Predictive modelling and parametric optimization of minimum quantity lubrication assisted hobbing process

Vishal Kharka[1], Neelesh Kumar Jain[2@], Kapil Gupta[3]

[1] Research Scholar, [2]Professor, Department of Mechanical Engineering

Indian Institute of Technology Indore, Simrol 453 552 (MP) India

[3] Associate Professor, Mechanical and Industrial Engineering Technology,

University of Johannesburg, Johannesburg, Republic of South Africa

[@]Corresponding author: e-mail: nkjain@iiti.ac.in;

Phone: +91 731 2438 700-989; Fax: +91 731 2438 721

Abstract

This paper focuses on parametric analysis, modelling, and parametric optimization of minimum quantity lubrication assisted hobbing (MQLAH) using environment friendly lubricant for manufacturing superior quality spur gears. Influences of hob cutter speed, axial feed, lubricant flow rate, air pressure and nozzle angle on the deviations in total profile, total lead, total pitch and radial runout and flank surface roughness parameters were studied by conducting 46 experiments using Box-Behnken method of response surface methodology. Results revealed that effect of air pressure is negligible but other parameters have significant impact on the considered responses. Back propagation neural network (BPNN) model was developed to predict microgeometry deviations and flank surface roughness values of the MQLAH manufactured spur gears. The BPNN predicted results found to be very closely agreeing with the corresponding experimental results with mean square error as 0.0063. Real-coded genetic algorithm (RCGA) was used for parametric optimization of MQLAH process to simultaneous minimization of microgeometry deviations and flank surface roughness. Standardized values of the optimized parameters were used to conduct confirmation experiment whose results had very good closeness with RCGA computed and BPNN predicted values and produced spur gear of superior quality. This study proves MQLAH to be a potential sustainable replacement of conventional flood lubrication assisted hobbing for manufacturing cylindrical gears of better quality.

Keywords: MQL; MQLAH; Hobbing; Flood lubrication; Modelling, Microgeometry; BPNN; Optimization; RCGA.

1. Introduction

Gears are the toothed mechanical components used for transmission of torque and/or motion between two shafts. Their classification is based on the relative positioning of their shafts. Cylindrical (i.e. spur and helical) gears are used for parallel shafts, straight and spiral bevel gears are used for intersecting shafts, and hypoid, crossed helical, worm, spiroid and helicon gears are used for non-parallel non-intersecting shafts. Spur gears are the most commonly used gears and have wide range of domestic, industrial, commercial, and scientific applications [1]. Gear accuracy and quality is ascertained by microgeometry deviations that refer to (i) inaccuracy in form or shape of gear teeth which is described by deviations in profile and lead, and (ii) inaccuracy in location of gear teeth which is determined by runout error and pitch deviations associated with the actual positioning of gear teeth [2, 3]. The functional performance characteristics of a gear are governed by the amount of errors in these parameters. Deviations or errors or in total profile 'F_a' and total lead 'F_β' significantly affect noise generation and load carrying capacity of a gear respectively whereas deviations in total pitch 'F_p' and radial runout 'F_r' are responsible for motion transfer and transmission accuracy of a gear. Surface roughness parameters such as average roughness 'R_a', maximum roughness 'R_{max}' etc. determine service life of a gear and to some extent govern their functional performance as well [1, 2]. Quality of a gear can be assessed by comparing its microgeometry deviations with the those specified by various international standards. American Gear Manufacturing Association (AGMA), Deutsches Institut fur Normung (DIN), and Japanese Industrial Standards (JIS) are the most widely accepted standards for defining gear quality. DIN quality standard 3961/62 applicable for cylindrical gears has 12 numbers with lower DIN number signifying better quality of a gear and vice versa [4].

Gear hobbing is one of the most widely used and economical process to manufacture cylindrical gears [1]. Gear teeth are generated as a result of progressive cuts made by the rotating cutting tool known as a hob. But, conventional hobbing uses flood lubrication (FL) technique where large amount of water mix hydrocarbon-based cutting fluids is supplied to the machining zone to control the generated heat. This adversely affects environment and human health [5]. Moreover, hobbed gears have quality in the range of DIN 9-12 therefore subsequent finishing processes are needed to produce gears of the desired accuracy and quality. It compels to explore sustainable substitute of flood lubrication assisted hobbing (FLAH). Minimum quantity lubrication (MQL) assisted hobbing (MQLAH) can be a potential substitute in which a small volume of cutting fluid is supplied to the machining zone with the help of compressed air in the form of aerosol medium. Use of MQL significantly brings about the required cooling and lubrication effects by improving the frictional behaviour at the tool-work interface [5]. The aerosol medium in it ensures better penetrability and enabling it to access the difficult-to-reach areas of the machining zone where the FL cannot reach. Moreover, lubricant in the form of air borne particles also enhances cooling due to the forced convective effect. Since, performance of MQL is significantly governed by its process parameters such as lubricant flow rate, air pressure and nozzle angle therefore appropriate selection and optimization of its parameters is necessary to increase effectiveness of MQL.

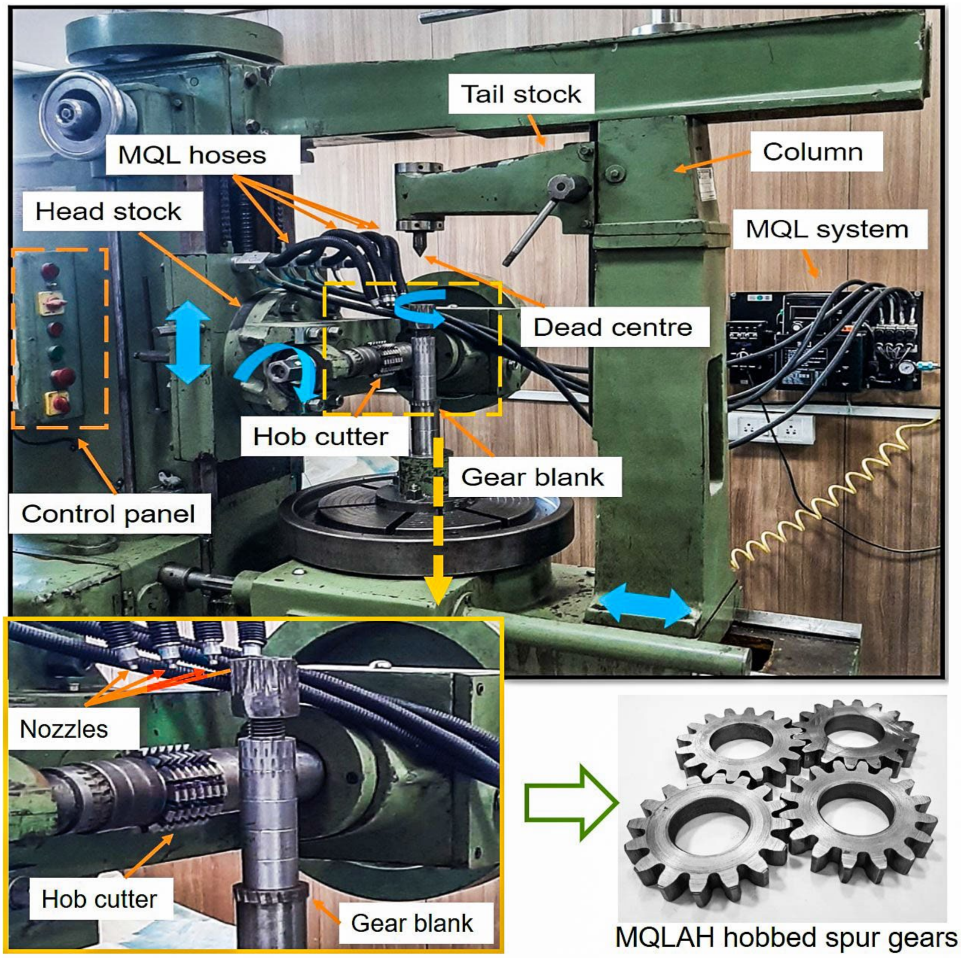
Though research has been carried out recently on machining-based gear manufacturing with an objective to explore possibilities in improving its sustainability by finding a potential replacement to the conventional FL technique but research on sustainable gear hobbing is scarce. Fratila [6] found that use of MQL technique in gear milling process resulted in better surface quality of helical gear flank surfaces with minimal hob cutter wear. Conventional FL and dry cutting (DC) also yielded comparable surface finish but with higher tool wear. It was concluded that MQL equipped gear milling is a sustainable and environment friendly alternative to conventional FL technique. Fratila and Radu [7] studied thermal stress and thermo-elastic displacements during the gear milling process under different cooling and lubrication techniques namely MQL, minimum cooling technique (MCT), minimum quantity cooling and lubrication (MQCL), FL, and DC and the analysis was made with steady state finite element thermal models. They concluded that MQL and MQCL showed better performance in terms of the strain and thermal stresses in comparison to DC and FL-based gear milling. Zhang and Wei [8] carried out experiments on MQL equipped gear hobbing and performed multi-performance optimization for gear surface roughness and hob wear. Their results revealed that MQL oil flow rate of 40 ml/hr, cold air temperature -45°C and a feed rate of 0.2 mm/rev were optimum parameters to obtain reduced flank surface roughness and hobbing cutter wear. Fratila [9] studied geometric accuracy of the milled gears under the influence of different cooling and lubrication techniques and reported that MQL equipped milling yielded better results in terms of tooth distances on gear circumference than conventional FL technique. MQL also gave similar results as compared to other lubrication and cooling techniques for other gear accuracy parameters.

