values at 30° of nozzle angle and increase again thus confirming 30° as optimum value of the nozzle angle. This is due to the effective penetration of the MQL lubricant particles into the machining zone and subsequently reducing the amount of heat generated and BUE formation thereby minimizing the microgeometry deviations and surface roughness [20]. Further increasing the nozzle angle results in inability of the mist particles to access and lubricate the heat generation zone of the machining area thus slightly increasing values of the considered responses. Though, deviations in total lead (F_β) and radial runout (F_r) showed very little increase with increase in nozzle angle beyond 30°.

3.2. *Flank surface morphology of the best and worst quality spur gear*

Fig. 6 presents scanning electron microscopic (SEM) images illustrating surface morphology of the worst quality (Fig. 6(a)) and the best quality (Fig. 6(b)) spur gears obtained out of the 24 experiments of the present study. Fig. 6(a) shows signs of degraded flank surface with distinct surface defects such as microcracks, adhered BUE fragments and feed marks for a spur gear manufactured using lower values of hob cutter speed (8 m/min) and lube flow rate (80 ml/h). But, use of hob cutter speed of 22 m/min and lube flow rate of 100 ml/h significantly improves morphology of spur gear tooth flank surface as shown in Fig. 6(b).

Lower hob cutter speed resulted in severe surface defects consisting of zones of BUE deposition on the flank surface along with prominent feed marks (Fig. 6(a)) arising out of the combined action of hob cutter speed and axial feed. This can also be due to inability of the oil aerosol mixture to form a lubricating layer over the machining zone due to higher cutting forces at lower hob cutter speed thus facilitating BUE formation [21]. Surface defects might also have originated from insufficient amount of lube mist quantity in the machining zone, which increased the frictional forces between the rotating hob cutter and gear blank. Increase in hob cutter speed and lube flow rate significantly reduced surface defects generated on tooth flank surface. This could be attributed to the enhanced lubricating effect achieved at higher lube flow rate of 100 ml/h which significantly minimized the friction at the machining zone while hobbing at higher hob cutter speed of 22 m/min. This is also due to significant reduction of the tool wear which is facilitated by the comparatively higher lube flow rate of 100 ml/h [22]. From Table 3, it is evident that MRR increased from 31.42 to 90.22 mm^3/min by carrying out the MQLAH at hob cutter speed of 22 m/min than that at 8 m/min with other parameters remaining constant. This is due to the superior cooling and lubrication action by MQL using lube flow rate of 100 ml/h which efficiently minimizes the heat generated in the machining zone by penetrating the air boundary layer of the rotating hob cutter and lubricating the difficult to reach areas thereby facilitating higher MRR.

Following are observations from the microgeometry investigations of the spur gear manufactured by MQLAH using 22 m/min hob cutter speed; 0.44 mm/rev axial feed; 1.125 mm depth of cut; 100 ml/h lube flow rate; 4 bar air pressure; and 30° nozzle angle:

- Deviation in total profile 'F_a' is found to be 49.75 μm which is obtained by taking the mean of left flank profile deviations (44.4 μm) and right flank profile deviations (55.1 μm) of randomly chosen four teeth. Deviations in total lead 'F_β' of this gear was obtained as 14.05 μm which is the average of mean values left hand lead deviations (15.6 μm) and right-hand flank lead deviations (12.5 μm) of the four chosen teeth.
- Deviations in cumulative pitch 'F_p' is found to be 99.75 μm obtained by averaging deviations in cumulative pitch for left hand flanks (83.4 μm) and right-hand flanks (116.1 μm). Radial runout 'F_r' was 117.35 μm.

- Based upon these observations, this gear was designated as the best quality spur gear among the 24 MQLAH manufactured gears.

4. Conclusions

The present work explored using MQLAH as sustainable gear manufacturing process by using environment friendly and biodegradable lubricant in it and study influence of its six parameters on microgeometry deviations and flank surface roughness of the spur gears. The following conclusions can be drawn based from the present study:

- Hobbing parameters namely hob cutter speed and axial feed and MQL parameters such as lube flow rate, air pressure and nozzle angle significantly influence the gear microgeometry deviations and flank surface roughness. Depth of cut was found to have insignificant effect on them.
- Gear microgeometry deviations and tooth flank surface roughness decrease with increase in hob cutter speed and depth of cut and increase with increase in axial feed. Therefore, higher values of hob cutter speed in range of 15−29 m/min, axial feed in the range 0.32−0.56 mm/rev and higher values of depth of cut as 2.25 mm are identified as their optimum ranges.
- It was found that there exist optimum ranges for three parameters of MQL i.e. lube flow rate, air pressure and nozzle angle because microgeometry deviations and flank surface roughness initially decrease with them, attain their minimum values and then start increasing again. Lube flow rate in a range from 60 to 100 ml/h; air pressure in 3–5 bar; and nozzle angle in a range 15−45° resulted in improved gear microgeometry and significantly minimized tooth flank surface roughness values of MQLAH manufactured spur gears. Therefore, they have been identified as their optimum ranges for sustainable manufacturing of spur gears.
- The best quality gear was obtained using hob cutter speed as 22 m/min; axial feed as 0.44 mm/rev; 1.125 mm as depth of cut; lube flow rate as 100 ml/h, air pressure as 4 bar and nozzle angle as 30°. It has total profile deviation as 49.75 μm; total lead deviation as 14.05 μm, total pitch error deviation as 99.75 μm, runout error as 117.35 μm and flank roughness values of R_a as 0.51 μm, and R_{max} as 5.23 μm.
- Present study proves that MQLAH with environment friendly fatty alcohol based biodegradable lubricant (having relatively higher kinematic viscosity) delivers better performance of gear hobbing process owing to the better reachability of fine lubricant particles in the form of aerosol and their retention on gear tooth flank surfaces for a longer time duration. Moreover, identification of optimum ranges of MQLAH process parameters will ensure manufacturing of better-quality spur gears with higher productivity.

Conflicts of interest

The authors declare no conflicts of interest.

Appendix A

Table A1 – Properties of the lubricants used in MQL assisted hobbing and conventional flood lubricated hobbing.

Property (unit)	Lubricant used in MQLAH Hyspray A 1536	Lubricant used in the conventional flood lubricated hobbing Servocut S
Minimum flash point (°C)	194	150
Kinematic viscosity at 40 °C (mm²/s)	28	20
Kinematic viscosity at 100 °C (SUS)	148	NA
Pour point (°C)	NA	0

Note: The lubricating properties of conventional water-mix cutting fluids like "Servocut S" further varies (decreases) according to the percentage of water mixed.

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