It can be summarised from review of the available literature that there is a lack of research on establishing MQLAH as sustainable alternative to the conventional FLAH, and predictive modelling and parametric optimization of MQLAH process with objectives to improve quality of the manufactured gear. Present work aims to fulfil these gaps by focussing on the following objectives: (i) understanding effects of MQLAH process parameters on microgeometry deviations and flank surface roughness of macro-sized spur gears through extensive experimental investigations, (ii) developing data driven intrinsic models for prediction of microgeometry deviations and flank surface roughness of MQLAH manufactured spur gears, and (iii) to optimize MQLAH process parameters using evolutionary optimization technique. Outcome of this work will be of great help to establish MQLAH as a sustainable option to manufacture high quality spur gears

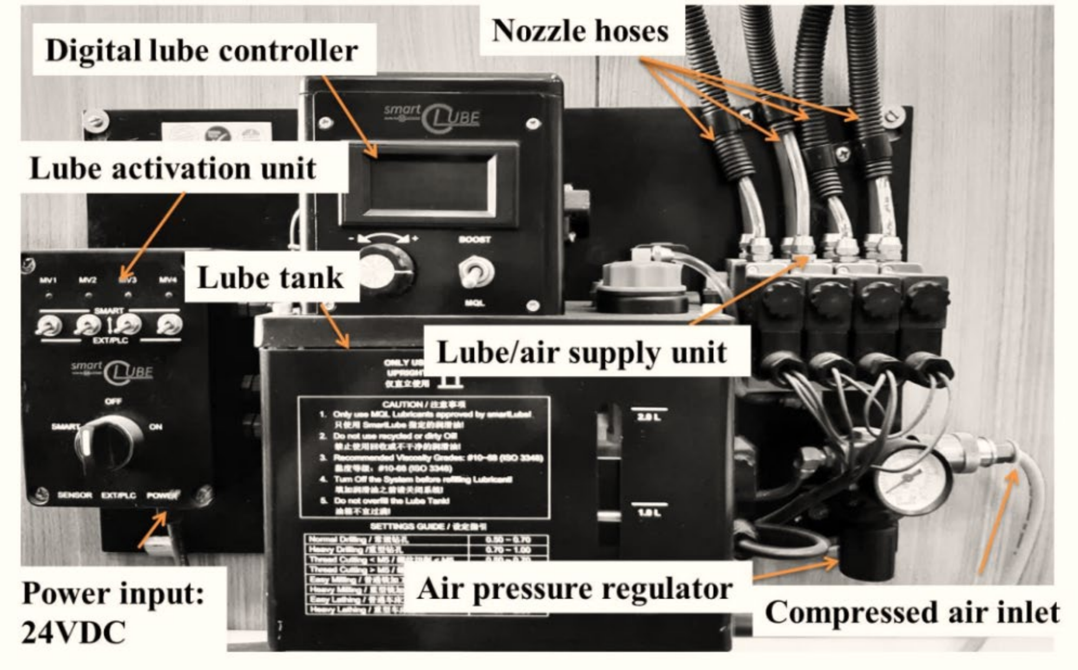
2. Experimentation

2.1 Materials and methods

Experimental apparatus for MQLAH process (depicted in Fig. 1a) was developed by integrating gear hobbing with MQL system MT-MQL V2.2 whose details are shown in Fig. 1b. Table 1 presents the technical specifications of the MQL system. An uncoated single thread hob cutter made of high speed steel (HSS) EMo5Co5 and having 3 mm module, 20º pressure angle, 80 mm outer diameter, and 69 mm overall length was used on the gear hobbing machine. Its chemical composition (by wt%) is: 6.4% W; 5% Mo; 4.8% Co; 4.1% Cr; 1.9% V; 0.92% C and balance Fe. Environment friendly fatty alcohol-based lubricant 'Hyspray A1536' was supplied by means of 4 micro-nozzles of the MQL system to the tool-work interface.



(a)



(b)

Fig. 1 Experimental apparatus developed for MQLAH: (a) gear hobbing machine equipped with the MQL system (b) details of the MQL system MT-MQL V2.2.

Set of 4 micro-nozzles of the MQL system were positioned at three different angles (i.e. 15; 30; and 45) to supply the lubricant to the tool-work interface as illustrated in Fig. 2. The gear material used for the experimental investigations was alloy steel 20MnCr5 (chemical composition by wt.%: 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) which is one of the most widely used materials for commercial production of cylindrical gears. Design specifications of the spur gears are: 3 mm module; 16 teeth; 48 mm pitch circle diameter; 54 mm outside diameter; 20°pressure angle; 10 mm face width.

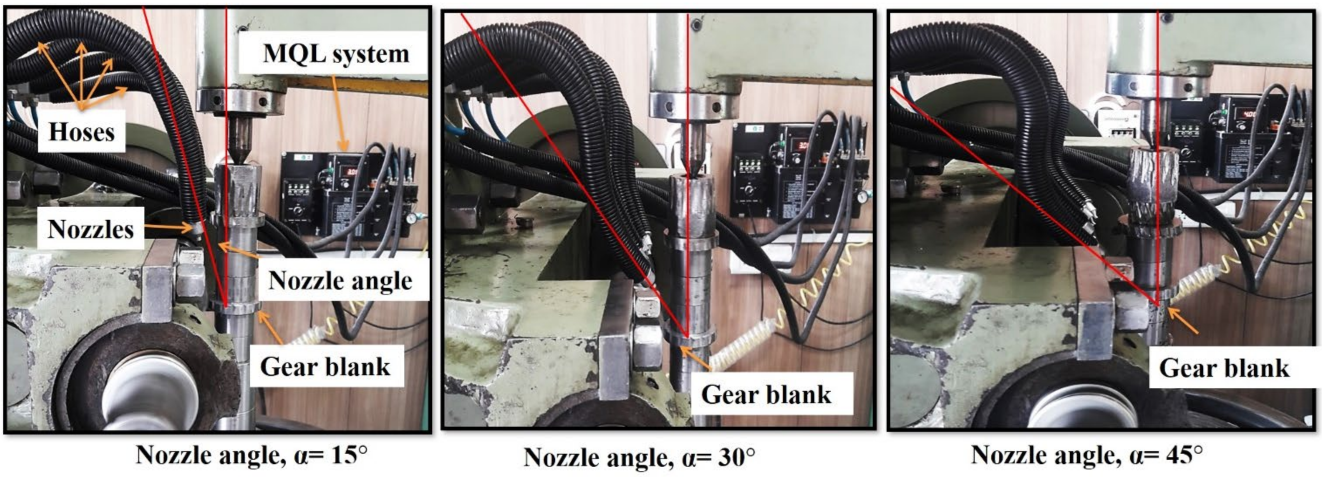


Fig. 2 Side view of the MQLAH apparatus showing three angular positions of micro-nozzles of MQL system for supplying the lubricant.

Table 1. Technical specifications of the MQL system MT-MQL V2.2

Working air pressure	1~6 bar
Maximum pressure of air inlet	8 bar
Power requirements	22VDC to 24VDC / 2.5A max. / 50W typ.
Operation temperature	5~35 ºC
Operation relative humidity	90% below 20 ºC / max. 60% at 35 ºC

Experimental investigation involved conducting 46 experiments (i.e. manufacturing 46 spur gears) designed using Box-Behnken approach of response surface methodology (RSM). It involved varying hob cutter speed 'V', axial feed 'f', lubricant flow rate 'Q', air pressure 'P' and nozzle angle 'α' at three levels each in their pre-identified ranges to study their effects on four parameters of microgeometry deviations (i.e. deviations total profile 'F_a', total lead 'F_β' and total pitch 'F_p', and radial runout 'F_r') and flank surface roughness avg. and max. values 'R_a' and 'R_{max}'. Table 2 presents the details of all variable and fixed input parameters and the considered response.

Table 2. Details of variable parameters and responses used in the experiments.

Variable parameters	Symbol	Levels I	Levels II	Levels III	Responses
					Total profile deviation *(F_a)*
Hob cutter speed (m/min)	*V*	15	22	29	Total lead deviation *(F_β)*
Axial feed (mm/rev)	*f*	0.32	0.44	0.56	Accumulative pitch deviation *(F_p)*
Lubricant flow rate (ml/hr)	*Q*	60	80	100	Runout deviation *(F_r)*
Air pressure (bar)	*P*	3	4	5	Average surface roughness *(R_a)*
Nozzle angle (degrees)	*A*	15°	30°	45°	Maximum surface roughness *(R_{max})*
***Fixed parameters**:* Depth of cut: 2.25 mm; No. of nozzles: 4					

Wenzel GearTec, Germany made *SmartGear 500* computer numerically controlled (CNC) gear metrology machine was used for measurement of microgeometry deviations of the manufactured gears. Deviations in total profile 'F_a' and total lead 'F_β' were measured by on left and right flanks of four randomly selected teeth of a manufactured gear corresponding to each experiment, whereas deviations in cumulative pitch 'F_p' and runout 'F_r' measured on both flanks of all 16 teeth of each spur gear. Arithmetic average of the measured values of the responses (F_a, F_β, F_p and F_r) for right and left-hand flanks of a gear were considered for further study. Average and maximum roughness values (R_a and R_{max}) of flank surfaces of four randomly selected teeth of a gear were measured using contour and roughness measuring equipment *MahrSurf LD 130* from *Mahr Metrology GmBh*, Germany and their average value was considered for further analyses. Analysis of variance (ANOVA) tool of *Design Expert* version 11 software was used to determine significant parameters, interactions between them, and their influences on the considered responses. Subsequently, regression analysis was used to determine quadratic equations for the responses in terms of the significant parameters and interactions.

3. Results and discussion

Table 3 presents values of input variable parameters and corresponding responses of microgeometry deviations and flank roughness parameters for spur gears for all the 46 experiments. ANOVA identified the significant MQLAH process parameters and their interactions which influence microgeometry deviations (i.e. F_a, F_β, F_p and F_r) and flank roughness parameters (R_a and R_{max}). Its results (not been included in the manuscript) suggest that microgeometry deviations and flank roughness parameters are significantly influenced by $V, f, Q, \alpha, f^2, Q^2, \alpha^2, V\times f, V\times Q, V\times P$ and air pressure is found to be insignificant parameter. Besides, V^2 was also found to affect F_a and R_{max}. Regression analysis of the experimental data yielded the quadratic models for F_a, F_β, F_p, F_r, R_a and R_{max} in terms of the significant parameters and their interactions. Equations (1)-(6) present them for F_a, F_β, F_p, F_r, R_a and R_{max} respectively. Higher p-value of lack of fit for all the proposed quadratic models indicate that it is insignificant i.e. these models satisfactorily fit the experimental data.

$$F_a = 140.7 - 0.67\,V - 208.04\,f - 0.65\,Q - 0.66\,\alpha - 0.013\,V^2 + 239.1\,f^2 + 0.005\,Q^2 + 0.01\,\alpha^2 + 2.02\,Vf - 0.012\,VQ + 0.23\,VP \quad (1)$$

$$F_\beta = 28.2 - 0.17\,V - 39.55\,f - 0.16\,Q - 0.07\,\alpha + 45.96\,f^2 + 0.001\,Q^2 + 0.002\,\alpha^2 + 0.38\,Vf - 0.002\,VQ + 0.04\,VP \quad (2)$$

$$F_P = 276.2 - 1.16\,V - 418.2\,f - 1.2\,Q - 1.2\,\alpha + 513.54\,f^2 + 0.01\,Q^2 + 0.02\,\alpha^2 + 3.64\,Vf - 0.026\,VQ + 0.48\,VP \quad (3)$$

$$F_r = 327.85 - 1.71\,V - 476.5\,f - 1.5\,Q - 1.46\,\alpha + 556.5\,f^2 + 0.012\,Q^2 + 0.02\,\alpha^2 + 4.65\,Vf - 0.03\,VQ + 0.52\,VP \quad (4)$$

$$R_a = 1.56 - 0.007\,V - 2.21\,f - 0.007\,Q - 0.008\,\alpha + 2.59\,f^2 + 0.000056\,Q^2 + 0.0001\,\alpha^2 + 0.018\,Vf - 0.00013\,VQ + 0.002\,VP \quad (5)$$

$$R_{max} = 16.1 - 0.05\,V - 23.0\,f - 0.065\,Q - 0.108\,\alpha - 0.002\,V^2 + 27.3\,f^2 + 0.0005\,Q^2 + 0.0008\,\alpha^2 + 0.27\,Vf - 0.0015\,VQ + 0.022\,VP \quad (6)$$

Figures 3, 4, and 5 depict effects of the significant MQLAH process parameters (i.e. hob cutter speed, axial feed, lubricant flow rate, and nozzle angle) on the deviations in spur gear teeth form (i.e. deviations in total profile 'F_a' and total lead 'F_β'), deviations in location of spur gear teeth (i.e. deviations in total pitch 'F_p' and runout 'F_r'), and flank surface roughness values (i.e. avg. value 'R_a' and max. value 'R_{max}') respectively using the developed models and the experimental results.

Table 3. Experimental results for the parametric combinations of all the experimental runs.

Exp. No	MQLAH process parameters					Responses					
						Microgeometry deviation parameters (μm)				Surface roughness (μm)	
	V (m/min)	f (mm/rev)	Q (ml/hr)	P (bar)	α (degree)	F_a	F_β	F_p	F_r	R_a	R_{max}
1	22	0.44	80	3	15	53.8	10.2	113.0	123.7	0.56	5.98
2	22	0.44	60	4	15	58.3	11.1	122.4	134.0	0.60	6.48
3	22	0.32	80	4	15	50.6	9.5	107.3	116.4	0.52	5.63
4	15	0.44	80	4	15	56.2	10.7	119.0	129.3	0.58	6.25
5	29	0.44	80	4	15	51.2	9.7	109.5	117.7	0.61	5.39
6	22	0.56	80	4	15	63.9	12.1	134.2	147.0	0.65	7.16
7	22	0.44	100	4	15	51.4	9.76	107.9	118.1	0.53	5.71
8	22	0.44	80	5	15	53.1	10.1	111.5	122.1	0.55	5.9
9	22	0.44	60	3	30	56.9	10.8	119.5	130.9	0.59	6.33
10	22	0.32	80	3	30	48.5	9.2	101.9	111.6	0.50	5.39
11	15	0.44	80	3	30	56.3	10.7	118.2	129.4	0.58	6.25
12	29	0.44	80	3	30	46.6	8.9	97.9	107.2	0.53	5.28
13	22	0.56	80	3	30	63.8	12.1	133.9	146.7	0.66	7.15
14	22	0.44	100	3	30	52.3	9.9	109.9	120.4	0.54	5.81
15	22	0.32	60	4	30	53.6	10.2	112.5	123.2	0.55	5.95
16	15	0.44	60	4	30	60.1	11.8	126.2	138.2	0.62	6.58
17	29	0.44	60	4	30	56.3	10.7	118.2	129.5	0.64	6.26
18	22	0.56	60	4	30	66.8	12.7	140.3	153.7	0.69	7.42
19	15	0.32	80	4	30	51.4	9.8	107.9	118.2	0.53	5.71
20	29	0.32	80	4	30	42.6	8.1	88.4	98.0	0.45	4.69
21	22	0.44	80	4	30	52.6	9.7	110.4	120.9	0.54	5.84
22	22	0.44	80	4	30	51.7	9.8	108.6	118.6	0.53	5.75
23	22	0.44	80	4	30	52.1	9.9	110.3	119.8	0.54	5.79
24	22	0.44	80	4	30	51.8	9.8	108.9	119.3	0.53	5.76
25	22	0.44	80	4	30	51.7	9.8	108.6	116.0	0.51	5.74
26	22	0.44	80	4	30	54.4	10.3	114.2	126.0	0.56	6.04
27	15	0.56	80	4	30	63.6	12.1	135.5	146.2	0.66	7.06
28	29	0.56	80	4	30	61.2	11.6	128.6	140.8	0.68	6.9
29	22	0.32	100	4	30	48.8	9.3	104.5	112.2	0.5	5.42
30	15	0.44	100	4	30	54.7	10.4	115.0	125.9	0.56	6.08
31	29	0.44	100	4	30	44.1	8.4	92.6	101.5	0.52	5.19
32	22	0.56	100	4	30	63.5	12.1	133.3	145.0	0.65	7.05
33	22	0.44	60	5	30	58.5	113	122.8	134.5	0.60	6.50
34	22	0.32	80	5	30	47.9	9.1	100.6	110.2	0.49	5.33
35	15	0.44	80	5	30	53.1	10.1	111.6	122.2	0.55	5.90
36	29	0.44	80	5	30	49.8	9.5	104.7	114.7	0.57	5.56
37	22	0.56	80	5	30	62.8	11.9	131.9	144.5	0.65	6.98
38	22	0.44	100	5	30	50.7	9.6	106.5	116.7	0.52	5.64
39	22	0.44	80	3	45	54.1	10.7	116.5	126.3	0.58	6.13
40	22	0.44	60	4	45	59.5	11.3	125.0	136.9	0.61	6.41
41	22	0.32	80	4	45	51.2	9.7	108.6	117.8	0.53	5.67
42	15	0.44	80	4	45	57.2	10.9	120.2	131.6	0.59	6.24
43	29	0.44	80	4	45	52.3	9.5	109.7	120.2	0.62	5.83
44	22	0.56	80	4	45	65.7	12.5	138.0	151.2	0.68	7.30
45	22	0.44	100	4	45	53.6	10.2	112.6	123.3	0.56	5.96
46	22	0.44	80	5	45	54.3	10.3	114.0	124.9	0.57	6.23

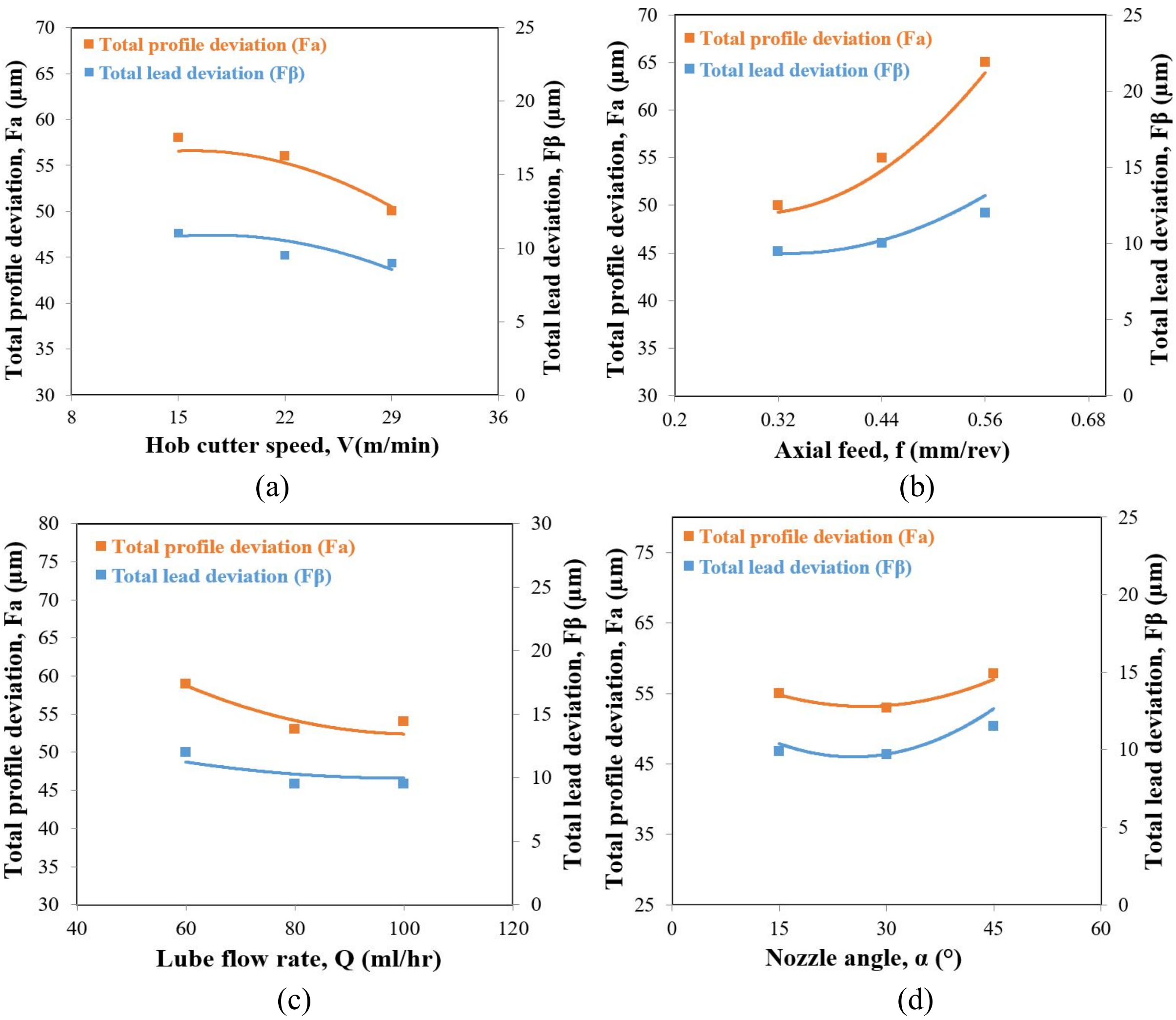
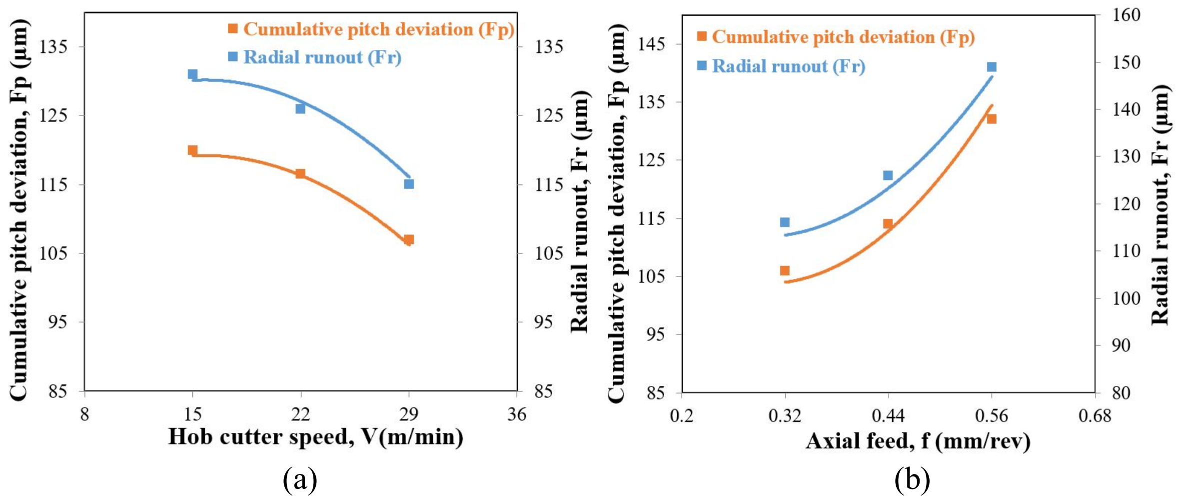


Fig. 3 Variation in form deviations of the spur gear teeth i.e. deviations in total profile and total lead with (a) hob cutter speed, (b) axial feed, (c) lubricant or lube flow rate, and (d) nozzle angle.



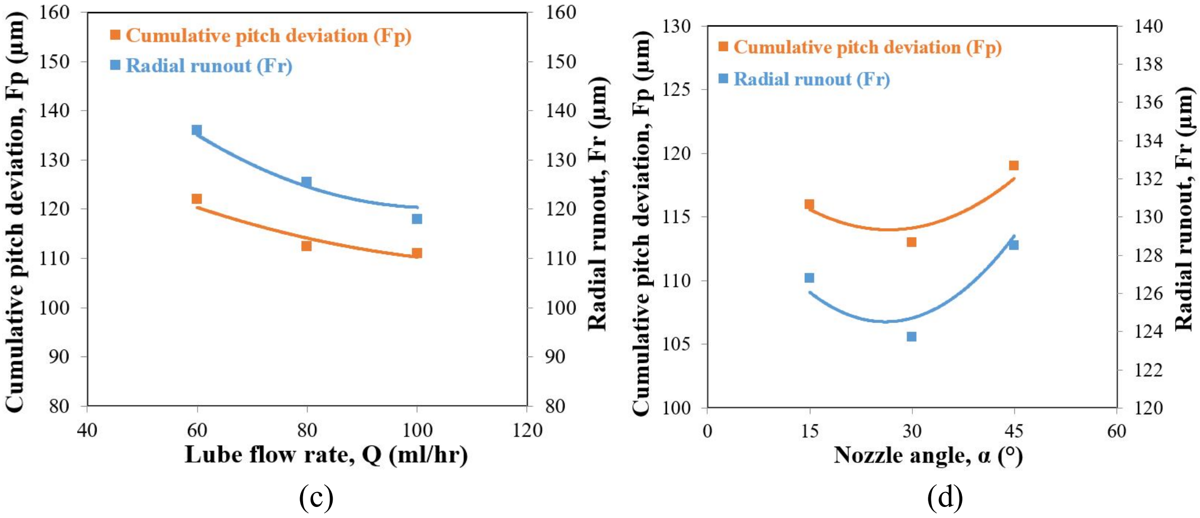


Fig. 4 Variation in location deviations of spur gear teeth i.e. deviations in cumulative pitch and radial runout with (a) hob cutter speed, (b) axial feed, (c) lubricant or lube flow rate, and (d) nozzle angle.

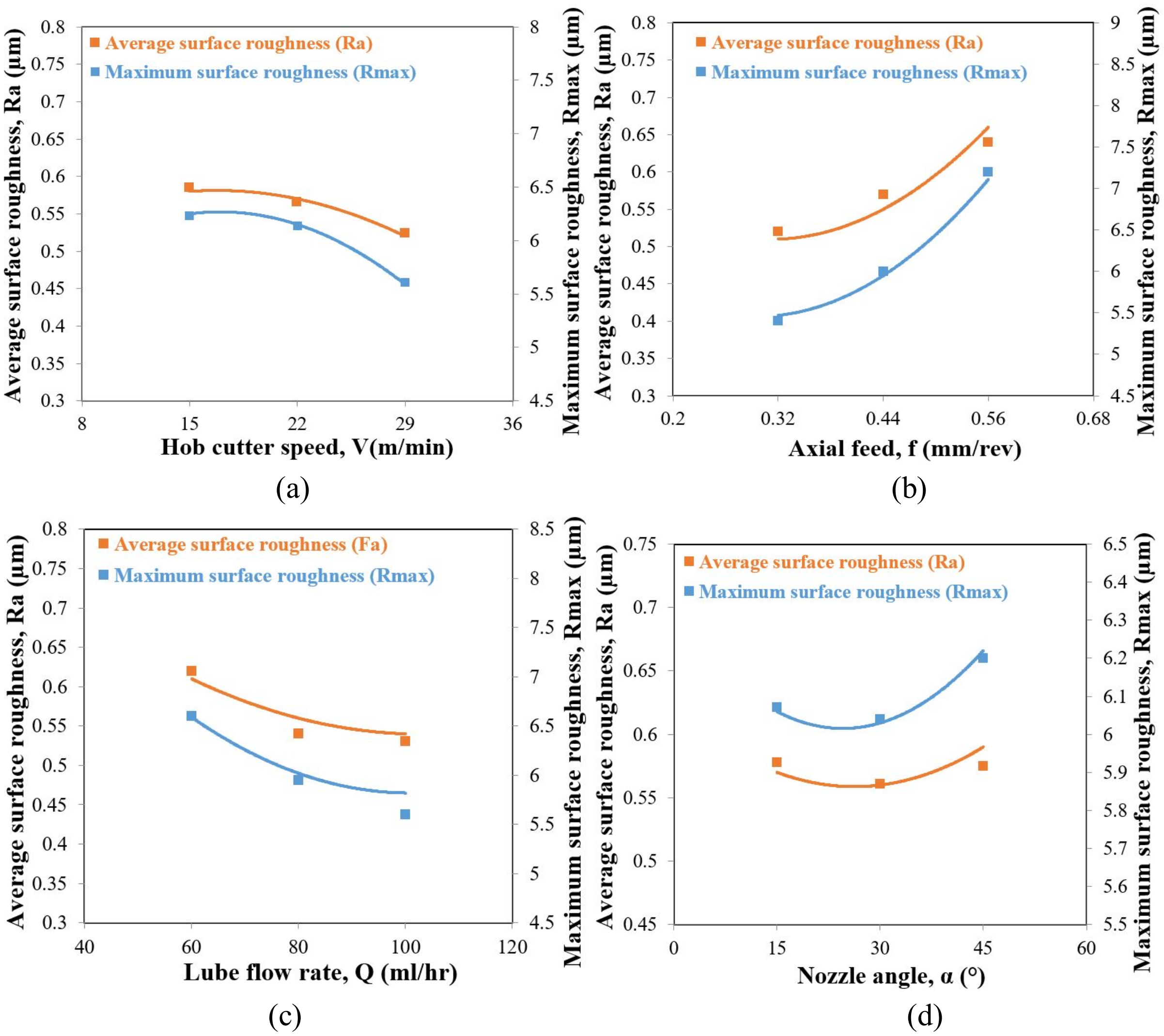


Fig. 5 Variation average and maximum values of in flank surface roughness with (a) hob cutter speed, (b) axial feed, (c) lubricant or lube flow rate, and (d) nozzle angle.

3.1 Effect of hob cutter speed

It can be observed from Figs. 3a, 4a, 5a that microgeometry deviations and flank surface roughness decrease with increase in hob cutter speed. This is due to decrease in cutting forces with increase in the hob cutter speed which significantly decreases the inherent vibrations between the hob cutter and the gear blank thus reducing microgeometry deviations of the manufactured spur gear [10]. Higher hob cutter speed also causes rapid chip flow which reduces heat transmission to the workpiece because most of the generated heat is carried away by the flowing chips. This reduces thermal deviations and consequently microgeometry deviations. Rapid chip flow also reduces formation of built up edge (BUE) giving smoother flank surface thus decreasing flank roughness R_a and R_{max} values as shown in Fig. 5a.

3.2 Effect of axial feed

It can be seen in Figs. 3b, 4b and 5b that microgeometry deviations and flank roughness parameters increase with increase in axial feed. This is due to increased heat generation at the machining zone which is caused by increase in the cutting forces with increase in the axial feed. It leads to thermal expansion of the gear blank causing its dimensional deviations thereby increasing microgeometry deviations. Generation of more amount of heat at the machining zone also facilitates formation of more BUE at the tooth flank surface which explains the increase in tooth flank roughness with increase in axial feed. Increase in microgeometry deviations and tooth flank roughness with axial feed can also be attributed to higher wear of the hob cutter caused due to higher temperatures which further increases the radial cutting force and vibrations [11, 12].

3.3 Effect of lubricant flow rate

Figures 3c-5c depict that microgeometry deviations and flank surface roughness decrease with increasing lubricant flow rate. It can be attributed to reduction in the friction at the workpiece-tool interface which decreases the cutting forces and the heat generation thereby reducing dimensional deviations caused by the thermal expansion. Reduced heat generation decreases tendency of BUE formation giving smoother flank surface. Moreover, increased lubricant flow rate also ensures better lubrication at the machining area which eventually decreases wear of the hob cutter leading to decrease in the microgeometry deviations and flank surface roughness of the MQLAH manufactured gears [13].

3.4 Effect of nozzle angle

It is evident from Figs. 3d-5d that there exists an optimum value of nozzle angle because microgeometry deviations and flank surface roughness decrease with increase in nozzle angle, attain their lowest values around 30^o, and again start increasing on further increase in the nozzle angle. At lower nozzle angle (α =15°), the lubricant particles fail to access the machining zone due to a barrier generated by the accumulated chips at the workpiece-tool interface rendering the lubricant incapable of reducing the friction and consequently effects of heat generation. This leads to higher values of microgeometry deviations and flank roughness. Inability of the lubricant particles to remain adhered to the tool and workpiece surfaces for a longer time duration at steep nozzle angle of 15° as they tend to fall off under the gravity thus leading to inefficient lubrication. As the nozzle angle is increased up to 30°, MQL mist can better penetrate the boundary layer of the air that surrounds the rotating hob cutter thus resulting in effective penetration of the lubricant particles into the machining zone and subsequently reducing the amount of heat generated and thereby reducing microgeometry deviations. Furthermore, the lubricant particles have better accessibility to cutting edges of the hob cutter thus reducing its wear rate and eventually enabling the microgeometry deviations and tooth flank surface roughness to attain their minimum values. Also, this value of nozzle angle results in better chip evacuation and prevention in accumulation of chips at the tool-work interface. But, increasing the nozzle angle up to 45° again reduces access of the lubricant mist particles to critical area of the machining zone and lubrication of flank surfaces of hob cutter thus increasing microgeometry deviations and surface roughness values [14].

4. Modelling using artificial neural network

Artificial neural network (ANN), which mimic working of neurons, has proven to be very useful tool for intrinsic predictive modelling particularly when relationship between input and output parameters is not known. Therefore, predictive models for the considered parameters related to microgeometry deviations (i.e. F_a, F_β, F_p and F_r) and flank roughness (i.e. R_a and R_{max}) were developed in terms of four parameters (i.e V, f, Q and α) of MQLAH process using feed forward back propagation neural network (BPNN) network using NN Toolbox of MATLAB software version 9.5 (R2019b). Table 4 presents details the BPNN used in the predictive modelling. The network architecture comprised of three layers: one input layer having four neurons corresponding to four input parameters (hob cutter speed, axial feed, lubricant flow rate and nozzle angle), one hidden layer with certain number of neurons, and one output layer having six neurons corresponding to the six responses i.e. deviations in profile, lead, cumulative pitch, radial runout, average and maximum flank roughness. For determining the number of neurons in the hidden layer, the networks were developed for recommended n/2, 1n, 2n, and 2n+1number of neurons in the hidden layer where n is the number of neurons in the input layer [15]. Trial and error was conducted by varying number of neurons in hidden layer. It revealed that network architecture having 8 number of neurons in the hidden layer as the optimal network. Figure 6 depicts the 4-8-6 structure of the developed ANN model. Training of the BPNN model was done using 60% (i.e. 28 sets) of the experimental data using Levenberg–Marquardt back-propagation algorithm because it yields rapid training for the moderate networks [16]. Validation check was carried out using 20% of data set to check that the network is generalizing and halt the training before over fitting. The developed BPNN model was tested using remaining 20% of those experimental data that were not used to train the model. Figure 7 compares BPNN-predicted results with corresponding experimental results for the parameters of form deviation (Fig. 7a), location deviation (Fig. 7b), and flank surface roughness (Fig. 7c) of MQLAH manufactured spur gears corresponding to 46 experiments. It is evident from these figures and 0.0063 value of mean square error (MSE) that the BPNN predicted results very closely agree with the corresponding experimental results. This validates the BPNN based predictive model and confirms its accuracy in prediction.

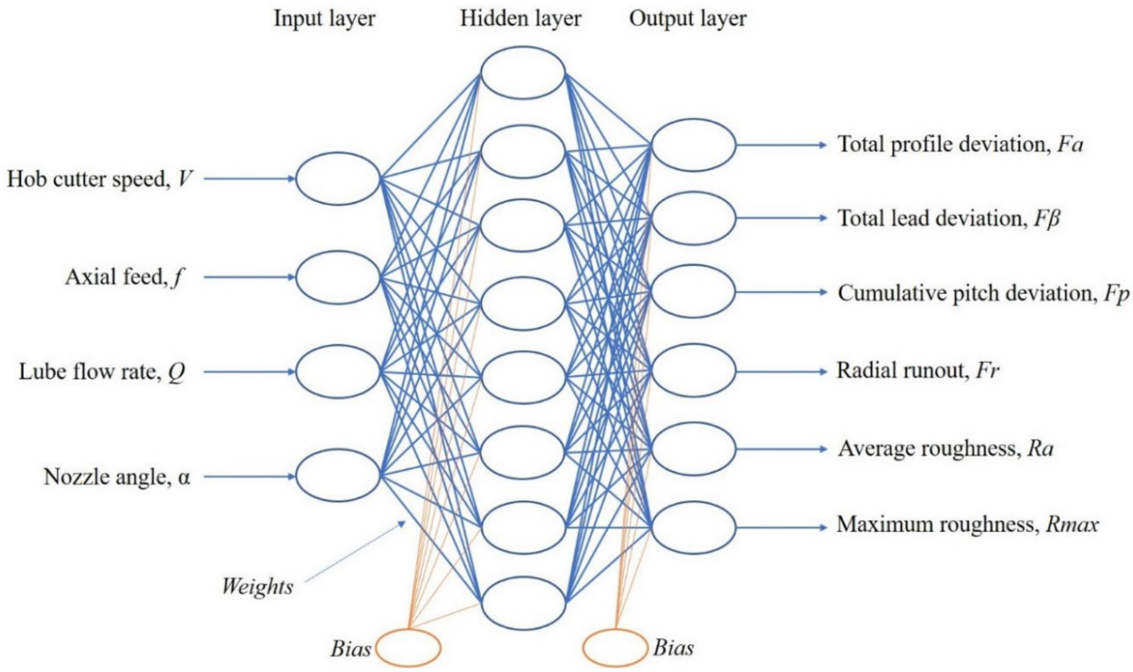
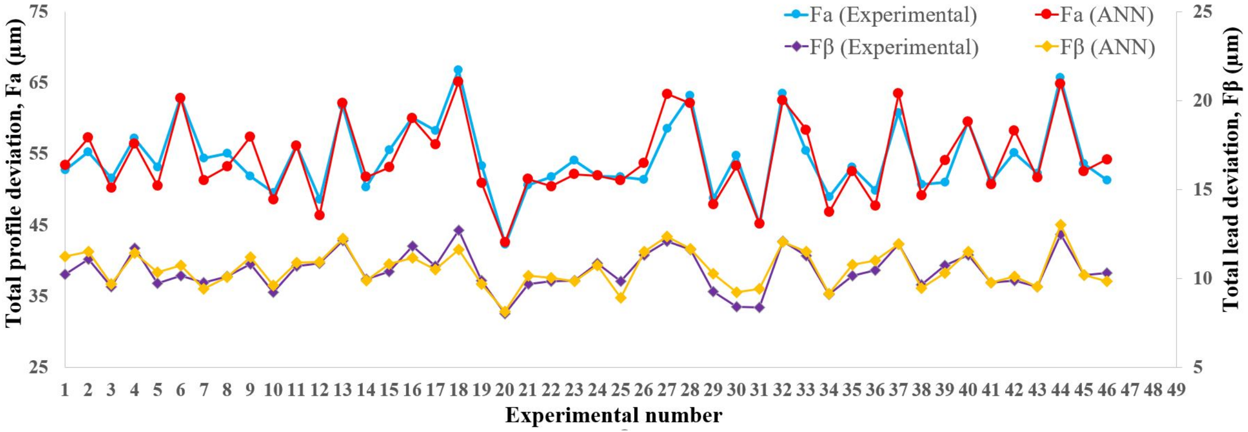


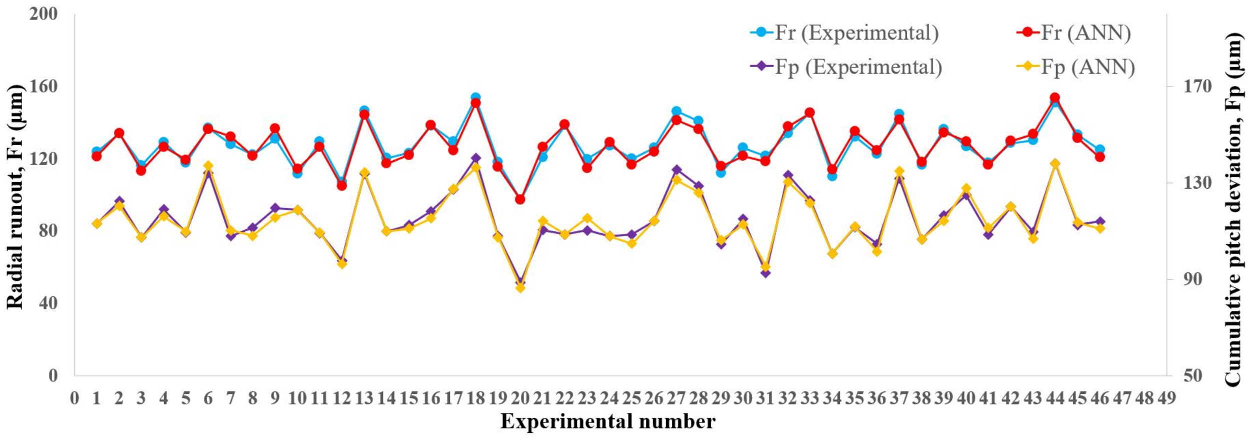
Fig. 6 Architecture of the BPNN model (4-8-6) used in predictive modelling.

Table 4. Details of BPNN used in the predictive modelling.

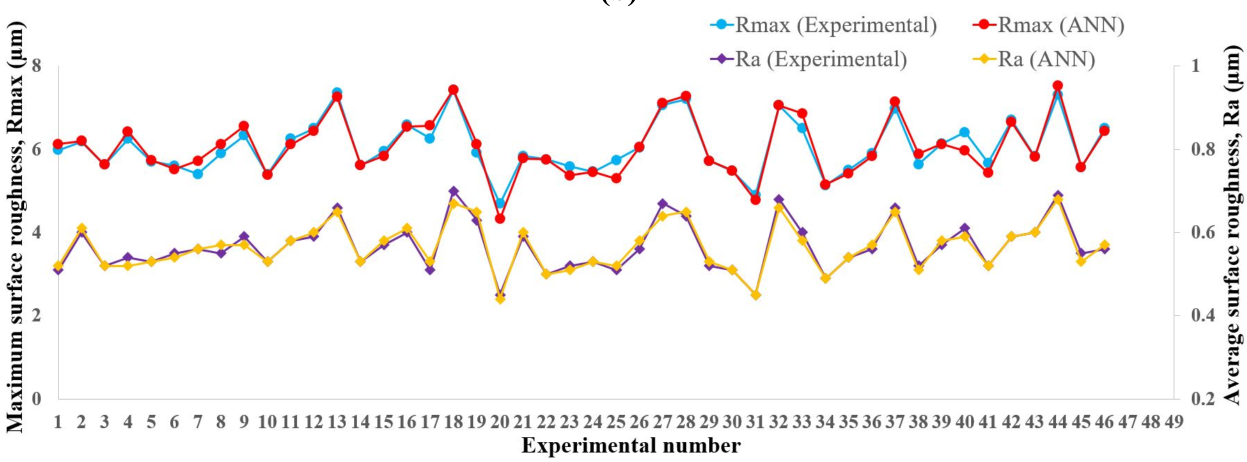
Distribution of experimental data for training, validation, and testing purposes	60%; 20%; and 20%
Network type	Feed-forward back-propagation
Training algorithm	Levenberg-Marquardt
Training function	TRAINLM
Adaption learning function	LEARNGDM
Performance function	MSE
Transfer function	LOGSIG



(a)



(b)



(c)

Fig. 7 Comparison of BPNN predicted and experimental results for different experimental runs for: (a) deviations in total profile and total lead, (b) deviations in cumulative pitch and radial runout, and (c) maximum and average flank roughness.

5. Genetic algorithm based multi-objective optimization

Genetic algorithms (GA) are one of the most prominent evolutionary optimization techniques that mimic the natural evolution process using reproduction, crossover and mutation operations based on principles of genetics [17]. Real coded GA (RCGA) with following parameters were used in the present study to optimize the MQLAH process parameters for simultaneously minimizing microgeometry deviations and tooth flank roughness using *optimization toolbox* of *MATLAB 9.5*.

Parameters of RCGA used in the present work:

Population type: Double vector;

Population size: 150;

Number of generations: 200;

Type of reproduction operator: Elitist selection;

Elite count: 0.05 times the population size;

Type of crossover operator: Single point;

Probability for crossover: 0.75;

Type of mutation operator: Adaptive feasible;

Probability of mutation: 0.1;

Following are the formulated optimization functions for multi-objective optimization:

$$Min. F_{a}(V, f, Q, \alpha) = 140.7 - 0.67\, V - 208.04\, f - 0.65\, Q - 0.66\, \alpha - 0.013\, V^{2} + 239.1\, f^{2} + 0.005\, Q^{2} + 0.01\, \alpha^{2} + 2.02\, Vf - 0.012\, VQ + 0.23\, VP \qquad (7)$$

$$Min. F_{\beta}(V, f, Q, \alpha) = 28.2 - 0.17\, V - 39.55\, f - 0.16\, Q - 0.07\, \alpha + 45.96\, f^{2} + 0.001\, Q^{2} + 0.002\, \alpha^{2} + 0.38\, Vf - 0.002\, VQ + 0.04\, VP \qquad (8)$$

$$Min. F_{P}(V, f, Q, \alpha) = 276.2 - 1.16\, V - 418.2\, f - 1.2\, Q - 1.2\, \alpha + 513.54\, f^{2} + 0.01\, Q^{2} + 0.02\, \alpha^{2} + 3.64\, Vf - 0.026\, VQ + 0.48\, VP \qquad (9)$$

$$Min. F_{r}(V, f, Q, \alpha) = 327.85 - 1.71\, V - 476.5\, f - 1.5\, Q - 1.46\, \alpha + 556.5\, f^{2} + 0.012\, Q^{2} + 0.02\, \alpha^{2} + 4.65\, Vf - 0.03\, VQ + 0.52\, VP \qquad (10)$$

$$Min. R_{a}(V, f, Q, \alpha) = 1.56 - 0.007\, V - 2.21\, f - 0.007\, Q - 0.008\, \alpha + 2.59\, f^{2} + 0.000056\, Q^{2} + 0.0001\, \alpha^{2} + 0.018\, Vf - 0.00013\, VQ + 0.002\, VP \qquad (11)$$

$$Min. R_{max}(V, f, Q, \alpha) = 16.1 - 0.05\, V - 23.0\, f - 0.065\, Q - 0.108\, \alpha - 0.002\, V^{2} + 27.3\, f^{2} + 0.0005\, Q^{2} + 0.0008\, \alpha^{2} + 0.27\, Vf - 0.0015\, VQ + 0.022\, VP \qquad (12)$$

These objective functions are constrained by the following variables bounds:

$$15 \leq V \leq 29 \quad (m/minutes) \qquad (13)$$

$$0.32 \leq f \leq 0.56 \quad (mm/revolution) \qquad (14)$$

$$60 \leq Q \leq \quad (ml/hour) \qquad (15)$$

$$15 \leq \alpha \leq 45 \quad (degrees) \qquad (16)$$

RCGA optimized values of MQLAH process parameters that resulted in minimum microgeometry deviations and flank roughness values are 29 m/min as hob cutter speed, axial 0.324 mm/rev as feed, 98.64 ml/hr as lubricant flow rate and 29.31^{o} as nozzle angle. Their standardized values (i.e. 29 m/min; 0.32 mm/rev; 100 ml/hr; and 30^{o} respectively) were used to conduct the confirmation experiment, and compute optimum values of the responses (F_a, F_β, F_p, F_r, R_a and R_{max}) by RCGA, also predict them using the developed BPNN model. Table 5 presents these values. RCGA computed and BPNN predicted values closely agree with each other and with the results of the confirmation experiment. This validates results of the optimization. DIN quality numbers assigned to the microgeometry parameters of the spur gear manufactured during the confirmation experiment are in the range from 7 to 11.

Table 5. Comparison of RCGA computed and BPNN predicted values of the responses with results of the confirmation experiment.

GA optimized MQLAH parameters				Standardized optimum values				Values of the responses (μm)					
								Computed by RCGA					
V (m/min)	f (mm/rev)	Q (ml/h)	α (deg)	V (m/min)	f (mm/rev)	Q (ml/h)	α (deg)	F_a	F_β	F_p	F_r	R_a	R_{max}
								42.87	7.29	87.56	97.14	0.47	4.28
								Predicted by the BPNN model					
29	0.324	98.64	29.31	29	0.32	100	30	42.13	7.84	86.21	98.23	0.44	4.32
								Values from the confirmation experiment					
								42.25	8.05	88.5	97.9	0.46	4.41

6. Conclusions

This paper reported analysis of the influence of process parameters on micro-geometry and surface roughness of MQLAH manufactured spur gears of 20MnCr5, predictive modelling using BPNN, and parametric optimization using RCGA. The investigation was aimed to find sustainable substitute of conventional flood lubrication assisted hobbing. Following conclusions can be drawn from this work:

- Hob cutter speed, axial feed, lubricant flow rate, and nozzle angle significantly influenced the microgeometry deviations and flank roughness parameters of MQLAH manufactured spur gears. Whereas, air pressure had no considerable effect on them.
- Reductions in gear microgeometry deviations and tooth flank surface roughness were observed with increasing hob cutter speed and lubricant flow rate, whereas increasing axial feed resulted in their higher values.
- There exists an optimum value of MQL nozzle angle as 30 degrees for minimum values of microgeometry deviations and tooth flank surface roughness.

- The developed BPNN architecture has been found to be very accurate in prediction of microgeometry deviations and flank surface roughness of MQLAH manufactured spur gears and showed very close agreement the corresponding experimental values with mean square error of 0.0063.
- RCGA optimized values of MQLAH parameters for simultaneous minimization of deviations in microgeometry and flank roughness are: hob cutter speed as 29 m/min; axial feed as 0.32 mm/rev; lubricant flow rate as 100 ml/hr; and nozzle angle as 30^{o}.
- Confirmation experiment carried out using the optimized values of MQLAH parameters found to have very good closeness with RCGA computed and BPNN predicted values of the microgeometry deviations and flank surface roughness parameters.
- Values of deviations in total profile (42.25 µm), total lead (8.05 µm), total pitch (88.5 µm) and runout (97.9 µm) obtained at optimum parametric levels identified by RCGA gave DIN quality number 11, 7, 10 and 10 respectively which are under the normal quality range obtained by MQLAH with comparatively lesser lubricant consumption.
- This study proves that MQLAH using environment friendly lubricant is a sustainable substitute to conventional fluid lubrication assisted hobbing for manufacturing of cylindrical gears of superior quality.

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